Green Technology Book Energy solutions for climate change

WIPO

In cooperation with our partners

UN Climate Technology Centre & Network

أكاديمية البحث العلمي والتكنولوجيا
Academy of Scientific Research and Technology

Green Technology Book Energy solutions for climate change

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Foreword by WIPO

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The energy transition is for everyone. Technology and innovation are democratizing the process.

Daren Tang, WIPO Director General

Energy is a fundamental aspect of modern life. It powers everything from basic daily needs to complex industrial processes. But this dependency comes at a cost, with rising demand amplifying energy's role as a leading source of the global greenhouse gas emissions accelerating climate change.

In recognition of this, last year at COP28 nations pledged to triple renewable energy capacity and double global energy efficiency by 2030. But despite this commitment, the current adoption rate of renewable energy and its enabling technologies is still insufficient to meet global climate targets. Compounding this challenge, climate change is already affecting energy systems and infrastructure, underscoring the urgent need for adaptive and innovative technologies that build resilience and energy security.

We know what needs to be done – our fossil fuel reliance needs to end, and the deployment and scaling of clean energy technologies ramped up. Addressing the gap between developed and developing countries in technology development and adoption is also crucial, necessitating enhanced international cooperation and more efficient technology transfer.

This year's *Green Technology Book* supports these efforts by serving as a practical guide for policymakers, practitioners, investors, researchers and the public. It offers valuable insights and solutions. Most are already available on the market and all are in the WIPO GREEN Database of Needs and Green Technologies, a comprehensive resource connecting technology seekers and providers featuring 130,000 technologies from over 140 countries – making it the largest green tech platform within the UN system.

Following previous editions, the 3rd edition of the *Green Technology Book* adopts an end-user perspective, focusing on practical technologies for energy use in cities, rural and agricultural areas, as well as service sectors, in particular, supermarkets, healthcare facilities, and data centers. Rising energy demand within these areas and sectors can be met head-on using existing technologies and there are innovative solutions on the horizon.

A key message of this year's edition is that the energy transition is for everyone. Technology and innovation are democratizing the process, enabling different forms of decentralized, renewable energy production and offering a wide range of options for energy efficiency and consumption management. This expanding array of flexible solutions creates numerous opportunities for active participation by cities, utilities, businesses, communities and citizens.

Lastly, we must emphasize that clean energy solutions are important not only for climate mitigation, but also for adaptation and resilience. New technologies strengthen energy systems against climate impacts, while at the same time providing sustainable energy for populations lacking access to energy. They provide a wealth of co-benefits as well, creating jobs, stimulating local economies, improving food security and leading to better health outcomes and general well-being.

I extend my sincere thanks to our partners at the Climate Technology Centre and Network (CTCN) and the Egyptian Academy of Scientific Research and Technology (ARST) for their ongoing collaboration and dedication to advancing climate technology and action.

Foreword by Partners

Climate Technology Centre and Network (CTCN)

This year's *Green Technology Book* focuses on energy technologies and the crucial role of energy efficiency at a time when it is needed most. As we look toward the future, energy efficiency has a crucial role to play in meeting global energy demands and tackling the urgent challenges of climate change.

Over the past decade, about 25 percent of the technical assistance requests made to the CTCN have focused on the energy sector, renewable energy and energy efficiency in particular. This highlights growing global demand for solutions that address rising energy needs while supporting sustainable development. For example, in the Bahamas, the CTCN supported grid stability assessments to enhance renewable energy integration. Within the Southern African Development Community, it helped establish Minimum Energy Performance Standards, so that households and utilities could transition to energy-efficient technologies. The CTCN has also supported the development of energy efficiency master plans in Tonga; energy-efficient building codes in Kyrgyzstan; and initiatives like biogas production in Mauritius and solar energy engagement for youth in Timor-Leste.

These and many other projects demonstrate energy efficiency technologies deliver significant benefits. They include reduced energy consumption, enhanced energy security and more equitable access to energy resources.

This edition of WIPO's *Green Technology Book* explores the key areas of cities, rural energy and the services sector. It illustrates how technology and innovation can accelerate the energy transition and provides actionable insights on integrating energy efficiency technologies, from individual households to major utilities.

With COP29 on the horizon, this publication highlights the critical role of technological innovation in meeting global climate objectives. It serves as a valuable resource for a broad range of stakeholders seeking clear information and insights into technological solutions within the energy sector.

Jonathan Duwyn, Officer in Charge of the CTCN

Academy of Scientific Research & Technology (ASRT), Egypt

We are living in an era when the consequences of climate change are no longer a distant threat but a present reality. The need for innovative and actionable solutions has therefore never been more critical than it is now. The WIPO *Green Technology Book* continues to be an indispensable resource in this global endeavor, providing a platform for the exchange of technologies that can mitigate and adapt to a rapidly changing environment. Egypt – one of the countries most vulnerable to climate change – is proud to stand alongside WIPO in this vital initiative.

The 2024 edition of the *Green Technology Book* is particularly significant in its zeroing in on the energy sector, a domain that is both vast and essential to the fight against climate change. This edition takes an end-user-oriented approach. It focuses on tangible energy-related technologies that can be immediately implemented to address climate change mitigation and adaptation. From rural communities adopting bio-energy and solar solutions to industries optimizing heating, cooling and transport through innovative technologies, this edition offers practical insights and tools to drive sustainable change.

As we face a future where energy needs and environmental concerns are increasingly intertwined, this edition provides a roadmap for how energy technology can be harnessed to create sustainable, resilient communities. Whether it is through renewable-powered farming technologies, energy-efficient household appliances or advanced waste-to-energy systems, the *Green Technology Book* for 2024 showcases the diversity of solutions available to address one of the most pressing challenges of our time.

I would like to express my deepest gratitude to WIPO, our partners, and all contributors who have made this edition possible. The collaboration between nations, organizations and individuals is the cornerstone of progress in the fight against climate change. By sharing knowledge, fostering innovation and accelerating technology transfer, we can collectively create a more sustainable future.

Egypt remains committed to supporting the *Green Technology Book* and to advancing global efforts toward a cleaner, greener and more equitable world. We invite all WIPO Member States and stakeholders to contribute their green technologies and innovations to this shared endeavor. Together, we can make a profound impact on this planet that we all share.

Professor Gina El-Feky, ASRT President

Acknowledgments

We are pleased to present the third edition of the WIPO *Green Technology Book*, putting the spotlight on energy technologies in essential areas of our lives. This edition has been made possible through the collective efforts and contributions of numerous individuals and organizations. We extend our heartfelt gratitude to all those who have supported this project.

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Acronyms

°C	degree Celsius
AC	air conditioner
AC	alternating current
AD	anaerobic digestion
AI	artificial intelligence
API	application programming interface
AST	automated storage tiering
BESS	battery energy storage system
BLDC	brushless direct current
BRT	bus rapid transit
CAV	connected autonomous vehicle
CCA	Clean Cooking Alliance
CFC	chlorofluorocarbon
CFL	compact fluorescent lamp
CHP	combined heat and power
CO_2eq	carbon dioxide equivalent
COP	(United Nations) Conference of Parties
DC	direct current
DER	decentralized energy resources
EPC	electric pressure cooker
ESCO	energy service company
EU	European Union
EV	electric vehicle
FAO	Food and Agriculture Organization (of the United Nations)
FESS	flywheel energy storage system
GGHH	Global Green and Healthy Hospitals
GHG	greenhouse gas
GIS	geographical information system
GPS	global positioning system
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HRES	hybrid renewable energy sources
HVAC	heating, ventilation and air conditioning
HVLS	high-volume low-speed
ICE	internal combustion engine
ICS	improved cookstove
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPCC	Intergovernmental Panel on Climate Change
IPF	international patent families
IoT	internet of things
ITS	intelligent transport system
LCE	low-carbon energy
LED	light-emitting diode
LFP	lithium iron phosphate (LiFePO4)

lm/W	lumens per watt
LPG	liquefied propane gas
MEPS	Minimum Energy Performance Standards
MPPT	maximum power point tracking
MRI	magnetic resonance imaging
NRW	non-revenue water
PEF	pulsed electric fields
PM	permanent magnet
PUE	power usage effectiveness
PV	photovoltaics
SDG	sustainable development goal
SHS	solar home system
SSA	sub-Saharan Africa
TRU	transport refrigeration unit
ULT	ultra-low temperature
UPS	uninterrupted power supply
UV	ultraviolet
VAV	variable air volume
VMM	virtual machine monitor
VPP	virtual power plant
VRF	variable refrigerant flow
VSD	variable speed drive
WFP	(United Nations) World Food Programme
WHO	World Health Organization

Executive summary

Technologies that curb energy demand offer a pragmatic approach to climate change

At COP28 in 2023, nations made a commitment to tripling renewable energy capacity and doubling global energy efficiency improvements by 2030, placing energy efficiency at the forefront of policy decisions. Despite an overall increase in global climate finance, energy efficiency investments are lagging behind (CPI, 2023a). There also remains a significant disparity in the development and uptake of low-carbon energy technologies between developed and developing countries. To bridge this gap, enhanced international cooperation and efficient technology transfer are essential. Consumers – prosumers, in particular – are playing an increasingly active role in clean energy adoption. But structural changes in policy and investment are needed to support broader and more equitable access to energy-efficient technologies and decentralized renewable energy production.

For so long as fossil fuel reliance persists, energy efficiency offers a pragmatic and universally beneficial contribution to the energy transition. Renewable energy production is the major solution to phasing out fossil fuels. But it also presents challenges, for example, land use conflicts, supply chain issues and waste management. Investing in energy efficiency and demand management represents a no-regret strategy that reduces energy consumption. Energy efficiency technologies and practices can be seamlessly integrated at all levels, from individual households to large-scale utilities. Moreover, energy efficiency measures enhance energy security by reducing dependence on imported fuels and increasing the resilience of energy systems faced by fluctuations in supply and demand.

End-use and enabling technologies leading clean energy technology innovation

Analyzing energy patent trends, while not necessarily indicative of market demand or commercial success, offers valuable insights into technological advancements and industry directions. Recent patent trends are dominated by enabling technologies such as batteries, hydrogen, smart grids and carbon capture, reflecting a broader focus on end-use solutions and decentralized energy systems. Clean energy innovations have witnessed a remarkable growth over the years, with solar leading the increase in renewable energy patent filings (WIPO, 2023). However, renewables represent less than a fifth of all clean energy innovation. Transportation is important in low carbon energy patents, particularly in relation to electric vehicles and charging technologies. Regionally, Europe, Japan and the United States have been dominant in patent filings, but China now leads in several sectors, highlighting a global shift in innovation leadership. In this third edition of the Green Technology Book, we showcase several of the most significant energy technology innovations within key segments of society, namely:

- urban
- rural
- essential services.

Making city energy use smarter

Cities are major hubs of energy consumption and have a pivotal role to play in the energy transition. The adoption of electric buses and autonomous vehicles presents opportunities for reducing fuel consumption, although challenges such as high initial costs and public acceptance persist. Innovations in the energy efficiency of buildings, renewable energy integration in public spaces and the urban water–energy nexus are also essential for the urban energy transition. Promising case studies – for example, Senegal's electric bus rapid transit system and London's Underground waste heat recovery project – illustrate technology's potential to create more sustainable urban environments when addressing socioeconomic inequalities.

However, effective energy management begins at the design stage, emphasizing the creation of dense, walkable cities, as well as well-insulated private and commercial buildings that take advantage of passive design principles. This serves to curb energy demand, by reducing dependency on transport fuel and energy-consuming heating and cooling technologies. Designing energy efficient cities brings numerous long-term cost-and-energy savings. Cities at the forefront are further optimizing energy and fuel use at various levels through automated and interconnected digital solutions such as intelligent traffic systems and smart streetlights. Yet, many growing cities fail to capitalize on this opportunity at the outset. Furthermore, the capacity to implement such measures – and adopt solutions that manage cities' energy demand, from households to end-use sectors – varies significantly across cities worldwide.

Optimizing heating, cooling and water use to meet rising demand

Heating and cooling account for the majority of household energy use. This highlights the importance of technologies like efficient heating systems, solar thermal collectors and smart appliances. Moreover, the integration of water and energy management is essential, because domestic hot water can account for a significant proportion of household energy use. Growing market for energy-efficient and water-saving appliances, coupled with supportive legislation and consumer awareness, offers opportunities to reduce energy expenditure and emissions. While minimum energy performance standards and labels have a proven impact on technology adoption, coverage has yet to extend to all countries and types of appliances.

As communities have started to explore decentralized energy production, so the concept of "prosumers" – households that both consume and produce energy – has emerged. Enabled by technology, it empowers residents to engage actively in the energy transition through collective initiatives. This consumer willingness play an active role is further evidenced by the large growth in household spending on climate mitigation solutions, largely driven by expenditure on electric vehicles, followed by residential solar PV, solar water heaters and home retrofits for energy efficiency.

Water utilities are coming under increasing pressure, because of dwindling water supplies exacerbated by climate change, while at the same time accounting for about 4 percent of global electricity consumption. Outdated infrastructure significantly contributes to this energy intensity. But technological advances such as efficient pumps, advanced aeration methods and smart water management systems offer opportunities to reduce energy consumption. The integration of digital technologies like smart meters and AI is gaining traction, including in the Global South. These facilitate real-time monitoring and optimization of water distribution. Furthermore, wastewater treatment plants are being explored as potential energy recovery facilities through anaerobic digestion and biogas production. Emerging technologies such as microbial fuel cells and heat recovery systems, alongside more energy-efficient desalination processes, are also poised to enhance efficiency within the water sector. This is increasingly essential as the demand for water rises in the face of climate change impacts.

Renewable energy solutions overcome rural energy challenges

Rural and remote communities face unique energy access challenges due to low population density, high capital investment and technical difficulties. Extending the electric grid to these areas is often costly. Off-grid solutions have up until now relied on fossil fuels, while household energy use in rural areas often relies on inefficient biomass fuels and kerosene, both of which contribute to greenhouse gas (GHG) emissions. Advances in renewable energy technologies, like solar and wind, and innovations in energy storage and energy efficiency are crucial to addressing this problem.

Mini- and micro-grids powered by renewables are emerging as cost-effective solutions for developing and developed countries alike. Decentralized solutions such as renewable-powered mini-grids and community-centric models are increasingly common. Advanced technologies like improved solar PV cells, battery storage and AI-powered control systems enhance energy management. Meanwhile innovations in microgrids, swarm electrification, small-scale hydropower, and solar and waste-to-energy technologies support rural development and climate resilience. Solar home and hybrid systems are effective for off-grid areas. Meanwhile clean cooking technologies and waste-to-energy solutions also offer opportunities to reduce energy consumption, while also capturing other significant benefits, such as improved health, air quality, reduced deforestation, and waste management.

Greening agriculture with energy efficiency innovations

Agriculture significantly impacts climate change through GHG emissions, in part from energy use. A new green revolution will need to maximize the use of technologies already available to green production and also feed a growing global population. Innovations such as agrivoltaics (solar panels combined with crops) and aquavoltaics (solar panels integrated with aquaculture) can contribute to both mitigation and adaptation, through co-locating panels for both renewable energy and crop production. Energy-efficient practices and technologies such as precision agriculture, solar-powered irrigation, electrified machinery, farm management software, and Internet of things (IoT) sensors help reduce emissions, conserve water and save energy. Innovative financing models such as pay-as-you-go, leasing and cooperative models, are important for both rural populations and farmers to be able to access and adopt these technologies.

Post-harvest processing and storage have proven highly energy intensive. Food loss and waste contribute significantly to GHG emissions, with about 30 percent of produced food lost or wasted, especially in low- and middle-income countries. Technological innovation like solar-powered and energy-efficient dryers can address energy demand as well as post-harvest losses, though access to such technologies is often limited for smallholder farmers. Energy efficient technologies for dairy processing, drying, milling, grain storage and renewable energy sources can mitigate energy demand. Innovations in cold chain logistics, packaging and refrigeration are essential for addressing energy consumption, halting food loss and reducing emissions.

Importantly, clean rural energy technologies are tools for adaptation as well as mitigation. They strengthen resilience to grid outages and disruption caused by climate change impacts; provide rural electrification access to underserved areas; and ensure a reliable energy supply in the face of climate-related challenges. The technologies here presented can bring a wide range of adaptation and resilience benefits to rural populations, including energy security and independence, improved air quality, health, economic standards and quality of life.

Often overlooked energy-consumers

Supermarkets, as significant energy consumers, present unique challenges and opportunities for energy efficiency and sustainability. Originating in the United States and Europe in the early 20th century and expanding globally, supermarkets utilize economies of scale to offer diverse products, but face high energy demands for refrigeration, lighting and temperature control. These demands, coupled with food waste and refrigerant emissions, amplify their environmental impact. The sector’s energy intensity, particularly in smaller stores, underscores the need for energy-efficient technologies. Advances in transcritical CO_2 refrigeration systems, efficient and automated HVAC systems, heat recovery and on-site renewable energy production can all drastically reduce energy consumption and emissions.

Health care facilities are crucial for patient care, but have significant environmental impacts that are often overlooked. These facilities also have high energy use intensity due to their round-the-clock operations, particularly with respect to HVAC systems, lighting and medical equipment. Moreover, they are vulnerable to extreme weather and power outages, which could threaten patient care, necessitating resilient energy infrastructure. Global initiatives such as Healthcare Without Harm are promoting greener hospitals through voluntary sustainability reporting, coordinated action and knowledge sharing on best practice measures. Efficient HVAC, lighting and decentralized energy systems, including solar and combined heat and power, are vital for reducing emissions and enhancing energy security. Technologies like adaptive ventilation systems, efficient medical freezers and MRI machines, and automated LED lighting are key to these efforts, alongside addressing standby power consumption.

Data centers – a critical infrastructure so essential for our digital lives – consume significant energy and water, raising concerns about their negative impact. While data also underpins many modern climate solutions, from climate forecasting to precision farming, the net impact of data usage on the climate is not commonly understood. The section on data centers examines innovative solutions to reduce their energy consumption and cooling needs. As the demand for data grows, particularly with the rise of AI, solutions such as on-site renewable energy generation and green hydrogen back-up power become crucial. The geographical location of data centers affects their climate impact, with areas rich in green electricity and cool climates attracting cloud computing facilities. Various strategies, including virtualization, load balancing and the use of energy-efficient hardware and software, improve efficiency and climate resilience. Meanwhile innovations in cooling technologies – for example, immersion cooling and free cooling – help optimize temperature management. Additionally, waste heat recovery systems are increasingly being explored for repurposing excess heat for local energy needs. Technological innovations developed for data center operations in particular are readily available and their adoption is vital for minimizing the climate impact of rising global data consumption.

Key messages

The energy transition is for everyone

Technology and innovation are driving the democratization of the energy transition by enabling decentralized energy production, enhancing grid flexibility and offering a wide range of energy efficiency and demand-side management solutions for households, communities, utilities, cities and businesses. Energy-efficient appliances, smart thermostats and IoT devices empower consumers to optimize energy use, reduce consumption and lower costs, making sustainable practices more accessible. By enabling consumers and end-users to actively generate, store and/or manage their own energy – complementing large-scale energy infrastructure investments – these advancements foster greater energy independence and resilience across all sectors.

Energy services becoming more important than supply

The energy transition marks a new era for energy security that revolves around energy services rather than energy commodities. Technologies will be more important than fuels. In the past, energy security was addressed in large part through supply-side measures, whereas managing energy demand was considered less important. The geopolitical landscape will shift toward more localized energy dependency, with nations relying primarily on regional sources and having a reduced need for distant fossil fuel imports. Global connections will persist through shared clean technology markets and supply chains. Increasing focus will be on developing countries and their access to technologies, financing and intellectual property knowledge. Centralized systems will give way to more decentralized solutions that engage consumers. Environmental, sustainability and climate resilience impacts – including energy source diversification – will be increasingly incorporated into planning and investment.

Macroeconomic advantages of green energy transition

Most countries have renewable resources they can harness for energy security and independence, reducing the need for imported fuels and exposure to volatile fossil fuel prices. The energy transition will provide opportunities for developing countries which often lack domestic fuel reserves and stand to benefit from maximizing the use of renewable energy resources. Renewable technologies may not provide absolute energy independence, but they do allow countries to enhance energy security and resilience by using their own resource advantages. Countries that are heavily dependent on imports of oil, gas or coal will have the possibility of leapfrogging fossil fuel-based systems and national grids. Technologies that enhance energy access in developing countries (e.g., off-grid, hybrid, decentralized energy resources) can often be more cost-effective than fossil fuels in the long run. Countries can save roughly USD 156 billion in costs through using renewable energy sources (IRENA, 2022). A solar home system (SHS) often has lower upfront costs compared to investing in a fossil fuel-based system or extending traditional grid infrastructure. Moreover, local and decentralized systems like SHS and microgrids can be deployed quickly compared to centralized fossil fuel infrastructure, and moreover can be more resilient to disruptions and natural disasters. Technologies can be tailored to local resources (e.g., small-scale hydropower in river areas) to increase practicality and sustainability. Governments and international organizations may move from fossil fuel subsidies to offering subsidies, grants or incentives for renewable energy projects, reducing cost burdens. The deployment and maintenance of renewable energy technologies can create local jobs and foster local entrepreneurship, and drive the development of small and medium-sized enterprises.

Decentralized renewable energy infrastructures enhance flexibility and diversity of energy access

Decentralized renewable energy infrastructure is an increasingly attractive option for electrification of off-grid rural areas. It can help meet climate mitigation and adaptation goals, provide access to clean and reliable energy in underserviced areas, and cater to a growing preference in emerging and developed economies alike for energy flexibility and independence. Off-grid electrification systems are available based on various technologies and designs, increasing their flexibility and adaptability to local conditions. Smart grids use digital technologies, sensors and smart meters to monitor the flow of electricity. They track usage patterns, adjust grid load according to demand, and reduce energy losses by detecting and addressing inefficiencies within the grid quickly. They facilitate the integration of decentralized renewable energy sources by managing variable output and coordinating with other grid resources. This is vital to enhancing the grid's resilience to disruptions and extreme weather events, thereby contributing to climate change adaptation. Microgrids, which can function independently of the main grid, are vital to the energy transition in rural communities, stimulating uptake of renewables while providing energy security, affordability and resilience.

New, efficient and cheaper energy storage solutions spread renewable energy solutions everywhere

As the use of decentralized renewable energy sources increases, balancing intermittent energy production becomes crucial to excess energy storage. Modern lithium-ion battery costs have decreased substantially in recent years, with batteries exhibiting improved energy density, longer lifespans and greater efficiency. Innovations in energy storage technologies have been on the rise, including flow batteries, pumped hydro storage, flywheel storage, and gravity storage exploiting gravitational potential energy, which is especially useful in rural and off-grid areas. However, energy storage needs to expand substantially to fulfil the COP28 pledge of tripling global renewable energy capacity by 2030 while at the same time maintaining electricity security.

Future global food demand must be met through new green solutions, not by business-as-usual

Renewable energy and energy efficiency are both central to feeding a growing population sustainably. Ironically, past innovation aimed at improving agricultural productivity has contributed to soil degradation, biodiversity loss, water pollution and greenhouse gas (GHG) emissions. During the first green revolution, machines increased productivity and drove an exponential rise in fertilizer and pesticide production that continues into the present day. But a new green revolution is underway, with many technologies currently available enhancing the sustainability of agricultural operations both on the farm and throughout post-harvest processing and storage. On-farm innovations include electric farm machinery, solar-powered pumps and incubators, energy-efficient livestock and greenhouse ventilation, renewable-powered aeration for aquaculture, and agrivoltaics systems producing both renewable energy and food. Drying technologies use less energy by adjusting air flow and using moisture sensors. Cold storage innovations are using solar power, electric transport units, advanced energy-efficient refrigeration technologies, smart monitoring and control systems, and alternative refrigerants with fewer climate impacts.

Energy efficiency and demand-side management is crucial for slowing the trend of growing energy consumption

Investing in energy efficiency is crucial for the energy transition. Although there is considerable patenting activity for energy efficiency and enabling low-carbon energy technologies in high-income countries, such investments remain significantly underfunded within the context of international climate finance. While renewable energy investments are essential, their current rate of penetration alone is insufficient to effectively combat climate change on a global scale. Continued reliance on fossil fuels, coupled with persistent national subsidies and the rapid growth of global energy demand, underscores an urgent need for progressive policies and innovative technologies that reduce energy consumption, increase energy recovery and introduce new ways of using appliances and goods. Emphasizing supply-side solutions while overlooking energy efficiency could lead to deeper challenges, including the need to secure sustainable raw material supply chains and mitigate land grabs that exacerbate social inequalities.

Look out for potential rebound effects and trade-offs from low-carbon energy technology investments

As evidenced throughout the chapters, investment in renewable energy, energy efficiency and demand management can cause unintended negative consequences and rebound effects. Examples include telecommuting which may reduce travel but also increases home energy consumption; electric vehicles and mobility-as-a-service (MaaS) solutions that risk replacing public transport and altering cycling patterns; and LED streetlights that affect urban fauna. The rebound effect of energy efficiency investment is better known, in which cost savings lead consumers to use more energy. Furthermore, there is the risk that decentralized energy investments and policies to enable more renewable energy “prosumers” are promoted at the expense of strengthening and greening national grid infrastructure. These trade-offs must be better researched and understood so as to mitigate harm and avoid reducing the expected gains from low-carbon energy investment.

Risk of stranded assets is not limited to fossil fuel infrastructure

The risk of a new form of stranded energy asset is real. There is the potential for rapid technological advancements to render existing renewable energy assets or infrastructure outdated. Like conventional vehicles and energy-inefficient buildings, early generation solar panels will become obsolete. Older wind turbines with lower efficiency, smaller capacity and less advanced control systems may be replaced by newer models that offer higher capacity, better performance and advanced blade design. Older battery storage systems may be rendered obsolete by newer technologies like lithium-ion or solid-state batteries that offer better energy density, longer life and faster charging. Ensuing negative impacts include excess waste, increased installation and upgrade costs, and declining value of renewable energy investments over time that in turn force earlier replacement. Though waste from renewables is projected to comprise a small fraction of total global waste in the future (compared to plastic waste, municipal waste, coal ash and e-waste), research and investment into advanced reuse and recycling programs and circular solutions for PV modules are imperative. This also brings the role of retrofits to the fore. Instead of manufacturing entirely new assets, retrofitting could be exploited further – for buildings, vehicles and industry. Retrofits not only save energy and material use, but can create new jobs, improve employee productivity and raise asset values.

Innovative technologies enable new energy solutions in challenging conditions

Recent advancements in low-carbon energy technologies are expanding their applicability worldwide, even in extreme climates. Innovations in electric vehicle batteries, for example, can enable advanced air heating and cooling systems, improved thermal management and new battery chemistry that allows electric buses to operate in cold northern regions. Solar panels are now designed with better efficiency in low-light conditions. New battery charging solutions are also making it possible to charge vehicles in those urban centers with weak grid systems. Additionally, sub-critical CO_2 cooling systems, which have been effective in saving energy in supermarkets within Europe, can now function efficiently in warmer climates thanks to improved system design. Furthermore, heat pumps – traditionally most effective in temperate climates – have also undergone significant improvement, enabling them to provide heating and cooling during severe winters and hot summers. These innovations mark significant milestones in the global energy transition, enabling widespread adoption of solutions regardless of location. Modular technologies provide increased flexibility and accessibility for households. They include modular anaerobic digesters for domestic use and pico (very small) solar home systems that can be installed in small expandable units, making it easier to build up a system over time. These innovations are the output of effective innovation ecosystems. Intellectual property rights are a cornerstone of a well-functioning innovation ecosystem and enable technology transfer, not only from laboratory to market but between markets.

Innovative financing models trigger adoption of energy technologies in low-income areas

Innovative financing models, such as pay-as-you-go (PAYG), energy-as-a-service (EaaS), microgrid-as-a-service, and software-as-a-service, are transforming access by making clean technologies more affordable and scalable in underserved areas. They reduce the upfront capital required for adopting clean technologies. PAYG models allow users to pay in small, manageable installments, lowering financial barriers and enabling a more rapid scale-up across diverse regions. They often include performance guarantees and maintenance services, which reduce the financial risk for consumers. Similarly, leasing and cooperative arrangements for energy-efficient farm equipment provide farmers with flexible, cost-effective solutions, enabling them to adopt advanced technologies without the burden of large upfront investments. Innovative programs are increasingly offering grants, rebates, incentives and low-cost financing for agricultural producers and rural small businesses to install renewable energy systems and make energy efficiency improvements.

Untapped potential for energy recovery

Innovation enables energy to be harvested from sources so far overlooked. More waste management utilities are looking at making use of organic content through anaerobic digestion, combined heat and power (CHP), and other means of on-site energy production such as emerging microbial fuel cell technology. In cities, experiments are underway into using kinetic energy harvesting to recover energy from pedestrian traffic movement, or flat absorber lines to absorb urban heat. In rural areas, the use of compact and modular anaerobic digesters designed for smaller-scale farms and communities is gaining momentum, not only generating renewable energy but also contributing to waste management. And there are successful examples of how supermarkets have turned into energy suppliers, by recovering heat generated by cooling display cases and freezers.

More innovation needed in emerging energy-consuming sectors

Large emerging sectors introduce new uncertainties regarding future energy consumption – innovation must be directed toward addressing their energy consumption. Electrification of end uses will transform energy consumption patterns. The technical challenges, costs, and environmental and social facets of modernizing infrastructure should be addressed from the start. For instance, data centers, which could see their electricity demand double by 2026, is one such sector covered in this publication. Similarly, desalination is expected to be the main contributor to the water sector's growing energy consumption as climate change further inhibits access to freshwater. Electric refrigeration systems used in transport vehicles to cool or freeze cargo are greatly needed within an expanding global supply chain. And considerable additional efforts are required to attract investment into renewables and grid expansion in less affluent countries, where certain areas are lagging because of ongoing investment and international support deficiencies.

Clean energy technologies also important for enhancing adaptation and resilience

Renewable energy and energy efficiency technologies bolster energy systems against the physical impacts of climate. This happens in several ways. They integrate different renewable energy sources and thus enhance grid resilience, increase flexibility and provide more options for managing extreme weather events. They also may reduce dependence on vulnerable infrastructure. And smart grid technologies and energy storage systems improve the grid's ability to manage and respond to disruptions. Investing in renewable energy can stimulate local economies and create jobs, which again increases local peoples' resilience to climate induced disruptions. Agrivoltaics optimize land use, so as to produce both energy and crops. This is especially important in those areas where agricultural land is under pressure from climate impacts and urbanization. Aquavoltaics, the integration of solar PV systems with water bodies, benefits off-grid remote fishing and aquaculture communities struggling with high fuel costs while also meeting food security needs.

Introduction and methodology

The *Green Technology Book* for 2024 presents an assessment of the global state of energy innovation for climate change. By showcasing concrete examples of technologies, we aim to make the energy transition debate tangible and inspire direct action. For this reason, the chapters are designed to target very specific end-user groups, ranging from individual household owners to supermarket chains and water utilities.

The *Green Technology Book* can be considered a climate technology catalogue meant for inspiration, but also a living project to which everyone can contribute. The publication links to the free public WIPO GREEN database of Needs and Green Technologies, where users can create a profile and share their particular climate solutions and needs. All solutions related to the *Green Technology Book* can be found in the dedicated *Green Technology Book* Collection in the database.

This year, energy solutions for climate change take center stage.

We provide insights and inspiration on how innovation and technology can contribute to transforming the way we extract, store, convert and use energy as part of the fight against climate change. We address both mitigation and adaptation aspects, as well as the many solutions that bridge the gap between the two. The energy innovation and technology field is too vast and diverse to fit into a single *Green Technology Book* edition. Hence, as reflected in the chapter titles, we have made pragmatic choices in terms of the focus area, with a view to addressing key segments of society and remaining as relevant as possible for end-users in both developed and developing countries.

We highlight technologies that address the water–energy nexus, where closed-loop solutions, water conservation and energy recovery are offering important opportunities for innovation in water utilities. Supermarkets, a sector thus far lacking in coordinated guidance on best practice and standards for climate mitigation and adaptation, has nonetheless seen numerous new low-carbon innovations specifically adapted for its use. We also take a look at the climate impact of health care facilities, a sector which itself is highly impacted by climate change. And as regards data centers, the growing need for cooling the servers that handle our ever-intensifying need for data has spurred innovation that makes use of both artificial and natural elements.

This year's publication also considers the role of individuals and communities in the energy transition. From household appliances to solutions that enable decentralized clean energy production, technology is enabling a form of democratization of the energy transition, by empowering consumers and end-users to take an active role. While the responsibility for responding to climate change should not be placed solely on individuals, it is clear that there is no reason to sit idle in wait for government action and large-scale energy infrastructure investments.

Action is also being taken within the agricultural sector, which is otherwise most often considered in terms of its vulnerability to climate change. Recognizing the energy footprint from agriculture – "from farm to fork" – technology offers opportunities to reduce fossil fuel reliance and increase energy efficiency on the farm and in post-harvest processing and storage. Recent advances are available across a range of farm sizes and operations, alongside innovative financing options that enable farmers to adopt technologies otherwise overlooked.

These technologies are creating a more sustainable agrifood system to feed a growing global population.

We hope that you will be inspired by the creativity, ingenuity and diversity of the technologies that we have chosen to present. And by this publication showing that there is already available a rich diversity of technologies needed to seriously accelerate the energy transition – at all levels of society.

How we wrote the book

For the purposes of this publication, we considered a broad set of scientific articles and gray literature, as well as technology databases and webpages developed by private, public and civil society entities and organizations. Search strings included broad terms related to climate mitigation and adaptation paired with key terms for the three thematic areas, as well as key terms related to specific technologies ("efficient water pumps," "immersion cooling," "solar home systems" and so on). Translation engines enabled us to search articles in several languages to ensure a broad geographical spread.

Owners of the technologies identified were contacted, and all technologies uploaded to the WIPO GREEN Database of Needs and Green Technologies, either by the owner or by us.

How we found the technologies

Throughout the publication, we operate with three concepts: innovation, solution and technology. Although sometimes used almost interchangeably, they do have different meanings.

Innovation is utilized as a term to cover all intellectual creativity that can result in a solution.

Solution broadly means to deploy the output of this innovation to solve a specific challenge.

Technology is a broad term, but we apply it more narrowly to any physical entity or technique, with or without additional equipment, that is deployed to resolve a specific challenge.

We are primarily interested in a technology's potential for mitigating and adapting to impacts from climate change. We therefore cover technologies broadly, ranging from the very simple to the highly complex. Often the scope of climate technologies is expanded to include enabling mechanisms such as ownership and institutional arrangements that pertain to the technology in question (e.g., building codes or energy management systems). While recognizing the importance of such mechanisms, we focus primarily on tangible technologies or actual techniques.

It is important to emphasize that the technologies presented here have not been tested or in any way vetted by WIPO, and that we rely on publicly available material. Inclusion in the *Green Technology Book* is therefore not a recommendation of a particular technology. Technologies presented here should be seen as examples of a technology area, of which there may be many similar offerings which to our knowledge are in no way inferior. Photos illustrating the technologies are used with permission from the technology owners. Where permission could not be obtained, we instead use relevant stock-photos. Photos of technologies may therefore not represent the actual technology in question.

The appropriateness of a technology is often highly context-specific and relates to factors other than geographical location. Therefore, no recommendations on where, when or how the technologies might be suitable are provided. Such an assessment should always be made with the involvement of local experts and stakeholders. Technology owners can freely upload their technology to the WIPO GREEN Database of Needs and Green Technologies and thereby become part of the project.

The following criteria were used when selecting technologies for the *Green Technology Book*:

– relevance for **climate change mitigation and adaptation**
– relevance for the three **thematic areas**: urban, rural and essential services (food retail, health and data).

These technologies should pertain to:

– a product or service **available for purchase or licensing**
– a product or service available for **free/open source**
– a **guidebook** on application of a method or technique
– a **research project** or similar (for horizon technologies).

In addition, the following factors were taken into consideration:

– **anticipated impact** from implementation
– availability of **sufficient quality information** or **third-party endorsements**
– **market availability** (for proven and frontier technologies)
– **cost** in relation to impact
– **geographical balance**
– **business balance** (large- and small-scale businesses, start-ups, research teams, non-governmental organizations and so on)
– **no-harm** principle.

We have divided technologies into three broad groups in order to indicate their maturity and availability.

Proven technologies have been on the market for some time and therefore rely on a tried and tested concept.

Frontier technologies are available, but still relatively new, and as such possibly less validated within a real-world setting.

Horizon technologies are those new concepts being developed and expected to become available within a few years' time; that is to say, technologies that are realistic and likely to become available very soon.

When presenting technologies, we have included a few classifiers as an easy guide to relevance for a reader. We have aimed for a broad representation of technologies at various stages of complexity and readiness. We classify technologies as either of a low, medium or high level of complexity. This is an indication only, and does not follow a strict definition of complexity. It reflects the relative level of human, material and monetary resources required to implement the solution.

Meanwhile, technology maturity was broadly assessed according to the standard Technology Readiness Level (TRL) definition. According to this measure, horizon technologies have the lowest readiness level, but are still close to full development (TRL 3–6), whereas proven and frontier technologies are validated and ready to be scaled-up if this has not already been done (TLR 7–9).

Many more relevant technologies can be found and added to the *Green Technology Book* Collection in the WIPO GREEN Database of Needs and Green Technologies. We welcome feedback and suggestions. These can be sent to us through the WIPO GREEN website.

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1. Green energy solutions for climate action

Renewable energy is essential for limiting global temperature rise to below 1.5°C, yet the adoption of renewable sources and enabling technologies is not progressing fast enough to meet targets. Innovations focused on electrification, energy efficiency, and demand management will also be critical in curbing rising energy consumption. While developing countries face challenges in accessing technology and financing, they may also have a unique opportunity to build more sustainable energy systems from the ground up.

The era of fossil fuels is over. The United Nations Conference of Parties (COP) 28 (2023) closed with an agreement officially marking the beginning of its conclusion and paving the way for a rapid energy transition. The world's first "global stocktake" called on 200 Parties to shift away from fossil fuels with the goal of maintaining the global temperature limit of 1.5 degrees Celsius, largely through the tripling of renewable energy capacity and doubling of energy efficiency improvements by 2030, while speeding the phase-down of coal power and fossil fuel subsidies. This sets a critical benchmark for accelerating climate action, emphasizing the urgent need to scale up renewable energy and energy efficiency deployment. Assuming that countries meet their shared climate goals, no new fossil fuel extraction projects are needed to meet the energy demands implied by the 1.5°C scenario of the Paris Agreement (Green *et al.*, 2024). This chapter outlines some of the low-carbon energy technology trends identified in this year's *Green Technology Book*. It also highlights advancements in international cooperation, climate finance and innovation activity essential for driving the energy transition.

Energy technologies beyond renewable energy

Ambitious commitments to renewables alone won't get us there

Renewable energy remains a critical enabler for keeping the average global temperature rise below 1.5°C. Innovations in solar photovoltaics (PVs), wind and battery technologies have enhanced energy conversion efficiencies and reduced costs. While countries are accelerating the share of renewables in the world through large-scale infrastructure investments and grid integration, numerous technological advances have enabled sub-national actors to partake in this energy transition. This publication explores some of these actors and end-use sectors, for which renewable energy technologies are both viable and meaningful alternatives to fossil fuels, now and in the future.

To name a few, hospitals and supermarkets can access reliable electricity at lower costs through hybrid power systems that combine renewable energy with conventional energy sources (Lazo *et al.*, 2023); urban municipalities are exploring building-integrated solar PVs and installations on novel surfaces; and data centers together with energy companies are developing green hydrogen-powered back-up generators that could potentially double as a renewable power bank that enhances the resilience of the electric grid.

Technologies such as smart meters and energy storage systems are enabling energy communities to come together and implement decentralized renewable energy systems in both cities and rural areas as "prosumers." Further, more and more rural communities are relying on solutions such as solar home systems, solar powered irrigation and community biogas to serve their energy needs, while mini- and micro-grids contribute to green electrification targets even in the most remote locations.

In 2022, the share of renewable energy from solar, wind, hydro, geothermal and ocean reached a record 5.5 percent of the total global energy supply. At the same time, the emission intensity of the power sector is expected to fall at an unprecedented rate in the next few years (IEA, 2024f).

However, renewable energy sources and their enabling technologies are still not accelerating at the pace needed to achieve global Net Zero emission targets (IEA, 2024f). Further, they bring about their own set of negative impacts which must be mitigated. For example, to stay below a 2°C temperature rise by 2050, we will need over 3 billion metric tonnes of energy transition minerals and metals for wind power, solar and more (International Resource Panel, 2024). In addition, global energy demand is steadily increasing, with emerging economies as engines of growth (BP, 2022). In 2021, primary energy consumption – meaning energy demand – experienced the largest increase in history (IEA, 2024c), and only 60 percent of the growth in electricity demand in the last decade has been met by modern renewables (REN21, 2023). Climate change impacts are further exacerbating this challenge, with the use of air conditioners expected to be one of the top drivers of global electricity demand (IEA, 2018a).

Renewable energy sources and their enabling technologies are still not accelerating at the pace needed to achieve global Net Zero emission targets

Against this backdrop, and despite more ambitious climate commitments, the demand for fossil fuels remains relatively unchanged (IEA, 2023l; BP, 2022). Further, emerging sectors introduce new uncertainties regarding future energy needs. Data centers – a sector which could see its electricity demand double by 2026 (IEA, 2024c) – are among the areas covered in this publication. Another example is the water sector, where desalination is expected to be the main contributor to a growing energy consumption, as climate change limits access to fresh water (IEA, 2020) . Consequently, energy technology innovations that emphasize electrification, energy efficiency and demand management – in addition to greening the supply – will be crucial in moderating the surge in energy consumption (box 1.1).

Box 1.1 The "negawatt" revolution

The "negawatt" approach, combining "negative" and "watt," was coined in 1985 by physicist Amory Lovins and refers to investing in reduced energy consumption, such as heat or electricity, more than increased supply capacity. In short, the cheapest and cleanest energy is the energy that is not used in the first place. Rather than placing all the burden on consumers, this involved encouraging efficiency through several approaches in parallel, including (in his words) *eliciting and rewarding innovation, taking risks, celebrating failures, and letting a thousand technological and institutional flowers bloom*. In practice, he referred to making better use of demand-side management and energy-efficient technologies – technologies which have improved significantly since 1985.

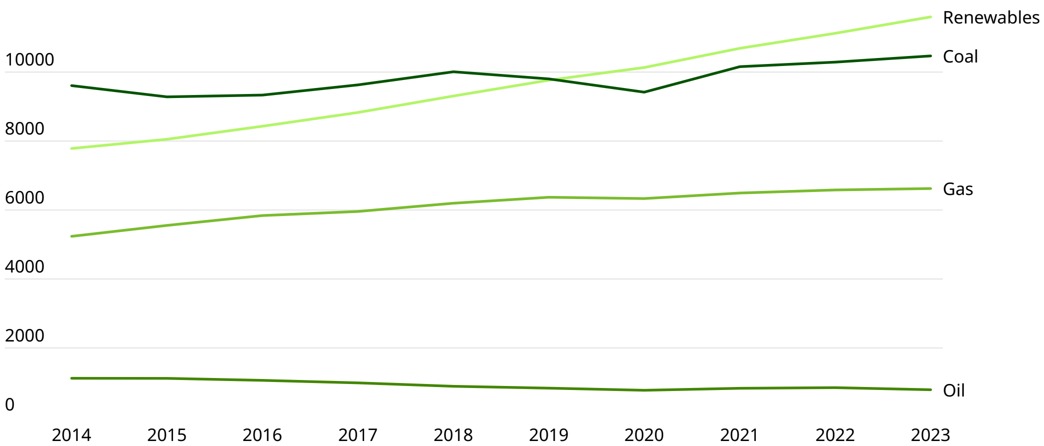
In this publication we outline some of these proven and recent technological advances, specifically designed for the end-user groups covered in the various chapters. A number of breakthrough technologies have already transformed these sectors to some extent.

Energy technology innovations that emphasize electrification, energy efficiency and demand management will be crucial in moderating the surge in energy consumption

Scaling demand-side energy technologies

Green electrification is central to decarbonization of the energy sector. The share of total electricity in final energy consumption reached approximately 20 percent in 2023, up from 18 percent in 2015, driven mainly by electrification of the residential and transport sectors (IEA, 2024c). Beyond renewables, technologies such as energy storage systems and smart grids are vital to this progress, and advances have been made for enabling electrification in end-use sectors, such as through heat pumps, private and public electric transport, vehicle-to-grid technology and steel electrification. The energy mix of the electricity grid plays a major role for the climate mitigation potential of electrification efforts. A major acceleration of renewables in global electricity supply has occurred since the mid-2010s (figure 1.1) but a much more rapid electrification rate is needed to reach global climate targets.

Figure 1.1 Global electricity production by source, 2014–2025



Source: Ember (2024).

Given the challenges confronting renewable energy and electrification amidst rising energy demand, energy efficiency remains a major opportunity for tackling climate change. Doubling energy efficiency improvements by 2030 would lower global CO_2 emissions by over 7 billion tonnes. This is the equivalent to the emissions from the entire global transport sector today, which accounts for approximately a quarter of all energy related GHG emissions (IEA, 2023; UNEP, 2024) .

Now is an opportune moment to build on the global policy momentum and to scale up the deployment of diverse, market-ready technologies

Following the COVID-19 pandemic and subsequent global rise in energy prices in 2022, countries are now strengthening their energy efficiency policies, and investments have grown by 45 percent since 2020. Improvements in global energy efficiency (measured through energy intensity) did experience a slowdown in 2023 (IEA, 2023d) . But considering the time lag between policies and impact, meaning the delay that occurs between the introduction of a policy and the time it takes to produce measurable effects, there is cause for optimism about the coming decade. Now is an opportune moment to build on the global policy momentum by accelerating building energy retrofits, heat pump installations, implementation of heat and energy recovery systems and through scaling up the deployment of diverse, market-ready technologies.

Energy-efficient devices, machines and appliances

To reach global climate targets, all sectors must significantly accelerate the adoption of energy-efficient appliances, machines and devices that cut down energy consumption. The introduction of Minimum Energy Performance Standards (MEPS) and labels has successfully promoted the replacement of everyday electric appliances with more efficient models. For instance, the best-available fridge-freezers now consume 60 percent less electricity than older models. This significant reduction highlights the impact of MEPS in driving energy efficiency in households. However, progress is highly uneven across different types of appliances. For instance, a mere 26 percent of distribution transformers and 33 percent of cooking appliances are subject to MEPS, compared to around 90 percent of fridges and air conditioners, marking a significant missed opportunity (Kurmayer, 2023).

In urban and public spaces, energy-efficient light-emitting diode (LED) streetlights are becoming more common, and some cities have explored the impact of intelligent and inter-connected streetlights on reduced energy usage. By moving to energy-efficient LED lighting, which is twice as efficient as conventional lighting, global lighting-related energy consumption could be reduced to 8 percent by 2030 (World Green Building Council, 2023). Predicting vehicle and pedestrian traffic can help foresee lighting needs and adapt traffic signaling systems to limit unnecessary idle time and fuel use. Meanwhile, building automation systems enable demand-controlled ventilation to optimize energy use in buildings and transportation networks.

Beyond household appliances and public spaces, technological advances have significantly improved the efficiency of devices designed for specific end-use sectors, such as hospitals, supermarkets and data centers. Energy-efficient medical and laboratory freezers, now covered by energy labels, are crucial for reducing energy use in health-care facilities. In supermarkets, energy-efficient transcritical cooling systems which use CO_2 as a refrigerant have become the norm for food refrigeration in Europe and are beginning to scale globally.

Technologies that address the water–energy nexus

Water and energy are closely interdependent. As highlighted throughout this publication, investments in water conservation and efficiency go hand in hand with energy savings. From water utilities to agriculture, significant energy and emissions can be saved by investing in the right innovations, including energy-efficient pumps, leak detection and solar irrigation. Yet, less than 1 percent of climate technology investments addresses the water sector (WEF, 2024a). This could be a missed opportunity in terms of addressing the water–energy nexus and managing the energy-consuming water cycles in both urban and rural areas.

For the water sector, aeration and pumping represent a major portion of energy consumption. Beyond more efficient motors and aerators, cutting-edge technologies such as intelligent pressure management and variable speed drives (VSDs) adapt pump speed and pressure to the varying water needs throughout the day, significantly reducing energy consumption. These advancements can nearly halve the energy consumed in these processes. The market for solar-powered water pumps in off-grid areas has grown rapidly since the early 2000s, while other irrigation innovations such as soil moisture sensors save water and energy by allowing more accurate water dosage. Technologies that address the water–energy nexus have been covered to some extent throughout the various chapters of this year's *Green Technology Book*.

Managing agriculture's energy demand

In on-farm agriculture operations, energy-intensive livestock ventilation systems similarly benefit from VSDs, high-volume low-speed (HVLS) fans, and phase change materials for insulation that absorb and release heat during phase transitions and maintain stable temperatures for heating and cooling. Other innovations enhancing energy efficiency include electric tractors, electric-driven robotic weeding and seeding machines using real-time kinetic technology enabling higher precision, and smart farm cloud management platforms that are digitizing cultivation processes while improving farmer decision-making.

Post-harvest and cold chain logistics capitalize on energy-efficient innovations, including thermal energy storage for warehouses, internet of things (IoT) sensors, and electrified transport refrigeration units (TRUs), which are transforming the transport of perishable products by serving as electrified alternatives to conventional diesel-powered TRUs. Grain drying systems can be improved without investing in entirely new systems using technologies that adapt dryer bins. And dairy processing is maximizing nonthermal processing techniques such as reverse osmosis, microfiltration, ultrafiltration, nanofiltration and the pulsed electric field method for pasteurization.

Advances in energy monitoring and management

End-use sectors such as households, health-care facilities, data centers, agriculture and other sectors covered in this publication consume and convert significant amounts of energy. A major by-product of their activities is rejected energy or waste heat, with one evaluation estimating that 72 percent of global primary energy consumption is lost after conversion (Forman *et al.*, 2016).

The need to understand our energy usage better has spurred the development of more and more intelligent energy monitoring technologies. IoT sensors and artificial-intelligence algorithms have further enabled integrated energy management systems that connect a multitude of systems – such as water pumps, streetlights and ventilation systems – to predict and adapt their activity to real-time energy demand. Such demand–response programs further optimize and balance energy usage, contributing to more resilient and stable grid systems. Automated systems for energy management are especially important as they can help overcome limited skill-sets and awareness of energy management practices in end-use sectors.

Understanding and responding to energy demand is crucial for avoiding energy losses in end-use sectors. But so is the adoption of systems and technologies that help recover these losses through various forms, such as through heat or even through the embodied energy of water loss.

Technologies that avoid losses and recover energy

Mitigation of household and utility water losses presents a great opportunity for energy-saving, considering the very energy-consuming water pumping and treatment processes. Both simple and advanced technologies, ranging from low-flow showerheads to sensor-or satellite-based leak detection systems, are readily available but underutilized. But as demonstrated through the numerous technology examples in the publication, sometimes the solution for avoiding energy loss can be simple. Using the right insulation in a building to avoid heat dissipation or maintaining the piping systems to avoid leaks can save on both costs and energy down the line. Or, as the example from Chapter 4 (Services) shows, equipping display cabinets with simple air curtains and doors to avoid frost formation on coils can offer energy savings of almost 40 percent (Markusson and Ollas, 2013).

Automated ventilation, heating and cooling for greenhouses maintains optimal growing conditions while minimizing energy loss. Livestock barns can employ simple HVLS fans that use the evaporative cooling effect for ventilation, while thermal screens and horticultural bubble wrap can be used in greenhouses to either retain heat or provide shading for crops. During post-harvest, dairy and grain processing are two of the most energy intensive sectors in the agrifood industry (Ladh-Sabur *et al.*, 2019b). Moisture sensors and dryers employing improved airflow patterns increase dryer energy efficiency, while nonthermal technologies based on membranes avoid using heat to conduct sterilization and pasteurization, which are typically quite energy intensive.

Technologies that aim to not only avoid energy loss but also recover energy from end-use sectors are diverse. As wastewater can contain significant amounts of embedded energy, more utilities are looking at making use of the organic content through anaerobic digestion, combined heat and power, and other means of on-site energy production, such as emerging microbial fuel cell technology. In rural households and agricultural areas, modular anaerobic digesters are increasingly used to transform household and agricultural waste into clean cooking gas and fertilizer. In cities, experiments explore kinetic energy harvesting as a way of recovering energy from pedestrian movements, or flat absorber lines to absorb urban heat. And successful examples show how supermarkets have turned into energy suppliers, by recovering heat generated by cooling display cases and freezers.

Adaptation of energy systems

Energy systems are also increasingly susceptible and vulnerable to climate change. Extreme weather events cause large-scale power outages, and the growing need for cooling places further constraints on capacity and infrastructure. Changes in temperature and water availability affect the performance of primary energy sources – especially renewable energy. Significant adaptation measures are required to avoid damages to energy infrastructure and to enhance energy resilience (EEA, 2019).

The Sharm El Sheikh Adaptation Agenda, introduced at COP27, has set a target for energy plans to include climate adaptation perspectives for energy generation, transmission and distribution infrastructure at national and sub-national levels. Here, focus is often on enabling decentralized energy systems through extended battery storage capacity and transmission and distribution networks. The targets also consider how transport infrastructure can become resilient to climate hazards through adoption of new technology, design and materials. While these technologies are not specified, and there is a global lack of standards on the topic, the *Green Technology Book* Adaptation edition presents a number of adaptation solutions for urban transport infrastructure.

With regard to the incorporation of energy resilience into national adaptation planning, the International Energy Agency (IEA) has found that even where countries have national strategies or adaptation plans, pressing needs for climate resilience in the electricity sector have not been addressed, evidenced by the fact that more than half of the 31 IEA member countries have limited or no information on the climate resilience of electricity systems. In fact, only 16 percent of these countries have articulated concrete actions in national adaptation strategies, covering the entire electricity value chain (IEA, 2020).

Micro-grids are increasingly useful to populations impacted by natural disasters whose frequency and severity have been exacerbated by climate change

In this edition on energy, climate adaptation of energy systems is addressed through an emphasis on technologies that enable decentralized energy systems. Understanding the link between energy access and climate adaptation is crucial, and yet this is often overlooked. Energy services themselves, such as cooling and back-up energy and water supply, are essential to respond to climate change impacts including drought, temperature rise, and natural disasters (Malekpoor *et al.*, 2019). The potential role of reliable and affordable modern energy services in bolstering adaptation to climate change impacts has not been widely acknowledged in policy or practice (Sharma, 2019). Increasing the distribution of renewable energy solutions and diversifying energy sources builds resilience for individuals and communities whose lives have been impacted by climate change. Deploying and scaling-up specific technologies that both enable energy access via renewable energy and energy efficiency, such as clean cookstoves and biogas digesters, achieves multiple benefits for vulnerable populations and builds resilience to climate impacts.

Agriculture and renewable energy production can successfully coexist using agrivoltaics. Maximizing land and water use via agrivoltaics and aquavoltaics (energy technologies that allow for simultaneous use for agri- or aqua-culture purposes) achieves synergies between mitigation and adaptation for rural communities, boosting both renewable energy supply and food production. This co-location provides solutions for land constraints, which will be increasingly important as the population grows and productive land becomes scarcer.

Micro-grids are increasingly useful to populations impacted by natural disasters whose frequency and severity have been exacerbated by climate change. In California, wildfires have become alarmingly frequent, more intense, and faster-moving due to the impacts of drought and increasing occurrence of extended heatwaves. These events have prompted regional power shutoffs that have incurred large costs, including lives, especially for those living in the so-called wildland–urban interface. Conventional micro-grids using diesel generators contribute to greenhouse gas (GHG) emissions and are costly. Local smaller-scale renewable energy sources can deliver more reliable services while mitigating climate change. An international team led by research scientists at the United States (US) Department of Energy's Lawrence Berkeley National Laboratory confirmed that clean energy micro-grids relying on solar and batteries provide a cheaper solution compared to conventional micro-grids. They cost well below what households typically pay for electricity and can reduce the impact of power outages (by minimizing power shutdown time) by a factor of up to 30 (Lawrence Berkeley National Laboratory, 2023).

As was also observed in the Adaptation and Mitigation editions of the *Green Technology Book*, many technologies bridge these two functional terms as they have qualities relevant for both. While maintaining a functional division between adaptation and mitigation is useful for programmatic and financing purposes, it is often less useful in relation to actual solutions implementation, including in innovation and technology development and deployment. In the *Green Technology Book*, we point out both adaptation and mitigation qualities of technologies and technical fields where feasible, although when it comes to energy solutions, mitigation will often be the primary climate change related quality of a technology.

International climate finance and cooperation

Energy security reimagined: an opportunity for every country

The energy transition will have a diverse and nuanced range of effects on global geopolitics. As the share of renewable energy rises, energy security will undergo a transformation. Energy security, once viewed primarily as an international question concerning access to commodities like oil, coal and gas, will become a national governance issue focused on providing continuous service (IRENA, 2024a).

> Energy security will become a national governance issue focused on providing continuous service

The transition from fossil fuels to renewable energy is ushering in energy systems that are more electrified, decentralized and digitalized. This shift is slated to amplify the prominence of electrification, while reducing both the trade and geopolitical power of fossil fuel resources. It will also importantly affect issues concerning technology access (IRENA, 2024a).

In 2022, 86 percent of the global population lived in countries that were net importers of fossil fuels (IRENA, 2024a). High fossil fuel prices are putting pressure on national government budgets. For example, Africa's reliance on gas and coal for electricity makes the continent vulnerable to economic shocks from fluctuating commodity prices. At least 28 African countries generate at least half their electricity from fossil fuels, with 16 of those relying on fossil sources for 80 percent or more of their energy needs (BloombergNEF, 2022).

Countries that provide energy subsidies are especially vulnerable, because rising commodity prices directly burden their national budget. A shift to renewables from local sources can bolster self-sufficiency, moving energy dependency from the global to the regional level and lessening vulnerability to geopolitical disruptions. However, countries will continue to be linked through global clean technology supply chains (IRENA, 2024a). Technology rather than fuels is driving renewable energy systems. In the past, energy security was addressed in large part through supply-side measures, whereas managing energy demand was considered unimportant. Now, the demand side of the equation will become increasingly vital in enhancing both efficiency and resilience (Van de Graaf, 2019).

As issues related to supply become less significant, a broader range of factors will need to be considered. They include flexibility (system digitalization, energy efficiency, demand management and response, batteries and storage technologies, and grid stability), infrastructure concerns, availability of and access to technology (resilient supply chains), economic and trade considerations, and decentralization (opportunities for using domestic resources and consumer involvement) (IRENA, 2024a).

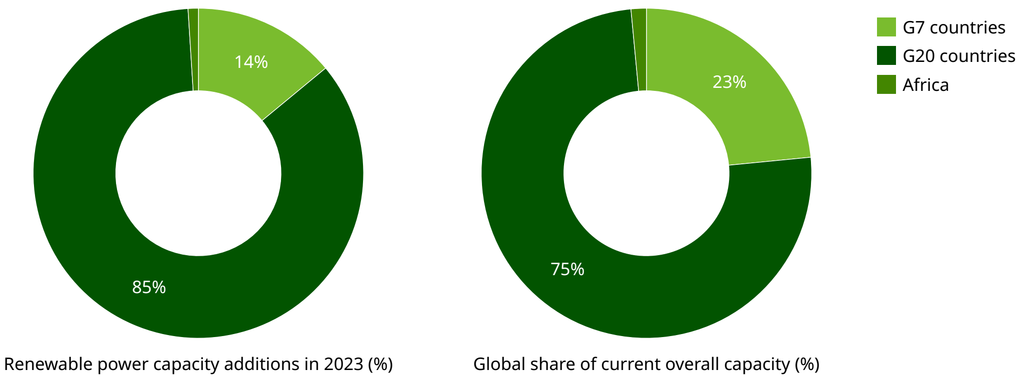
Developing countries often lack access both to technology and finance for the energy transition

Developing countries lack access both to technology and financing, exemplified by Africa, whose share of global renewable capacity is only 1.6 percent. Figure 1.2 depicts the 2023 share for Africa as compared to the G7 and G20 countries for capacity additions and global share of current overall capacity. Developing countries face challenges in accessing low-cost capital for renewable energy investment, high interest rates having made such projects less attractive than fossil fuels. Additionally, concerns about investment risks, inadequate regulatory frameworks and insufficient incentives further elevate the cost of capital compared to developed nations (Aydos *et al.*, 2022).

Africa's share of global renewable capacity is only 1.6 percent

However, developing countries that lack domestic fuel reserves may benefit the most from a shift to renewable energy. Renewable energy has increasingly become a viable alternative in developing countries due to a combination of falling costs and mobile banking. Indeed, off-grid solutions (standalone and mini-grids) could supply roughly 60 percent of the additional generation needed to achieve the goal of universal energy access by 2030 (Van de Graaf, 2019).

Figure 1.2 Disparities in renewable capacity, by selected country groups, 2023



Source: IRENA (2024).

Of course, effort is needed to ensure that the energy transition does not disproportionately impact those countries with fewer resources to develop technologies. Several countries have limited access to technologies and face high capital costs. This makes it increasingly necessary to facilitate technology transfer alongside providing access to intellectual property rights in support of deployment and to promote an equitable energy transition. Knowledge sharing will also be important for new market creation, as well as nurturing local expertise. The opportunity to decrease energy import spending while at the same time increasing resilience could especially benefit the Small Island Developing States (SIDS), for whom imported fossil fuels account for 8 percent of GDP (Van de Graaf, 2019).

SIDS are particularly vulnerable to the effects of climate change, but do have access to plentiful renewable energy sources. International cooperation in support of their renewable energy ambitions is essential, as more than half of the collective renewable power targeted capacity in the SIDS' Paris climate pledges is conditional upon financing, technical assistance, technology transfer or capacity-building (Rana, 2022). Energy-related support has not been allocated consistently between the SIDS. Moreover, there has been scant correlation with income level or with energy access gaps, and improvements in electricity access have been lagging in those countries where the gap is widest (Atteridge, 2019). That said, the SIDS countries have committed to reach 13 GW of cumulative renewable power capacity by 2030, as stated in their national energy plans, up from 5.2 GW in 2021 (Rana, 2022).

Closing the innovation divide through technology transfer

As mentioned, Parties at COP 28 committed to tripling renewable energy capacity and doubling energy efficiency improvements, placing energy efficiency at the core of policymaking (UNFCCC, 2023). This means countries must consider energy efficiency options more prominently, in view of technology-related investment decisions, as well as climate finance and technology transfer.

Many least developed and emerging economies have a unique chance to build sustainable systems from the ground up

Many least developed and emerging economies possess significant potential for advancing the energy transition. With high unexploited potential for energy efficiency improvements, abundant opportunities for solar energy, and the emergence of new cities and industries, there is a unique chance to build sustainable systems from the ground up. However, progress in these regions has been hampered for several reasons – one of them being the fact that about 80 percent of the world's financial assets are held in advanced economies. Another reason is the high up-front costs associated with key technologies supporting the energy transition (IEA, 2023m). In addition, most climate technologies are developed and traded by developed countries, with China being the major exception (Yu, 2023).

Stronger international cooperation is needed to enable efficient technology transfer for low-carbon energy technologies. The disparity between developed and developing countries in terms of developing, accessing and producing climate technologies domestically, is not conducive for collective progress toward sustainable development and effective climate action under the Paris Agreement (Yu, 2023).

Various political measures have been put in place to incentivize and attract low-carbon energy investments to emerging markets and developing economies, promote energy decentralization and reduce geopolitical risk. This includes international climate finance mechanisms which are expected to increase technology investments in developing countries, business-to-business interactions and carbon trading schemes.

Internationally, the Clean Energy Ministerial is a high-level global forum to promote policies and programs that advance clean energy technology, to share lessons learned and best practices, and to encourage the transition to a global clean energy economy. It has 29 member countries pursuing 20 workstreams to facilitate the transition. The European Union (EU)–India Clean Energy and Climate Partnership and the Africa–EU Green Energy Initiative are other examples of international initiatives that aim to support countries' increase in renewable energy capacity while enabling energy efficiency and broader access to affordable and reliable energy (EC, 2022).

Energy and transport major climate finance recipients, with energy efficiency lagging behind

Majority of climate finance flowing from developed to developing countries goes toward climate change mitigation, with lower levels of adaptation finance which may act as a bottleneck. In 2021, total climate finance amounted to USD 89.6 billion – an increase of 7.6 percent over the previous year. Of the total climate finance provided between 2016 and 2021, 31 percent targeted the energy sector (OECD, 2023a).[1] Of the total mitigation finance between 2021 and 2022, the energy sector received 44 percent, of which 97 percent went to renewable energy. Meanwhile, the transport sector was the second largest recipient receiving 29 percent of total mitigation finance, followed by energy efficiency, AFOLU, water and other sectors at significantly lower levels of funding (CPI, 2023a).

Comparisons in climate finance between renewable energy generation and energy efficiency can be tricky, but a 2018 breakdown of climate finance by use and sector shows how the prevalence of funds are focused on renewable energy. That year, energy efficiency saw only a tenth of the climate finance directed toward renewable energy (CPI, 2023a). The relative lack of funding for energy efficiency is a major concern, in particular when viewed in relation to global energy demand and future impacts of climate change on renewable energy capacity. The reasons for this may be many.

For instance, renewable energy policies frequently garner more political attention and resources than energy efficiency measures, leading many countries to prioritize renewable energy over efficiency when setting targets (Ollier *et al.*, 2020). The visibility of renewable energy projects can instill public support due to social norms, leading to higher investments for such initiatives – even at a financial cost (Vesely *et al.*, 2022). In contrast, energy efficiency measures, like better insulation or more efficient appliances, are often invisible and less tangible.

Renewable energy projects also generate clear, long-term revenue streams through the sale of electricity, often through power purchase agreements. This makes them more attractive to investors who can easily calculate returns. Energy efficiency savings, on the other hand, can be harder to quantify and monetize, particularly because they are based on avoided costs rather than generated income. The savings are often spread over time and can be less predictable, making them less appealing to traditional investors, including at household level. In fact, while households are playing an increasingly active role in the energy transition (box 1.2) they often overlook energy efficiency investments despite them being cost-effective (Ameli and Brandt, 2015). Energy services companies (ESCOs) offer various models for achieving energy savings on commercial basis. Based on a detailed energy audit, an ESCO may provide the finance and undertake the technical installations for, e.g., a production facility while retaining part of the achieved savings as reward. This would allow the production facility to implement energy efficiency measures with limited effort and risk. One barrier sometimes encountered for such arrangements is the aversion of banks toward providing loans against expected future savings rather than traditional physical asset collateral, and banks may need to develop new financial products to support such arrangements.

Box 1.2 Financing the energy transition as consumers

Consumers are playing an increasingly active role in clean energy adoption, through purchases such as electric vehicles (EVs), heat pumps and energy-efficient household appliances. Household spending on climate mitigation reached USD 184 billion in 2021–2022, up from USD 130 billion in 2019–2020. This was mainly driven by global EV purchases, followed by residential solar PVs, solar water heaters and energy-efficiency home renovation (CPI, 2023a). Estimates

1 This includes bilateral public climate finance from aid agencies and development banks; multilateral public climate finance provided by multilateral development banks and climate funds; climate-related export credits and private finance mobilized by bilateral and multilateral public climate finance.

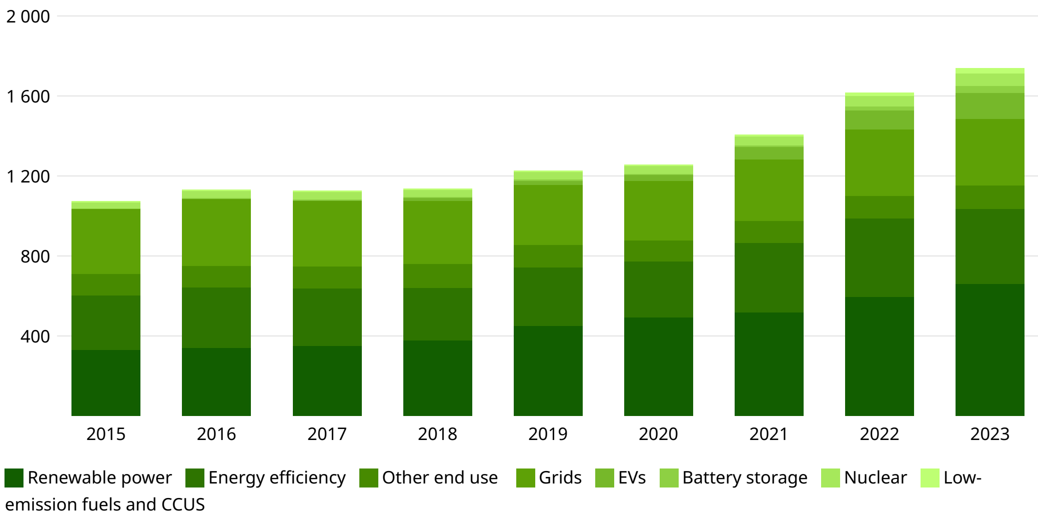
suggest that household consumption accounts for up to 60 percent of GHG emissions, with the largest emissions stemming from mobility, housing and food (Ivanova et al., 2015). How private consumers choose to adopt and use technologies is playing an increasingly important role for climate change mitigation. Fortunately, prosumers (who both produce and consume energy) are also being presented with new opportunities to sell excess energy and participate in peer-to-peer trading platforms. However, while consumers *can* play a key role, they should not be centered in the energy transition. Consumers hold collective power to some extent, but they possess limited individual influence on decisions that lead to major necessary changes such as national policies and budgets, fossil fuel subsidies, building codes and corporate investment priorities.

While the world added 50 percent more renewable energy capacity in 2023 than in 2022 (Wood, 2024), fossil fuels still accounted for 82 percent of the global energy mix in 2023 amid a record energy consumption (Energy Institute, 2024). Record-breaking growth in coal consumption in countries such as China, India and Indonesia more than offset decreases on a global level (IEA, 2023). In addition, climate change threatens to impact future renewable energy capacity. A drought-driven shortfall in hydropower generation (which remains the largest renewable source of electricity) was considered a key contributor to the record-high global CO_2 emissions in 2023 (IEA, 2024b).

Technologies for demand management and energy efficiency will pay off financially regardless of the level of climate change related impact

This also further emphasizes the importance of curbing our energy demand. Technologies for demand management and energy efficiency represent no-regret investments as they will pay off financially regardless of the level of climate change related impact. And while investment in energy efficiency has been increasing, as shown in figure 1.3 below, it is not doing so with the same rate as renewable energy investments, which may have consequences for meeting more ambitious climate scenarios (IEA, 2023k).

Figure 1.3 Annual clean energy investments, 2015–2023 (in billion USD, 2022)



Note: CCUS = carbon capture, utilization and storage; EVs = electric vehicles.
Source: IEA (2023d).

Specific sectors also remain largely underfunded. More specifically, agrifood systems writ large may be underfinanced, and strikingly so in several regions. However, projects, startups and technologies that intersect with energy have seen significant investment in recent years. Most project-level private finance (USD 2.81 billion) for agrifood systems was spent on projects at the intersection of agrifood and energy systems. And commercial financial institutions invested in 2019–2020 USD 1.6 billion in projects almost entirely supporting renewable energy in relation to agrifood activities (CPI, 2023b). This reflects the reality that commercial institutions prefer to provide capital for renewable energy (CPI, 2021) due to the sector's stable risk–return profile (CPI, 2022) .

Despite a significant increase in venture capital investment into climate technology between 2013 and 2019, and unprecedented levels in 2021–2022 (PwC, 2022), climate technology for agriculture, food and land use is underinvested when compared to their share of global emissions and when compared to other sectors, including energy and mobility. This underinvestment points to lacking technological maturity (PwC, 2022) as well as the need for supportive regulations and a stronger business case (CPI, 2023a) .

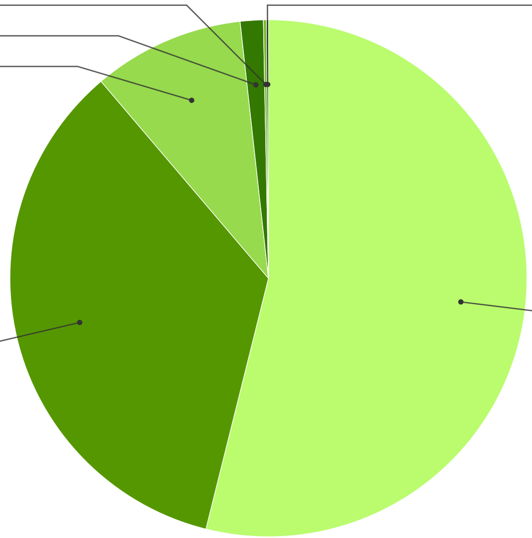
Renewable energy as a new waste and recycling stream

Some have voiced concerns that such a large increase in renewable energy infrastructure deployment can have negative impacts due to the risk of obsolescence as technology rapidly advances. Newer technologies deliver better performance and efficiency, making older systems less useful and competitive. This can lead to increased maintenance costs, higher economic pressure, and challenges in upgrading or replacing outdated equipment.

For example, electronic waste (e-waste) is a rapidly growing environmental issue driven by the increasing consumption of electronic devices such as smartphones, computers and appliances. As technology advances and consumer electronics become obsolete, vast amounts of e-waste are generated. This waste poses significant environmental and health risks due to the presence of hazardous materials like lead, mercury and cadmium in electronic devices.

There is rising concern regarding renewables due to the predicted increase of decommissioned PV panels. A commonly cited statistic projected that 60 million tonnes of PV panel waste would be produced by 2050 (IRENA and IEA-PVPS, 2016). A more recent study incorporating prolonged PV lifetime from 12 to over 35 years as well as increased estimated required PV capacity to 75 TW by 2050, arrived at a similar level with cumulative PV waste in the range between 54 million to 160 million tonnes by 2050 (Mirletz *et al.*, 2023). However, 35 years of cumulative PV module waste (2016–2050) is drastically overshadowed by the waste generation from fossil fuel energy and other waste streams (assuming constant annual waste at present rates, figure 1.4). For example, in the same time span, coal ash would generate 300–800 times more waste and oily sludge 2–5 times more (Mirletz *et al.*). Moreover, both coal ash and oily sludge are known to be toxic. It is necessary to provide this perspective to policymakers, government agencies, and the public to avoid unfounded concerns that may ultimately slow deployment.

Figure 1.4 Global cumulative waste in 2050 (in million metric tonnes)



Source: Mirletz et al. (2023).

That said, it remains prudent to continue researching, scaling and advancing circular pathways for PVs. This starts at the design stage by improving the longevity of renewable energy components and designing them for easy replacement and upgrades, which can facilitate easier recycling and reduce waste. Also, there is the need to invest in and develop specialized recycling facilities that can handle complex materials from solar panels, wind turbine blades and batteries. Exploring alternatives to using rare materials is becoming more critical, alongside promoting recycling programs that recover valuable materials and integrate them back into the supply chain to reduce the need for new raw materials. And finally, it is imperative to effectively implement extended producer responsibility policies that require manufacturers to take responsibility for the end-of-life management of their products, including recycling and disposal (IRENA, 2016).

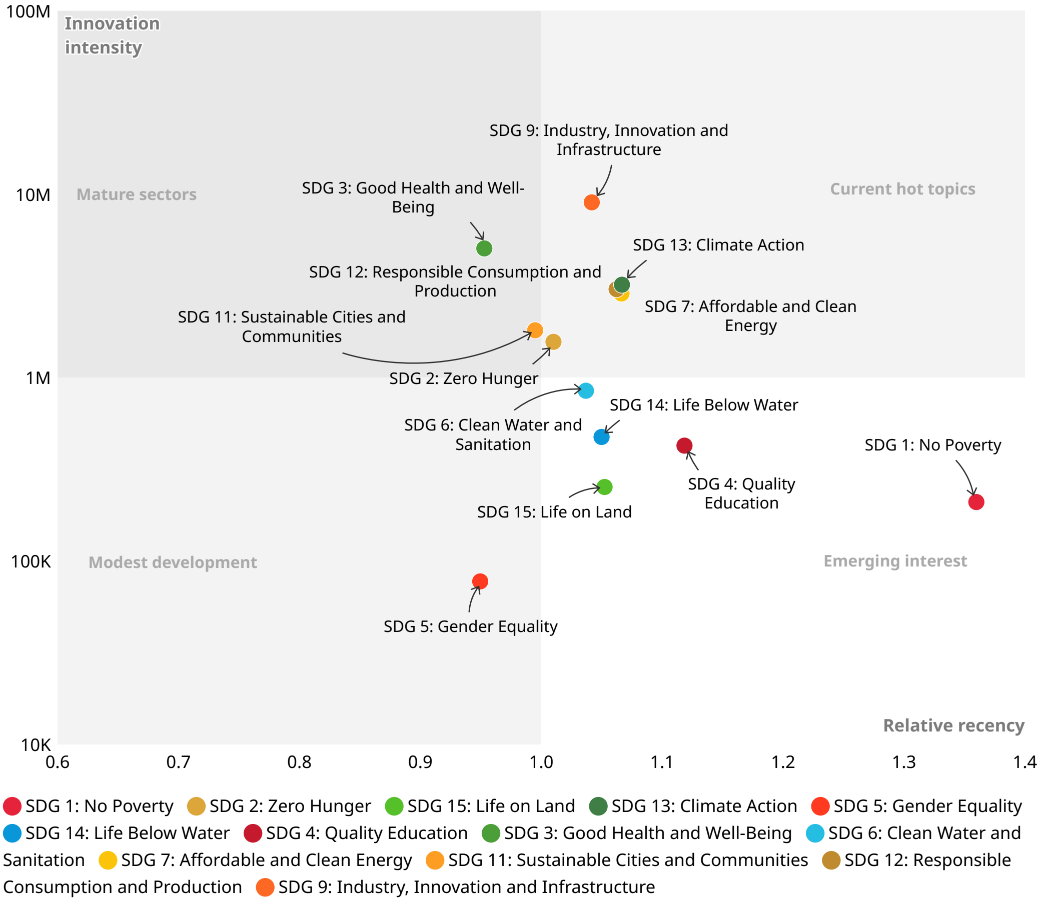
EVs can be up to 50 percent more efficient than internal combustion engine (ICE) vehicles and achieving full electrification globally could reduce global transport energy demand by up to 22 percent (WEF, 2024b). However, electrification is still in early stages for heavy vehicles, which constitute 38 percent of transport emissions (WEF, 2024b). Retrofitting, where a traditional ICE-based drive unit is replaced with an electric one while retaining the rest of the vehicle, could provide an alternative in this case, and others. Retrofitting lowers resource consumption and waste associated with new EV production, reduces environmental impact by extending the life of existing vehicles, and can be more cost-effective.

The role of innovation and intellectual property rights for clean energy technologies

Clean energy technology patents have increased, with nearly half of applications in solar energy

When mapping innovations across the Sustainable Development Goals (SDGs), SDG 7 Affordable and Clean Energy shows an upward trend in patent activity – slightly stronger compared to most other SDGs. When considering factors such as innovation intensity and relative recency (meaning the frequency and freshness of new patents being filed), SDG 7 comes out as a topic of emerging interest and current hot topic for innovation (figure 1.5). This trend highlights the increasing focus and investment in technologies aimed at improving energy efficiency, harnessing renewable energy sources and reducing carbon emissions.

Figure 1.5 Innovation Maturity Index for SDG-related patent families, 2000–2023

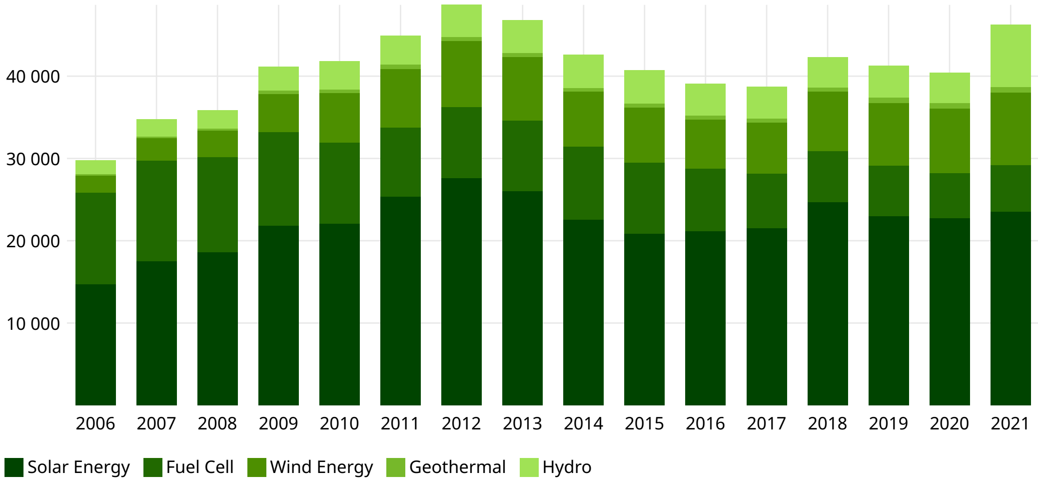


Source: WIPO, 2024.

While energy patent trends do not necessarily reflect market demand or indicate whether a technology will be commercially available or successful, analyzing them does provide us with insights into technological developments, industry directions and geographical innovation hotspots. For a discussion on the innovation ecosystem for climate change technologies and intellectual property rights systems, see Chapter 2 of the *Green Technology Book* Adaptation edition.

Innovation in renewable energy technologies has seen a fluctuating but mostly upward trend. The number of published patent applications increased from around 29,800 in 2006 to around 46,300 in 2021. Solar represented nearly half of these innovations in 2021 (WIPO, 2023). Here, notable innovation trends include a focus on technologies that enable more cost-effective installation and manufacturing, and new types of solar PV design. A shift from inorganic to new types of organic PV cells enables their integration into windows, wearables and other objects (EPO, 2021). After solar, most renewable energy innovation was seen for wind energy (19.1 percent), hydro energy (16.4 percent), fuel cell technology (12.2 percent) and geothermal energy (1.4 percent) (figure 1.6) (WIPO, 2023).

Figure 1.6 Trend in patent applications in energy-related technologies, 2006–2021



Source: WIPO (2023).

When examining progress over time, it is worth noting how innovation intensity evolves as technologies develop and mature. As a technology matures, often less research and development (R&D) effort is allocated to it, which is reflected in decreasing patenting activity (Zhai and Lee, 2019). And with patents being a long-term investment, many of the inventions patented during the "renewable energy boom" at the start of this century are likely emerging in commercially available products and services today (Nurton, 2020). This also highlights the time lag that often exists between initial innovation and the widespread availability of new technologies.

Most inventions relate to end-use sectors and enabling energy technologies

Beyond energy supply, most innovation is taking place for end-use solutions and enabling technologies, reflecting recognition of the global challenge to curb energy demand. While technologies that enable fuel switching and energy efficiency represented 60 percent of all low-carbon energy (LCE) international patent families (IPFs) between 2014 and 2019, renewable energy only represented 17 percent – despite drawing significant attention. Meanwhile, enabling technologies such as batteries, hydrogen, smart grids and CCUS saw the biggest growth, representing 34 percent of LCEs in 2019 (EPO, 2021). While the high levels of patenting activity for energy efficiency may seem counterintuitive in view of renewable energy receiving significantly higher levels of climate finance and capital flow, as described above, this disparity can be attributed to several factors.

> Most innovation is taking place for end-use solutions and enabling technologies, reflecting recognition of the global challenge to curb energy demand

For instance, renewable energy technologies, like solar and wind power, have reached a certain level of maturity. As these technologies have developed over the years, the focus has shifted from innovation to large-scale deployment. Consequently, more capital is directed toward building and expanding renewable energy infrastructure rather than investing in new innovations, leading to less patenting activity. On the other hand, energy efficiency encompasses a broad range of technologies and applications that are still evolving. As new ways to optimize energy use across various sectors are explored, there is more room for innovation, resulting in higher patenting activity. Further, energy efficiency covers a wide array of sectors, including buildings, transportation, industry and appliances. Each of these areas offers unique opportunities for incremental innovation.

The growing importance of end-use and enabling LCE technologies has also led to a lot of innovation overlap with other sectors, such as buildings, consumer products and agriculture. What is worth noting is that inventions in these fields often support a shift toward more flexible and decentralized energy solutions that enable more climate-resilient energy systems.

Over the years, the share of LCE patents generated by research institutions has been growing, except for end-use technologies which dominate patenting activity. LCE technologies for end-users are often characterized by small unit sizes and a competitive market. Here, most innovations come from the private sector rather than universities and public research organizations (EPO, 2021).

Transport and industry dominate end-use energy innovations

Transportation leads in patenting activity for LCE technologies, accounting for over 40 percent of IPFs in end-use sectors from 2000 to 2019, with road transportation alone constituting about 35 percent. EV patents, including fuel cells and charging technologies, have grown rapidly, surpassing other road transport technologies in 2011. Another key area of technological development relates to the industry's transition and energy intensity, representing nearly a third of end-use technology IPFs (EPO, 2021).

Notably, metal and mineral processing saw dynamic growth, averaging 12 percent annually from 2010 to 2019, while clean energy patents in the chemical and oil sectors declined after 2015. Clean energy technologies for agriculture, production of consumer goods and other industrial production sectors accounted for 16 percent of IPFs during that period. Building technologies, covering efficient lighting, heating, and construction, accounted for more than 17 percent of end-use IPFs but saw a decline after 2013. The information and communications technology sector has experienced a significant rise in LCE patents, growing at an average annual rate of 10 percent from 2000 to 2019, driven by the need for energy savings in computing and communications (EPO, 2021).

Most energy innovation happening in China and high-income countries

The regional distribution of patent filings can also highlight countries that are leading in specific technological domains. Looking more broadly at the low-carbon innovation landscape, Europe, Japan and the United States accounted for more than three quarters of all IPFs generated from 2000 to 2019 (EPO, 2021). However, in 2021, the largest share of total global applications in solar, fuel cell, wind, geothermal and hydro energy were filed in China, except for fuel cell technologies, which was led by Japan (WIPO, 2023).

Industrialized countries often have national agencies for developing energy technologies. Countries such as Japan, which suffer from limited access to energy sources, spend a significant percentage of total government spending on energy R&D. The biggest growth in energy R&D spending can again be seen in China, which was a key factor behind the 10 percent global growth in public spending on energy R&D in 2022 (IEA, 2023k).

The high regional imbalance and concentration for clean energy technologies is also evident when looking at manufacturing operations. In 2023, four countries – China, United States, India, Viet Nam and the European Union accounted for around 80 to 90 percent of global manufacturing capacity for solar PVs, wind, batteries, electrolyzers and heat pumps (IEA, 2023i).

Overall, the growing levels of innovation in clean and low-carbon energy technologies underscore the importance of continued investment in R&D to meet global climate goals. The upward trend in patent activity signals a strong focus on advancing technologies that enhance energy efficiency, expand renewable energy use and reduce carbon emissions. While the shift from innovation to deployment in mature technologies like solar and wind has led to less patenting activity in those areas, the ongoing development in energy efficiency and enabling technologies highlights the critical role of innovation in driving progress across many sectors active in the energy transition.

Recent innovation and patenting in the agrifood sector

Patents within the agrifood sector comprise more than 3.5 million published patent families (inventions) filed over the past 20 years. The United States has long been a major player, but recent surges in R&D investment by China and Japan seem to be altering the global patent landscape within the sector (WIPO, 2024a). Interestingly, with respect to energy technologies, recent patent growth within the AgriTech subdomain (one of two under agrifood, alongside FoodTech) is attributable to an increasing interest in agricultural automation and IoT technologies, with the most patents for *connectivity/sensors/smart farming* and *precision agriculture and mapping/imagery*. Top inventor locations for these are the United States, followed by Asian countries such as China, Japan and the Republic of Korea. The top patent applicants are industrial manufacturers of agricultural machinery from the United States, Japan and Europe, alongside agrochemical companies from Germany, China and Japan, and technology companies from Asia in IoT-related sub-domains.

One of the top four key research hotspots in AgriTech identified by WIPO is precision agriculture, including advancements in robotic/autonomous agriculture vehicles and automation through AI and software. Data analysis from 1,500 international patent families in the *predictive models in precision agriculture* field shows a significant recent annual growth rate of 27.1 percent, indicating an upswing of interest within the topic sector (WIPO, 2024a).

2. Green urban energy solutions

Energy technology innovation in cities is transforming how urban areas manage energy and water. Smart grids, energy-efficient buildings, renewable energy integration into public spaces and infrastructure, and advanced water management systems are improving resource efficiency, reducing waste and lowering costs. These solutions help cities meet growing demand while mitigating the impacts of climate change.

How can cities best use technology and innovation to manage clean energy use? What is the role of households in the energy transition? And how can technology help address the water–energy nexus in cities? This chapter sheds light on the myriad of proven, frontier and horizon technologies – beyond solar photovoltaics – that serve as tools for aligning urban lives with sustainable energy systems.

Introduction

Energy consumption determined at the design stage

As major engines of growth, cities demand more energy than rural areas. Hosting little more than half of the world's population, cities consume about 75 percent of global primary energy (UN Habitat, 2021). Population growth and urbanization drive the demand for heating, cooling, transport, lighting and other energy-consuming activities.

The energy hierarchy emphasizes that our top priority should be to conserve energy and reduce demand. A crucial yet frequently neglected fact is that the greatest potential for energy demand management lies in the design phase. This applies to the planning of cities, the architecture of buildings and even the engineering of individual devices.

Hosting little more than half of the world's population, cities consume about 75 percent of global primary energy

For instance, designing dense cities can significantly reduce travel time and fuel consumption. The concept of the "15-minute city," where residents can fulfill most of their needs within a short walk or bike ride, has gained popularity in recent years. However, regional differences are stark, with pro-car policies often hindering progressive urban planning. In the United States of America, for example, driving accounts for 75 percent of household-level CO_2 emissions, while dense cities with accessible public transport can nearly halve these emissions (Prieto-Curiel and Ospina, 2024; Ramaswami *et al.*, 2008).

Where policy allows, growing cities can make use of the enabling technologies highlighted in this chapter to guide the development of more efficient cities – from road networks to public spaces and infrastructure. The chapter also highlights how water utilities can use technology to both conserve and recover energy, and how household energy usage can be managed by better building design choices and by deploying innovative devices, materials and software.

Digital solutions for visualizing and managing energy demand

A recurring trend for urban energy systems is the growing need to understand our energy consumption. From increasingly smarter and interconnected thermostats and meters at household level to sensors integrated in streetlights, technology is helping us visualize our consumption. This in turn has spurred the development of intelligent and automated systems that optimize our energy and fuel use, such as intelligent traffic systems and building energy management systems. Automation, rather than relying on behavior change, may in fact be the key to actual energy savings, as data visibility alone is not always enough to spur action (Brandon *et al.*, 2022; Chen *et al.*, 2020).

The water–energy nexus in an urban context

The water–energy nexus (box 2.1) underscores the intrinsic link between water and energy, where technology plays a crucial role in addressing efficiency and climate change and sustainability challenges. Integrated management is gaining traction, as evidenced by technologies like air-to-water heat pumps and solar thermal collectors that provide both space and water heating. At household level, efficient water usage and innovative household appliances such as low-flow showerheads and leak detection sensors are low-hanging fruits that can significantly reduce both water and energy consumption, as can advances in wastewater treatment technologies and infrastructure improvements. Moreover, energy recovery from wastewater and on-site renewable energy systems are becoming viable options for many water utilities.

Policymakers and planners are increasingly focusing on exploiting these technological advancements to reduce energy use and enhance sustainability in the water sector, which is essential as global water and energy demands continue to rise. However, investing in clean energy solutions and introducing innovative technologies in public utilities is a challenge. Such organizations are generally risk adverse and have long buying cycles (WEF, 2024a).

Box 2.1 International Energy Agency (IEA): The water–energy nexus in short

Over the period to 2040, the amount of energy used in the water sector is projected to more than double. The largest increase comes from desalination, followed by large-scale water transfer and increasing demand for wastewater treatment (and higher levels of treatment). Electricity consumption rises by 80 percent by 2040. However, there is significant potential for energy savings in the water sector if all the economically available energy efficiency and energy recovery potentials in the water sector are exploited. Wastewater contains significant amounts of embedded energy that, if harnessed, could cover more than half of the electricity needs of municipal wastewater utilities. There is also a major opportunity to reduce water losses along the supply chain – from leaks, bursts and theft – which would save water and energy.

Source: IEA (2020a).

Energy-efficient appliances, machines and devices

The rapid expansion of energy-efficient appliances, machines, and devices is crucial for reducing global electricity consumption and thereby also greenhouse gas (GHG) emissions. Plug-in options, such as balcony-attached solar photovoltaics (PVs), are making it easier than ever to power the growing number of energy efficient household devices with renewable energy, regardless of the grid's energy mix. In water utilities, cutting-edge motor technologies, smart interconnected pumps and efficient aeration processes have evolved significantly to optimize energy use.

Standards and labels, such as the European Union (EU) energy label and "ecodesign" requirements, have successfully promoted energy-saving household appliances in some countries. However, progressive legislative frameworks and policies on a global level play a crucial role in accelerating the adoption of best-available technologies, ensuring energy efficiency and sustainability across all the sectors covered in this chapter and beyond.

Energy recovery technically feasible but costly

Energy cannot be created or destroyed; it just changes form. In recognizing this first law of thermodynamics, innovators spanning various sectors have developed both simple and complex energy recovery methods. This chapter covers solutions ranging from hot shower water at household level to sewage sludge and wastewater. In fact, wastewater holds significant potential to generate numerous value streams from cellulose and bioplastics, biochar and fertilizers. Recent innovations, like microbial fuel cells for energy recovery from wastewater, are being explored but are not yet widely scalable. Many energy and resource recovery processes show potential but are yet far from the norm, often due to high investment and operational costs (Zarei, 2020).

Meanwhile, technologies such as kinetic energy harvesting from pedestrian movements further illustrate the diverse potential for energy recovery on even smaller scales. And there is a growing interest in exploring new sources of energy recovery in cities. Examples covered in this chapter include using waste heat from data centers, and pilot projects that recover heat from underground transport systems and harness energy from metro brakes to power electric vehicle (EV) charging stations.

Decentralized energy enables cities to go their own way

Technological innovation is crucial for enabling decentralized clean energy production. Initiatives supporting local energy generation empower residents to form energy communities, allowing them to collectively invest in renewable energy and enabling technologies like solar PVs, smart meters and energy storage systems. These communities facilitate a citizen-led energy transition, transforming household owners into “prosumers” who produce, use, store or sell electricity back to the grid. Despite legislative barriers, an increasing number of countries are adopting frameworks to support decentralized energy production. Technological advancements also play a pivotal role in integrating renewable energy into public spaces and transport systems, such as solar panels on novel surfaces. These innovations, combined with improved grid stability, energy storage solutions and smart grid technologies, are essential for maximizing the efficiency and impact of renewable energy sources, thereby supporting the transition toward a more sustainable and resilient energy system.

Smart energy in urban households

Households are fundamental pillars of the global energy landscape. Energy is essential for heating and cooling spaces, supplying water, lighting and cooking, and fulfilling numerous other daily needs. Growing consumer awareness has increased competitiveness on the market for innovative and low-carbon technologies, supported by legislation and standards to guide consumers toward real impact.

Technological developments and trends

Urban households can manage energy demand

While the manufacturing of building materials such as steel or cement is highly energy-intensive, about 85 percent of a building’s life cycle energy consumption occurs in the operational phase (Minde *et al.*, 2023). With nearly 70 percent of the world’s population expected to live in urban areas by 2050 (UN Habitat, 2022), urban consumers hold significant power to drive the transition toward clean and efficient energy use. In fact, a quarter of global energy is consumed at household level, marking a key opportunity for consumers to increase efficiency (OECD, 2023b).

Finding comparisons of energy use at urban household level between countries can be difficult, owing to differences in dwelling size, energy source and electricity access. Within countries, the relationship between income and energy use is complex and dynamic, impacting the quantity of energy used, how many appliances a household owns and their energy efficiency. While income and energy consumption are closely related at national level, several studies highlight a strong inverse relationship between household income and energy use, emphasizing the importance of global efforts to curb demand (Shabur and Ali, 2024; Zheng *et al.*, 2024).

Technologies for urban energy access

Global energy access has improved significantly over recent years, but 760 million people still lack access to energy (IEA, 2023l). While urban centers are better connected, large regional disparities persist. For instance, most urban households in countries such as Chad, Niger and Liberia lack access to electricity (Ritchie *et al.*, 2019). While this chapter focuses on households with access to electricity, it is also crucial to acknowledge that approximately a quarter of urban residents live in slums or similar conditions with inadequate access to electricity, sanitation, water or other infrastructure (United Nations, 2023).

Many slums have access to some level of electricity, but it is often unreliable, unsafe or unaffordable. Despite their relatively low energy consumption, these households often rely on firewood and kerosene for cooking and lighting, which pose significant health risks and adverse environmental impacts. The technologies outlined in Chapter 3 (Green rural energy solutions) highlight technological solutions to address these challenges such as clean and efficient cookstoves, distributed renewable energy, solar lanterns and combined toilet and biogas solutions.

Space heating and cooling account for most global household energy use

Heating and cooling is the largest energy end-use (IRENA, 2023a). It is no surprise that colder regions consume more energy for heating, while warmer areas require more for cooling. For instance, in the European Union, space heating comprises 64.4 percent of a household's energy consumption, while only 0.5 percent is used for cooling (Eurostat, 2023). In warmer parts of the world, air conditioners (ACs) have become integral to modern society, with their demand further driven by global warming. By 2050, approximately two-thirds of households globally could own an AC (IEA, 2018a).

In 2020, greenhouse gas emissions from space cooling and refrigeration accounted for over 10 percent of global emissions

In 2020, greenhouse gas emissions from space cooling and refrigeration accounted for over 10 percent of global emissions (Dong *et al.*, 2021). While not strictly considered cooling, ceiling fans in India represent a major share of household electricity use, and more than 90 percent of households rely on them for ventilation (CEEW, 2020). This underscores regionally differentiated needs for decarbonized and efficient heating and cooling technologies.

Households' ability to influence technology choices can also differ vastly. In apartment buildings with central heating and cooling systems, residents have limited influence over the energy sources utilized and the technologies that deliver these services. Further, households' energy usage and carbon emissions are heavily dependent on choices made during design and construction phase of the building, such as insulation, heat-storing abilities (thermal mass) of walls and floors, and orientation for optimal passive solar heating and cooling.

Good design and insulation are essential, and digital tools and software can help simplify such design choices. However, installing efficient ACs and heat pumps for space (and/or water) heating and cooling can have a massive impact on a household's carbon footprint. The most efficient ACs are more than 30 percent more efficient than average ACs on the market (U4E, 2024b). In fact, heat pumps are expected to be so critical for reducing reliance on fossil fuels that the United States significantly boosted support for their domestic production through the National Defense Production Act, aiming to meet national defense and emergency preparedness needs (Casey, 2024).

For a closer look at the range of proven and innovative heat pumps, insulation and other technologies for efficient heating and cooling in cities, see the *Green Technology Book* edition on climate change mitigation, accessible here.

Greening and conserving household water use

There is a growing trend toward integrated management of water and energy, as the two are intrinsically linked (Meireles *et al.*, 2022). In Sweden for instance, around one-fifth of the energy consumption of a single-family household is typically used for domestic hot water (Swedish Energy Agency, 2024). However, the amount of energy needed to heat water is subject to a large variety depending on the country, outside air temperature, energy efficiency of the building and not least the type of technology used to produce hot water (Meireles et al., 2022).

Technologies that heat space and water are often linked, such as air-to-water heat pumps that can provide both space and water heating for radiators or underfloor heating systems. Solar thermal collectors placed on roofs of single and multi-family houses are a common option where there is abundant sunshine and high demand for hot water. These collectors can channel hot water to bathrooms and kitchens, but also be combined with heat pumps for space heating. Not all heat pumps are designed to serve taps and showers, as hot water for these must be accessed immediately on demand, in contrast with space heating. However, by adding storage tanks, heat batteries or hybrid heat pumps (which use both electricity and back-up energy sources such as a gas boiler), hot water can be provided more quickly.

Decarbonizing household water supplies is essential. Additionally, significant energy savings can be achieved through efficient water use, as municipal wastewater plants can consume up to 2 kWh of energy per cubic meter of treated water (Hamawand, 2023). Consumers are often unaware of the many household appliances available on the market, and their green features. For instance, innovative dishwashers now include soil sensors that adjust water cycles and energy use by adapting them to how dirty the dishes are. Efficient jets and improved water filtration systems can further minimize water and detergent usage.

While consumer awareness of such functionalities is important, willingness to pay for more advanced and efficient appliances is driven more by potential cost savings over time than an interest in technical features or sustainability. For instance, a survey of 1,400 urban households in Ethiopia found that 86 percent of households were driven by reduced energy expenditures when considering energy-efficient technologies and energy conservation activities, while only 12 percent did it out of concern for the environment (Hassen *et al.*, 2023).

Many low-hanging fruits for household water savings

Beyond energy- and water-saving dishwashers and washing machines, households often overlook simple and available solutions for efficiency. Readily available low-flow showerheads can halve the energy consumed compared to an old showerhead, without sacrificing pressure (Swedish Energy Agency, 2024). Faucet aerators can be attached to mix in air with water, creating a more powerful stream with less water. Meanwhile, toilet tank inserts, which can be as simple as placing building bricks or similar in the tank, displace some of the water in a toilet tank, reducing the amount of water used to flush. This has an indirect energy-saving impact, as less water needs to be treated and pumped through the system.

Another simple solution is sensor-based leak detection devices that can be attached to appliances such as washing machines and send alerts to your smartphone. However, the use of such electronics can often be avoided by simply inspecting leaks visually or listening to dripping sounds. Regardless, these technologies are only a selection of the options available to complement water-saving user behavior in households.

Currently, such choices are far from being standard, with many households experiencing barriers such as high up-front costs and lack of information and incentives. Here, subsidies, bans on inefficient technologies and information campaigns can have a positive influence on the adoption of energy-efficient and water-saving technologies (Hesselink and Chappin, 2019).

Energy-saving household appliances

The market for consumer products geared toward energy efficiency is expanding rapidly. Legislative frameworks, such as the EU energy label, minimum energy performance standards (MEPS) and "ecodesign" requirements, have demonstrated success in promoting the replacement of everyday electric appliances in some countries. While exact figures are challenging to gather, adoption rates still remain limited on a global level, and small appliances and consumer electronics continue to be unregulated in most countries (IEA, 2023a).

With the growing global demand for residential appliances, stringent policies are necessary to incentivize the adoption of best-available technologies and reduce overall electricity consumption. For instance, the best-available fridge-freezers consume 60 percent less electricity than comparable less modern products. As demand for residential refrigerators increases, their electricity consumption will continue to grow; according to some estimates by over 53 percent until 2040 (U4E, 2024a).

Many household technologies are plug-in options and easily adopted, such as smart chargers and automated timers and dimmers. Advanced power strips with built-in features reduce energy use from consumer electronics and stop them from drawing power when they are switched off. Such "phantom loads" have been estimated to cost American households billions of dollars' worth of electricity annually (NRDC, 2015).

For cooking, gas remains prevalent in urban households in developing countries (Stoner *et al.*, 2021a), while electric cooking and the more efficient induction cooktop have overtaken gas in more high-income countries. At the same time, nearly half a billion urban residents still use solid cooking fuels (Westphal *et al.*, 2017). The climate and health benefits of electric stoves are significant, but depend on the energy mix of the electricity and transmission losses, highlighting the importance of considering upstream factors in evaluating energy-efficient technologies.

LED lights – a global success story

The development and large-scale adoption of light-emitting diode (LED) lamps is a well-known success story, with residential sales rising from 5 to 50 percent between 2013 and 2022 (IEA, 2023g). At the same time, technological advances continue to make lighting even more efficient. The efficacy and quality of lighting is usually measured by the amount of light per unit of energy (usually in lumens per watt, lm/W) and the lifetime of the lamp. LED lamps typically have an efficacy of over 100 lm/W, whereas regular fluorescent lamps have between 50 and 100 lm/W. With a growing efficacy of about 4 lm/W per year, the best available options can now achieve over 200 lm/W, producing more light while consuming less energy and for a longer time (IEA, 2023g).

The development and large-scale adoption of LED lamps is a well-known success story, with residential sales rising from 5 to 50 percent between 2013 and 2022

Other areas of technological development include smart LED lighting that can be controlled remotely through mobile apps or automated through integration with other home systems for more efficient energy management. Micro-LED displays, composed of tiny LEDs, have emerged to reduce energy consumption of TV screens. Further efficiency gains are expected from white organic LEDs (OLEDs), given their ability to emit light over a large surface area without the need for additional filters and optics. They are composed of thin organic materials that emit light when an electric current is applied to them. Interesting advances are also seen in direct current (DC) lighting, that could ultimately reduce conversion losses from alternating current (AC) to DC necessary for LED lights.

Thermostats' impact hindered by user behavior

A simple thermostat can monitor a household's temperature and regulate heating and cooling. However, the technology is experiencing significant evolution. With the advent of artificial intelligence (AI), sensors and algorithms, intelligent thermostats available on the market today can perform a range of services such as energy consumption monitoring, remote control and demand predictions that help turn data into energy-saving action. This is often enabled by wireless connectivity and internet of things (IoT) technologies which allow for easy control through smartphone apps.

In terms of energy savings, the usefulness of thermostats is strongly linked to user behavior. In a simulation study, thermostats that adapt to the occupancy of residents were shown to save between 11 and 34 percent of energy without significant impacts on thermal comfort (Wang *et al*., 2020). On the other hand, field experiments from more than 1,000 households found that users frequently override temperature settings, which can lead to increased electricity and gas consumption. More specifically, users override predetermined settings with a bias toward even warmer temperatures in winter and cooler temperatures in summer (Brandon *et al*., 2022).

Further, an OECD survey reported that 52 percent of households using smart meters do not actually use the information provided to help them optimize energy use, suggesting more work is needed to address behavior change in unison with technology adoption (OECD, 2023b).

Unlocking the potential of integrated smart home systems

While the challenge of influencing sustainable user behavior deserves attention, thermostats have continued to develop even further, with some devices able to integrate with other smart home systems. Integrated systems enable other building systems such as heating, cooling and ventilation (HVAC), advanced sensors and lighting to communicate with each other to enhance performance and save energy. With the growing adoption of renewable energy technologies and decentralization of energy systems in urban areas, integration is even possible with solar panels and mini-grid systems to best balance energy use through demand–response programs and home energy management systems.

However, such smart and integrated systems are far from being widely adopted. While they have potential for energy optimization in residential buildings, they are still more common in commercial buildings. Yet, only 1 to 2 percent of US commercial buildings have advanced lighting controls (DOE, 2020).

Technologies supporting urban energy communities and "prosumers"

Inhabitants of a residential building rarely have a say in the type of energy used to produce electricity, even though 39 percent state they would be interested in a renewable option if this was available to them (OECD, 2023b). As a response, initiatives facilitating decentralized local energy production have emerged to enable the formation of energy communities.

Through collective investments and government subsidies, residents can come together to integrate renewable energy in their building's energy system and undertake citizen-led energy renovations.

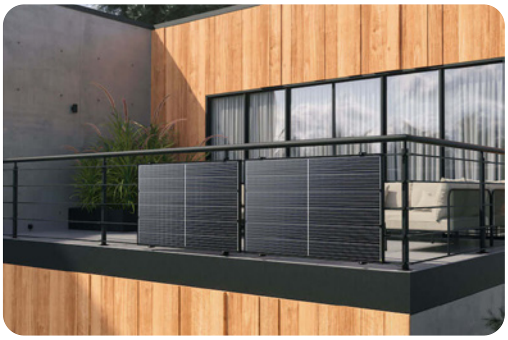
By forming energy communities to adopt renewable energy technologies and to retrofit buildings, household owners can become "prosumers" of energy rather than mere consumers.

Household owners can become “prosumers” of energy rather than mere consumers

Prosumers are also called active consumers or renewable energy self-consumers. While legislation presents barriers in many places, more countries are catching up with citizen’s demands to produce their own decentralized energy and use, store or sell that electricity back to the grid. Technologies that enable these activities typically include solar PVs, smart meters, energy storage systems, DC nanogrid systems and energy community management platforms (Menniti *et al.*, 2022).

Innovation examples

Germany’s solar balcony revolution



Source: PluginEnergy (https://pluginenergy.de/)

In Germany, a trend has emerged where individual apartment dwellers can easily purchase and set up small solar power plants on their balconies or terraces without requiring permits or installation by a tradesperson. Dubbed "Contracting type," these installations are available in retail outlets such as supermarkets, and consist of just two solar modules and a microinverter that can simply be plugged into an electric outlet (see technology example *PluginEnergy*). Owners must consume all generated electricity themselves, as it cannot be sold back to the grid. Despite their modest capacity of typically up to 600 W, they can power appliances like small refrigerators, laptops and routers. At current price levels, the payback time for such an investment can be more than six years, but it is seen as an important tool in mobilizing urban residents in the energy transition. And the collective power of these installations contributes to Germany’s renewable energy goals and reduces dependence on fossil fuels. In 2021 alone, between 140,000 and 190,000 units were sold, totaling a capacity of around 60 MW (Bergner *et al.*, 2022).

Energy-efficient injera stoves

Source: Getty Images/Goddard-Photography

Injera stoves are traditionally used in Ethiopian and Eritrean households for cooking injera, a staple food in the region. While traditional injera stoves are often inefficient and contribute to indoor air pollution, there have been efforts to develop and promote energy-efficient alternatives. In Ethiopia, the Ethiopian Rural Energy Development and Promotion Center (EREDPC) and various non-governmental organizations (NGOs) have collaborated to introduce energy-efficient injera stoves that are designed to reduce fuel consumption, minimize indoor air pollution and improve cooking efficiency. One notable project involved the dissemination of “Mirt” stoves, which are designed specifically for cooking injera. The Mirt stove incorporates innovative features such as insulated cooking surfaces, improved combustion chambers, and chimney vents to enhance heat retention and airflow, resulting in more efficient combustion of biomass fuels. The implementation of Mirt stoves was accompanied by community training programs to educate households on proper stove usage and maintenance practices (Energypedia, 2024).

Building–vehicle integration in Chinese cities

Source: Beijing Shiji Yunan New Energy Co

China’s rapid adoption of EVs has placed it at the forefront of global efforts to transition to greener transportation. As of 2022, nearly a quarter of all new cars registered in China were electric or plug-in hybrids, outpacing Europe and the United States. This surge is driven by ambitious government policies, including a five-year plan aiming for 2 million EVs on the road by 2025. However, this swift growth presents challenges, particularly in residential areas where charging infrastructure is often inadequate. In Beijing, a local property management company faced a significant challenge at one of their locations at Yuanda Park, where just 30 charging units served 400 parking spaces across 600 households. The company needed a scalable solution to accommodate the growing demand for EV charging without overloading the existing power grid. Partnering with Beijing ShijiYunan New Energy Co., Ltd, they implemented an innovative technology that optimizes power distribution within the building. Their platform integrates charging piles with the building’s existing power load, allowing for real-time adjustments and efficient energy use without requiring costly grid upgrades. Facilitated by the WIPO GREEN China Cities Acceleration Project, this solution has already shown promising results at Yuanda Park, demonstrating the potential for broader adoption both in China and globally.

Technology solutions

Proven technologies

Energy efficiency: energy-saving water heat pump
Guangdong PHNIX Eco-energy Solutions Ltd.

Source: Getty Images/Douglas Cliff

The “all-in-one” hot water heat pump is an energy-efficient domestic heat pump which can provide stable and reliable hot water with lower energy costs. The PHNIX R290 hot water heat pump with smart grid (SG) functionality uses smart meters to receive signals from power companies, allowing them to operate during times of low-cost energy and avoid high-cost periods. The heat pump uses a natural refrigerant with low global warming potential (GWP) and is compliant with EU standards for energy efficiency.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: smart thermostat for water-based heating systems
Ngenic

Source: Ngenic

Ngenic Tune is a smart thermostat for household use which consists of three digital components that gather information on weather, indoor and outdoor temperature, humidity and sunlight. The data enable optimization of your home’s heating system according to a preferred preset temperature entered into an app. The app also makes it possible to plan energy savings while you are on holiday and restore it automatically upon return.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Sweden
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: ultra-efficient LED lighting
Philips

Source: Getty Images/zhudifeng

Philips ultra-efficient LED light series claims to consume around 40 percent less energy than conventional LED bulbs and were the world's first commercially available 200 lm/W LED lamps. Lumens per watt is a useful metric to compare the brightness of a light bulb to its energy consumption, with a higher value indicating greater efficiency. Typical LEDs perform at around 85 lm/W, while typical incandescent lights are around 16 lm/W. Further, the lifespan of the ultra-efficient LED lamps is 3.5 times longer than conventional LED lamps. These lamps were previously known as the Dubai Lamp, as it was developed in collaboration with the Dubai Municipality where it was previously exclusively available.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: The Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: tumble dryer with heat pump technology
Gorenje

Source: Gorenje

The most energy-efficient way to dry clothes is by simply hanging them up to dry. But for households that have space limitations or prefer the use of a tumble dryer, heat pump tumble dryers can save up to 50 percent energy compared to conventional dryers by way of heat recovery. Heat is extracted from the air within the drum and transferred to a condenser. Here, a refrigerant is compressed, causing it to release heat which is then used to warm incoming air. Operating under lower temperatures, the wear- and-tear on clothes is also lower.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Slovenia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy generation: balcony plug-in solar modules
PluginEnergy

Source: Plugin Energy

PluginEnergy provides balcony power plants in the form of plug-in solar modules. The products consist of combined solar modules and an inverter that allows you to plug the system into a wall outlet. Specially developed brackets, which can also be customized, allow you to hang the solar modules from a balcony railing. Up to four solar modules can be combined totaling around 600 W. Different products are available depending on the household's energy consumption, to cover power needs such as refrigerator, WiFi routers, laptops and microwaves.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Germany, Austria
- Contact: WIPO GREEN Database

Energy generation: non-electric slow cooker
Wonderbag

Source: Wonderbag

The Wonderbag is a non-electric slow cooker shaped like a thick textile jacket that is wrapped around pots of food. Food is first heated on a stovetop to reach desired cooking temperature. The food is then transferred to the Wonderbag where the insulating material traps the heat from the pot for as long as possible in order to slowly cook the food. Heat can take up to eight hours to dissipate completely, which is very beneficial in a context of soaring energy prices and carbon emissions.

- Contracting type: For sale
- Technology level: Low
- Country of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier

Energy efficiency: AI-enabled intelligent thermostat
Ecobee

Source: Getty Images/zhudifend

Intelligent thermostats are more advanced versions of smart thermostats, making use of AI, sensors and machine learning algorithms. In addition to monitoring and controlling temperatures, they can also analyze energy consumption patterns, resulting in further optimization and energy savings. Ecobee's ECO+ thermostat consists of five different features including detection of fluctuations in indoor humidity, a scheduling assistant and an automatic detection of when you are not at home, adjusting temperature and saving energy. In addition, intelligent precooling and preheating targets times during the day when electricity is less expensive, and reduces heating and cooling when electricity is costlier.

- Contracting type: For sale
- Technology level: High
- Country of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: glass coating on windows to filter solar radiation
FUMIN CO., Ltd.

Source: FUMIN CO., Ltd.

Households often overlook window insulation, although there are many accessible solutions available on the market in the form of thermal windows, spray foam, films, thermal curtains etc. A new patented innovation developed by FUMIN CO., Ltd. is a film that is applied using a spray gun. It forms an even layer of conductive metal oxide on the glass surface which absorbs and blocks infrared and ultraviolet rays, reducing the need for cooling on hot days.

- Contracting type: For sale
- Technology level: Low
- Country of origin: Japan
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: aerogel additives to give insulating properties to roofs, floors and panels

Svenska Aerogel

Source: Svenska A erogel

Aerogels are a type of synthetic porous material derived from a gel. Air bubbles are captured in the gel material, giving them low density and low thermal conductivity, and thereby good thermal insulation properties. Silica aerogels are the most common type of aerogels. They can for instance be reinforced with fiber to create insulation boards that can reduce thickness by about 50 percent compared to conventional materials, making them suitable in dense urban areas. Swedish company Aerogel has developed the novel material Quartzene®, a variation of the classic aerogels which can be applied as an additive to give materials thermal insulating and energy saving properties. The porosity of the material creates an effect known as the Knudsen effect, in which air molecules collide with the pore wall instead of other air molecules, resulting in a highly insulating effect.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Sweden
- Availability: Europe, Asia, North America
- Contact: WIPO GREEN Database

Energy efficiency: water-and energy saving shower sensor

Aguardio

Source: Aguardio

Danish company Aguardio has developed sensors that are easily installed in bathrooms to help monitor leaking toilets and save energy and water from showers. Up to 30 percent of hot shower water can be saved using smart IoT sensors. The sensors can be easily installed without any need to change existing bathroom fixtures. They can integrate with smart building systems and send data to an online cloud using mobile phone networks. Making the data visible also creates a gentle nudging effect toward behavioral change. The solution can be of particular interest for housing complexes, lowering utility costs for tenants.

- Contracting type: For sale
- Technology level: Medium

- Country of origin: Denmark
- Availability: Denmark, United Kingdom
- Contact: WIPO GREEN Database

Energy efficiency: battery-connected induction stove
Channing Street Copper

Source: Channing Street Copper

Induction stoves are up to three times more efficient than gas stoves, and up to 10 percent more efficient than conventional electric units. However, switching from a gas stove to an induction stove can require costly installations and wiring, as induction stoves use high power intensity not provided by normal domestic power outlets. This solution adds energy storage to induction stoves to enable them to more easily adapt to existing infrastructure. The stoves can load up on ordinary power supply continually over time, then tap into their battery power to deliver the surges needed for high-intensity cooking. This dynamic is similar to how electric-vehicle chargers are paired with batteries. Overcoming the barrier of costly installations can enable more homeowners to switch to efficient stoves.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: United States
- Contact: WIPO GREEN Database

Energy efficiency: DC lighting
Microsens

Source: Microsens

DC lighting refers to lighting systems that use a DC electrical supply, which may or may not involve LEDs. As power grids distribute AC, most power outlets will provide AC. This means LED fixtures and other appliances that use DC such as microwaves need to convert AC to DC. During such conversions, energy can be lost in the form of heat. If LED lighting could be supplied with DC directly, inefficient AC to DC conversions could be avoided. Microsen's DC Smart Lighting System is a central smart lighting controller which can convert AC to DC and control up to 24 connected LED lamps. The system has the added benefit of being able to connect to sensors to receive input signals related to brightness, presence, temperature and humidity. Being connected to a data network, it integrates with other building systems such as HVAC.

- Contracting type: For sale
- Technology level: High
- Country of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: tailor-made insulation panels
Ecoworks

Source: Getty Images/vitranc

A German startup has developed an insulation technology that provides tailor-made insulation panels that wrap around old buildings like a second "skin," reducing heating bills and GHG emissions. The company uses laser scanning technology to first create a digital twin (virtual model) of the building. Prefabricated panels are then made of wood, with cellulose used for the insulation. The total installation process can take as little as three weeks.

- Contracting type: For sale/service
- Technology level: High
- Country of origin: Germany
- Availability: Germany
- Contact: WIPO GREEN Database

Horizon

Energy efficiency: shower tray energy recuperator
Cerian Shower LS

Source: Cerian Shower LS

A shower tray can help direct the flow of water to the drainage point in your bathroom. Cerian Shower LS has developed an innovative shower tray which not only directs water, but also helps recuperate up to 40 percent of the energy used to warm up the shower water through a simple heat exchanger in the shower tray. As heated water from the shower passes over the heat exchanger, it heats up fresh cold water to 25 degrees Celsius. The water then mixes with even hotter water from the network to produce a final comfortable temperature for use in the shower. The shower tray can be easily installed during new construction or renovations.

- Contracting type: Under development
- Technology level: Medium
- Country of origin: Spain
- Availability: N/A
- Contact: WIPO GREEN Database

Energy efficiency: a fridge powered by magnets
Camfridge

Source: Camfridge

Magnetic cooling technologies have been the interest of researchers for quite some time, driven by a need to reduce energy consumption and phase out refrigerants. Camfridge is a private company founded at the University of Cambridge, which has invested over USD 19 million in the development of magnetic cooling technology. The company has now developed a simple, low-cost magnetic cooling system which consists of a solid-state magnetic chiller, heat exchangers and natural fluids for transporting heat. This avoids the need for harmful refrigerant gases. While the company currently collaborates with large end-users, the concept itself has so far been tested on a standard mass-produced fridge cabinet.

- Contracting type: Under development
- Technology level: High
- Country of origin: United Kingdom
- Availability: N/A
- Contact: WIPO GREEN Database

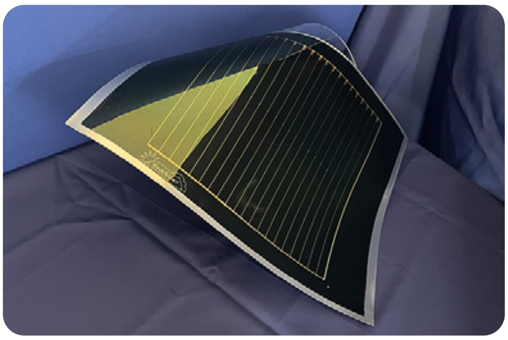
Energy efficiency: hot water storage for showers
Heaboo

Source: Getty Images/onurdongel

The Hoterway is a thermal battery that acts as a heat exchanger. It enables hot water to be available from the taps instantly, reducing wait time and associated water waste. It uses a phase-change material that instantly releases heat to the piped water as it transitions from liquid to solid. Once hot water (≥50 °C) arrives from the central or district heating unit, the process reverses, and the thermal battery material returns to its liquid, energy-storing phase. The heat preservation system experiences less than 20% heat loss over 24 hours. This is a completely reversible physical process, ensuring that the equipment does not degrade over time. The battery has a guaranteed lifespan of 20 years.

- Contracting type: N/A
- Technology level: High
- Country of origin: Portugal
- Availability: Portugal
- Contact: WIPO GREEN Database

Energy generation: Perovskite solar cells for housing
Mitsui Fudosan Residential Co., Ltd.



Source: Mitsui Fudosan Residential Co., Ltd.

Mitsui Fudosan Residential Co., Ltd. and EneCoat Technologies Co., Ltd., a spin-off company from Kyoto university involved in development of high energy efficient Perovskite solar cells, have partnered to conduct joint research on integrating Perovskite solar cells into housing. This collaboration, in conjunction with Kyoto University's Wakamiya Lab, aims to accelerate the practical application of Perovskite solar technology in residential environments. Perovskite solar cells are being researched for their high efficiency, thin and lightweight structure, and lower production energy requirements. They offer a cost-effective alternative to traditional silicon-based cells. The project will test these cells in Mitsui Fudosan's apartments, incorporating them into well-designed lighting and furniture in the common areas as well as in the interiors of condominiums it supplies, to store solar energy during the day for use at night.

- Contracting type: N/A
- Technology level: High
- Country of origin: Japan
- Availability: Japan
- Contact: WIPO Green Database

Green solutions for public spaces and infrastructure

Public spaces and infrastructure, such as streets, parks, roads and public buildings, are enjoyed by everyone. Energy is essential in this context to power streetlights, commercial buildings and transport networks, facilitating the movement of people and goods. Beyond progressive policy measures, cities and urban planners can adopt both proven and innovative technologies to accelerate the energy transition. This chapter explores the intersection of energy consumption, technological innovation and renewable energy integration into the public sphere.

Technological developments and trends

Energy efficiency in public buildings

Energy solutions for public and private buildings often overlap, whether they involve technical, operational or behavioral interventions. Updating building codes is essential for improving energy efficiency in buildings. Key technical improvements include better insulation, energy-efficient lighting, advanced HVAC systems, renewable energy integration and demand response programs. However, public facilities such as swimming pools, sports centers and malls also operate under unique conditions that significantly contribute to energy consumption, bringing about their own set of challenges and solutions.

Swimming pools, for example, consume enormous amounts of energy for heating, pumping and cleaning pool water. Supermalls have significant electricity demands for temperature control, lighting and escalators. Hospitals need extensive ventilation systems to ensure a healthy indoor environment, while supermarkets primarily consume energy for refrigeration (see Chapter 4). Targeted innovations aim to improve the energy efficiency of these activities. In Poland, combining insulation, heat recovery and solar panel installations reduced a public school's heat consumption by 60 percent (Barwińska-Małajowicz *et al*., 2023). In Greece, retrofitting a swimming facility with a solar-combi system, heat storage tank and back-up heat pump is expected to save over 77 percent of the energy used for hot water production (Katsaprakakis *et al*., 2023).

Renewable energy integration in public spaces

Installing solar panels and wind turbines diversifies the energy mix of public buildings. The new EU Solar Energy Strategy aims to make rooftop solar energy installations compulsory for all new and existing public and commercial buildings over 250 m2 by 2027. This strategy also promotes innovative solar deployment models such as floating PV systems on lakes and solar panels on highways and railways. Similar initiatives are underway globally, such as in China where provinces are encouraged to install solar on 40 percent of public buildings like schools and hospitals (Ye, 2023).

Innovative governance structures such as municipality-led renewable energy communities can be effective tools for scaling renewables in public buildings, such as the case of solar PV installations on two school rooftops in Crete (Barwińska-Małajowicz *et al*., 2023). Beyond rooftops and parking spaces, technologies such as building-integrated PVs are exploring novel surfaces for solar energy generation. While the construction sector is yet to take up the challenge, some countries have taken steps to support innovative use of surfaces through their national energy frameworks (European Commission, 2022). Solar pavement technology, on the other hand, does not yet appear to be able to withstand the effects of traffic loads while providing efficient electricity (Hu *et al*., 2021).

Higher integration of renewables in public buildings and infrastructure invariably has an impact on the electricity grid. In addition, energy losses occur when converting solar energy from DC to AC to feed into the grid, and then back to DC again to be stored or used. M\any systems, including batteries, operate on DC. Therefore, further research and development (R&D) and innovations in conversion efficiencies, such as better-performing inverters, are essential to further enable renewable energy integration at building level (European Commission, 2022).

Efficient and intelligent streetlights

Streetlights installed around the world already account for around 15 percent of global energy demand and this is expected to rise further (Agramelal *et al*., 2023). The need for enhancing efficiency of public spaces has led to emerging innovations in LED technology, intelligent streetlight systems, solar lamps and integration with EV charging stations.

While they are undoubtedly more efficient, the wide-scale impact of LED streetlights is uncertain. For instance, recent findings suggest that white LED streetlights can harm biodiversity. The light, particularly white light, disrupts insects' circadian rhythms, reducing certain insect populations by over half compared to 42 percent for conventional sodium streetlights. However, this issue can be mitigated by dimming and using blue-light filters (Boyes *et al*., 2021).

Recent advances have upgraded smart streetlights from basic to more advanced adaptive control systems with sensors and cameras. Examples include sensors that can detect light, traffic and electrical consumption. By gathering and analyzing such data, streetlights can use dimming functions. Alternatively, they can be turned off late at night or based on scheduled or real-time lighting needs, potentially reducing energy use by up to 80 percent (Gagliardi *et al*., 2020).

Smart streetlights can be decentralized, with local control at each pole, or centralized, integrated into IoT communication networks for data collection and central control (Omar *et al.*, 2022). This has enabled developments where monitoring devices are integrated with streetlamps to gather data on temperature, rain, humidity and air quality, providing dual functions in terms of lighting and environmental monitoring. Innovations for streetlight connectivity and energy monitoring can further help enable a more balanced grid load and integration with demand response programs. However, these solutions face high up-front costs, technical complexities and data security issues (Agramelal *et al.*, 2023).

Harnessing the power of movement

Over the last decade, unconventional climate solutions for public urban spaces have emerged. As cities are full of movement, energy can be harvested in innovative ways. Regenerative braking systems, which convert kinetic energy into electric energy for trains and metro systems, is already a mature technology and can restore up to 25 percent of a train's energy (Ahmad *et al.*, 2022). Other emerging innovations include energy-generating playgrounds, kinetic energy pavements and piezoelectric tiles that can generate energy from pedestrians or from dancers in a club.

One study examined piezoelectric energy harvesting in an Australian public library, finding that tiles covering 3 percent of the floor area could only meet 0.5 percent of the building's annual energy needs. With the then high up-front costs (USD 3,850/tile), the technology would not have been a feasible solution (Li and Strezov, 2014). However, the efficiency of such tiles have improved, and they hold potential as complementary energy sources, harvesting energy from floors, pavements and roads (Sharma *et al.*, 2022).

Energy can also be harvested from urban heat. Austrian researchers have shown promising results by absorbing excessive heat from buildings and roads. Installing flat absorber lines that collect urban heat and feeding it into a borehole thermal energy storage can provide heat to nearby buildings while mitigating the urban heat island effect (Energy Innovation Austria, 2022).

Improved planning for public transport[1]

The "avoid, shift, improve" framework describes the broader strategies a city can adopt in order to plan for more low-carbon public transport. These include (i) avoiding unnecessary travel, (ii) shifting unavoidable travel demand to more efficient modes of transport, and (iii) reducing the GHG intensity of technologies used to meet the demand for travel (UDP, 2021).

The COVID-19 pandemic highlighted the effectiveness of remote work in reducing travels. Key technologies that have supported this shift include digital communication tools, teleconferencing systems, and integrated land-use planning software designed to foster livable, work-friendly neighborhoods. However, estimating the overall impact of teleworking on energy consumption remains challenging due to potential rebound effects like increased home energy use (EEA, 2023).

Designing dense, mixed-use areas, enhancing access to public transport and planning interconnected street networks can help avoid unnecessary travel

1 The previous two editions of the Green Technology Book include a chapter on smart mobility that delves more into the topic of low-carbon transport, and urban infrastructure and services that presents further perspectives on climate adaptation of road networks.

The density, diversity and design of urban spaces are particularly critical for minimizing unnecessary trips and fuel consumption. For instance, designing dense, mixed-use areas, enhancing access to public transport and planning interconnected street networks can help avoid unnecessary travel. Developing such urban environments typically leads to lower per capita emissions, reduced reliance on motorized transport and decreased building energy demands (ESMAP, 2014; Hoornweg *et al*., 2020). For instance, while New York and Denver are both cities in the United States, average emissions for New York residents are half those for Denver, mainly due to the greater density and public transport availability in New York (Ramaswami *et al*., 2008).

Fast-growing, poorly planned cities with low-income populations often face severe congestion, inadequate infrastructure and limited accessibility to essential services like public transport. The high transport costs and safety issues further exacerbate socio-economic inequalities. These challenges require coordinated urban planning and substantial investments into public transport infrastructure. While this involves a range of enabling policies, infrastructure and investments, there is an increasingly important role played by innovative technologies such as mobile apps for real-time tracking, digital ticketing and route planning that can alleviate and contribute to efficient, affordable and safe public transport systems.

Digital technologies promote accessible public transport

Global public transport capacity must double by 2030 if the world is to limit global warming to 1.5°C. Despite growing access, many urban areas still experience that less than 10 percent of the public has convenient access to public transport (Welle *et al*., 2023). Technology can enhance the efficiency, access and use of public transport in a number of ways.

Aggregated data from mobile ticketing and fare collection can help operators improve route and time-table planning. Innovations in mobile apps and data analytics provide real-time information on transport routes, allowing individuals to plan their journeys more efficiently. Integrated applications make it possible to not only purchase fares on buses, but also layer in parking tickets, e-scooters, trams and other modalities. Smart ticketing systems, with multi-trip options, further enhance access to public transport for women. As women more often bear responsibility for tasks involving health care, educational institutions and purchases, they tend to favor shorter, flexible trips to these various institutions rather than direct transport to and from any given workplace (Ng and Acker, 2018).

A better and more seamless user experience can further help promote the use of public transport. Innovative technologies such as e-fare validators and near-field communication (NFC) can be used by transport companies to activate tickets purchased through mobile applications, eliminating the need for physical interaction with drivers. Transport cards with NFC technology have even enabled subway passengers in Shanghai to connect to an app, which generates carbon credits when the card is swiped (Min, 2023).

Distributed ledger technology, such as blockchain, enables permanent records of transactional data through a centralized database. One function of this technology, relevant for public transport systems, is its ability to optimize supply chains and inventory management. A recent focus has been on the potential of blockchain to improve urban mobility through mobility-as-a-service (MaaS) solutions such as ridesharing. This includes for instance elements of smart contracts between users, safe exchange of information and payments that are automatically triggered upon verification of preset conditions (IUTP, 2022).

Optimizing traffic flows in cities

Fuel consumption in cities can also be reduced by optimizing traffic flows to avoid congestion and idle time spent in vehicles. Smart traffic lights and intelligent transportation systems (ITS) have become game-changers for several cities. Meanwhile, advances in cooperative ITS (C-ITS), which facilitate communication between vehicles and systems, can improve driver safety during extreme weather conditions (Mitsakis and Kotsi, 2019).

Sensors, AI and machine learning are often integral components to ITS for traffic optimization. Innovators and city officials are testing new adaptive traffic control systems to reduce journey times and fuel consumption. Examples include systems that use video feeds to automatically detect the number of road users, pedestrians and type of vehicle at an intersection. AI software then processes this information in real time to optimize the traffic flow, sharing the information with neighboring intersections for autonomous decision-making.

The impact of connected autonomous vehicles (CAVs) on fuel consumption and climate change is yet uncertain. Private and public fleets of self-driving cars *could* reduce fuel consumption by connecting with traffic systems and adjusting speeds to avoid idling at intersections. Research on machine-learning is exploring the control of entire fleets of AVs as they move through intersections and traffic (Zewe, 2022). By some estimates, CAVs could reduce GHG emissions by up to 34 percent of total transport emissions by 2050 (Ercan *et al.*, 2022). On the other hand, models also estimate that the computational power required to power self-driving cars could equal the total carbon footprint of a country such as Argentina, if widely adopted (Zewe, 2023).

Autonomous public transport

With human error being the main cause of traffic accidents, safety is driving the push for autonomous public transport (or shared autonomous vehicles, SAVs). However, automated shuttles, robot buses, driverless trains and other autonomous transport options are also considered for improving efficiency in and accessibility to public transport, especially in low-density cities. Another important function is providing first- or last-mile connectivity, with on-demand services (EEA, 2023). The recent introduction of autonomous buses in a Scottish city is expected to reduce fuel consumption by 20 percent, enabled by an integrated intelligent traffic system. AI and machine learning technology are key enablers of automation, supplemented by lidar, radar and camera sensors to detect traffic (CAVForth, 2024).

Despite these advances, low public acceptance of AVs poses an important barrier (Goldbach *et al.*, 2022). Autonomous public transport may be more appealing for shorter, quicker and cheaper trips (Alessandrini *et al.*, 2014; Winter *et al.*, 2019). While some cities have piloted autonomous buses, their market share is currently negligible (EEA, 2023). Further technological development is needed, and it is still uncertain if full automation without a back-up driver will be technically feasible (Schmidt *et al.*, 2021). Additionally, there is a risk that autonomous buses could replace walking or cycling instead of reducing private car use (EEA, 2023).

Electrifying public transport

While metro rail and light rail transit primarily rely on electricity, most buses worldwide continue to operate on diesel or other fossil fuels. In 2021, electric buses comprised only 4 percent of the global bus fleet, despite a 40 percent growth in sales (Welle *et al.*, 2023). China is leading the market, and in Finland 75 percent of bus sales in 2022 were electric (IEA, 2023e). India, in turn, plans to deploy 50,000 electric buses by 2030, equal to the total global sales of electric buses in 2023 (Konda, 2023; IEA, 2024e).

Bus electrification has been spurred by innovations in battery technology, battery-swapping stations and vehicle-to-grid solutions

Bus electrification has been spurred by innovations in battery technology, battery-swapping stations and vehicle-to-grid (V2G) solutions – the latter with particular promise for electric school buses. But high initial costs and lack of charging infrastructure present barriers to scaling (Ribeiro *et al.*, 2024). The surge in critical mineral demand is also causing widespread water shortages, land grabs and ecosystem destruction (Lakshman, 2024; Lawal, 2024; Kaunda, 2020). Recent advances include new battery recycling techniques, ultra-fast-charge electric buses with hybrid back-up and innovations that enable electric buses to function under more challenging circumstances. These include advanced systems for air heating and cooling that adapt electric buses to cold northern climates, and battery-charging solutions that enable charging in urban centers with weak grid systems.

Hybrid buses are a mature alternative for when charging infrastructure is inadequate, with the market witnessing a shift toward plug-in hybrid buses and introduction of hydrogen-fuel-cell-powered hybrid buses. In developing countries, integrating electric buses with infrastructure like bus rapid transit (BRT) systems can accelerate the transition. For example Dakar, Senegal, has implemented Africa's first all-electric BRT system (see innovation examples below) (Chen *et al*., 2023). Urban transport is also seeing innovations such as solar panels on bus, tram and train stations, or even solar integration directly onto buses. India has pioneered solar energy in rail systems, and London has implemented a system to recover waste heat from the underground metro system to provide heating and hot water to over 1,350 homes (see innovation examples).

To maximize the positive impact of public transport, coordination is needed with the promotion of private EVs. For instance, Norway achieved a 93 percent EV share for new vehicles in 2023. While this has potential for climate mitigation, there are also serious concerns over potential ways in which EVs could undermine public transport investments and the development of dynamic car-free urban centers. In Norway, public transportation budgets were partly funded through road tolls that national government exempted EV owners from paying. As more EVs were purchased, falling transit revenues threatened major investments like metro lines. While this is a policy design concern, it is clear that modal shift must be supported alongside electrification efforts so as not to stimulate further car use. Also, more than half of Norwegian households owning battery EVs were found to have three or more of these vehicles in 2022, indicating an uneven accumulation of this technology amongst the wealthiest (Qorbani *et al*., 2024).

Innovation examples

Electric BRT network in Senegal

Source: Getty Images/IgorSPb

BRT systems with designated lanes and specifically adapted stations are relatively low-cost and flexible alternatives for relieving traffic problems in urban areas. They are especially common in countries in Latin America and Asia but are growing in popularity in Africa. Dakar, Senegal, has recently launched Africa's first fully electric BRT system, stretching over 18 km. The system aims to transport 300,000 passengers daily, cutting travel time from 95 to 45 minutes. It features 144 electric buses, each with a 560 kWh battery capacity and a six-hour charging time. Further, real-time bus monitoring has been incorporated in order to optimize charging based on passenger demand.

Solar panels on highway sound barriers in the Netherlands

Source: Rijkswaterstaat and Heijmans

The Solar Highways project, led by the Ministry of Infrastructure and Water Management in the Netherlands, integrates innovative double-sided solar panels into noise barriers along motorways. This dual-purpose barrier mitigates traffic noise while generating renewable electricity. Constructed along a 400 m stretch, the solar barrier was completed in early 2019 and supplies electricity to 40–60 households. It is expected that if the installation of solar panels on highway sound barriers were to be replicated throughout the country, it could generate enough electricity for 250,000 households (European Commission, 2022).

Waste heat recovery from London Underground station

Source: Islington Council

The Bunhill 2 Energy Centre, a pioneering energy facility in London, now provides heating and hot water to over 1,350 homes, a school, and two leisure centers by utilizing waste heat from the London Underground. This project is the first of its kind and offers a model for decarbonizing urban heat supplies, reducing both heating costs and carbon emissions. The center extracts warm air from the Northern Line tunnels and transfers it to a 1.5 km network of underground pipes to heat local buildings. Additionally, it generates low-cost, green electricity for the London Underground and a nearby tower block. A key feature of the system is its ability to reverse the fan direction in summer, providing cooling to the Tube tunnels. The system reduces heating costs for connected council tenants by 10 percent and cuts CO_2 emissions by 500 metric tonnes annually (Lagoeiro *et al.*, 2024).

Technology solutions

Proven

Energy efficiency: electric buses
Roam

Source: Roam

Roam is an electric mobility company based in Kenya that designs and develops electric motorcycles and buses for emerging markets. The company offers infrastructure, fleet management software and after-sales services along with tailored solutions to local market demand. Business segments include Roam Transit which provides mass transit and shuttle electric buses for public transport in Kenya and other African countries. Roam Energy & Charging is another segment of the company that distributes energy and charging products, while Roam Canopy delivers customized software applications for fleet owners, business operators and financiers. The electric buses are produced in Kenya.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Kenya
- Availability: Africa
- Contact: WIPO GREEN Database

Energy supply: solar streetlights
HeiSolar

Source: HeiSolar

The solar street light system converts solar energy into electricity during the day, which is stored in a lithium battery to power the light and camera at night. The camera captures images and videos, transmitting data via the internet for remote live streaming on apps or personal computers (PCs), and storing them on an SD card or online cloud. This innovative solar-powered system combines lighting and surveillance, featuring a choice of WiFi cameras and a 4G dome camera option. The solar panel (70–120 W) supports a 30–60 W LED light with motion detection, all powered by a rechargeable lithium iron phosphate battery. Applications include parking lots, parks, streets, security perimeters, hospitals, bridges, airports and industrial areas.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

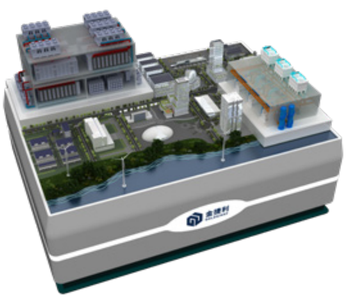
Energy efficiency: energy-saving public pool
Sunny Shark

Source: Getty Images/email2ying

Sunny Shark's Smart Pooling® solution is an intelligent control tool that reduces the energy consumption of public pools by up to 30 percent with less than three years return on investment on average. A combination of hardware and software tools manage all energy-intensive equipment at pool facilities through sensors, a centralized control box, a link to the building's building management system (BMS) and a user interface. Energy is saved through the system's predictive capabilities in terms of heat demand, and steering for control of temperature, humidity, filtration and ventilation rates across pre-defined and monitored time schedules and activities.

- Contracting type: For sale
- Technology level: High
- Country of origin: France
- Availability: Europe
- Contact: WIPO GREEN Database

Energy efficiency: energy-saving optimization of central air conditioning and water
Goldginny

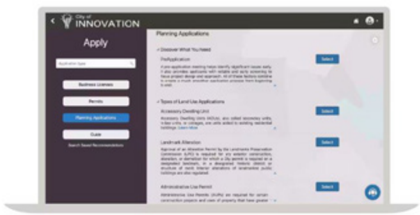


Source: Goldginny

Jinjieli's digital platform deploys an advanced central system for optimizing and maximizing the energy efficiency of entire air-conditioning systems, including chillers, refrigeration pumps, cooling pumps, cooling tower fans and electric water valves. The system dynamically adjusts optimal energy-efficiency control parameters in real time based on varying outdoor conditions and system loads. This comprehensive approach ensures system control, minimizes losses and achieves energy savings while maintaining comfort. It is currently compatible with a wide range of mechanical and electrical equipment brands and supports various equipment communication protocols.

- Contracting type: For sale
- Technology level: High
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy supply: software for planning of livable work-friendly neighborhoods
Oracle



Source: Oracle

Oracle's planning and zoning software is designed to manage community land use, promoting the development of livable and workable neighborhoods. The technology provides the public with a self-service experience, enabling online application submissions, fee payments and plan revisions ahead of public hearings. It also equips staff with tools to efficiently manage applications, schedule hearings and expedite approvals, streamlining the entire planning process.

- Contracting type: For sale
- Technology level: High
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier

Energy supply: solar-equipped buses
Sono Motors

Source: Sono Motors

The Solar Bus Kit is a ready-to-install solution designed for buses, providing solar energy to power electrical systems like HVAC and for charging the vehicle battery. It can generate up to

2,000 kWh per bus annually. This integration can achieve fuel savings of 3 percent or more, depending on the region, addressing high energy demands, rising diesel costs and urban pollution challenges in public transport.

- Contracting type: For sale
- Technology level: High
- Country of origin: Germany
- Availability: Germany
- Contact: WIPO GREEN Database

Electrification: level-4 autonomous bus

King Long United Automotive Industry Co., Ltd

Source: Getty Images/Kinwun

AVs are often categorized in 5 levels depending on the degree of automation, with Level 1 representing the most basic features such as cruise control. King Long Bus on the forefront when it comes to transport innovations such as intelligent, networked, electric and shared vehicles. In recent years, the company has developed and tested China's first Level 4 autonomous buses, the *robobuses*. The buses operate with a speed of 40–60 km/h. Equipped with lasers, cameras and so-called vehicle-to-everything (V2X) technology, the buses can communicate real-time information with smart roadside units to navigate traffic and enhance efficiency.

- Contracting type: For sale
- Technology level: High
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Electrification: robotic swapping stations for electric buses

SUN Mobility

Source: Getty Images/zssp

Present in 18 cities in India and growing, SUN Mobility offers battery swapping stations for electric buses, two-wheelers and three-wheelers. The swapping stations are equipped with a robotic arm and IOT computing unit to enable analytics and remote interventions. The stations cater to lithium-ion batteries and compared to the four to eight hours of conventional charging times, buses can swap batteries at these automated stations in under three minutes. Each swapping station can do more than 300 swaps per day.

- Contracting type: For sale
- Technology level: High
- Country of origin: India
- Availability: India
- Contact: WIPO GREEN Database

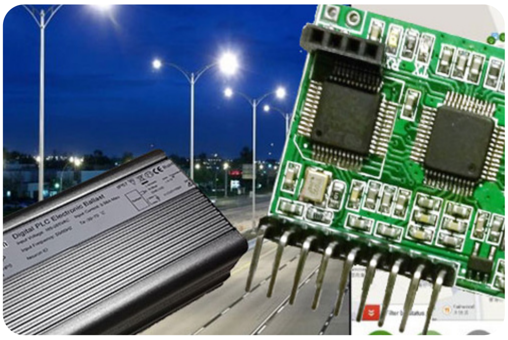
Energy efficiency: intelligent traffic management
Miovision

Source: Getty Images/Blue Planet Studio

Miovision Surtrac is a centralized intelligent traffic management system powered by AI that adapts to changes in traffic in real time. It is optimized for complex urban grid networks, not only single corridors, and can integrate vehicles, pedestrians, buses and bicycle traffic flows. In addition, the system has been designed to accommodate CAVs. Surtrac optimizes traffic signals according to the number of vehicles on the road, reducing congestion and fuel consumption. According to the technology providers, waiting times at intersections can be reduced by over 40 percent.

- Contracting type: For sale
- Technology level: High
- Country of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: intelligent streetlights
gridComm

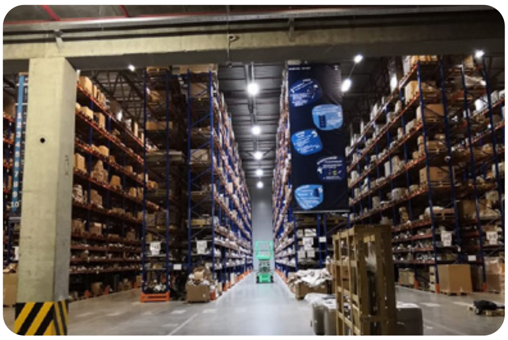


Source: gri dComm

gridComm provides networked and intelligent streetlights connected to IoT sensors across urban areas. The process of installation is simple and involves opening the street light hatch, installing a gridComm controller, and repeating this for all the streetlights you want to connect in the city. Each module communicates data through the city's power lines. This network is then used to connect thousands of sensors that monitor weather, pollution and traffic. Connecting the sensors to a streetlight control software enables significant electricity savings for cities.

- Contracting type: For sale
- Technology level: High
- Country of origin: Singapore
- Availability: Worldwide
- Contact: WIPO GREEN Database

Lighting: lighting control sensors for parking areas, ports, streets and parks
Intelar



Source: In telar

While passive infrared sensors (PIRs) are prevalent in smaller enclosed settings, such advanced lighting sensors for large spaces such as underground parking areas, ports and warehouses can be expensive. Intelar provides long-range motion sensors (K2150 sensors) suitable for spaces up to 3,000 m2 that can monitor and control lighting and security systems by reacting to moving objects. For instance, the sensors can be used for cities' smart street projects to automate pedestrian crossings and enhance energy-efficient lighting of buildings and streets.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Montenegro
- Availability: Worldwide
- Contact: WIPO GREEN Database

Smart energy: vehicle to building integration
Beijing Shiji Yunan New Energy Co.

Source: Beijing Shiji Yunan New Energ y Co.

This technology offers a solution for vehicle to building integration for property management companies. It dynamically matches clusters of charging stations with building power loads, optimizing the use of existing power resources. The goal is to enable EV owners to charge their vehicles conveniently, safely and affordably at home, without needing to increase the original power capacity. The system involves a one-time installation of charging infrastructure, followed by the addition of charging terminals as demand grows, all managed through a unified system based on the building's power load. Technologically, this solution includes two main innovations. First, an intelligent energy management system uses data planning, collection and analysis to make the most of the existing power load and meet increasing customer demands. Second, a multi-energy interconnected and coupled smart micro-grid is developed to flexibly balance energy supply and demand within the grid, significantly improving the efficiency and utilization of electricity resources. This technology has been deployed as part of the WIPO GREEN China Cities matchmaking acceleration project.

- Contracting type: For sale
- Technology level: High
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy supply: building-integrated photovoltaics and low-e glass
Kaneka Corporation

Source: Getty Images/davidhills

The vertical sides of buildings often offer a significantly larger surface area than rooftops, presenting an untapped opportunity for energy generation without compromising aesthetics or design flexibility. Kaneka's innovative PV technologies seamlessly integrate energy generation into building materials and their applications, transforming building envelopes into power sources while maintaining their visual aesthetics and architectural integrity.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Japan
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy supply: retrofitted EV-charging streetlights
Ubricity/Shell Group

Source: Ubitricity

Ubricity, part of the Shell Group, is one of Europe's largest installers of EV chargers. The company has installed over 8,000 public charging points in the United Kingdom, and 10,000 across Europe. Among its products, the company provides charge points designed to be retrofitted onto existing lampposts and bollards. With charge point accessibility being one of the biggest obstacles to EV adoption, Ubricity's lamppost and bollard charge points offer a convenient solution for near-home charging.

- Contracting type: For sale
- Technology level: High
- Country of origin: Germany
- Availability: Europe
- Contact: WIPO GREEN Database

Energy efficiency: urban vehicle data platform
DST EV rental

Source: DST EV rental

DST is a company that operates EVs, focusing on providing efficient transportation services for courier logistics and urban deliveries. The company's digitalization efforts are centered on three areas: storing information and service data online, enabling real-time connections between people and vehicles, and enhancing services by tracking and learning from service patterns. The service offers several advantages, including the use of digital services for self-learning and data analysis, and the support of multiple live settings through its digital platform.

- Contracting type: For service
- Technology level: High
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon

Energy supply: energy-generating noise barriers
TechSafe Industries

Source: Getty Images/Wirestock

TechSafe Industries is making use of innovative surface areas in the urban public space to generate energy. Their SunScreens are a range of noise barriers designed to generate electricity from solar energy, while offering noise protection to homes along transport networks. In France, more than 850,000 homes are located in areas in need of noise barriers, and the SunScreen not only generates energy but achieved up to 22 dB in acoustic reduction compared to the 8–10 dB reduction of conventional barriers. The company is also currently developing the WindScreen, a noise-cancelling wind barrier that harnesses both wind and solar energy. The product is designed to reduce vehicle fuel consumption by allowing air currents generated by moving vehicles to pass through, capturing the airflow along roads to generate electricity.

- Contracting type: For sale
- Technology level: High
- Country of origin: France
- Availability: Europe
- Contact: WIPO GREEN Database

Energy supply: floating solar PV

Ocean Sun

Source: Ocean Sun

Ocean Sun has developed a patented floating solar power system based on a thin, hydroelastic membrane that supports customized PV modules. This innovative design offers several advantages over traditional floating PV systems, including the lowest material usage and levelized cost of energy (LCOE), easy and safe installation, increased efficiency through direct water cooling, and robustness in harsh conditions. The system also reduces material logistics costs and water evaporation. Founded in 2016, Ocean Sun operates globally, with R&D, demonstration and pilot installations in Norway, Albania, the Philippines, Singapore, and China. Their business model involves licensing their technology to developers and independent power producers, using locally sourced materials and workforce to ensure cost-effectiveness.

- Contracting type: For licensing
- Technology level: High
- Country of origin: Norway
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy supply: urban efficiency diagnosis and solutions platform
Bright Cities

Source: Getty Images/Laurence Dutton

Bright Cities is a technology company based in São Paulo, Brazil, founded in 2018. It offers a platform that helps public managers diagnose and improve the efficiency of urban areas under their control. The platform analyzes 10 key areas of urban management, including governance, education, health and mobility, and connects cities with solution providers. By evaluating city performance, it builds a roadmap for improvement and helps cities meet international standards. Bright Cities' platform was developed from over five years of research by UNICAMP researchers and was officially launched at the Smart City Expo World Congress in 2018. The platform also offers a marketplace where solution providers can connect with cities in need of their services, helping cities become smarter and more efficient.

- Contracting type: For service
- Technology level: Medium
- Country of origin: Brazil
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency for water utilities

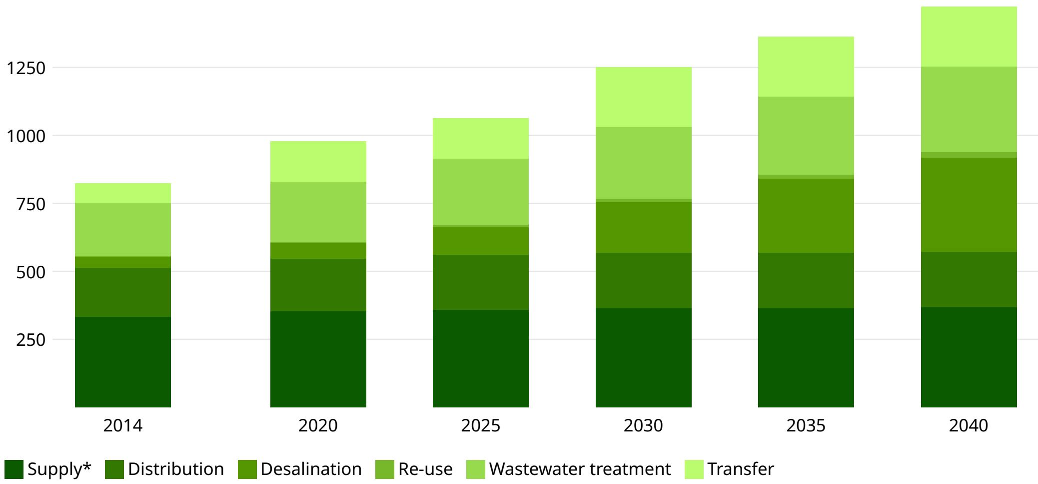
Water utilities require significant amounts of electricity to ensure the continuous distribution of clean water to consumers. Much can be done by switching to efficient pumps, reducing leaks and managing pressure. Technology and innovation have a key role to play, not only for reducing the energy consumption of water utilities but also for transforming wastewater treatment plants into energy recovery facilities.

Water is exceptionally energy-consuming

Global water supply and wastewater services are under enormous pressure, as adequate water supplies are dwindling under a warming climate (UNESCO, 2021). At the same time, water utilities are extremely energy-intensive, largely owing to outdated infrastructure and technologies (Wakeel *et al.*, 2016).

The energy sector is the largest water user of all industrial sectors (IRENA, 2023e). In turn, the water sector itself accounts for significant energy consumption; around 4 percent of global electricity consumption, with water supply and water treatment being the two largest consumers (figure 2.1) (IEA, 2018b; Wakeel et al., 2016). In some municipalities, drinking water and wastewater treatment plants can even account for up to 40 percent of total energy consumption (US EPA, 2024). Attention to the water–energy nexus and the significant energy-saving potential in the water sector is of growing concern for planners and policymakers.

Figure 2.1 Electricity consumption in the water sector by process, 2014–2040 (TWh)



Note: * Supply includes ground and surface water treatment.
Source: IEA (2020).

Efficient water supply and treatment: motors, pumps and aerators

Incredible amounts of water must be treated and moved daily, to meet domestic, business and industrial needs of communities. In fact, humans have pumped such a large mass of water out of the ground that the changed distribution of water added almost a meter to Earth's tilt (Seo *et al*., 2023). For water utilities, energy is used largely to operate motors for pumping water around. Although many utilities still use outdated and inefficient infrastructure, technological advances have led to the development of efficient pumps and appliances.

Cutting-edge innovations in motor technology now present higher torque and power density that can cut energy losses by nearly half compared to conventional motors. In addition, complementary sensors can easily be added to convert traditional motors into smart and connected devices that monitor the pump's performance for further efficiency gains. This can complement software – some of which is in the public domain – that models the water flow in distribution systems to optimize tank and pump operation and reduce energy usage.

Smart multi-pump functions can further enable control of several pumps at the same time and adapt performance to sensor-derived data on flow and pressure demand. Such interconnected smart pumps are typically more energy efficient and require less maintenance. Meanwhile, variable speed drives (VSD) enable utilities to avoid running pumps and other equipment at a constant maximum speed, but instead adapt them to the varying water needs throughout the day. Simpler methods of managing the flow of water involve using valves and throttles, which are essential elements of water supply networks.

Aeration of water for microbial growth promotion is another key process in most wastewater treatment plants, accounting for 50 to 60 percent of the energy consumption (Yingsong Chen *et al*., 2022). The efficiency of aeration is dependent on the surface contact between air and water. Various equipment and air blowers dissolve and diffuse air in different ways. More energy-efficient options including fine bubble diffusers that increase the surface contact between water and air, and more recent membrane-based solutions which allow bacteria to "breathe" as oxygen is diffused through the membrane wall. Other key ways of managing energy use include optimization of aeration blowers and use of screw blower technology, replacement of surface aerators with more efficient bottom aerators, reparation of leaky aeration piping and installation of thermal mass flow meters to measure airflows.

Digital technologies have higher adoption rates in the distribution systems

Typically developed and deployed in the Global North, digital water technologies are increasingly being implemented in cities of the Global South. Half of the utilities in large cities of the Global South are expected to have incorporated digital technologies such as advanced metering infrastructure within the 2020s (Amankwaa *et al*., 2021). For instance, SCADA (Supervisory Control and Data Acquisition) control systems for real-time monitoring and operations control are already widely used by water utilities around the world. Some of the most promising innovations relate to sensor technologies and data analytics for monitoring real-time consumption and distribution (WEF, 2024a).

Energy-saving digital water innovations cover a wide range of applications including telemetry systems, hydraulic monitoring software, smart meters and forecast and demand planning. Enabling technologies such as geographical information systems (GIS), sensors, remote sensing and IoT have been around for a while, allowing for monitoring of energy use and water flows, intelligent pressure management systems and leak detection. Sophisticated leak detection technologies are particularly important for addressing the challenge of non-revenue water (NRW) (box 2.2). Meanwhile, recent advances in machine learning, AI and virtual reality have spurred greater optimization and efficiency savings in the industry.

The adoption of digital technologies by water utilities is primarily driven by economic incentives, such as gaining a competitive advantage, as well as by government regulations. Globally, water distribution systems are the component of the urban water cycle most likely to adopt and benefit from digital solutions. For instance, implementing automatic control schemes to optimize water distribution and sewage operations can lead to energy savings of up to 10 percent (Daniel *et al.*, 2023).

Box 2.2 Addressing NRW

For water utilities, further energy savings can be achieved through water conservation and recycling measures, covered partly in the water chapter of the *Green Technology Book* on climate change adaptation. For instance, NRW (i.e. water lost through leaks and inefficiencies in distribution systems) is a key challenge for utility providers and nearly 350 million cubic meters a day is lost (Liemberger and Wyatt, 2018).

Technologies that manage water pressure and detect leaks, such as sensors combined with IoT and information and communications technology (ICT), have played a key role. Together with automated control systems for water rationing, they make more effective water use possible (Oksen and Favre, 2020).

Wastewater treatment plants as energy recovery facilities

Depending on the content of the wastewater it can contain up to five times more embedded energy than it consumes, some of which can be recovered (Rani *et al*., 2022). While far from being the norm due to the large capital costs, water utilities have started looking beyond energy-saving measures toward on-site energy production. On-site wind and solar power systems are employed by several utilities, but combined heat and power systems and incineration that make use of the embedded energy and resources of wastewater are the most widely explored and used energy production options. Mainly, these technologies have been taken up in Europe and North America (Bohra *et al*., 2022).

Harnessing organic matter for energy production

Organic matter in wastewater is better viewed as a resource than pollution or waste. Activated sludge systems can prepare the organic content for anaerobic digestion, where biogas is produced. CHP involves capturing the heat produced during biogas combustion and converting the thermal energy into electricity. This dual-purpose approach not only enhances the overall efficiency of energy production but also reduces greenhouse gas emissions by making full use of the energy content in biogas. In fact, anaerobic digestion and power generation from biogas in wastewater treatment plants can reduce up to 40 percent of GHG emissions (De Haas *et al.*., 2008).

Implementing electric generators fueled by biogas can provide substantial hot water resources, further reducing utility bills and promoting energy sustainability within water treatment facilities. Anaerobic digesters are a widely tried and tested solution, with small-scale anaerobic digesters and composting being most relevant for low- and middle-income countries (IWA, 2021).

Another promising avenue is the conversion of dewatered sludge solids into energy. While the processing of sludge does come with its own energy requirements, this process not only mitigates waste disposal issues but also taps into a largely untapped energy resource. In Europe, 53 percent of sludge produced in wastewater treatment is reused as fertilizers and compost (Bohra *et al*., 2022). Some plants also incinerate dewatered sludge to produce energy for district heating.

Innovation in microbial fuel cells and hydrogen

At the forefront of innovation, microbial fuel cell technology has shown promise to recover both energy and nutrients to produce electricity. The technology involves harnessing microorganisms' metabolic activity in sewage, as they release electrons that can be captured and used to generate electricity. However, it is not yet at the stage of being able to scale the output enough to be able to turn sewage treatment plants into bio-electricity plants (Malik *et al.*, 2023; Wang *et al.*, 2022).

More recently, innovative utility companies have partnered up with power-to-X companies to pilot the use of wastewater in the electrolysis process for green hydrogen production. Large amounts of water, up to 15 liters of water per kilogram of hydrogen, are needed to convert electricity into hydrogen. Freshwater withdrawals for global hydrogen production could more than triple by 2040 (IRENA, 2023e). While desalinated sea water can be used, this comes with its own set of operational and energy challenges. There is some R&D progress on direct use of sea water for hydrogen electrolysis, but this approach has so far only been proven effective at laboratory scale (Liu et al., 2024). Thus, the use of wastewater would be instrumental in alleviating potential conflicts over freshwater resources. This is of particular concern as around 30 percent of ongoing or planned hydrogen projects are in regions where populations face water scarcity (Cassol *et al*., 2024).

Heat recovery from wastewater

While it is more common for water utilities to recover heat from biogas, heat recovery from wastewater is another emerging area, enabled by heat pumps and heat exchangers. On average, 3.5 times the energy needed for running a heat pump can be recovered from wastewater heat, and used within the plant's own operations or circulated through district heating networks (Bohra *et al*., 2022). This underscores the importance of grid investments beyond power grids to enable recovery and export of not only electricity, but also heat through district heating systems, and methane through gas transmission networks. Additionally, energy recovery can be utilized for cooling purposes, including district cooling, which may be particularly relevant for tropical countries.

Desalination is highly inefficient – and growing in demand

Some forms of water treatment are more energy-intensive than others, such as desalination, which turns saline water like sea water into potable water. As climate change leaves more and more territories with inadequate access to fresh water, cities in these regions may increasingly need to rely on desalination technologies to supply their drinking water. In fact, energy demand for desalination nearly doubled in the past decade and is expected to be the main contributor to the water sector's growth in energy consumption in the next few decades (figure 2.1) (IEA, 2023l; m).

Already, desalination accounts for 6 percent of the total energy consumption in the Middle East (IEA, 2023l). The *Green Technology Book* edition on adaptation covers a chapter on water treatment, including desalination technologies. It noted how cleaner and membrane-based desalination technologies, and breakthroughs in solar and batch reverse osmosis may help overcome some of the energy challenges of this sector.

Since then, further advances have included a potential breakthrough in redox flow desalination (RFD), an emerging desalination technique which could have additional benefits with regard to integrating renewable energy and energy storage into the system (Maclean *et al*., 2024). Other innovations involve extracting water from sea water as vapor through osmotic distillation, eliminating the need for energy-intensive reverse osmosis (Cassol *et al*., 2024). The energy consumption of desalination is highly dependent on the salinity of the water and the desalination technology. Table 2.1 below provides a comparison between the energy consumption of various desalination technologies.

Table 2.1 Energy consumption of different desalination technologies

Desalination technology	Energy consumption (kWh/m^3)
Reverse osmosis[1]	0.36–0.47
Reverse osmosis[2]	0.79
Nanofiltration[1]	0.92
Electro dialysis[1]	0.5–1.7
Multistage-flash-distillation (thermal process)	26.42–68.69
Multistage-flash-distillation (thermal + electrical)	4.7
Multiple-effect distillation[2]	39.71–105.7
Vapor compression[2] (thermal process)	7.9–15.85

Note: 1 brackish water; 2 sea water.
Source: Wakeel et al. (2016).

Innovation examples

Energy-efficient aeration at Scottish water utility

Source: Getty Images/maradek

Scottish Water's Nigg wastewater treatment plant, serving a population of 250,000, has significantly enhanced its operations by replacing its traditional lobe air blowers used for the critical aeration process in its biological air-flooded filter (BAFF). In this process, the blowers typically supply a flow of air from the bottom of the water tanks to "aerate" and provide oxygen for the growth of organic bacteria used to treat the wastewater. This is a highly energy-consuming stage of water treatment, with intense maintenance needs and air leaks. Instead, new aeration technology was introduced, replacing roots blowers with more efficient screw blowers with modern variable speed drive (VSD). The integration of these blowers into the plant's system has enabled better control and monitoring, ensuring reliable operation in addition to energy efficiency improvements. More specifically, the upgrading has led to fewer interrupted operations, reduced maintenance and up to 25 percent savings in energy costs, with potential for further savings through system optimization (Scottish Water, 2024).

Energy-producing water utilities in Aarhus, Denmark

Source: Aarhus Vand A/S

Denmark's second largest city, Aarhus, has become a leader in energy efficient water utilities. Several of the cities' water treatment plants have become net energy producers instead of consumers. The Marselisborg water treatment plant, for instance, produces 50 percent more energy than it uses by operating as a form of biorefinery that makes use of energy in wastewater. Technologies adopted include an advanced SCADA[2] control system to enable process automation, a new turbocompressor for efficient aeration as well as fine bubble aeration. Meanwhile, new biogas engines for combined heat and power enabled on-site electricity production and a heat exchanger was installed with the aim of selling surplus heat to the district heating grid (Aarhusvand, 2024).

Solar-driven desalination of brackish water in Madagascar

Source: Elemental Water Makers

Desalination technologies remove salt and impurities from sea water and brackish water, making it safe for drinking and irrigation. While the integration of renewable energy in desalination projects is yet to scale up, it is crucial for addressing the high energy consumption associated with desalination. Solar-driven desalination can be especially significant for small communities in the Global South, in areas where access to fresh water is limited and traditional desalination methods can be prohibitively expensive and energy-intensive. For example, a project implemented by the technology provider Elemental Water Makers brought solar desalination to a coastal community in Madagascar. This small desalination plant, complete with an 11 kW roof-top installation of solar panels, provides daily access to 15,000 liters of fresh water for the community (Elemental Water Makers, 2024).

2 A control system architecture comprising a combination ofhardware and software, namely computers, networked data communications and graphical user interfaces for high-level supervision of machines and processes.

Technology solutions

Proven

Water/Energy efficiency: telemetry system for monitoring of pumps and water flow

African Horizon Technologies

Source: Getty Images/Rat0007

African Horizon Technologies has developed a telemetry system, InstraLink, for monitoring operations of various industrial processes, including water and wastewater treatment systems. The solution is multipurpose remote data collection hardware and software, which can be controlled via SMS or email. Data are stored in an online cloud and a digital dashboard displays the plant's operational data, enabling utilities to optimize water flows and energy consumption.

- Contracting type: For sale/service
- Technology level: Medium
- Country of origin: South Africa
- Availability: Worldwide
- Contact: WIPO GREEN Database

Water/Energy efficiency: advanced metering infrastructure

Kamstrup

Source: Getty Images/LordRunar

Kamstrup offers a range of digital water technologies that enable efficiency and energy savings for water utilities. The company's advanced metering infrastructure (AMI) includes a collection of smart meters – the flowIQ® 2200, 3200, and 4200 series – which leverage ultrasonic technology for precise data collection. This enables utilities to gather near-real-time water consumption data for better decision-making on operational efficiency. The smart meters can be integrated with in-house software solutions like READy Manager and Leak Detector for more advanced water management such as automated leak detection.

- Contracting type: For sale/service
- Technology level: Medium
- Country of origin: Denmark

- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy supply: advanced anaerobic digester
Royal HaskoningDHV

Source: Royal Haskon ingDHV

Many wastewater treatment plants generate energy through biogas production. Current practices involve capturing methane-containing biogas from anaerobic digestion (AD) of sludge, which can be used on-site or processed off-site. However, inefficiencies in digestion currently limit biogas yield. Helea® from Royal HaskoningDHV is an advanced AD technology that integrates heating, pasteurization and biological hydrolysis to improve sludge breakdown and biogas production. This technology enables wastewater treatment plants to achieve higher biogas yields, while enabling the production of high-quality biosolids for agricultural use as a by-product.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: The Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

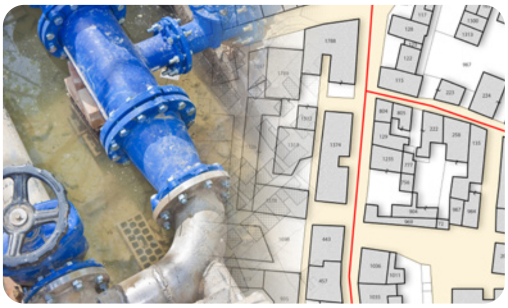
Energy efficiency: screw blower and variable speed drive for energy-efficient aeration
Atlas Copco

Source: Getty Images/photovs

For wastewater treatment plants, air blowers to aerate the water can account for majority of electricity costs. In these plants, large amounts of air are needed to support bacteria that break down waste. Atlas Copco provides a series of more energy-efficient aeration blowers, through the ZS+ screw blower technology series. Estimated to be 30 percent more energy-efficient than traditional models, the screw blowers can also be integrated with a variable speed drive for further efficiency gains. This version varies the speed of the drive motor to meet the air demand, consuming only the necessary energy. In addition, Atlas Copco's Elektronikon® system can be used as an operating system to control the blower's speed and monitor system performance.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Sweden
- Availability: Worldwide
- Contact: WIPO GREEN Database

Water/Energy efficiency: network information system (NIS) for water utilities
Keypro



Source: Getty Images/Francesco Scatena

KeyAqua is a cloud-based NIS designed for managing water supply, sewer and stormwater networks. This integrated system allows authorized personnel and contractors to collaborate on network data in a unified platform. KeyAqua facilitates asset management, network behavior analysis, maintenance planning and customer communication. It features tools for data visualization, hydraulic modeling and risk assessments. By connecting to remote meters, IoT sensors and automation systems, water utilities can receive real-time data to improve resource allocation and response times.

- Contracting type: For service
- Technology level: Medium
- Country of origin: Finland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: submersible aeration mixer for water treatment plants
Landia

Source: Getty Images/NARIN EUNGSUWAT

Submersible mixers for mixing and creation of flow in large water volumes can help water utilities save energy. Unlike surface mixers, they don’t need to transfer energy through long shafts or surface layers, which can dissipate energy. Landia’s POPL-I is a low-speed mixer with adjustable propeller blades, making it possible to further adjust the energy consumption by changing the blade angle.

- Contracting type: For sale
- Technology level: Medium

- Country of origin: Denmark
- Availability: Worldwide
- Contact: WIPO GREEN Database

Water/Energy efficiency: Epanet2: software to model hydraulic behavior of water distribution pipes
US EPA

Source: Getty Images/PJ66431470

EPANET 2 is a globally adopted software application designed to model water distribution systems. Developed to understand the movement and fate of drinking water constituents within these systems, EPANET 2 is utilized for various distribution system analyses. Engineers and consultants rely on it to design and size new water infrastructure, retrofit aging systems, and optimize the operations of tanks and pumps. The software helps reduce energy usage, investigate water quality issues, and prepare for emergencies. Additionally, EPANET 2 can model contamination threats and assess resilience to security threats or natural disasters.

- Contracting type: Free
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Water/Energy efficiency: smart wastewater pump
Xylem

Source: Xylem

Xylem's Lowara smart pump series are connected via IoT technology to allow water utilities control constant pressure, temperature and flow of water. The system makes it possible to operate single, twin or multi-pump systems which can communicate with other building systems in real time. The pump meets the standard for the highly efficient IE5 motor and is claimed to enable energy savings of 70 percent compared to a conventional pump. Includes edge computing capabilities with built-in intelligence which allows the pumps to operate at optimal energy saving conditions.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

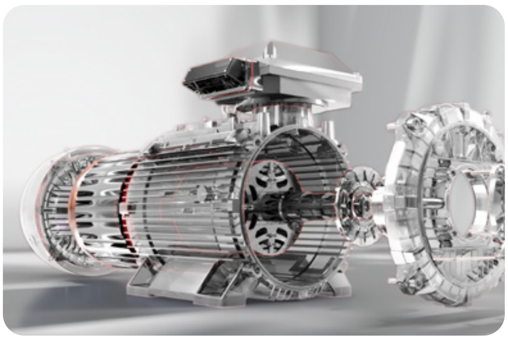
Energy efficiency: smart pump with variable speed drive
KSB

Source: KSB

The PumpDrive is German company KSB's flagship variable speed system. The variable speed system continuously monitors water flow rate at water treatment plants and adjusts the pump speed in order to match it with the actual demand and system requirements. Such demand-driven operation is said to save up to 60 percent of energy. With a built-in wireless module, the pump can be monitored and controlled using a smartphone as a remote control. To enable further energy savings, the drive can be combined with the PumpMeter monitoring unit and KSB's efficient magnet-less pump motor.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: high-efficiency motors for water utilities
ABB



Source: ABB

The global demand for electricity necessitates significant advancements and scaling of efficient motors. ABB has developed a new generation of efficient motors – IE5 synchronous reluctance motors (SynRMs). SynRMs leverage advanced variable-speed drive (VSD) control, offering significant improvements in energy efficiency, reliability and maintenance over traditional induction motors (IMs). Notably, SynRMs do not rely on rare-earth materials and exhibit minimal power losses. ABB's IE5 SynRMs, launched in 2019, feature ultra-premium efficiency as defined by the International Electrotechnical Commission (IEC) and claim up to 50 percent lower energy losses compared to IE2 motors. The technology's compatibility with existing systems facilitates easy upgrades and broader adoption.

- Contracting type: For sale
- Technology level: High
- Country of origin: Sweden & Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier

Water/Energy efficiency: 5G for smart water grids
Ericsson

Source: Ericsson

5G and IoT-based solutions can significantly enhance water utilities' ability to monitor, manage and monetize water distribution. Traditionally managed by SCADA systems – a common control system – the centralized setup of pumping stations, treatment plants and reservoirs often lack comprehensive monitoring of the distribution network. This leads to undetected issues like water leaks. Implementing 5G and IoT enables a two-way monitoring and management system across the water distribution network, improving water loss prevention and efficiency. IoT devices, such as sensors and actuators, collect real-time data on water pressure and temperature, allowing for immediate response to abnormalities.

- Contracting type: For service
- Technology level: High
- Country of origin: Sweden
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: energy-efficient reverse osmosis water treatment
Aquaporin

Source: Aquaporin

Aquaporin Inside® CLEAR series membranes are an innovative municipal wastewater treatment solution which is claimed to reduce energy consumption by 30 percent. Leveraging biomimicry and advanced membrane chemistry, the membranes utilize aquaporin proteins, which are highly efficient and selective water channels found in all living cells. This natural efficiency surpasses traditional synthetic membranes, enabling faster and more selective water filtration.

The membranes are available in flat sheet or hollow fiber forms for both forward and reverse osmosis applications for use in municipal wastewater recycling operations.

- Contracting type: For sale
- Technology level: High
- Country of origin: Denmark
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy supply: solar-based sludge drying for water utilities

Huber Technology

Source: Getty Images/Arpon Pongkasetkam

Sludge, an organic by-product of wastewater treatment plants, may be dried to facilitate future handling, and reduce pathogen contents and odors. This is an energy-intensive process, which the SOLSTICE® sludge turner from HUBER uses solar energy to fuel. In the automated process, sludge is dried completely (90 percent) in hot environments or in summertime, while 50 to 75 percent drying may be achieved in spring or autumn. The technology can be used in temperate climate zones all year round. It operates in a greenhouse structure featuring the sludge turning machine, fans and sensors which optimize ventilation, air humidity and temperature with respect to local weather conditions. The product is a pea-sized granulate that may be used in agricultural or waste-to-energy applications.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: membrane aerated biofilm reactor (MABR)

OxyMem

Source: OxyMem

Wastewater treatment may involve either suspended or membrane-attached microorganisms in its biological treatment steps, which are used to decompose and remove pollutants. OxyMem's

MABR enables the latter by providing a porous habitat for biofilm growth. The modular design allows existing treatment plants to be retrofitted to the desired degree, as the drop-in unit can be employed in one or several phases of treatment. OxyMem's patented biofilm thickness control automatically ensures optimal removal of carbon- and nitrous pollutants in the final effluent. The technology has been shown to deliver its full capacity for at least seven years without maintenance interventions in municipal wastewater treatment, with an expected lifespan of 20 years. It can reduce energy demand in aeration by up to 75 percent, while also reducing sludge volumes and increasing the biological treatment capacity of a tank by up to 50 percent.

- Contracting type: For sale
- Technology level: High
- Country of origin: Ireland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Water/Energy efficiency: data-as-a-service control platform for water utilities
Dryp

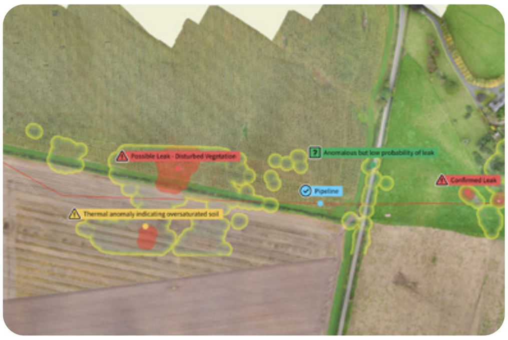
Source: Dryp

Dryp has developed plug-and-play gateways and sensors for more resource-efficient water management. The technology can be used in urban water networks to detect leaks or flood risks; in stormwater management and hydraulic modelling; and in monitoring the quality, flow patterns and biodiversity in natural water bodies. Its application can help prevent costly water losses or flood damages and mitigate negative impacts on aquatic ecosystems. These gateways and sensors are designed to be compatible with a wide variety of existing infrastructure, such as older sensor models, and can operate in both wired and wireless networks.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Denmark
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon

Water/Energy efficiency: AI-based leak prediction technology
Sensat



Source: Sensat

When leaks occur in water distribution pipes, more water needs to be pumped and treated to compensate for the loss, leading to more energy consumption. Sensat is a software company that helps industries visualize their data using AI-based algorithms. In 2021, Sensat and United Utilities piloted an AI-based water leak detection service to help water utilities predict leaks before they occur. Utilizing unmanned aerial vehicle (UAV) technology, thermal data are mapped and combined with high-resolution photogrammetry to gather and visualize data.

- Contracting type: Under development
- Technology level: High
- Country of origin: United Kingdom
- Availability: United Kingdom
- Contact: WIPO GREEN Database

Energy recovery: in-pipe turbine recovering energy from fast-moving water
InPipe Energy

Source: InPipe Energy

The InPipe HydroXS energy recovery system is a form of micro-hydro solution for wastewater plants and water distribution systems. Designed as an in-pipe turbine that generates electricity from fast-moving water with a differential pressure inside water pipelines. The innovation targets municipal water and wastewater treatment plants. This small-scale hydropower system is mounted inside one section of a pipe which can be installed directly into the water transmission pipeline. The modules are standardized and turnkey and can be easily installed in a series.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: United States
- Contact: WIPO GREEN Database

Water/Energy efficiency: digital twins for water utilities
DHI

Source: DHI

DHI provides digital twins for physical water systems, such as water distribution networks and treatment plants. Examples include MIKE+, Future City Flow, TwinPlant, and the Leakage Monitor. These are integrated automation and/or system modelling platforms that provide for instance automated reports for water and sewage pipe networks of entire cities or treatment plants. They combine physical data with model-derived data, allowing managers to monitor and prevent leakages or flood risks, ensure a stable inflow to treatment plants, and plan according to targets and weather forecasts using scenario modeling. This can optimize the energy consumption of the water utility system, thereby lowering both costs and GHG emissions.

- Contracting type: For sale
- Technology level: High
- Country of origin: Denmark
- Availability: Worldwide
- Contact: WIPO GREEN Database

Water/Energy efficiency: digital twin for water treatment plants
Ainwater

Source: Getty Images/photovs

Chilean company Ainwater leverages AI and machine learning to optimize operations and efficiency at water treatment plants, saving up to 30 percent in energy costs. With a focus on digital twin technology, the company provides an online tool that helps simulate plant processes, trigger predictive alerts and monitor various control parameters through a simple centralized dashboard.

- Contracting type: For service
- Technology level: High
- Country of origin: Chile
- Availability: Chile, Mexico, Brazil
- Contact: WIPO GREEN Database

3. Green rural energy solutions

Innovation in rural areas is helping to reduce energy consumption by introducing renewable energy and energy efficient technologies. These solutions enable households, communities, farmers and producers to improve energy access, decrease energy consumption, lower costs, and enhance resilience to the impacts of climate change.

How can rural communities harness opportunities to improve energy sustainability while improving health and boosting local economies? What is the role of rural households in the energy transition in the fight against climate change? And how can farmers maximize renewable energy and energy efficient technologies to improve productivity while fostering sustainable agriculture practices?

Rural areas are uniquely positioned to capitalize on clean energy technologies due to their access to local natural resources and potential for innovative, decentralized energy systems. This chapter explores an array of proven, frontier and horizon technologies that support rural communities in meeting energy challenges while addressing broader climate and sustainable development goals.

Introduction

The energy transition is not just for cities

Energy is consumed in rural areas for a variety of critical functions including residential needs, agricultural operations, water supply and sanitation, and community services. Addressing the unique energy needs of rural areas involves overcoming infrastructure challenges. Grid connection in rural areas is often challenging due to long distances, difficult terrain, low population density, high capital investment and regulatory barriers.

Integrating green energy technologies into rural electrification efforts not only supports climate goals but also improves resilience and quality of life for rural communities

Fortunately, a multitude of innovative energy solutions is now available in rural areas, enabling residents to reap benefits ranging from electricity access to cost savings to energy independence. Decentralized renewable energy systems can help fill the energy access gap in remote areas while promoting the uptake of renewable energy and energy efficiency solutions. Integrating these technologies into rural electrification efforts not only supports climate goals but also improves resilience and quality of life for rural communities.

Challenges in rural areas overcome with decentralized renewable energy

The number of people with access to decentralized renewable energy solutions, including solar home systems (SHSs) and mini-grids, rose from 12 million in 2010 to 39 million in 2019 (IEA, 2023h; IRENA, 2018). Micro-grids and mini-grids are serving rural communities in both developing and industrialized countries alike, building resilience and providing adaptation advantages to populations at risk of grid outages and weather events. Residents desiring more energy independence can capitalize on these systems in areas with lacking or unstable grid connections.

Rural households and communities are taking advantage of the falling costs of solar PV and policies promoting clean energy. Solar panels and SHSs have become more affordable and efficient, providing a reliable source of electricity for rural areas. Innovations across a host of different appliances, including solar lanterns, fans, water pumps and refrigerators, offer advanced technology, affordability and practicality. Small-scale wind turbines generate electricity for rural households and communities, while small hydroelectric systems harness the energy of flowing water in rivers or streams. New financing plans such as pay-as-you-go solar models allow users to pay for energy access in small, manageable installments, while modular and scalable systems enable easy expansion as needs evolve.

Community solar drives the democratization of the energy transition

In the United States of America, community solar projects are booming; cumulative community solar installations are slated to surpass 14 GW direct current (DC) in existing state markets by 2028 (CCSA, 2024). Residents can gain access to clean power by subscribing to a solar array located nearby, sidestepping the need to install their own. Incentivized by the Inflation Reduction Act, the solar developer Nexamp is planning for about 400 new community solar projects around the United States in the coming years. Microsoft also announced a five-year, 500 MW deal with the community solar specialist Pivot Energy that will bring 150 new solar arrays to about 100 different communities through a renewable energy credit agreement (Clean Technica, 2024).

Prosumers also on the rise

Prosumers (who produce, use, store or sell electricity back to the grid) are increasing in rural areas, which is driving demand for decentralized energy production, energy storage systems and energy management software, as well as new technologies like blockchain (Neagu et al., 2019). Swarm electrification, or mesh grids, enable users of SHSs to sell excess energy, which generates income for prosumers while providing or extending access for others (Sheridan *et al.*, 2023).

Energy storage solutions are seeing rapid innovation, boding well for rural areas

Given the natural intermittency of renewable energy sources, battery storage systems are crucial, making this a fast-growing sector. In fact, battery storage in the power sector was the fastest growing commercially available energy technology in 2023, with deployment more than doubling year-on-year (IEA, 2024a). Battery capacity in decentralized systems reached 5.3 GWh in 2022, representing a fourfold increase since 2015, driven mainly by SHSs. However, more generally, energy storage needs to increase six-fold in order to triple global renewable energy capacity by 2030 while maintaining electricity security (IEA, 2024a).

Advances in battery technologies, such as lithium-ion batteries, are improving energy storage from renewable sources and enabling a stable power supply. Flow batteries and gravity storage are being explored for larger-scale energy storage need in rural communities to balance intermittent renewable energy. These can last long periods in the absence of electricity production from renewable sources.

The rise of the clean cookstove, a silver bullet of sorts

Nearly one-third of the global population still relies on rudimentary cooking methods with serious consequences in terms of air pollution, health impacts and deforestation (IEA, 2023c). In rural communities, replacing conventional stoves with improved stoves is an important first step to improved health (IEA, 2024d). Commercially available improved cookstove technologies reduce fuel consumption and emissions compared to traditional open fires. They deliver both mitigation and adaptation benefits to rural populations, while also reducing the labor and distances needing to be traveled, typically by women, engaged in collection of firewood. This section features a diverse set of clean cookstove solutions, including solar cookers, electric pressure cookers and improved biomass stoves.

Anaerobic biodigesters also gaining traction

The use of biogas digesters is rising in both developed and developing countries. Its expansion in Africa and parts of Asia and South America has been driven by governmental and non-governmental institutional support over the last several decades. These systems convert organic and agricultural waste (like animal dung and crop residue) into biogas that can be used for lighting and cooking, and to operate on-farm machinery. Biogas from biodigesters can replace traditional fuels like wood or charcoal, which helps tackle deforestation. The leftover slurry produced is a valuable organic fertilizer that enhances soil fertility, which is particularly beneficial for smallholder farmers. This chapter presents small-scale and modular technologies for rural households and communities, alongside other solutions more suited to small farms.

Agriculture technologies increase productivity while saving energy

Agriculture is the backbone of rural society and the central economic activity in many regions globally. Enhancing agricultural productivity is essential to food security and livelihoods. The key challenge facing the agriculture sector is how to continue expanding production while increasing its sustainability. Unfortunately, past innovation driven by access to fossil fuels has enhanced agricultural productivity while simultaneously increasing greenhouse gas (GHG) emissions, deforestation, soil degradation, water pollution and resource depletion (WIPO, 2024b).

The agrifood chain, comprising on-farm and post-harvest production, retail and transport, accounts for 30 percent of the total energy used globally

Energy is required for all inputs, machinery, irrigation and post-harvest processing associated with agriculture. The agrifood chain, comprising on-farm and post-harvest production, retail and transport, accounts for 30 percent of the total energy used globally (Vourdoubas and Dubois, 2016). Globally, on-farm agriculture in 2020 comprised roughly half of total agrifood systems emissions, while pre- and post-production processes contributed one-third, and land-use change one-fifth (FAO, 2021a).

Thus, agriculture is a major source of GHG emissions across the agrifood system, yet can also be part of the mitigation solution through carbon sequestration in soils and biomass. This chapter, however, highlights energy technologies for agrifood systems for on-farm and post-harvest activities.

On-farm agriculture benefits from energy efficiency and renewables

Farmers everywhere look for tools and solutions that maximize productivity with fewer costs and less risk. This means that farmers often need information and education on new technologies and lower risk methods by which to experiment with technologies, as achieved through leasing, rental, or cooperative agreements and pay-as-you-go services that offer savings on up-front costs.

Precision agriculture supports energy efficiency using global positioning system (GPS) and geographical information system (GIS) technologies, as these systems enable precise mapping and management of fields, optimizing planting, irrigation and fertilization and minimizing excess use. Technologies such as drip irrigation, smart irrigation systems and recent innovations that measure stem water potential contribute to water and energy efficiency, water conservation and ultimately more sustainable farming practices. Farm management software solutions are using sensors to improve farmer decision-making and optimize farming operations. IoT devices collect data from sensors, improving monitoring and automated responses in fluctuating conditions. The use of solar-powered water pumps for agriculture and residential needs is expanding in developing countries. They enhance energy efficiency by using renewable energy, reducing operational costs and providing reliable water access in a sustainable fashion.

Agrivoltaics and aquavoltaics are dual-use systems that maximize the use of natural resources for renewable energy and food production. Agrivoltaics allow for the co-location of solar panels and agricultural activities on the same land, while aquavoltaics achieve similar ends by placing solar photovoltaic (PV) panels on the surface of bodies of water such as lakes, reservoirs or ponds. These systems offer environmental, economic and operational benefits.

Post-harvest innovation plays a big role in greening food production and processing systems

Energy-efficient equipment reduces energy consumption in post-harvest processing and can also reduce costs. Mini-grids are used for post-harvest processes, including milling, oil-pressing and ice-making, but these need further scaling. Solar milling and drying technologies, which dry crops efficiently and reduce dependence on fossil fuels, are available but are largely in the pilot phase and need further uptake in developing countries compared to solar for on-farm or residential energy consumption (IRENA, 2021).

Dryers in developed countries are benefiting from the expansion of automated systems to regulate temperature, airflow and drying time to ensure consistent drying conditions and save energy. Sensors measure grain moisture content to prevent over-drying or under-drying. Additionally, continuous flow dryers and modern batch dryers improve energy efficiency for small to medium-scale operations.

Dairy processing, too, is the site of much innovation particularly for nonthermal technologies used in food processing. Membrane-based technologies are a boon to energy-intensive dairy processing activities like sterilization and pasteurization. Other nonthermal innovations include pulsified electrified fields and high-pressure processing for milk preservation.

Cold storage innovation curbs energy use and combats food loss and waste

Food loss due to deficient cold chain management is a significant global issue. The shortage of efficient cold chains is responsible for 9 percent of perishable food loss in developed countries and more than 17 percent in developing countries (IIIF, 2020). Developing countries often face more severe challenges due to less developed infrastructure, while developed countries still experience losses due to operational inefficiencies in the cold chain.

Refrigeration systems have advanced in recent years, as more attention has turned to the need for environmentally friendly refrigerants with lower global warming potentials (GWPs). Innovations in refrigeration have fortified the cold chain across all industries. Solar PV has again come to the rescue of refrigeration and freezer appliances, with solar fridges and freezers, walk-in rooms and mobile cold rooms proliferating in recent years, especially in Asia and Africa. Modern cold storage facilities are embracing energy-efficient solutions, as technologies that enable controlled atmosphere storage are becoming more common in silos and warehouses used for cold storage. Electric refrigerated transport systems ensure that optimal conditions are maintained throughout the supply chain. Fisheries and aquaculture benefit from energy-efficient pumps, aerators and water circulators, alongside renewable energy integration.

Green energy solutions for rural households

Globally, 760 million people are without access to electricity. Even after efforts to extend electricity access outpaced population growth in 2013, the number of people lacking electricity in sub-Saharan Africa (SSA) rose from 580 million in 2019 to 600 million in 2022 due to increased complications resulting from the COVID-19 pandemic and geopolitical tensions affecting energy markets (IEA, 2023h).

Household energy access is integral to daily lives in rural areas for cooking, cleaning, heating, cooling, lighting, working, washing and leisure activities. Innovation and technologies for energy conservation, energy efficiency and renewable energy can help mitigate climate change while granting rural populations energy access as well as opportunities to improve their health and resilience, energy independence, carbon footprints and overall quality of life.

Technological developments and trends

Energy access in rural areas is still lagging in parts of the world

There is often a stark divide between energy access in urban and rural areas. Electrification efforts face a myriad of obstacles inherent to rural and remote or isolated communities. Expanding energy access to rural populations occurs more slowly than in urban areas. This is in part due to the simple reality that lower population densities and larger areas render it expensive and inefficient. Difficulties may also be exacerbated by technical complexity, grid extension obstacles, deficient access roads, weak policies and natural disasters (Liu, 2019). Global averages indicate that 98 percent of urban residents have electricity access compared to only 85 percent of rural households (IRENA, 2023d). Electricity access rates are extremely low for developing countries compared to global averages, and in the least developed countries the average access rate is just 56 percent. Approximately 500 million people who lack a reliable electricity connection live in rural areas (Babayomi et al., 2023).

Impacts of rural household energy on emissions

Household energy use contributes roughly half of black carbon emissions while also emitting methane and carbon monoxide through inefficient combustion (CCAC, 2023c). Black carbon is a type of fine particulate matter composed of pure carbon formed through the incomplete combustion of fossil and biomass fuels. Biomass fuel and charcoal production for cooking and heating, and kerosene lamps used for lighting, have been commonly used in rural areas particularly in developing countries. Fuelwood and charcoal are often harvested unsustainably, which contributes not only to CO_2 emissions, but to deforestation and degradation, land-use change and biodiversity loss. Globally, rural household GHG footprints have increased significantly since the millennium, at roughly 1 percent a year between 2005 and 2015, mainly in emerging economies (Yuan et al., 2022).

In order to achieve universal sustainable energy access by 2030, technologies that decarbonize energy use will be necessary

According to the International Energy Agency's (IEA) Net Zero Emissions by 2050 scenario, the first half of the population to gain access to electricity by 2030 will rely on off-grid solutions such as mini-grids (31 percent) and standalone systems (25 percent), and roughly 90 percent of new connections in this scenario are based on renewable energy, largely solar and wind (IEA, 2021). In order to achieve universal sustainable energy access by 2030, technologies that decarbonize energy use will be necessary, including not only solar and energy efficiency, but also a growing arsenal of internet of things (IoT) and artificial intelligence (AI) technologies to enable energy savings across a wide range of sectors (Phillips et al., 2020).

Rise of mini- and micro-grids in rural areas

Rural areas are increasingly overcoming electrification impediments with micro-grids and mini-grids. Mini-grids are sets of small-scale electricity generators interconnected to a distribution network that supply electricity to a small, localized group of customers (UNIDO, 2021). Renewable energy mini-grids that are powered by solar, wind or hydropower have emerged as a silver bullet of sorts for energy access particularly in rural areas, where they provide reliable and high-quality electricity when grid extension is not a viable option. Micro-grids are typically grids that connect small residential consumers, while mini-grids are larger and can provide power to commercial operations, schools, factories and islands.

Renewable energy mini-grids provide reliable and high-quality electricity when grid extension is not a viable option

Both mini-grids and micro-grids can complement national or larger power grids, maintain supply during outages and restore electricity supply faster, and importantly, they can support rural communities in gaining more reliable access to electricity (IEC, 2024). They are a less costly way to extend energy access to rural communities when compared with grid extension and present a way of harnessing renewable energy potential and integrating this into the energy mix, which is key for developing countries looking to leapfrog fossil fuel-based grid electricity. According to the World Bank, providing power to 380 million Africans by 2030 will require 160,000 new mini-grids at the cost of USD 91 billion (World Bank, 2023).

Solar PV technologies save the day

Currently, three main types of solar panel technologies are used for residential solar installations: monocrystalline, polycrystalline and thin-film. Monocrystalline panels exhibit high efficiency and produce more power output per square meter than other types, therefore rendering them ideal for areas with limited space – like rooftops. However, they're slightly more costly. Polycrystalline panels can be produced cheaply and quickly, albeit with lower efficiency. Thin-film solar panels are flexible and light, and despite lower efficiency, they are finding new value when used in technologies such as agrivoltaics, where flexibility is necessary to provide for varying optimum shading levels for plants and crops growing in tandem with PV installations (Uchanski et al., 2023). Recent innovations in solar PV include bifacial panels, which capture sunlight from both front and back, and therefore can be installed above water or in sandy areas or used in solar fences. Perovskite solar cells are thin-film lightweight cells, a frontier technology that achieves high efficiency with more flexibility.

SHSs for off-grid access and energy storage

Renewable technologies provide electricity access to so-called last-mile communities. Solar PV technology for off-grid solutions has been increasingly deployed in rural areas, due in part to its modularity, and of course its utility in areas with abundant sunshine (IRENA, 2023d). SHSs can either be grid-connected, standalone (off-grid), or hybrid. In rural areas, the focus is on off-grid or hybrid systems. These systems contain batteries to store excess energy for use during nighttime or periods of lower sunlight such as cloudy days. Since they are not always connected to the grid, they depend entirely on their battery storage solutions for back-up power. Innovations in SHS technology have brought about third-generation solar home systems (3G-SHSs) that are smaller, more efficient, cheaper and easier to install and use than previous generations (IRENA, 2023c). They are typically plug and play, contain fewer solar panels, use light-emitting diode (LED) lighting instead of fluorescent lamps, and have lithium-ion batteries as well as microelectronics that are integrated into the battery box.

Microelectronics are small-scale electronic components and devices that are integral to the performance, efficiency and management of solar energy systems. They are used to monitor the performance of individual solar panels, detect faults and perform diagnostics, while also supporting conversion of the direct current (DC) generated by solar panels into alternating current (AC) used by household appliances. Microelectronics also help monitor and manage the charging and discharging of batteries used to store solar energy. Table 3.1 gives a brief comparison of SHS evolution from 2G to 3G.

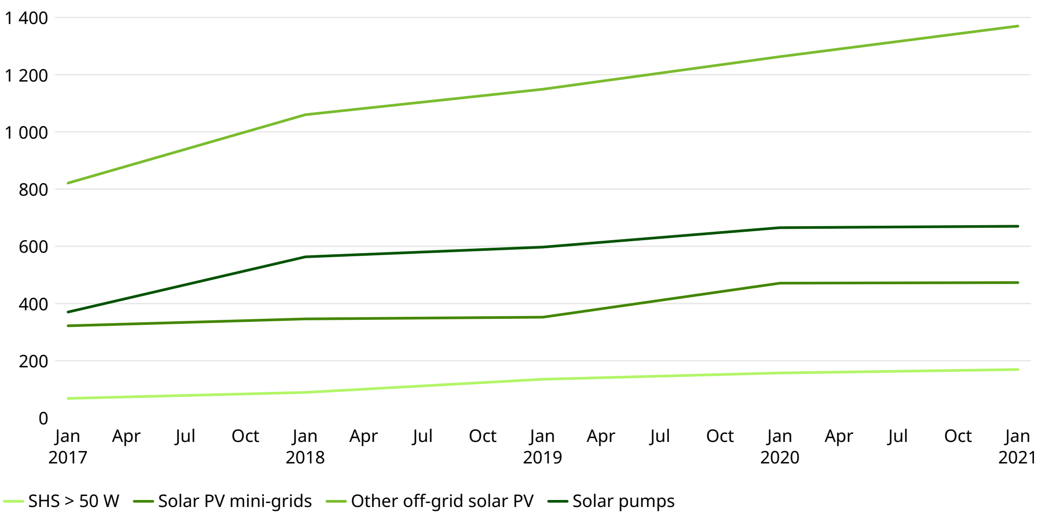
Table 3.1 Technology comparison of SHSs

Component	Description	2G-SHS	3G-SHS
Solar Panel	*Technology*	Mono- or poly-crystalline	Mono- or poly-crystalline
	Capacity (Wp)	50-80	20-50
	Supply (Wh)	200-250	100
Lighting	*Technology*	Fluorescent lamps	LEDs
	Capacity (W)	7-11	3
Battery	*Technology*	Lead-acid	Lithium-ion
	Capacity (Ah)	100-120	6-10
Regulator		External solid-state power electronics	Microelectronics integrated into the battery box
Connection		Splices	Plug and play
Weight (kg)		3-50	6
Cost/kW (USD)		1000	350-650

Note: * Get the data.
Source: Eras-Ammedia et al. (2019).

Hybrid solar systems or hybrid renewable energy sources (HRES) integrate solar panels and battery energy storage, and grid connectivity. If the back-up battery is full, the electricity generated from energy collected from PV panels is transmitted to the electricity grid. The solar system can recharge the battery if there is a prolonged grid outage. Hybrid systems can thus be useful in grid-connected areas, as they can operate independently in emergencies while maximizing the reliability of the grid and leveraging both solar and grid power to optimize efficiency. Figure 3.1 depicts global trends of off-grid solar PV adoption for SHSs greater than 50 W, solar PV mini-grids, other off-grid solar PV, and solar pumps.

Figure 3.1 Global trends of off-grid solar PV adoption, 2017–2021 (capacities, MW)



Source: IRENA (2023c).

Pico PV

Pico solar PV systems are small-capacity plug-and-play devices that generate fewer watts of power than larger PV systems. Pico, meaning “very small” is emerging as a category of low-power solar PV electric systems that can power residential LED lighting and other small household portable appliances and chargers. They have the advantage of modularity and can be installed in small expandable units, making it easier to build up a system over time. The power output of pico solar cells ranges from 0.1 to 5 watts-peak (Wp) for powering portable devices and charging, while systems of 15–20 Wp are used for larger devices and home use (Keane, 2014). Therefore, pico systems typically have a power density of about 100–150 Wp/m2, depending on their efficiency. Demand is growing for solar home and garden lighting, and off-grid solar lanterns are now maximizing the use of LEDs, charge controllers, built-in lithium-ion batteries and pico PV panels. These systems can also help to counteract the barrier of up-front purchase and installation costs for traditional solar PV systems.

Prosumers benefit from renewable energy technologies and can sell back excess energy

As mentioned in Chapter 2, homeowners can become “prosumers” of energy rather than just consumers (also called active consumers or renewable energy self-consumers) when they adopt renewable energy technologies if they have grid access. Certain systems allow residents to sell excess energy back to the grid. With the help of cutting-edge applications, they can even support prosumers in determining the cheapest times of day to charge systems, enabling them to sell back electricity during peak pricing.

Energy-saving household appliances are abundant

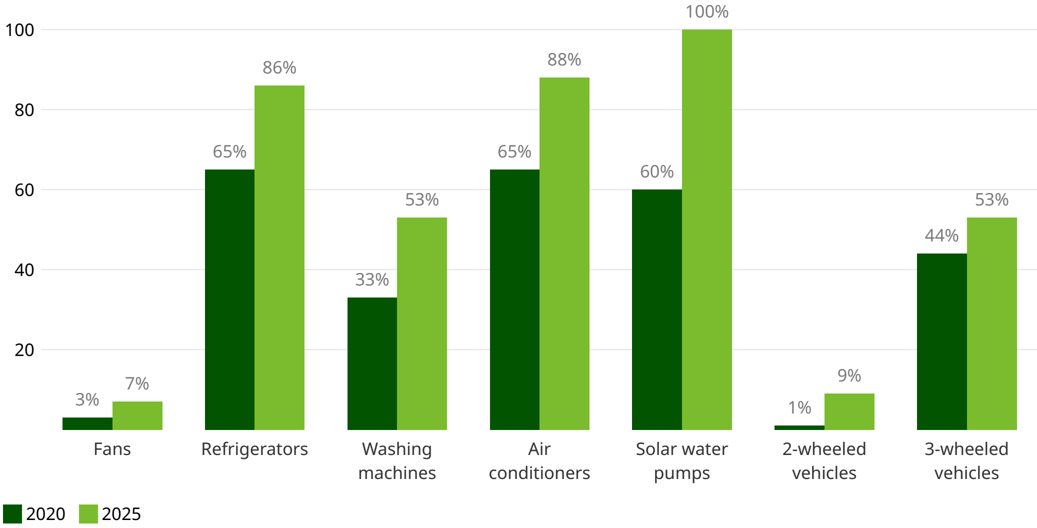
Rural household appliances powered by renewables include refrigerators, televisions, lighting, fans and cooking devices, and offer up a more climate-friendly alternative to diesel-fueled systems and kerosene-based appliances. Technologies for solar lanterns, fans, cookers, refrigerators, water pumps

other home appliances have been in use for several decades but have proliferated in rural areas and are now easy to find – if at times they remain expensive. In higher-income countries, the convenience of solar-powered devices and appliances, and even SHSs, has gained traction in areas prone to power outages, or where residents desire to be off the grid. Therefore, interest in the off-grid appliances market is growing (CLASP, 2021b), and further innovation is taking place. According to CLASP, electric pressure cookers were not prevalent even as recently as 2017, but have burst onto the scene in recent years, spurring innovation and demand among both grid-connected and weak and off-grid consumers (CLASP, 2021b).

Additionally, an increasing number of manufacturers entering the off-grid home appliance market alongside falling prices have facilitated a faster transition of mature household products to full commercialization, including fans, televisions and refrigerators. Advances in energy-efficient motors have also increased energy savings. For example, the use of permanent magnet (PM) motors can reduce appliance energy consumption by 22 to 42 percent (CLASP, 2021a) across several solar household appliances. PM motors are a type of electric motor that uses PMs on the stator (stationary part of the motor) to create the magnetic field required for operation, unlike conventional motors that use electromagnets for this. The magnets produce a constant magnetic field. As the rotor turns, it creates a rotating magnetic field that interacts with the stator’s magnetic field, causing the rotor to spin. PM motors are also more compact and lighter than traditional motors.

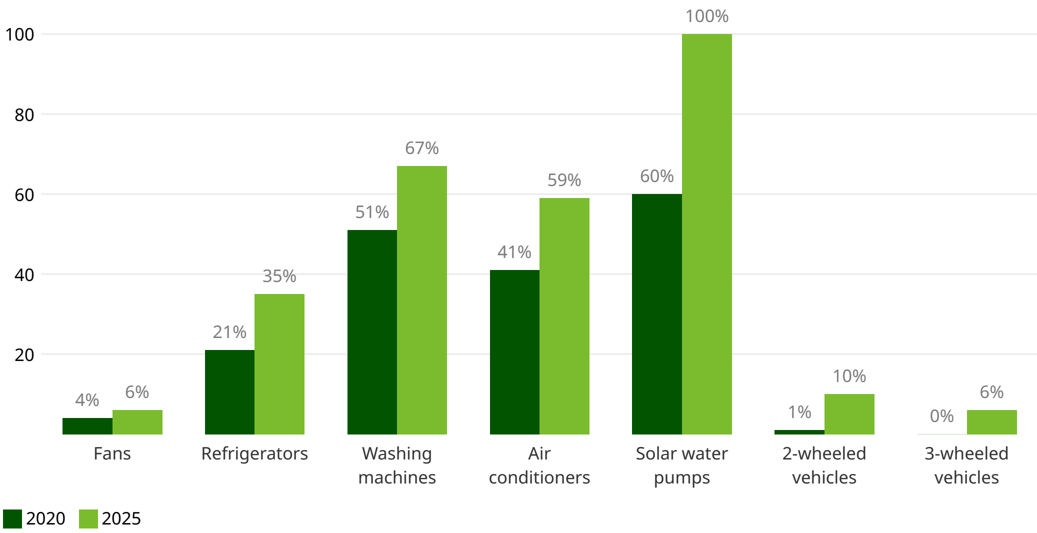
The PM motor penetration for refrigeration is slated to jump from 65 percent in 2020 to 88 percent in 2025 in South Asia and from 41 percent to 59 percent in SSA, while the same increase is predicted for solar water pumps (60 percent in 2020 to 100 percent in 2025 in both South Asia and SSA) and washing machines (33 percent to 53 percent in south Asia and 51 percent to 67 percent in SSA) (CLASP, 2021a). Figure 3.2 shows the market expected penetration of PM motor appliances in South Asia, while figure 3.3 depicts the same for SSA (2020 and 2025).

Figure 3.2 Market penetration of PM motor appliances in South Asia (2020 and 2025)



Source: CLASP (2021a).

Figure 3.3 Market penetration of PM motor appliances in SSA (2020 and 2025)



Source: CLASP (2021a).

Rural household appliances maximize solar power

Solar water heaters

Active solar water heater systems use circulating pumps and controls to transfer heat from collector panels to a storage tank, while passive systems rely on natural convection to move the water, are much slower and are generally used in small applications. Simply put, residents can determine which type they need depending on whether the water supply has sufficient pressure to transfer water. Heat pumps, solar air collectors, insulation and other heating and cooling technologies can be found in the *Green Technology Book* edition on climate change mitigation, accessible here.

Off-grid refrigeration

Off-grid refrigerator manufacturers have typically used three types of refrigerants, propane (R290), isobutane (R600a) and 1,1,2-tetrafluoromethane (R134a), of which the latter is classified as a hydrofluorocarbon (HFC) and a potent GHG with a high GWP of 1,430 over a 100-year timescale. Strikingly, the GWPs of R600 and R290 are both rated at only 3. Currently, the majority of off-grid refrigerator manufacturers continue to use high GWP refrigerants; however, some leading manufacturers have begun transitioning to climate-friendly refrigerants, and policies prohibiting the use of high-GWP refrigerants can help to accelerate this transition (CLASP, 2023a). Recent regulations in the European Union, United States, Canada, China, Japan and Australia have taken steps to ban those with high GWPs.

The popularity of freezers and multi-temperature refrigerators (with compartments that can serve as either refrigerator or freezer) has recently risen, and these are currently the most prevalent on the market. DC refrigerators are limited due to higher costs, reliance on traditional AC models and a continued lack of investment in DC market and development in several countries due to customer preference to continue relying on AC units paired with inverters, for which they are already equipped. This occurs because solar panels produce DC electricity, but most household appliances and the grid use AC electricity. An inverter is needed to convert the DC electricity from the solar panels into AC electricity.

Solar direct drive is a newer technology in limited availability on the market that bypasses the use of a battery and charge controller, and instead uses solar energy to freeze water or other phase-change material (or ice bank), the cooling of which is then used to keep the refrigerator cold. The name derives from the fact that the refrigerator is connected directly to the solar PV panel (WHO, 2013).

Solar fans

Fans are decent cooling solutions and will be increasingly important as climate change exacerbates extreme heat. They are relatively inexpensive and technologically straightforward. The fan market in SSA has recently expanded, especially in West Africa, where it contributed 40 percent of 2022 global sales. The off-grid fan market accounted for 60 percent of all appliances during the second half of 2022 with South Asia topping off-grid fan sales (CLASP, 2024). An array of buying arrangements exist in different parts of the world: fans in SSA are typically bundled with SHSs and purchased using pay-as-you-go arrangements, while in South Asia they are typically purchased with cash and not paired with SHSs.

Newer solutions integrate brushless direct current (BLDC) and PM motors, which can cut energy consumption in half. Improving fan blade design renders further efficiency, such as tapered and twisted blade designs that can enable higher airflow at the same speed, increasing fan efficiency by as much as 15 percent (CLASP, 2021a).

Solar water pumps

During the last 20 years, the solar water pump market has grown significantly due to the reduced cost of PV panels, increased support of national governments, and expanded system capacity and efficiency (CLASP, 2023b). These systems have become more affordable as competition has driven prices down. In rural areas where residents suffer from unreliable access to the grid and erratic fuel prices, solar pumps provide a useful alternative to traditional electric and diesel pumps (CLASP, 2023b). Solar PV-powered water-pumping systems are important in rural areas and households for a variety of reasons, including irrigation and livestock watering, and play a role in residential settings to supply drinking water for homes and gardening needs.

Additionally, water purification technologies are progressing in this area, as seen in ultraviolet (UV) water treatment systems, and the invention of hydropanels that draw in ambient air, forcing it through a water-absorbing material to capture water vapor and condense it into liquid water.

Further consideration of solar water pumps is provided in the section “Green energy solutions for agriculture on-farm” below.

Unlocking the multiple wins of clean cookstoves in rural areas

Access to safe and sustainable cooking fuels and technologies is a critical component of addressing both energy poverty and food security (Bisaga et al., 2022). Globally, 2.3 billion people, one-third of the population, lack access to clean cooking (IEA, 2023j), with 1.8 billion living in rural areas (IEA, 2023h). This population continues to cook over open fires or basic stoves to the detriment of their health, as they inhale harmful smoke from burning firewood, charcoal, coal and agricultural wastes. Approximately 3.2 million deaths in 2020 were attributed to indoor air pollution, which also contributes to other diseases such as lung cancer, heart disease, and acute and chronic respiratory illnesses (CCAC, 2023b).

In households, globally, about 35 percent of the population used wood fuel for cooking in 2019, with 37 percent relying on liquefied propane gas (LPG), natural gas or biogas and 10 percent on electricity (ESMAP, 2020). Recent decades saw a decline in the number of people without access to clean cooking globally. The rural population primarily using polluting fuels fell from 2.5 billion in 2003 and is expected to decline further to 1.7 billion in 2030 (Stoner et al., 2021b). Asia has seen the most progress on clean cooking in recent years., while the share without access to clean cooking is highest (and still growing) in SSA and lowest in Latin America and the Caribbean (IRENA and FAO, 2021).

Importantly, a lack of technologies will not hinder reaching universal access to clean cooking, as the solutions are known; funding and implementation capacity are proving a more formidable hurdle (IEA, 2023j). Given the number of people needing access to cleaner cooking, more robust efforts in making these technologies known and accessible across rural areas are needed.

There are a multitude of benefits to clean cookstoves, including significantly reduced air pollution, fuel-use savings, decreased deforestation and faster cooking. Electric stoves deliver efficiencies in both labor and time; however, inadequate access to reliable electricity remains a substantial barrier to uptake – especially in rural areas. Here, technological progress toward cheaper PVs and efficient cooking appliances with integrated battery systems have improved the situation; however, they remain expensive for many rural households. Improved biomass cookstoves (ICSs) present a decent transitional option in rural areas. ICSs decrease biomass use compared to traditional stoves by 20 to 75 percent depending on efficiencies, which renders benefits through reduced smoke production (IEA, 2023j).

Thus, a variety of options are available, and though most do offer energy savings, many do not substantially reduce CO_2 emissions and other harmful pollutants. Biogas is increasingly being employed in rural areas, alongside solar cookers, which use solar radiation to concentrate heat on a cooking vessel.

Given the increasing ubiquity and benefits of solar energy in rural households, these are good options to reduce social, economic and environmental costs of black soot and CO_2 emissions. Achieving clean cooking access can save up to 1.5 Gt CO_2eq by 2030 (IEA, 2023h).

Trash to treasure: waste-to-energy technologies are transforming household waste

Waste-to-energy systems for households serve many functions and provide a host of benefits for homeowners and the climate. Biogas is a renewable energy source that can be created during the anaerobic digestion process from all types of organic materials, including plant and animal products when they are broken down by bacteria in an anaerobic (or oxygen-free) environment in reactors. Biogas reactors are scalable solutions ranging from farm-level to large industrial installations. Biogas is renewable and can be used for heating, lighting, cooking, as a transport fuel, and to generate electricity to supply power grids. It also provides digestate (solid or liquid substances) as by-products that can be used as fertilizers or even to create bio-based construction materials. Biogas production has grown in certain regions and depends largely on enabling policies, with the United States, Europe and China constituting 90 percent of global biogas production (IEA, 2023f). The industry is expected to grow, especially in the Global South.

Gasification is a thermal waste-to-energy method that uses waste as a feedstock and converts it into syngas, which can be used for fertilization and transportation. A main benefit of gasification is that plastics can be used without emissions of harmful pollutants. Pyrolysis, the high-temperature treatment of an organic material in the absence of oxygen, is the most common technology employed to produce biochar, also occurring early in the combustion and gasification processes (Biochar International, 2024). Biochar is created through heating biomass in the absence of oxygen. It can be used as a soil ameliorant and fertilizer in farms and home gardens. A similar benefit here is that organic household waste, crop residues and manure can be used and transformed into useful materials rather than going to waste. Though biochar has been used for thousands of years, it's becoming more popular among home gardeners, farmers and land managers as a soil amendment to increase soil health and fertility. Simple biochar kilns for home gardening have come onto the market, streamlining and simplifying the process of creating biochar in households. See the 2023 *Green Technology Book* edition on climate change mitigation for further discussion of biochar, accessible here.

Micro-hydropower: a convenient option at household level

Hydroelectric power is indeed one of the oldest renewable energy technologies, having been used since the era of the ancient Greeks to grind grain (IRENA, 2024c). It is now an extremely economical method of electricity generation, providing over 15 percent of the world's electricity (IHA, 2023). Despite major energy savings across several countries, there has been significant opposition to mega-dam projects that impact local populations, change river flow regimes, reduce biodiversity, and cause flooding and forced relocation of villages, farms and wetlands, shorter than projected life-span due to reservoir siltation, and irregular processes around entrepreneur contracting, resettlement and compensation. Nonetheless, the potential for small-scale hydroelectric generation at a household level shows promise. Small-scale hydropower has been adopted since the 1980s to meet a wide array of energy needs in off-grid areas, while also boosting rural economies through household income generation and job creation (ESMAP, 2022; IRENA, 2023b). The number of people connected to hydro-based mini-grids increased from 5.7 million in 2012 to about 7.2 million in 2021 (IRENA, 2024b).

Although often seasonal, micro-hydropower can supply energy 24/7 while also serving irrigation needs and connecting communities to the grid, even allowing for the sale of excess power (IRENA, 2023b). Homeowners in rural areas with access to flowing water may be able to tap into the potential for hydroelectric electricity generation. The technology uses a combination of water flow and vertical drop ("head") guiding it toward a turbine to produce energy. The impulse turbine is commonly used in micro-hydropower systems due to its simplicity and greater resistance to particles like stones, sand and grit.

Innovation examples

Luz en Casa ("Light at home") Ngäbe-Buglé Programme, Panamá

Source: Acciona

Acciona.org Panamá, one of the three winners of the ILO Just Energy Transition Innovation challenge, is bringing affordable energy access to isolated rural indigenous Panamanian households through its Luz en Casa Ngäbe-Buglé programme, part of the global acciona.org's rural electrification initiative "Luz en Casa" (Light at home). Up to now, the organization, with the support of its partners, has improved the off-grid situation of about 4,000 households in Ngäbe-Buglé, one of Panama's least developed and least electrified areas, through the provision of basic electricity via 3G-SHSs. Introducing third-generation compact and efficient plug-and-play systems, which incorporate photovoltaic solar panels, high-efficiency LED lamps, lithium batteries and long lifespans of minimum 20 years, more than 22,000 beneficiaries in 170 communities have been provided with electricity. Local small businesses also host "Light at Home Centers" and training to support installation and maintenance of the systems while generating income for their efforts. Now the project can provide up to 11 million h/year available lighting, 3.6 million h/year for additional activities at home, EUR 120,000 per year in energy expenditure savings and 1,700 metric tonnes of CO_2 emissions avoided annually (acciona, 2024).

Clean Cooking Alliance (CCA) bolsters clean cookstove expansion in Nepal

Source: Clean Cooking Alliance

In Madhesh province, almost 70 percent of households cook with wood and dried manure in biomass stoves or open fires, which has contributed to a trend of early mortality in the country. Women and children also devote significant time to collecting wood. The Government of Nepal has committed to achieving universal access to clean cooking by 2030, including the adoption of electric cooking by 25 percent of households. The Government is working with the CCA on an innovative project aimed at selling affordable electric stoves to 1,000 households in Madhesh. In Nepal, nearly all electricity is generated from hydropower, and therefore electric cooking has potential to further accelerate the renewable energy transition. However, the largest obstacle for many households is the cost for a high-quality electric cookstove, which has made the uptake of electric cooking limited. The technology employed in the newly developed stoves embeds data capabilities to monitor stove use and helps project developers calculate avoided emissions and sell carbon credits, significantly reducing the price. The demonstration project revealed that most homes also require some electrical improvements, underscoring the need for community-scale infrastructure. This has paved the way for the next government initiative (Clean Cooking Alliance, 2023).

Technology solutions

Proven

Solar home system: solar inverter
Sun King

Source: Sun King

The PowerHub 3300 offers reliable power for households and businesses in off- and weak-grid environments. It is wall-mounted, containing solar panels, an inverter and a lithium iron phosphate (LiFePO4, LFP) battery, which stores solar or grid-delivered electricity. The hybrid inverter powers appliances directly while charging its battery. The battery reserves can provide power during low sunlight, nighttime, power outages and periods of high demand when grid electricity is often more expensive.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Kenya
- Availability: Africa and Asia
- Contact: WIPO GREEN Database

Solar home system: compact home battery
Tesla

Source: Source: Getty Images/Petmal

Powerwall is not a standalone wall, but a compact home battery that stores energy generated by solar or from the grid. Because of its size, it can be mounted in many locations, including the wall, floor, or even outside. When the solar system generates more energy than needed, it can be stored for later use. The Powerwall can recharge from the grid when utility prices are low. The system can power homes, including heating and cooling, and large appliances. It optimizes the stored energy by having access to usage history, utility price projections and weather forecasts. In some cases, homeowners can sell their excess energy to the grid.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Solar appliance: high-autonomy solar lamps
LAGAZEL

Source: LAGAZEL

Lagazel Kalo lamps provide lighting to those without an electrical grid, especially in SSA. The Kalo 3000 has steel housing, making it weather-resistant. It provides up to 38 hours of light from one day of charging and contains a universal serial bus (USB) slot to enable the recharging of mobile phones. It uses an LFP battery for extended life and polycrystalline solar panels.

- Contracting type: For sale
- Technology level: Medium

- Country of origin: France
- Availability: Africa
- Contact: WIPO GREEN Database

Solar appliance: pico PV fan
d.light

Source: d.light

The d.light solar fan SF21 contains a long-lasting rechargeable battery, enabling it to last for up to eight hours at the fastest setting. The in-built LED light provides hours of light, eliminating the need for a separate light for other activities. It can illuminate up to four rooms. It has a built-in timer to conserve battery and maximize efficiency, provides six speed settings, and has AC/DC charging capabilities.

- Contracting type: For sale
- Technology level: Low
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Solar appliance: solar refrigerator kit
Amped Innovation

Source: Amped Innovation

The EasyFreeze is a high-performance solar-powered 100 liter refrigerator or freezer for households in areas with no grid power or limited access to AC grid power. It uses R600a refrigerant, which is at least 38 percent more energy-efficient than the R134a refrigerant, an HFC with much higher GWP. It has a 225 W compressor and 75 m closed cell polyurethane insulation and can maintain cold storage during power outages or times of low sun exposure. It uses an LFP battery and high-quality compressor. The system will refrigerate to 8°C in less than 20 minutes, freeze in under an hour, and remain cold for up to 40 hours during blackouts. There is an associated mobile app and optional pay-as-you-go keypads, wheels, and AC wall adapters.

- Contracting type: For sale
- Technology level: Medium

- Country of origin: Kenya
- Availability: Worldwide
- Contact: WIPO GREEN Database

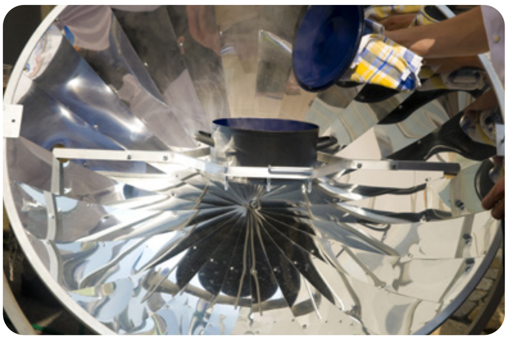
Clean cooking system: ECOA electric pressure cooker and induction cooker
Burn

Source: Burn

Electric pressure cookers use steam and heat inside a sealed chamber and are energy efficient because they require less liquid than traditional cooking methods and as the pressure makes water boil at lower temperatures. The insulation keeps energy from being lost during cooking. The ECOA electric pressure cooker reduces cooking time by 50 percent, provides localized custom presets to enable consistent cooking results, comes in a large 8 liter pot for family cooking, and features automatic temperature, pressure regulation and lid detection for safety purposes. The electric induction cooker is 85 percent energy-efficient (compared to 73 percent efficiency for LPG cooking and 31 percent efficiency for traditional cookstoves), contains customized presets as well as adjustable timer and eight levels of power for temperature control, and features child lock, pot detection, error detection and anti-slip technology.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Kenya
- Availability: Africa, China, United States
- Contact: WIPO GREEN Database

Clean cooking system: solar oven
GoSun



Source: Getty Images/ZU-09

GoSun Fusion™ hybrid solar oven is "the world's first solar oven that can also cook without sun." A solar and electric oven runs on sunshine or 12 V from an automobile, boat, recreational vehicle, or powerbank. It can provide four to six meals per load using a 3.2 liter cook tray, cooks at a maximum temperature of 288°C, has a maximum power output of 200–225 W in the full sun, and yet functions under cloud cover and at nighttime. The Fusion's hybrid solar and electric technology uses GoSun's advanced thermal performance to enable cooking anywhere and keeps food hot for up to 12 hours with its vacuum tube, which acts as a thermos. GoSun also offers Solar Kitchen and Solar Kitchen Pro, which are equipped for all off-grid needs for cooking, refrigeration, water purification, coffee brewing, sink or shower, and a GoSun Table 60 to charge devices.

- Contracting type: For sale
- Technology level: Low
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Hydropower: micro-hydroelectric systems to 100 kW
Canyon

Source: Canyon

Canyon micro-hydroelectric systems are small hydro systems for residential projects that range from 4 kW to 25 MW. Complete hydro systems are available (as well as individual parts) that include a water turbine, housing, generator, drive system, electronic governor and assembly frame. The water turbines, Pelton wheels (an impulse turbine), are efficient single units that have been designed to maximize hydraulic energy transfer to the turbine shaft.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Waste to energy: backyard systems/anaerobic digesters
HomeBiogas

Source: Getty Images/Toni Jardon

The HomeBiogas system is a biodigester that transforms kitchen waste into clean cooking gas and liquid biofertilizer. It helps users manage up to 8 liters of kitchen waste every day and obtain up to four hours of cooking gas. Smaller systems are available that are tailored to backyards that manage up to 4 liters and yield two hours of cooking gas, as well as 8 liters of liquid fertilizer for the garden. The Homebiogas 6 works for small-scale farms and manages up to 12 liters of daily kitchen waste or 43 liters of animal manure, provides six hours of cooking gas, and 24 liters of liquid bio-fertilizer or up to 120 liters mixed with water-diluted animal manure. The BioToilet is a solution intended for suburban homeowners and those living off-grid whereby the anaerobic digester converts the waste into cooking gas.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Israel
- Availability: Worldwide
- Contact: WIPO GREEN Database

Waste to energy: biochar kiln
Earthly Biochar

Source: Earthly Biochar

Earthly Biochar's clean burning biochar kiln was designed for gardeners. It is used to make biochar in a safe and sustainable fashion at home using smokeless technology. The biochar kiln enables domestic gardeners to create soil amendments in one hour using a process that creates carbon neutral heat. The kiln heats up to temperatures of 600–800°C. The wood smoke produced is funneled to a combustion zone and mixed with oxygen to produce heat, CO_2 and water vapor, delivering biochar that can be added to soil as a natural plant fertilizer. The kiln has a 25 liter chamber that can produce 7–10 liters of biochar from every burn. It is tripod mounted, has a modular design, and is equipped with a grill plate to allow heat energy to be used for cooking.

- Contracting type: For sale
- Technology level: Low
- Country of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Waste to energy: biomass boiler
Zhongzhen Lvtan (Henan) Energy Group Co., Ltd.

Source: Zhongzhen Lvtan (Henan) Energy Group Co., Ltd.

The company's biomass fuel boilers can be used in rural areas to solve winter heating problems. Biomass fuel boiler heating is a low-carbon, clean, environmentally friendly and economical renewable energy heating method that can replace coal-fired boilers for heating and reduce air pollution. Biomass fuel boilers use agricultural and forestry biomass raw materials (such as crop straw and forestry residues) that are physically compressed into rod-shaped, block-shaped or pellet-shaped fuels. The company's biomass boilers have 68 patented technologies. The boilers feature fully intelligent control, simple operation, and emissions that meet environmental requirements in China.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: China
- Availability: China
- Contact: WIPO GREEN Database

Frontier

Solar home system: plug-and-play battery with mini-grid
PowerBlox

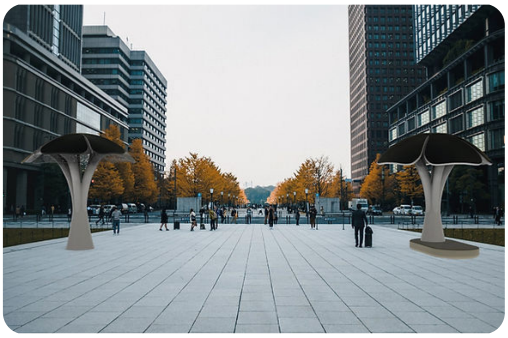
Source: Getty Images/onurdogel

The PBX-200 system is a plug-and-play technology comprised of intelligent energy cubes with an integrated LFP battery, where each cube provides 200 W AC current with in-built converter and control systems, providing versatility in terms of input and output energy for households or small business with electricity. Its modularity means it therefore can be used as a building block for use when electricity demand increases; homeowners can start with one unit and expand as needed with additional units.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Switzerland
- Availability: Africa, Asia, Middle East, Switzerland
- Contact: WIPO GREEN Database

Solar home system: solar tree (aesthetically attractive alternative to solar panels)

SolarBotanic



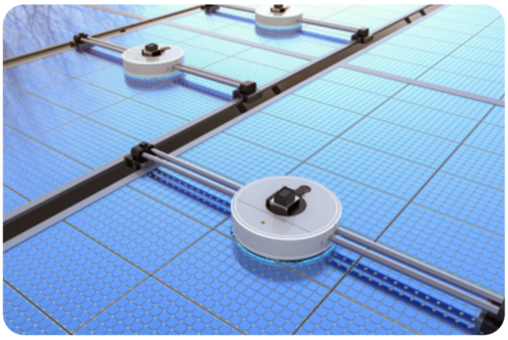
Source: SolarBotanic

The SolarBotanic™ Tree is an aesthetically pleasing solar panel alternative that can generate energy for a small home or charge an electric vehicle (EV) while mimicking natural trees. Excess energy can be sold back to the grid. SolarBotanic trees can incorporate battery storage to deliver power at night or in cloudy conditions. Multiple trees can be used to create a "forest" or a micro-grid to power a whole neighborhood. A new design, the fully integrated SolarBotanic Tree version v2 with energy management system, battery storage and rapid EV-charging system will be available commercially in late 2024.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United Kingdom
- Availability: United Kingdom, Europe
- Contact: WIPO GREEN Database

Solar home system: AI-powered solar panel washing machine

Solarwashing



Source: Getty Images/PhonlamaiPhoto

Solarwashing has developed a fully automated solar panel washing machine that increases energy output by up to 35 percent. It is the first hands-free fully automated fixed washing robot that uses AI to predict when and where to wash in order to extend the lifetimes of solar panels and maximize their energy output. The patent-pending technology therefore saves energy, water and CO_2 emissions.

- Contracting type: For sale
- Technology level: High
- Country of origin: Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

Solar appliance: solar water heater
Sunpad

Source: Sunpad

Sunpad is a solar water heater that integrates the heat carrier tank into the insulation to create an extremely compact system. Due to the small quantity of components, the system requires less maintenance than others over its lifetime. The storage tank contains 150 liters of water. The special solar coating on its surface heats a transfer fluid in the tank when it's exposed to sunlight and this heated fluid is pumped into a heat exchanger located in the water tank, which heats the water. Depending on the conditions and temperature of the system, it can provide up to 380 liters of water at 40°C. The tank is wrapped in 50 mm thick insulation composed of high-quality extended polypropylene foam, which also holds the UV-resistant cover insulation and the solar safety glass.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Austria
- Availability: Worldwide
- Contact: WIPO GREEN Database

Solar appliance: hydropanel for drinking water
SOURCE

Source: SOURCE

SOURCE® Hydropanels™ technology incorporates multiple patented inventions. It is an off-grid solution that can be powered with solar energy. It contains fans that draw in ambient air and force it through a water-absorbing material, trapping water vapor and condensing it into liquid water. This water is then transferred to a pressurized tank in the home, where it is mineralized for taste, and then becomes clean drinkable water which can be distributed from the tap or refrigerator. The system operates in a wide range of conditions, even in low sunlight and humidity, and can produce 90–150 liters of water per day.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

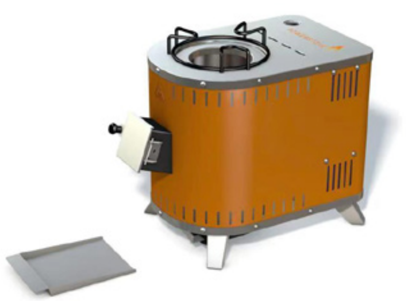
Energy storage system: SOLIX X1 home energy storage
Anker

Source: Getty Images/kyoshino

The SOLIX X1 is equipped with a power density of 8.7 W/ft3, packaged into an all-in-one design including battery and power modules. Each battery pack contains an energy optimizer for independent charging and discharging. The application monitors power generation and consumption in real time. The NEM 3.0 mode in the application enables charging of the X1 with cheaper electricity prices during daytime and selling back electricity during peak price periods. The X1 has seven energy modes and four off-grid features to deal with pre-outage, and for power during short outages, blackouts and extended outages. It also provides 100 percent power in temperatures ranging from –20°C to 55°C. Thermal boosting starts at 0°C and keeps the battery operating at 20°C, while it can also operate in extremely hot temperatures due to its modular design and cooling system.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Clean cooking system: hybrid cookstove using IoT
Powerstove



Source: Powerstove

Powerstove is a smokeless clean cookstove that burns 70 percent less biomass and cooks five times faster than a traditional stove. Using only pellets, Powerstove produces 50 W of electricity, stores excess power in a lithium-ion battery, and is able to charge phones, lights, and so on. Using a precision airflow system alongside the built-in battery and four-speed fan, the fan regulator enables users to control the temperature while cooking. The stove includes IoT technology, which enables users to track and control stove performance, manage energy consumption and receive notifications and updates.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Nigeria

- Availability: Africa
- Contact: WIPO GREEN Database

Horizon

Clean cooking system: mobile, solar-powered bakery
SOLARBAKERY

Source: SOLARBAKERY

SOLARBAKERY is a mobile and energy self-sufficient container bakery which started as a bakery chain in Senegal. The vision is to create a global network of sustainable bakers that bring jobs to the Global South. The first pilot project is in Democratic Republic of Congo, where more SOLARBAKERYS are slated to be constructed. They are plug-and-play, with an integrated mill for the processing of raw materials. Utilizing solar panels and batteries, the bakeries can bake up to 3,000 loaves per day and project an ROI pay-off in the fourth year of operations.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Africa
- Contact: WIPO GREEN Database

Solar appliance: saline water lantern
National Institute of Ocean Technology (NIOT)

Source: National Institute of Ocean Technology (NIOT)

A team of scientists at the National Institute of Ocean Technology (NIOT) in India have developed the Renewable Ocean System for Harnessing Novel Illumination (ROSHNI) seawater lantern. The lantern uses the process of ionization to produce electrical energy when saltwater electrolytes react with magnesium inside the device. The lantern is useful for fishing communities and island populations, and in cases of emergency or grid disruptions. It can operate for up to 12 continuous hours for every seawater replacement and the electrodes have a lifetime of 500 hours of lantern usage. Tap water can be used with table salt in cases where sea water is unavailable. Alternative lanterns offer mobile charging.

- Contracting type: For licensing
- Technology level: High
- Country of origin: India
- Availability: N/A
- Contact: WIPO GREEN Database

Energy storage system: EV battery as electricity storage for households
E.On Bi-ClEVer project

Source: E.On Bi-ClEVer project

Bidirectional charging technology makes it possible for electricity to be fed back into the grid. As part of the Bi-ClEVer project, E.On and its partners are conducting a pilot project to determine how an EV battery in combination with a PV system can be used as an electricity storage system in households. Preliminary results show that the degree of independence from the electricity grid can more than double through bidirectional charging. Using a PV system and EV with a 42 kWh battery as intermediate storage, 51 percent self-sufficiency on average is feasible. To achieve this, the EV charging times are monitored to ensure the battery is charged as much as possible with self-generated solar power. With an additional stationary battery, this can be increased to up to 59 percent. The charging and discharging processes will be automated using a home energy management system. Continuous improvements to the algorithm are planned that account for weather forecasts and individual usage and mobility behavior of residents.

- Contracting type: Under development
- Technology level: High
- Country of origin: Germany
- Availability: N/A
- Contact: WIPO GREEN Database

Electrification: Automatic and bidirectional home EV charging stations
Volterio

Volterio

Volterio's home charging robot consists of a ground unit on the parking floor and an underbody vehicle unit. The units sense each other using a low frequency positioning system and guides the driver into position. Once the vehicle is parked, charging automatically begins and delivers

22 kW AC or up to 50 kW DC. The automated conductive charging system is bidirectional, allowing users to store excess energy, and can also employ manual or automatic scheduling considering fluctuations in electricity costs or a scheduled departure time. The charging process can be controlled and monitored via an app, and the underbody vehicle unit is retrofittable onto almost any electric vehicle. The system is currently in development and is piloted with major OEMs and Tier-1 suppliers.

- Contracting type: Under development
- Technology level: High
- Country of origin: Austria
- Availability: N/A
- Contact: WIPO GREEN Database

Climate-resilient solutions for rural communities

Decarbonization is key to reducing carbon emissions and meeting global UN Paris climate goals. Major drivers of decarbonization include scaling up renewable energy deployment and energy efficiency innovations. As underscored in the rural households section above, rural communities also need access to efficient and reliable energy. The UN Sustainable Development Goal (SDG) 7 endeavors to ensure access to affordable, reliable, sustainable and modern energy for all while acknowledging energy's key role in improving overall quality of life (United Nations, 2023). The IEA warns that in the absence of progress toward reaching this goal, 560–660 million people in SSA alongside 70 million people in Asia could remain without access to electricity by 2030 (IEA, 2023h).

Thus, the decarbonization of the energy system can help seize synergies between achieving sustainable rural electrification for communities and transitioning away from fossil fuels. Even better, these options provide both climate mitigation and adaptation benefits to rural communities.

Technological developments and trends

As discussed in the rural households section, electrification rates in rural areas lag behind urban areas for a variety of reasons, including lower population densities, difficult terrain and long distances, grid extension obstacles, low electricity demand, lack of infrastructure, proclivity to natural disasters, and even weak policies and governance. Due to low demand, costs incurred and up-front expenditures to extend grid access to remote communities, it is often less expensive to expand access to rural communities using mini-grids than to extend the grid (ESMAP, 2019).

An important component of further increasing uptake in remote communities is ensuring that residents are made aware of technologies and how they can benefit from using them

Remote communities include not only remote rural populations with sparse population density, but also small islands (65 million people living in 57 small island states), mountain communities (12 percent of the global population, or 720 million people), indigenous populations (roughly 6 percent of the world's population, or 476 million people in 90 countries) and displaced populations, which are constantly growing, but estimated to be 94.7 million (IRENA, 2023d).

The UN's High-Level Dialogue on Energy recommended that "the last mile of energy access must become the first mile to be tackled" (United Nations, 2021). The inaccessibility of these so-called "last mile" communities renders them dependent on off-grid energy sources, which have historically proven to be inefficient, insufficient and reliant upon fossil fuels that contribute to pollution and GHG emissions.

Decentralized solutions have become increasingly common in the form of standalone and mini- and micro-grids that are powered by solar, wind and hydropower. Communities have been offered an increasing number of options to benefit from these renewable energy sources. In SSA, where roughly 60 percent of Africans reside in rural communities, already approximately 5 percent of these people have access to clean electricity through the 11 million mini-grid connections which are active (Babayomi et al., 2023). Solar mini-grids constitute roughly one-third of mini-grids providing electricity today, and are now recognized to be the least expensive option, enhanced by their scalability and simple deployment (IEA, 2023k).

Community-centric models for electrification have been a boon, as they ensure ownership and enable communities to co-design projects, set tariffs and be actively involved in managing them and overseeing operations and maintenance. Policies that promote community engagement are vital to ensuring alignment between local community needs and decentralized renewables, and support community engagement in creating sustainable energy pathways (IRENA, 2023d).

Box 3.1 describes a trend that emerged in the early 2000s, energy kiosks.

Box 3.1 Early energy kiosks

An earlier community solution to meet rural electrification needs involved energy kiosks, which gained ground between 2005 and 2014. Generally, the kiosks produced electricity using a solar panel and sold it through charging devices. Kiosks provided community services, such as simple mobile phone and lantern charging and on-demand refrigeration (Babayomi et al., 2023). They then started serving as multi-service stations offering retail products, and even education and entertainment (Joy Kellen, 2022). These initiatives were promulgated by a wide range of actors in Africa, India, Southeast Asia and the Caribbean, including non-governmental organizations (NGOs), startups, multinational companies and governments (Knobloch and Hartl, 2014). As technologies have improved, expanded models drawing upon the original idea are still employed in certain areas, improving last-mile logistics and pay-as-you-go services, as profiled here in the technologies section.

An important component of further increasing uptake of renewable energy and energy efficiency solutions in remote communities is ensuring that residents are made aware of technologies and how they can benefit from using them. This includes the positive impacts they can have on livelihoods and employment opportunities, resilience to the impacts of climate change, energy independence, and health and well-being. A broader and more inclusive approach to involving communities in technology adoption and development, that considers traditional knowledge and includes rural and indigenous communities in decision-making processes, relies on the CARE principles for indigenous data governance. CARE stands for "Collective Benefit," "Authority to Control," "Responsibility" and "Ethics." These can guide the co-development of technological solutions amidst increased adoption of AI technologies and the emergence of big data and open data as integral to research and innovation (Carroll et al., 2020).

Mini-grids and micro-grids: the backbone of rural community electrification

Mini- and micro-grids have recently benefited from more advanced technologies, rendering them more resilient and less expensive (USAID, 2023). These improvements in grid management, efficiency and stability include new materials for solar PV cells, such as perovskite; improved battery technologies; hybrid technologies incorporating renewables with conventional energy; and increased use of AI and advanced control algorithms.

Micro-grids are local decentralized energy grids that operate independently or in concert with a traditional grid. They are self-sufficient and offer communities energy security and independence. Micro-grids integrate renewable energy alongside renewable energy storage technology and demand response and can reduce costs by optimizing energy resources. They are not novel but have been gaining traction in recent years among communities desiring to integrate decentralized energy resources (DER). Diesel generators have been used in micro-grids in the past, but moving away from their use is essential for climate change mitigation.

The increased integration of renewable energy contributes to halting the use of fossil fuels and meeting global climate change mitigation goals. Fortunately, the facilitation of DER with renewables also helps expand energy access, increasing resilience for communities in need and vulnerable to the impacts of climate change.

New smart technologies for improved efficient micro-grids

As various new technologies, including micro-grid controllers, software and energy storage systems have advanced and proliferated, more communities are choosing to build micro-grids. Due to their isolation and vulnerability, increasing the mix of renewables can also introduce grid stability issues. Innovative technologies are combating this and other challenges.

Energy storage systems. Storage is essential, as the intermittent nature of renewable energy sources causes disruptions in power supply. Various advanced energy storage technologies are under development and gaining traction, such as flywheel energy storage systems, flow batteries, fuel cell technologies and gravity storage.

Flywheel battery energy systems are mechanical energy systems that can be paired with wind energy. A flywheel stores energy for the shorter term by using a rotating mass in the form of kinetic energy (Mahmoud et al., 2020). Flywheels have a long lifetime and decent efficiency, and are free of chemicals. Amending flywheels to a renewable micro-grid can prevent power quality and sag and surge issues (Aktas and Kircicek, 2021). They can be expensive to install and are often more appropriate for applications requiring rapid response and high power output, making them suitable for balancing short-term fluctuations in supply and demand within mini-grids. They are typically used in combination with other energy storage technologies.

Flow batteries are electrochemical rechargeable batteries in which energy in the form of two electrolytes stored in large tanks is pumped through a system separated by an ion exchange membrane. Flow batteries have a quick response time, versatility and a longer lifetime. They contain environmentally friendly materials, such as vanadium, that are not flammable, rendering them safer (Haisheng Chen et al., 2022). They are also cheaper and can operate under a wide range of temperatures. Although the technology has not yet been perfected, it's promising for large-scale storage of intermittent power (Kamran, 2022).

Fuel cell technologies for micro-grids. Fuel cells are now considered efficient, safe and reliable, functioning either within micro-grids or standalone. Micro-grids paired with fuel cells provide predictable energy 24/7 to complement renewable power. They do not require a large land area, and are small and quiet, unlike diesel generators. Fuel cells convert chemical energy from hydrogen into electrical power, heat and water using an electrochemical process. They can operate continuously as long as hydrogen is supplied, which can be produced by electrolyzers and stored over time in compressed, liquated or metal hydride form and then consumed by the fuel cell (Valverde et al., 2015). However, due to the complexity of the systems and the hydrogen storage process, this solution is relatively costly.

Gravity storage. Newer technologies such as gravity storage can repurpose former mining areas, which could be advantageous to rural mining communities already equipped with mining infrastructure and technology. Gravity storage uses potential energy of heavy masses elevated to certain heights to store energy. Gravity storage can be an efficient and cost-effective solution to support renewable energy sources. Pumped storage hydropower can also be used in hillier terrain, using a configuration of two water reservoirs at different elevations that generates power as the water moves down from one reservoir to the other through turbines. The system uses renewable power when available to pump water to the upper reservoir, and then releases it when needed, serving as a large battery.

AI-powered optimization. As mentioned, balancing energy demand and supply when using distributed energy sources can lead to power outages and inefficiencies. AI-powered solutions using machine learning and other algorithms help to optimize energy use while supporting the integration of additional renewable energy sources.

Blockchain technologies. Blockchain provides a transparent method to manage energy distribution and payments and may include smart contracts that automatically carry out transactions when predefined conditions are met. It has become more commonly used for peer-to-peer energy trading in micro-grids, and ensures security while allowing participants to control their system without a centralized regulatory authority, thus avoiding costs (Tsao and Thanh, 2021). However, some regions are at earlier stages of exploration in using blockchain for peer-to-peer energy trading.

Virtual power plants. A virtual power plant (VPP) is a network of small-scale distributed energy resources such as rooftop solar panels, energy storage systems, EV chargers and water heaters, that are aggregated and connected with grid operations to provide similar services as traditional power plants (Rocky Mountain Institute (RMI), 2024). They can be built quickly, bypass transmission and distribution constraints, and transform electric devices into power supplies for communities during grid outages, while also offering additional revenue streams to incentivize the adoption of electric technologies. VPPs can optimize energy use and predict demand through the use of cloud computing (StartUs Insights, 2023).

Micro-grid-as-a-service. Numerous micro-grid services are easing high up-front installation and maintenance costs, which have deterred many communities from their adoption. Using micro-grid-as-a-service, users pay only for the energy used, which provides enhanced access in remote areas . IoT sensors and analytics used by micro-grids help monitor energy use and streamline management to reduce energy waste (StartUs Insights, 2023).

Swarm electrification: a novel concept gaining traction

The concept of swarm electrification entails “swarm grids” that are similar to micro-grids, with the distinction that they are assembled in an ad hoc (rather than planned) fashion and connect equipment that is available to grow organically as more resources become available. The concept is fairly new, but has been gaining traction as a means to providing last-mile electrification (Sheridan et al., 2023). Swarm grids can also be called organic micro-grids, mesh grids, bottom-up grids, or ad hoc micro-/pico-/nano- grids. Swarm electrification also enables users of small SHSs to sell excess energy while others can then obtain an electricity connection, thereby generating income for the prosumer while increasing access for others (Sheridan et al., 2023).

Small-scale hydropower a potential boon with co-benefits for communities

Small-scale hydropower systems, as discussed in the rural households section above, offer multiple benefits for communities including irrigation services and even connection with the central grid. Mini-grids are increasingly tapping into multiple renewable energy sources, and small hydropower can play a role and exploit an abundant natural fuel source, long equipment lifespans and minimal maintenance needs.

Community-based hydro mini-grids may also provide a nature-based solution, depending on the hydropower solution, that incentivizes the conservation and restoration of watersheds (IRENA, 2023b). This in turn creates additional livelihood opportunities in hydropower value chains, especially when factoring in necessary infrastructure investments for watershed conservation that would protect communities and hydro mini-grids against natural disasters (IRENA, 2023b). Innovative micro-hydropower solutions that can be used in rural communities are featured in this section, whereas pico (very small) systems are highlighted in the rural households section.

Solar pumps, drinking water and waste-to-energy innovations benefit rural communities

Solar-powered water-pumping systems are affordable and reliable solutions for rural communities. Water purification services combined with these pumping systems provide clean drinking water for communities, while also providing revenue collection and management services. Clean cookstoves provide a multitude of environmental, energy-saving and social benefits. Solutions devised for larger institutional cooking settings found in communities, such as schools, are also improving energy access, energy savings, and health and air quality issues.

Waste-to-energy technologies provide a critical solution to transforming organic waste on-site. These can service larger loads of waste to create energy on-site and provide innovative solutions such as using forest biomass residue from thinning and logging operations to produce electricity and heat. Several home solutions are featured in the rural households section.

Solar appliances and rural e-mobility innovations ease burdens on rural women

Rural women are involved in a large share of agricultural work and take charge of managing households as well, spending significant time and physical effort walking long distances to obtain water for cooking, cleaning and washing. Electric mobility has typically been focused on urban areas and on four-wheel models, while the potential of electric two- and three-wheelers for rural areas has not been fully exploited. Some technologies for rural communities are addressing this problem via solar tricycles and carts.

Additionally, some industries, such as the silk industry, are dominated by women who have employed either traditional thigh-reeling techniques that can inflict physical injury, or diesel-powered spinning machines. Solar-powered machinery has been rare in rural areas like India. Solar-powered spinning machines, which are now on the rise, decrease emissions and also help to connect the silk industry with others in the value chain, such as solar-powered sewing machines (Dialogue Earth, 2023), which can ultimately bolster the scale-up of renewable machinery.

In the end, the influx of solar-powered machinery and appliances into rural communities provides a multitude of climate benefits for both mitigation and adaptation. The expansion of renewable appliances not only lessens dependence on fossil fuels, a win for climate mitigation, but also increases the energy resilience of communities, rendering them less vulnerable to energy access disruptions, and boosts overall economic resilience through livelihood diversification.

Innovation examples

US Department of Energy Alaskan Tribal Energy Sovereignty

Source: Getty Images/GeorgiNutsov

Eight remote Alaskan tribal communities that are inaccessible by road currently rely upon diesel for 100 percent of their electricity production. In collaboration with the Alaska Village Electric Cooperative, the US Department of Energy Alaskan Tribal Energy Sovereignty project aims to deploy high-penetration solar PV and battery storage systems in existing micro-grids. The project will renovate grid infrastructure while providing job training to tribal communities, and support the development of Alaska's largest tribally owned and operated independent power producer. Lowering diesel consumption by 40 percent will decrease energy costs, improve air quality and reduce GHG emissions by 1,550 tonnes over its 25-year lifetime. The tribal ownership model is slated to create net income of USD 150,000 per year to be shared across tribal governments and used to develop further renewable energy projects. Ultimately, the project will advance the eight communities' micro-grid reliability, resilience and energy security (US Department of Energy, 2023).

UN World Food Programme (WFP) Innovation Accelerator Electric Pressure Cookers for Schools (EPC4S), Lesotho and Kenya

Source: Getty Images/PixelCatchers

Many schools in Lesotho and Kenya rely on biomass-based cooking, which can cause health issues and increase firewood demand, exacerbating deforestation. This WFP project aims to address these problems while also saving on community cooking costs. It provides electric pressure cookers (EPCs) to replace biomass-based cookers in school canteens. These stoves are cheaper than other solutions, having been shown in Kenya to incur 10 times lower operating costs than cooking with charcoal. The WFP team tested EPCs in an initial school pilot called the “WFP Sprint Programme” to determine the feasibility and viability. Results were positive on energy savings, but also on cost reduction, faster cooking times, safer practices with less food contamination, and reduced food waste due to the need for measuring specific amounts to load the pots. Following the pilot, EPCs were planned for implementation in 20 schools in Lesotho and Kenya. Once these have been established, the team plans to scale up the project to 10 WFP Country Offices across 1,200 schools, providing clean cooking to 480,000 children (WFP, 2022).

Carbon neutral Samsø Island, Denmark

Source: Getty Images/Melbye

In 1998, the 3,700 residents of the 114 km2 Danish island of Samsø started developing and executing a plan to make the island carbon neutral. Since 2012, energy has been supplied entirely by wind and solar, except for the transport sector and roughly 30 percent of residential heating outside the district central heating system. Following significant communal planning and cooperation among the local municipality, citizen cooperatives and the private sector, several windmills were constructed, along with an offshore windmill park and district heating based on biomass (mainly locally produced straw). Samsø now generates more power than it consumes, and the surplus electricity is sold to the national utility company NRGi on the mainland to offset the remaining fossil fuel use. Several of the 2,000 households on the island now have heat pumps using renewably produced electricity from the grid. The transport sector is still partially reliant on fossil fuels; however, feasible solutions are being explored, such as a transition to the use of bioethanol. Samsø´s present goal is to entirely phase out fossil fuel by 2030. The island’s successful transition to green energy is attracting visitors and new residents, too, as it has gained considerable attention in recent years (Sustainable Success Stories, 2020).

Technologies

Proven

Solar kiosk: E-HUBBs
Solarkiosk

Source: Solarkiosk

Solarkiosk's solar power integrated infrastructure solutions have been deployed in 15 countries to reach 5 million people via 250 E-HUBBS. The hubs combine solar products with turnkey solutions to create sustainable business in off-grid markets, functioning as trading platforms, system integrators and service providers. The kiosks provide entirely renewable energy-based tools to conduct operations in remote locations, including for health-care support, drinking water access, humanitarian interventions, telecommunication networks, access to safe drinking water, and education facilities.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy management platform: digital platform for managing mini-grids
Engie

Source: Engie

Engie mini-grids digital platform connects customers in remote African communities, either standalone or by combining mini-grids with modular SHSs. MySolGrid is connected using smart electricity meters to small industries and workshops, small businesses, families and individuals, and public services like schools and health-care centers. The projects use Paygee, a pay-as-you-go software suite developed by Engie, now with more than 1.6 million using its services, including a built-in technician application to resolve technical issues remotely. The service provided includes trainings in safety and appliance use, business incubation programs for entrepreneurs and a dedicated support agent assigned to each mini-grid. Mini-grids can also provide hubs to meet needs beyond electricity, such as water purification and pumping services, fish-drying facilities and ice-making devices, as well as e-mobility solutions.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: France
- Availability: Africa
- Contact: WIPO GREEN Database

Energy management platform: EcoStruxure Micro-grid Advisor cloud-based software platform
Schneider Electric

Source: Getty Images/ArLawKa AungTun

The EcoStruxure micro-grid advisor cloud-based software platform is a demand-side energy management software platform that collects real-time data from decentralized energy resources and with the help of predictive algorithms optimizes consumption, production and energy storage. The web-based interface is user-friendly and provides insights into real-time savings, earnings and carbon emissions data. It contains a storm hardening mode that uses weather forecasts to reduce downtime, as well as providing support for tariff management and battery charging with excess solar during peak periods, or discharging or idling the battery.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy management platform: hybrid micro-grid solution with battery energy storage system (BESS)
Micropower

Source: Getty Images/Leonid Sorokin

Micropower Energy provides hybrid micro-grid solutions with solar integration and storage for remote areas. The BESS delivers back-up energy during outages, helping to reduce downtime. It also provides tariff optimization through reduced consumption by discharging stored energy during peak charges and recharging when cheaper to do so. Micropower is the first Brazilian company to offer energy-as-a-service. It sells energy and services to the customer, meaning that the company owns and operates the micro-grid, which eliminates operating and investment risks and responsibilities.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Brazil
- Availability: Brazil
- Contact: WIPO GREEN Database

Hydropower: turnkey hydropower systems from 50 kW to 20 MW
Gilkes

Source: Gilkes

Gilkes turnkey hydropower systems are tailored to customer mini-grid requirements and range from 50 kW up to 20 MW. The systems can integrate into new or existing networks, provide capabilities to connect with national grids in the future, respond quickly to changes in load demand, have the ability to restart after a partial or complete shutdown, and generate in tandem with other generators in the same network. Turgo impulse turbines are often used in these set-ups, which are simple, reliable in silty or abrasive water, and efficient under a wide range of flows.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Solar-powered pump: off-grid dispensing and management system
LORENTZ

Source: LORENTZ

The solar water pumps from LORENTZ deliver a sustainable and cost-effective water supply powered by solar energy. With features for water level measurement and remote monitoring and management, their systems can ensure reliable access to drinking water for households and communities, and meet the irrigation needs ranging from that of small subsistence farmers up to large commercial growers. The company also offers hybrid solutions, which blend energy sources such as grid and solar, guaranteeing a constant flow of water. Their trained partners provide expert installation and ongoing support, ensuring optimal performance and sustainability. For a comprehensive off-grid water solution, the pumps can be integrated with the LORENTZ smartTAP water dispensers. This enables community access to controlled, pay-per-use clean water, while promoting conservation and equitable distribution for individuals and larger communities.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Waste-to-energy: anaerobic digesters
Waste Transformers

Source: Waste Transformers

Waste Transformers is a modular containerized anaerobic digester placed on-site that converts organic (food) waste into energy and organic fertilizer. It can process between 500 and 3,600 kg of organic waste per day and converts it into biogas for electricity, residual heat, recovered water and organic fertilizer. It functions as a plug-and-play system with 24/7 online monitoring. Waste Transformers contributes to creating on-site circular economies within communities. The “business in a box” program empowers communities by providing local entrepreneurs with support to operate their own Waste Transformers as a business, giving their neighborhoods waste solutions.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Netherlands
- Availability: Worldwide
- Contact: WIPO GREEN Database

Solar-powered silk machine: silk reeling and spinning machines
Resham Sutra

Source: Resham Sutra

The solar silk reeling and spinning machines, such as the Unnati model, are portable and provide solar-powered silk yarn reeling and twisting. They create high-quality twisted yarn that is useful for warp and weft, and for tassar, eri and muga silk yarns. The Silky Spin machine is solar-, electric- or pedal-powered, and spins silk yarn from cocoons. It is suitable for spinning eri silk and open cocoons of tassar, muga and mulberry. These machines save energy while also easing the work of rural women who have traditionally used the thigh reeling technique to make yarn out of the cocoon, which can take a physical toll.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: India
- Availability: India
- Contact: WIPO GREEN Database

Frontier

Energy management platform: Ugrid energy trade among neighbors
Powerledger

Source: Powerledger

Ugrid enables participants to trade energy with each other at prices that are competitive with grid tariff rates. UGrid allocates shares of renewable energy among neighbors who are sharing energy generated using community solar PV, while they can also trade excess energy beyond the meter using the xGrid platform. xGrid uses a blockchain system to track this exchange across customers using the same utility or across different utilities. The system uses dynamic pricing, factoring in preferred buying/selling prices with supply and demand.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Switzerland
- Availability: Europe, North America, Asia, Australia
- Contact: WIPO GREEN Database

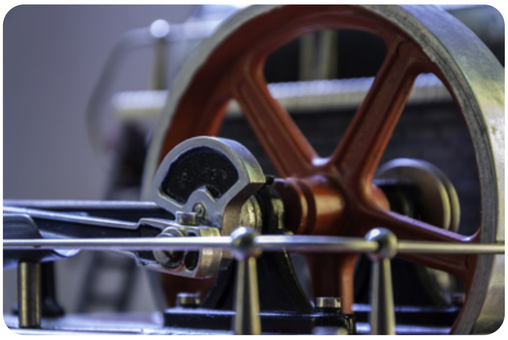
Energy management platform: platform connecting underserved areas with clean energy access, services and utilities
Bboxx

Source: Bboxx

Bboxx is a data-driven platform that connects underserved rural communities with access to renewable energy technologies, clean cooking, smartphones, financial products and e-mobility, along with financing services. The platform combines Bboxx Pulse®, the integrated operating system, with an on-the-ground network supporting last-mile logistics and pay-as-you-go services. The platform matches those in need with products and technologies, supporting the provision of plug-and-play solar systems, residential solar installations, energy kiosks and related accessories, while also developing innovative energy systems and business models tailored to meet electrification needs.

– Contracting type: For sale
– Technology level: Medium
– Country of origin: Rwanda
– Availability: Africa, Asia, Europe
– Contact: WIPO GREEN Database

Energy storage system: flywheel energy storage system (FESS)
Torus



Source: Getty Images/enrico-lapponi

The Torus FESS uses electricity from renewables (or from the grid) to spin a heavy metal disc and motor-generator. The flywheel is encased in a vacuum chamber that minimizes air resistance and therefore energy loss, while a high-efficiency motor-generator charges the battery by converting electrical energy into kinetic energy and storing it until needed, at which point the kinetic energy is turned back into electricity. This conversion is managed by an electronics system. FESS offers benefits over chemical batteries, including up to three times longer lifespan, faster charging and discharging rates, and better performance in extreme weather conditions.

– Contracting type: For sale
– Technology level: Medium
– Country of origin: United States
– Availability: United States
– Contact: WIPO GREEN Database

Energy storage system: vanadium flow batteries for off-grid and micro-grid
Invinity

Source: Invinity

Flow batteries store and convert chemical energy into electrical energy through the circulation of liquid electrolytes in external tanks that flow through an electrochemical cell. The VS3 battery uses vanadium redox flow technology, which stores energy in a liquid electrolyte that never degrades, is non-flammable, and has a safe chemistry that renders it lower risk than other battery storage technologies. The energy storage systems require little maintenance and work in extreme environments where conventional batteries encounter challenges.

- Contracting type: For sale
- Technology level: High
- Country of origin: United Kingdom
- Availability: United States, Europe, Australia
- Contact: WIPO GREEN Database

Energy storage system: fuel cell for micro-grid/off-grid
Intelligent Energy

Source: Intelligent Energy

The IE-POWER 4 stationary fuel cell can be used for micro-grids and generates electricity through an electrochemical reaction where the by-products are water and heat. Fuel cells for off-grid applications are about 30 to 40 percent energy efficient, compared to 25 percent with internal combustion engines, when considering the hydrogen lifecycle. The modular unit can be integrated into existing systems and can operate in a wide range of temperatures from –10°C to +40°C, at altitudes of 0-4000 m, and in 10 percent to 90 percent humidity. It has low maintenance and operational costs, operates quietly, and the stored excess energy in the form of hydrogen won't degrade over time as with other battery types.

- Contracting type: For sale
- Technology level: High
- Country of origin: United Kingdom, United States, Japan
- Availability: Worldwide
- Contact: WIPO GREEN Database

Hydropower: containerized small hydropower
Hydrobox

Source: Melbye

Hydrobox uses small run-of-river hydropower plants that generate maximum power output while inflicting minimal environmental impact because there is no need for dams. The Hydrobox is standardized, pre-built and containerized, uses smart sensors for monitoring and forecasting, and can be co-financed where needed using an energy-as-a service model. Hydrobox is also offered as a serviced product, wherein the customer owns and finances the power station.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Kenya
- Availability: Africa
- Contact: WIPO GREEN Database

Solar-powered vehicle: renewable-powered electric tricycles for rural off-road environments
Mobility for Africa

Source: Orest Lyzhechka

The Hamba, an electric tricycle, provides a way for women, children and families to travel longer distances to services and for water collection, and contributes to local economies. The Hamba is powered using community-based off-grid energy supply, transports goods or people up to 400 kg, is designed for women with no straddling needed, uses an LFP battery pack, can travel off-road with 12-inch (30 cm) wheels and good suspension, and has a range of 100 km on a single charge.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Zimbabwe
- Availability: Mauritius, Zimbabwe, Zambia
- Contact: WIPO GREEN Database

Horizon

Energy storage system: gravity energy storage system

Gravitricity

Source: ghornephoto

GraviStore is capitalizing on old mineshafts in former mining areas to store renewable energy, using existing infrastructure in communities that were once dependent on mines. Gravity is free, accessible and undeterred by environmental and other complications inherent to hydrogen or even lithium-ion batteries. The GraviStore underground gravity energy storage technology uses the force of gravity to thousands of tonnes of mass to store electricity. It supports increased energy access in rural and off-grid areas, as storage can be built into mini-grids to reduce infrastructure costs with small physical footprints and no harmful chemicals, no lifecycle limit or degradation, levelized costs below lithium-ion batteries, fast response time (zero to full power in one second), and a modular and flexible system. The technology will be launched officially by Gravitricity with its first full-scale system in 2024.

- Contracting type: N/A
- Technology level: High
- Country of origin: United Kingdom
- Availability: N/A
- Contact: WIPO GREEN Database

Data transmission: light-based wireless communication technology

LIFI-LED

Source: LIFI-LED

LIFI-LED provides data transmission services for remote areas using light. LiFi is a wireless communication technology that uses light to transmit data using LED bulbs as transmitters; they modulate their brightness similar to optical Morse code and encode binary data into light signals. Remote populations can be connected to the internet using a data traffic extender that can transmit at speeds of up to 200 mbps over a 300 m range through already extant electrical wiring, then transmitting via WiFi. LiFi is thirty times faster than WiFi and more economical. The added value is that LiFi can contribute to the supply of solar electricity in rural areas and promote energy savings using LEDs.

- Contracting type: For sale
- Technology level: High
- Country of origin: Cote d'Ivoire
- Availability: Africa
- Contact: WIPO GREEN Database

Energy access: off-grid mobile infrastructure to access energy
S Mile Solutions (Pty) Ltd

Source: ArLawKa AungTun

S Mile Solutions (Pty) Ltd, a spin-off from Fraunhofer IST and Fraunhofer ISE, aims to revolutionize access to energy in rural areas. Based in South Africa, this startup offers smart, small-scale off-grid infrastructure mounted on commercially available pick-up trucks. This setup allows companies and institutions to reach remote communities with essential services and products. S Mile Solutions focuses on enhancing living conditions in rural SSA by providing clean water and electricity including their storage, and telecommunications for the establishment of primary health care with telemedicine and data management. The company plans to expand into sectors such as wildlife conservation, agriculture, mining, tourism, disaster relief and research.

- Contracting type: For collaboration
- Technology level: High
- Country of origin: South Africa
- Availability: Sub Saharan region
- Contact: WIPO Green Database

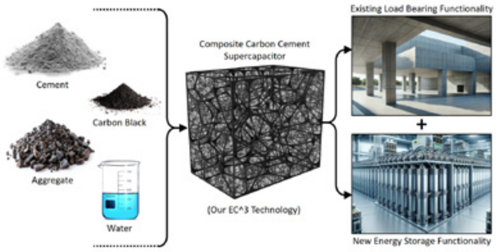
Energy generation: Airborne wind energy
Kitepower

Source: Kitepower

Kitepower is developing a kite-powered Battery Energy Storage System (k-BESS) at the Delft University of Technology. Their two systems, the Hawk and Falcon, are estimated to have rated power outputs of 30 and 100 kWs respectively. The system operates on a pumping cycle where electricity is generated as the kite is reeled out and flown in a cross-wind figure-of-eight pattern. The tether by which it connects to the ground is coupled to a generator converting mechanical force into electricity, and subsequently charging it to a 400 kW battery. When the tether reaches its maximum, the kite is reeled in, consuming part of the generated electricity. The technology is undergoing further testing and development as part of an EU-funded project in Ireland.

- Contracting type: Under development
- Technology level: High
- Country of origin: Netherlands
- Availability: Netherlands
- Contact: WIPO Green Database

Energy storage: electron-conducting carbon concrete (EC3) supercapacitor
Massachusetts Institute of Technology (MIT)



Source: Image courtesy of Stefaniuk et al. (2024) (https://eccube.mit.edu/files/2024/09/ec%5E3-Overview.pdf)

Engineers at the MIT Concrete Sustainability Hub (CSHub) and the MIT Electron Conducting Carbon-Cement-Based Materials Hub (ec3 hub) are developing an energy storage technology in the form of a multifunctional concrete made from cement and hydrophobic nanocarbon black, a black powder used as ink for the Dead Sea Scrolls 2,000 years ago. Carbon black is an electrical conductor. When combined with cement and water in a specific fashion, it develops a branching network of carbon wires as the cement sets. This allows the material to function as a supercapacitor, a device designed to store electric charge. This electron-conducting carbon concrete (EC3) stores energy and but provides an added use for carbon black produced as an industrial byproduct, such as in hydrogen production. EC3 technology may ultimately be used to build structures that can store and supply energy on demand. These could enable the creation of energy autonomous shelters that reduce dependence on external power sources while decreasing energy losses related to transmission and distribution.

- Contracting type: Under development
- Technology level: High
- Country of origin: United States
- Availability: N/A
- Contact: WIPO Green Database

Green energy solutions for agriculture on-farm

Increasing pressure on the global food production system presents a threat to achieving climate change mitigation goals as outlined in the 2015 UN Paris Agreement. Deploying sustainable methods and technologies for agricultural production is and will continue to be essential, as the UN Food and Agriculture Organization (FAO) projects that agricultural production will need to increase 60 percent globally by 2050 to feed a global population of 9.3 billion (FAO, 2023).

FAO projects that agricultural production will need to increase 60 percent globally by 2050 to feed a global population of 9.3 billion

Technological developments and trends

Agriculture is unique, in that it can both contribute to and mitigate climate change. Emissions from energy use in agriculture are only about 20 percent of the total in CO_2eq generated from crop and livestock production (Tubiello et al., 2021); however, they still represent an important contribution in terms of CO_2, with the other significant on-farm CO_2 emissions source being the drainage of organic soils (Flammini et al., 2021). Moreover, on-farm emissions resulting from energy use increased by 25 percent worldwide from 1990 to 2018 (Tubiello et al., 2021).

Agriculture can also be employed as a mitigation approach, whereby agricultural and forested lands can serve as natural sinks or reservoirs, with soil organic matter and biomass sequestering carbon. Importantly, decarbonizing energy systems used in agricultural production can provide adaptation opportunities for populations reliant upon fossil fuel use, which can be expensive, unreliable and unsustainable.

Decarbonization in food production contributes to climate change mitigation

In food production, energy is consumed to operate machinery, tractors and irrigation infrastructure, for protected cropping like greenhouses, sowing and tillage, during aquaculture and fishing operations, and to produce fertilizer and feed (IRENA and FAO, 2021). In developed countries, 25 percent of total energy is used in production (crops, livestock and fisheries), while in developing countries a smaller portion of energy is used during this stage (SEforALL, 2022).

Since the millennium, energy consumption has risen in developing regions as fossil fuels have enabled increased fertilizer production, farm mechanization and transportation. The use of machinery has greatly expanded to boost productivity, while fertilizers and chemicals have become ubiquitous to enhance short-term crop yields (Kargwal et al., 2022). These trends continue to pose a significant challenge for global food systems to ensure food security and empower the agricultural community, while increasing sustainability and reducing reliance on fossil fuels that exacerbate climate change (FAO, 2015).

Climate mitigation in agriculture production will necessitate decarbonization and energy efficiency technologies across all parts of the agrifood value chain. Research has indicated that decarbonization of the energy sector by 2050 would decrease global warming from food consumption by roughly 17 percent by 2100, or an additional 0.15°C. If complemented by improved production practices, transition to healthy diets and reduced food waste, it could decrease warming by more than 55 percent (Ivanovich et al., 2023). Thus, energy decarbonization is one tool that can be deployed to curb GHG emissions and help farmers adapt to the impacts of climate change by increasing resilience and enabling energy independence.

Farmers can reduce fertilizer input through precision agriculture, which saves indirect energy (used for inputs to production processes), reduces GHG emissions, lessens fossil fuel use in some cases, and avoids nitrate discharge (FAO, 2011). Conservation agriculture practices such as no-tillage also reduce necessary energy inputs, which can lower fuel consumption for cultivation by between 60 and 70 percent, while improving soil water retention and reducing soil erosion (FAO, 2022a). The integration of renewable energy into on-farm systems clearly contributes to mitigation and also enhances adaptation by bolstering resilience to extreme weather events and food and resource shortages caused by climate change (IRENA and FAO, 2021). For a general discussion of agriculture and livestock in climate change adaptation and mitigation see the 2022 and 2023 editions of the *Green Technology Book*.

Energy-efficient livestock and greenhouses

Livestock farming involves rearing animals such as cattle, poultry, pigs and sheep that are kept outside in pastures or in barns. Bolstered by advances in automation and digital technology, the global livestock farming market is projected to grow significantly and reach USD 2,446 million by 2028 globally (PR Newswire, 2024). Energy management systems, automation and AI can boost the optimization of resources and improve energy efficiency.

Ventilation systems for livestock that circulate air within barns can be quite energy-intensive. Technologies for livestock ventilation systems include sensors that can control the system automatically and can be enhanced using variable speed drives (VSDs) that reduce energy loss by matching motor speed to the required load and work alongside sensors to monitor conditions (NYSERDA, 2022).

High-efficiency fans can also be used. High-volume low-speed (HVLS) fans exploit the evaporative cooling effect, whereby their large diameter creates a large column of air flowing down to the floor and outward in all directions, which thereby produces a horizontal air circulation in large spaces. This quickly evaporates moisture, distributes air evenly, and can move warm rising air down into occupied areas. HVLS fans are also very quiet due to their slow movement.

Insulation in buildings can reduce fossil fuel energy consumption while protecting crops and livestock. There exist numerous options for limiting heat transfer and regulating indoor temperatures to enhance crop and livestock yields and minimize losses, and to create an optimal microclimate by altering photosynthesis and water balance in crops while reducing energy loss. Certain materials, such as natural agricultural textiles can be used to insulate farm structures, while polyethylene and nylon provide more protection from extreme weather. Aerogels are low-density porous materials derived from gels that can tolerate extremely hot temperatures (up to 650°C) and humid conditions, while also serving as a barrier to repel pests. Phase-change materials are composites that absorb and release heat during phase transitions, helping to maintain stable temperatures and reduce energy consumption for both heating and cooling. Lastly, the planting of cover crops and trees or shrubs for shade plays a key role as a biological insulation option to protect crops (Global Ag Tech Initiative, 2024).

Specifically, in greenhouses, similar opportunities are on hand to increase energy efficiency, incorporating heating, cooling, ventilation and insulation, alongside lighting. LED lights can save up to 40 percent of the energy consumed by compact fluorescent lamps and up to 90 percent compared to incandescent bulbs. For insulation, thermal screens help with retaining heat, while also serving as shades to combat overheating in warmer climates or during summer months, reducing the need for cooling. Horticultural bubble wrap has been increasingly adopted by all types of growers to line the inside of the greenhouse to increase heat retention without impacting light transmission. Digital greenhouse and other farming systems facilitate all aspects of on-farm management while promoting energy savings.

Other on-farm technologies include solar-powered poultry and egg incubators, which again maximize the power of the sun to increase farm efficiency.

Agrivoltaics: solar panels in fields and pastures

Solar energy is key to reducing emissions and tackling climate change, and large-scale solar power is on the rise. However, suitable locations for solar installations often conflict with crop or grazing land, and historically these have been placed without sufficient consideration for the ecosystems around them (The Conversation, 2024). The Solar Futures scenarios was developed by the National Renewable Energy Laboratory in the United States. It predicts that at the highest deployment level in 2050, ground-based solar technologies will require a land area equal to 0.5 percent of the contiguous US surface area, which could be achieved using less than 10 percent of potentially suitable disturbed lands, thereby avoiding conflicts with high-value lands in current use (Prasanna et al., 2021). Ground-mounted solar is projected to require about 2.3 million hectares by 2035 (0.3 percent) and increasing to as much as 4.1 million hectares by 2050 (0.5 percent). Agrivoltaics can be a potential solution to land constraints.

Agrivoltaics optimizes land use efficiency of solar energy by pairing crop production and grazing with solar farms. This can be achieved by installing efficient solar panels and trackers that tilt panels to follow the sun while allowing plants to grow beneath. Trackers can be expensive, though the cost varies depending on several factors. There are two types: single-axis trackers follow the sun's movement from east to west and are generally less expensive than dual-axis trackers that adjust both horizontally and vertically, optimizing solar capture throughout the day and year. This is more complex and enables higher precision. Cost can also vary based on the size of the agrivoltaics system and on installation and maintenance needs.

This can then serve as an adaptation tool to support increased farm productivity while also meeting mitigation needs.

Innovations in semitransparent modules and sun trackers reduce plant evapotranspiration and optimize shading to improve crop yields and quality (US Department of Energy, 2022). Other technologies incorporate specific designs and mounting systems for fruits and vegetables, offer mobile varieties, or use thin-film or bifacial panels, and even AI to guide trackers in more precisely optimizing panel positioning. Land managers and farmers can arrange panels to maximize panel angles to channel precipitation where it is most (or is not) needed. This helps avoid precipitation imbalances caused by the redistribution of rainfall in certain locations caused by PV panels. Agrivoltaic systems can even be used in solar pollinator fields to support biodiversity promotion by integrating native plant species in spaces between panels to create habitat for pollinators, birds and butterflies (Monarch Joint Venture, 2022).

Agrivoltaics installation capacity has increased from 5 MW in 2012 to more than 14 GW in 2021 (Fraunhofer ISE, 2024), with China, Japan, South Korea, France and the United States dominating the space. By the end of 2020, China oversaw the largest share, generating 1900 MW. Japan has 2,000 agrivoltaics installations generating 200 MW of electricity and providing cover for 120 crops (Fraunhofer ISE, 2021). However, there remain barriers impeding the expansion of the technology, including high installation costs, crop yield reduction and the complexities of incorporating agrivoltaics design into farm logistics (US Department of Energy, 2022).

Aquavoltaics: solar panels and fish ponds

By 2050, aquaculture, or the cultivation of fish and aquatic animals and plants (NCAT, 2019), is projected to double its current production, requiring energy among other key inputs. This broadens the scope and need for scaled-up renewable energy across small-scale fisheries and aquaculture value chains (FAO, 2022b).

Aquavoltaics enables the coproduction of aquatic animals and solar power, which is particularly beneficial for aquaculture systems that require high energy input due to their need for artificial oxygen supply (Hermann et al., 2022). Solar PV systems can power aquaculture equipment such as pumps, aerators and feeders, and can charge fishing boats. Micro-hydroelectric power can also support electricity for aquaculture. Renewable energy can provide value addition opportunities to off-grid remote fishing and aquaculture communities lacking access to reliable energy and struggling with high fuel costs (FAO, 2022b). Therefore, aquavoltaic technologies can be advantageous for climate change adaptation, too.

Using floating, elevated or other forms of PV modules offers the possibility to substitute fossil-based energy sources without the occupation of additional land (Hermann et al., 2022). This provides myriad benefits, including increased PV generation through the cooling of PV modules and reflecting sunlight; energy savings achieved through using power to control energy-consumptive equipment in fish ponds; improved water quality, whereby PV acts as a protective layer that prevents excessive sunlight and algal blooms, which supports ecological balance and a reduction of water evaporation; and the creation of jobs through PV plant operations (Chen and Zhou, 2023).

On-farm waste-to-energy systems bolster the circular economy

As detailed in the rural households and rural communities sections, anaerobic digesters (or biodigesters) are receptacles where organic wastes such as animal dung or crop leftovers are disposed of and left to ferment and produce biogas, which can then be used for cooking, lighting or operating on-farm machinery to fuel boilers or heaters for on-farm operations, or to produce electricity for on-farm use or grid injection. The World Bank reports that biogas energy can address energy access obstacles in SSA, particularly in rural areas (World Bank, 2019), and global trends indicate that small-scale decentralized biodigesters for rural and remote areas are rising in popularity. Highlighted in this section are mobile and modular systems for small and medium-sized farms, as well as for colder climates.

Crop cultivation is seeing widespread innovation

Crop cultivation can achieve energy efficiency by tapping into electric tractors and innovative no-till machines while reducing GHG emissions through low tillage methods. The latest methane tractors enable the use of biomethane produced from biodigesters as tractor fuel. Crop cultivation can also be supported through robotic weeding and seeding machines that employ real-time kinetic technology, which aids in precision (and wastes less energy) using surveying techniques that correct errors in GPS systems. For more on no-tillage and robotics technologies, see the 2023 *Green Technology Book* climate change mitigation edition.

Fertilizer production consumes large quantities of energy. Fertilizers have long been produced using technologies such as the Haber–Bosch process, which has typically relied on non-renewable resources such as natural gas as the main source of hydrogen. The production of this hydrogen by renewable energy-powered electrolysis instead of steam methane reforming has the potential to reduce the emissions from fertilizer production. The second step in the process (the Haber–Bosch reaction), which also requires a large quantity of energy to synthesize ammonia (NH_3) from nitrogen (N_2) and hydrogen (H_2) gases, can also be powered by renewable energy sources (Yüzbaşıoğlu et al., 2021).

Smart farming cloud management platforms facilitate digitized cultivation processes, providing a wealth of information to farmers to improve decision-making and enhance farm energy efficiency and productivity. These devices can support decision-making on inputs for specific crops under certain climatic conditions, providing information on weather forecasts, pests and insects, and algorithms to promote sustainable practices such as soil, water and energy conservation.

Leasing arrangements and cooperative models make energy-efficiency technologies accessible

Upgrading farm equipment is critical to increasing energy-efficiency and improving productivity, and the rising demand for sustainable practices and precision farming further stimulates the need for specialized equipment.

Leasing has emerged as a financing option that can provide farmers a cost-effective alternative to purchases and loans, allowing them to access specialized equipment that may be prohibitively expensive to purchase. Additionally, payments on leases can be tailored to match preferred payment schedules. Leases often offer flexibility when they end, with options to renew, purchase, trade or return the equipment. Leasing can provide tax benefits, depending on the type of lease. Leasing also ensures that the equipment is maintained for optimal functioning throughout the leasing term.

Additionally, cooperative models are an option offered through farmers' associations. These allow farmers to use expensive machinery through cooperatives or shared equipment businesses. Farmers sign contracts or pay membership fees to use a piece of machinery for a certain amount of time each year. They may also use tool-lending networks or direct co-ownership models.

Irrigation innovations and solar-powered pump systems save water and energy

The imperative to use less water is vital to meet water and energy efficiency, climate change and sustainable development goals. Various techniques, discussed in more detail in the climate mitigation and adaptation editions of the *Green Technology Book*, can support efficient irrigation. Drip irrigation pumps use low-pressure systems, requiring less fuel and therefore less energy. Drip irrigation is also more efficient than sprinkler irrigation and enables plants to better use water due to its application at the plant's root zone while reducing evaporation and runoff as well. Variable rate irrigation can optimize agricultural irrigation by scheduling according to soil variations using irrigation prescription maps paired with software-driven variable rate irrigators and individual sprinkle control (Hedley et al., 2010). Precision spraying enables farmers to spray pesticides solely in areas where needed, such as on targeted weeds, thereby reducing the overall amount used on crops. Weed detection sensor technologies can support precision spraying in target areas.

Sensors that track soil moisture status can help farmers know where and when to irrigate crops, and are now connected to applications in smartphones and farm management platforms that provide real-time data around the clock. The sensors allow farmers to monitor and optimize water use and control irrigation remotely. Some newer sensors can be inserted into trees to measure stem water potential, providing accurate data to monitor water status in crops.

Seizing on the power of gravity, micro irrigation technologies present alternatives to flood irrigation, which tends to waste water. Simple, reliable and used for hundreds of years, hydro-powered pumps use energy from flowing rivers and canals to pump water for agriculture without requiring any fuel or electricity, while solar pumps are proving to be a boon to small-scale farmers globally, providing an array of options for off-grid operations.

The solar water pump market has grown significantly due to the reduced cost of PV panels, increased government support, user-friendliness and expanded system capacity and efficiency

Since the early 2000s, the solar water pump market has grown significantly due to the reduced cost of PV panels, increased government support, user-friendliness and expanded system capacity and efficiency (CLASP, 2023b). In developing countries, the agricultural sector represents an enormous opportunity for the solar water pump market. In rural areas where farmers suffer from unreliable access to the grid and erratic fuel prices, solar pumps provide a useful alternative to traditional electric and diesel pumps (CLASP, 2023b).

The two main types of solar water pump technologies are the centrifugal pump that uses high-speed rotation to pull water in through the middle of the pump, used mostly in conventional AC pumps, and positive displacement pumps that force water out of a chamber using a piston or helical rotor. Positive displacement pumps can be less effective when operating at low power, which occurs during cloudy conditions, whereas centrifugal pumps are slower, but work well under low power conditions and can achieve high lift.

Additionally, solar pumps are either DC or AC, whereby DC solar pumps are suited to small applications and are relatively inexpensive because they do not need inverters to produce AC power from the solar panels. AC solar pumps utilize inverters that convert the solar or battery DC current into AC power. They are suitable across a wider range of applications (higher water head and volume) but are more expensive and require slightly more maintenance.

Two main types of water pumps most used in solar-powered irrigation systems are surface and submersible pumps. Surface pumps use suction to lift water into the pump and then push it to where it is needed. These pumps are best for accessible water sources and are optimized for a higher flow rate. Submersible pumps must be fully submerged and are often found in boreholes and deep wells (below the suction depth limit of surface pumps).

BLDC solar water pumps have emerged as an option with several advantages, including increased energy-efficiency. They integrate with solar power systems and using their precise control can counteract the intermittency of solar energy and optimize solar power. BLDC motors do not use brushes to deliver current into the coils on the rotor (since the rotor is a permanent magnet), so they are also quieter and present fewer needs for maintenance while enabling a longer lifespan.

Significant advances in pump controllers, which enable monitoring and control of the pump speed, have also been supporting the implementation of efficient irrigation. Incidentally, VSD technologies enhance energy efficiency across a range of farm machinery. They adjust a motor's speed based on a range of parameters rather than just using a simple on/off switch that runs the motor at full power and does not adapt to the actual need (AgriTech Tomorrow, 2023). This helps to increase control over the flow of electricity and enable automation. Additionally, maximum power point tracking (MPPT) in the VSD on solar pumps helps to ensure that the highest power output possible is extracted from solar panels for the pump, while also enabling the drive to operate the pump motor when power sags during cloudy periods.

Farmer education on energy efficiency is key

Farmers are often eager to transition toward more sustainable and energy-efficient technologies and machinery. However, they may need support in learning about and adopting technologies, including comprehensive information and educational and training programs. They may also benefit from incentives for energy efficiency improvements that can benefit climate change while enhancing their operations. Through agriculture extension services, farmers can be connected with subsidized energy audits and expertise to enable them to better understand current energy expenditures and how they can be improved.

For example, programs such as the Rural Energy for America Program (REAP) provide grants, rebates, incentives and low-cost financing for agricultural producers and rural small businesses to install renewable energy systems and energy efficiency improvements. Energy audits are often a prerequisite or a recommended step. They help identify where energy improvements can be made, providing data and insights to inform decisions about future investments in energy efficiency or renewable energy systems.

Innovation examples

Project Nexus dual-use systems in the Central Valley of California

Source: Solar AquaGrid

Project Nexus is implementing a series of pilot projects to test the placing of solar panels over canals and aqueducts. They are slated to become dual-use systems that can conserve water in a notoriously drought-prone area that is used heavily for agriculture and requires large quantities of irrigation water. The dual-use systems will ultimately reduce evapotranspiration while maximizing the generation of renewable energy, saving land, and achieving other environmental, social and economic synergies. The project is a collaboration between Solar Aqua Grid, a development firm focused on innovative solutions for water and energy issues, California's Department of Water Resources, the public irrigation district and University of California-Merced. It will establish the technical knowledge needed to enable scaling up of the technology in narrow and wide aqueducts and will also test the incorporation of battery storage alongside the solar canals. Connecting solar canals to local energy users could reduce both costs and energy losses, which have become prolific in the state over the last few decades. The project could also increase energy access for vulnerable groups that are impacted by high electricity costs in less energy-efficient homes. In the long run, the project is transforming an aging canal infrastructure and repurposing it for the future. It is scheduled for completion in 2024 (UC Merced, 2024).

Iberdrola's WineSolar project maximizes solar while improving wine grape cultivation

Source: Getty Images/Marina Lohrbach

Iberdrola has implemented the first agrivoltaics plant in Spain, a project called WineSolar, at the González Byass and Grupo Emperador vineyards located in Toledo. The installation enables PV modules to be adapted to the cultivation needs of the vineyards to modulate sun exposure and temperatures using shade created by the panels. The project is a collaboration between Iberdrola, the solutions provider Techedge, and PVH, a solar tracker and panel manufacturer. It was executed through the Iberdrola group's international startup program PERSEO, which aims to connect the company to innovative and sustainable technologies while fostering the startup ecosystem in the electricity sector. The solar trackers are controlled by an algorithm to determine the optimal position of the panels throughout the day, with the degree of inclination determined using information collected by the vineyard's sensors that monitor data on soil humidity, wind conditions, solar radiation and the width of vine trunks. The installation's objectives include improving the quality of the grapes, reducing irrigation water consumption, improving crop resistance to rising temperatures and increasingly frequent heat waves, and maximizing multiple land uses. The project exhibits the benefits of using land to simultaneously produce solar energy and agriculture products to improve sustainability, productivity and efficiency. Iberdrola plans to replicate the system across additional Spanish vineyards, which currently constitute 13 percent of vineyards globally (Iberdrola, 2022).

Technology solutions

Proven

Solar-powered pump: solar pumps for one acre/two acres
Futurepump

Source: Futurepump

Futurepumps are surface water pumps that can pump from shallow wells, streams, rivers, lakes or water pans. The SE1 is a pump designed for farms up to one acre, while the SF2 is designed for farms of up to two acres. The pumps have a suction depth of 7 m. Flow rates are affected by the vertical pump height and the quantity of sunshine; for the SE1 the average rate is 1,600 liters/h, while the SF2 is 3,600 liters/h. The pumps are compatible with sprinklers, hosepipes and drip irrigation.

- Contracting type: For sale
- Technology level: Low
- Country of origin: India
- Availability: United Kingdom, Kenya, Netherlands, Nepal, India
- Contact: WIPO GREEN Database

Solar-powered pump: ACQ80 solar pump drive
ABB

Source: ABB

The ACQ80 VSD for solar water pumps works with both DC solar panels and AC grid power sources, enabling it to operate continuously by blending both AC and DC input supplies. It has a wide input voltage range from 225 to 800 V DC and uses built-in MPPT that ensures optimal power output from solar panels throughout the day to maximize pump performance. This enables the drive to operate the pump motor even during periods of low sunlight. The ACQ80 has built-in pumping features including flow calculation, dry-run protection, pump cleaning and multiple smart-operating modes and fieldbus connection for integration into control systems. It is compatible with induction motors and permanent-magnet-assisted synchronous reluctance motors in both submersible and surface type pumps.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Sweden & Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Greenhouse insulation: horticultural bubble wrap

Solawrap

Source: Solawrap

Polydress® SolaWrap is a lightweight polyethylene material that provides uniform illumination via air cushions (at 1,000 bubbles per square meter) while creating a microclimate that promotes plant growth. It provides UV protection and is extremely durable to prevent leaks, ensuring that 95 percent of the heat radiation is retained. However, it is still easy to cut with scissors or a knife, which simplifies installation. SolaWrap offers higher light transmission than glass, decreasing the need for supplemental lighting, while also providing insulation for colder climates. It is 100 percent recyclable. Solawrap also provides greenhouse kits.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Irrigation: gravity-powered micro irrigation
N-drip

Source: Orest Lyzhechka

N-drip is gravity-powered micro irrigation technology aimed at serving as an alternative to flood irrigation and producing higher yields while saving water and energy. It maximizes leveled fields, flood infrastructure and gravitational force for irrigation. The proprietary dripper does not require water filters, as it is resistant to a high level of suspended particles. Given that transitioning from flood irrigation (which typically wastes water) is expensive, N-drip is more affordable and provides a solution with easy deployment to help farmers achieve more precise and efficient irrigation while utilizing existing infrastructure.

- Contracting type: For sale
- Technology level: Low
- Country of origin: Israel
- Availability: Worldwide
- Contact: WIPO GREEN Database

Waste-to-energy: prefabricated modular biodigester package for small/medium-sized farms
Sistema.bio

Source: Sistema.Bio

Sistema.bio is a prefabricated high-efficiency modular biodigester package that includes a set of biogas appliances. The biodigester systems are designed for small and medium-sized farms and transform waste (including manure from cows, pigs, sheep, rabbits, goats, horses and even humans) into biogas, which can be used either for cooking, heating, as mechanical energy supporting farm activities or for electricity production, and organic fertilizer. It offers a pay-as-you-go model and assistance and training for installation and operation, with training hubs offered on five continents. Biodigesters are available in 11 different sizes.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Mexico
- Availability: Mexico, Kenya, Colombia, India, Malawi, Uganda, Ghana
- Contact: WIPO GREEN Database

Aquaculture: solar shrimp feeder

Ecowater China Aquaculture Technology

Source: Ecowater China Aquaculture Technology

Solar shrimp feeders use renewable energy to automate the feeding process in shrimp ponds. The system contains two 100 W solar panels, and energy is stored in a 12 V, 100 A-h battery that can last for 5–7 days. A 600 W pure sine wave inverter converts DC into AC to drive two 220 V motors within the feeder, which dispense the shrimp feed. Using a controller, the feeder is set to automatically dispense feed at predetermined intervals. This ensures consistent feeding and maintains water quality.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: China
- Availability: China
- Contact: WIPO GREEN Database

Aquaculture: floating PV for ponds (floating platforms and floating body)

Sungrow

Source: Getty Images/Tomwang112

Sungrow provides floating PV systems for ponds. The floating body is made from food-grade materials that are environmentally friendly and resistant to hydrolysis. The inverter and booster floating platform ensure safety, minimizes DC cable loss, and enables convenient on-site installation, operation and maintenance. The customized anchoring system can be tailored to project-specific conditions, such as varying water depths and water level variations.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier

Crop cultivation: methane power tractor
New Holland

Source: New Holland

The T6 Methane Power tractor enables the use of biomethane produced from biodigesters as tractor fuel. The tractor produces 98 percent less particulate matter and when running biomethane enables a 10 to 15 percent reduction of CO_2 emissions. Compressed natural gas can also be used. Multiple fuel tanks provide a 185 liter capacity, and a front-mounted range extender provides an additional 270 liter capacity for extended periods between tank fill-ups.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

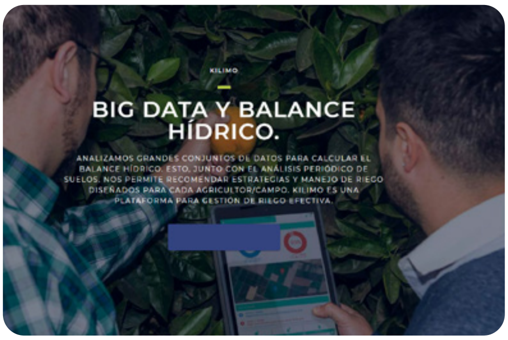
Irrigation: water consumption sensor
Telaqua

Source: Getty Images/SafakOguz

Telaqua employs sensors connected 24/7 that measure water flow and pressure in real time. MANO is a plug-and-play sensor that allows farmers to monitor and control their water consumption. The web and mobile application IrrigEase can be paired with MANO, which provides farmers with the ability to control the opening and closing of valves remotely, and to control the entire system. IrrigEase can also be used to alert farmers if issues arise. The estimated water consumption savings using MANO are 12 percent and energy savings can be up to 30 percent.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: France
- Availability: Argentina, Chile, Mexico, Spain, Cote d'Ivoire, Ghana, Cameroon, Tanzania, South Africa
- Contact: WIPO GREEN Database

Irrigation: data management platform
Kilimo



Source: Kilimo

Kilimo's technology focuses on optimizing irrigation practices to improve water use efficiency in agriculture. The company offers a software-as-a-service-enabled marketplace, or data management platform, that uses AI to help farmers reduce irrigation and allows them to sell water offsets to companies pledging to be water neutral. The platform uses data to enhance decision-making, optimize water use and improve crop yields. It integrates weather forecasts, soil moisture levels and satellite imagery to enable a better understanding of the conditions affecting irrigation needs. The platform can also automate irrigation processes, reducing the need for manual adjustments and ensuring that water is applied more precisely and efficiently, thereby saving water and energy. Kilimo currently serves farmers in six countries, including large corporations and micro farmers, helping them reduce water use by 20 percent.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Argentina
- Availability: Latin America
- Contact: WIPO GREEN Database

Aquaculture: windmill aerator
Koenders

Source: Getty Images/thyegn

The single diaphragm windmill is designed for smaller ponds of up to one acre and 7.5 m depth, and can transfer up to 25,000 cubic feet of oxygen per month. The dual windmill systems are designed for larger or irregularly shaped ponds larger than one acre and provide twice the air volume (50,000 cubic feet) for additional aeration. The systems work well in remote and off-grid locations and in places where additional aeration is needed, such as larger lakes where windmill aeration can complement electric systems to support efficient oxygen distribution.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Canada
- Availability: Worldwide
- Contact: WIPO GREEN Database

Solar appliance: solar fishing lantern
WeTu

Source: WeTu

The rechargeable solar WeTu Hunter and NIWA Lago 600 fishing lanterns are intended for use in Lake Victoria. They use lithium-ion batteries instead of lead–acid batteries or kerosene-powered lanterns. The lanterns are provided to clients via rental agreements and recharged exclusively though the WeTu hubs, which helps ensure that they are reused and recycled. They operate for up to 12 hours and have built-in vibration protection that secures the lanterns in rougher fishing waters. The lanterns are also capable of floating, which ensures they won't be lost or contribute to waste or damage to the lake.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Kenya
- Availability: Kenya
- Contact: WIPO GREEN Database

Livestock: variable speed ventilation fan with inverter technology for egg, poultry, or pig houses

Big Dutchman-Asia

Source: Getty Images/Polawat Klinkulabhirun

Air Master EVO is the upgrade of the existing Big Dutchman's V130/140 fan series suitable for tunnel ventilation environments in egg, poultry or pig production houses. It uses an IE3 (premium efficiency and ideal for continuous or near-continuous operations) inverter motor and is composed of high-quality galvanized steel structure with fiberglass reinforced blades and pretensioned V-belt. The fan achieves uniform ventilation using lower power consumption. Compared to traditional fans with on/off switches that use more energy with every stop-start cycle, the AirMaster ECO uses a variable speed inverter motor to adjust the fan speed, which reduces energy consumption by as much as 70 percent in most applications. The motor often operates at a top capacity of only 60 percent since it does not need to compensate for lost energy. It is available in three- or six-blade configurations.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Malaysia
- Availability: Asia
- Contact: WIPO GREEN Database

Livestock: livestock tube ventilation system

Cow-Welfare

Source: Cow-Welfare

The Cowsy Breeze Tube Ventilation System provides fresh air induction for enclosed spaces. It employs a tube design with a long tube or sleeve running along the internal length of the building through which fresh air is supplied from fans and is directed to the animal housing boxes. The height of the tube is adapted to the individual barn. Openings that are evenly placed ensure steady airflow reaches ventilated and unventilated areas. This introduces fresh air without creating drafts, thereby also reducing airborne bacteria that can cause respiratory diseases. This single fan tube of up to 70 m can replace numerous conventional fans and reduce electricity costs.

- Contracting type: For sale
- Technology level: Medium

- Country of origin: Denmark
- Availability: Europe
- Contact: WIPO GREEN Database

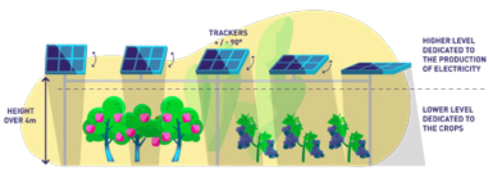
Livestock: solar-powered poultry incubator
Lifeway Solar

Source: Lifeway Solar

The semi-automatic solar incubator can hatch 100 quail, 40 chicken or 25 goose eggs. It contains fully automatic heat control inside a fiberglass cabinet with puff insulation that improves temperature stability and operational efficiency. The electric proportional thermostat is protected against power variations and a battery is also provided for power stability, to which a 12 V/40 W PV panel is connected with charge controller to ensure 24-hour supply. The fan provides fresh airflow, and humidity is supplied manually using a water bowl kept outside the incubator and connected to perforated PVC piping system. The capacity ranges from 200 to 500 eggs. The incubator was developed for unemployed women in rural India as a self-employment project to support their families, and Lifeway Solar works with various NGOs to train women to use the product where there is no electricity. The incubators can also be rented.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: India
- Availability: India, Africa
- Contact: WIPO GREEN Database

Agrivoltaics: agri-PV systems using algorithms to control solar shading
SunAgri



Source: SunAgri

SunAgri systems control solar shading according to the crop's needs using algorithms that are based on weather forecasts, plant growth patterns, temperature and humidity sensors, and cultivation objectives. The company devises a sunlight management strategy adapted to specific needs. The metal mounting system accounts for planting density, plant height and the use of machinery; the lower level is for the plants and the upper level is for electricity production. A third party carries out agronomic monitoring for five years to regularly collect data. There is an application, MySunAgri, that can track the collected data via mobile phone or tablet.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon

Crop cultivation: zero-carbon nitrogen fertilizer
Atlas Agro

Source: Atlas Agro

Atlas Agro zero-carbon nitrogen fertilizer is made without burning natural gas. First, hydrogen is produced through water electrolysis using renewable energy; then nitrogen is split from air within an air separation unit and mixed with hydrogen to produce ammonia, which is then converted into nitric acid and later into calcium ammonium nitrate. The patent was developed using a combination of the technologies that have been adapted to the use of renewable energy.

- Contracting type: Under development
- Technology level: Medium
- Country of origin: Switzerland
- Availability: N/A
- Contact: WIPO GREEN Database

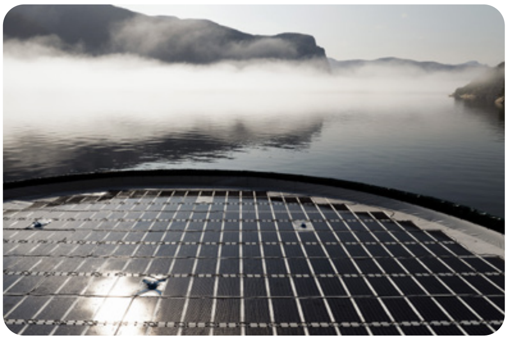
Aquaculture: oyster fishing solar-powered boats
VoltaViewAfrica

Source: VoltaViewAfrica

Women in the Gambia traditionally fish for oysters with hand or petrol-powered boats, which can be difficult, time-consuming and expensive. Electric motors enable faster and more efficient trips. The batteries can also fuel cool boxes to keep the oysters fresh. Fraunhofer HHI and partner company VoltaMove GmbH collaborated to produce compact e-outboard motors specifically designed for SSA. The battery systems use sodium-ion battery cell technology, which is only recently commercially available. This technology has several advantages, including that it requires no scarce raw materials, carries no risk of fire or explosion, and offers recycling possibilities. The batteries can be charged using a foldable solar roof mounted on the boat. An initial prototype was tested on a tourist boat in the Gambia.

- Contracting type: Under development
- Technology level: Medium
- Country of origin: The Gambia
- Availability: The Gambia
- Contact: WIPO GREEN Database

Aquaculture: floating solar farm for aquaculture (salmon/trout)
Alotta



Source: Alotta

Alotta solutions to electrify fish farms are intended for salmon and trout. Areas without a connection to the grid can use the floating solar power plant with battery storage, reducing noise and a reliance on diesel generators. The Solar Hybrid phase 1 technology complements onshore power or fossil energy sources and be fully integrated into aquaculture facilities and to the existing energy system on feeding barges, which are now often equipped with energy management systems and can create hybrid feeding barges. Recycled floating cages are used as floating solar plants. Clean hybrid phase 2 will combine solar and hydrogen by integrating the floating system with a hydrogen fuel cell system on the feeding platform. Clean vision phase 3 enables the independent production and storage of green hydrogen produced through water electrolysis, and larger quantities of energy can be stored to supply the aquaculture facility year-round.

- Contracting type: For sale (phase 2 and 3 under development)
- Technology level: High
- Country of origin: Norway
- Availability: Norway
- Contact: WIPO GREEN Database

Aquaculture: solar oyster production system
Solar Oysters LLC

Source: AJ Metcalf – Chesapeake Bay Foundation

Solar Oysters has partnered with Blue Oyster Environmental to further develop the Solar Oysters Production System (SOPS) in Maryland, USA. The SOPS prototype contains solar panels that rotate 575 oyster cages on five ladders to 16 feet depth and a solar-powered spray wash system. It functions by increasing the oysters' access to dissolved oxygen, food, and salinity and exposes them to sunlight, which can reduce biofouling. The prototype is projected to produce up to 200,000 oysters in a 0.02-acre space. The project produced 400,000 spat on shells in 2022/23 using one-third of this capacity. Further refinements to the technology will be made. One SOPS is operational on an active oyster aquaculture farm, and a final SOPS product will then be introduced to the aquaculture market by Blue Oyster Environmental, the North American distributor.

- Contracting type: Under development
- Technology level: Medium
- Country of origin: United States
- Availability: N/A
- Contact: WIPO GREEN Database

Waste-to-energy: farm powered anaerobic digestion facilities
Vanguard Renewables

Source: Getty Images/manfredxy

VANGUARD Renewables are developing manure-only and co-digestion anaerobic digestion facilities in multiple states in the United States, focusing on transforming organic waste into renewable energy, low-carbon fertilizer and dry animal bedding. They collect organic waste from various sources, including food and beverage manufacturers, and use advanced processing to divert waste from landfills. Their farm-powered anaerobic digestion process converts this waste into carbon-negative renewable natural gas, supporting regenerative agriculture and providing clean energy to utilities and businesses. Their solution accommodates farms of all sizes and generates valuable by-products for agricultural use. They plan to expand across the United States, aiming to commission over 100 anaerobic digestion (AD) facilities by 2028. Starting from April 2024, through a joint venture with TotalEnergies, they have plans to lead the development, construction and operation of numerous AD facilities nationwide.

- Contracting type: For sale/collaboration
- Technology level: Medium
- Country of origin: United States
- Availability: United States
- Contact: WIPO Green Database

Green energy solutions for agriculture post-harvest

The global agrifood system plays a large role in contributing to climate change and currently accounts for 30 percent of total global energy demand, most of which is fossil fuel-based (SEforALL, 2022). Perpetuating a vicious cycle, GHGs emitted using fossil fuels contribute to climate change that, in turn, impacts the agriculture sector and food security.

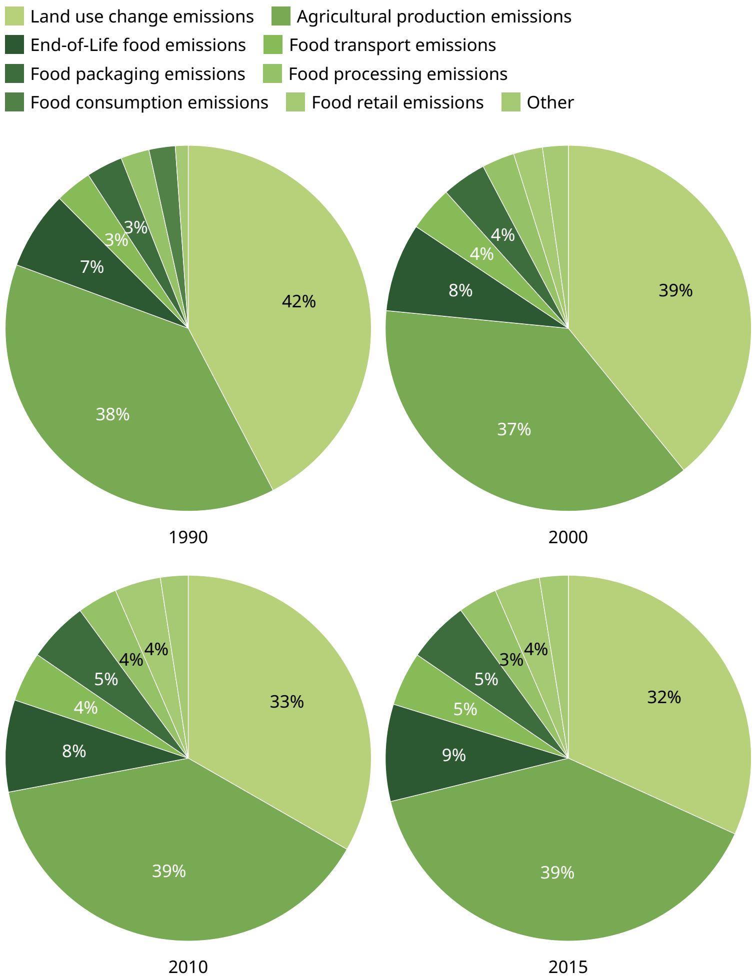
Major challenges facing the global agrifood system are ensuring food security, sustaining farmer livelihoods, and enabling environmental protection, including decarbonizing the energy system underpinning food production. Deploying decentralized renewable energy and energy efficiency technologies for post-harvest processing and storage is key for climate mitigation and enabling sustainable agriculture globally (OECD, 2021). The integration of renewable energy also bolsters adaptation, as it increases resilience to climate-related weather events.

Technological developments and trends

The global food system emits about one-third of global annual GHG emissions, of which food loss and waste constitute a staggering 50 percent share (Zhu et al., 2023). The Food and Agriculture Organization of the United Nations (FAO) defines food loss as “the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, excluding retail, food service providers and consumers” (FAO, 2019), and estimates that roughly 30 percent of all produced food is lost or wasted throughout the supply chain (FAO, 2021b). Post-harvest losses of horticultural crops are high in low- and middle-income countries where small-scale farms play a vital role in production (Jarman et al., 2023). For an overview of technologies addressing food loss, see also Galanakis and Oksen (2020).

While agrifood supply chains operate in all countries, their level of technological development differs, which is visible in various GHG emissions patterns. In developed countries, the post-harvest stages of value chains contribute to roughly half of the agrifood system’s total emissions, whereas the share is about 25 percent in developing countries (Crippa et al., 2021). Losses in these countries also disproportionately occur within the first mile between harvest and processing. FAO estimates that 37 percent of food products lost in SSA perish during this stage (IRENA and FAO, 2021). Figure 3.4 shows global GHG emissions from food by life-cycle stage for 1990, 2000, 2010, and 2015.

Figure 3.4 Global emissions from food by life-cycle stage



Source: Crippa et al. (2021).

Generally, energy efficiency and renewable energy technologies are available now and costs are falling, as exhibited in the case of solar PV since the 2000s (IRENA, 2021). These technologies can achieve multiple wins across all stages of the supply chain and contribute to the scale-up of sustainable energy pathways necessary for decarbonization.

Despite a growing number of available solutions, several technologies favor commercial farmers over smallholders due to costs. Therefore, other aspects must be considered in the scale-up of the adoption of technologies to reduce post-harvest losses. These include improved access to micro-finance, deployment of mini-grids, micro-enterprise training, support of farmer cooperation (e.g. collective production services and marketing) and improved understanding of the integration of smallholder farming into commercial supply chains (Power for All, 2022).

What happens during post-harvest processing?

During the post-harvest period, produce undergoes drying, cutting, threshing, milling, winnowing and other forms of processing before distribution. Food processing also encompasses evaporation, fermentation, pasteurization, sterilization, livestock slaughter and processing, cooling and cold storage, value addition and retail. Energy is used as an input to all these stages (IRENA, 2022).

Drying is a crucial step following harvest to maintain crop quality, lessen storage losses and lower transportation costs. It is a key step for most staple crops; additionally, 20 percent of perishable horticulture crops are dried for preservation (Grabowski et al., 2003). Moisture levels need to be kept low to prevent mold growth and losses, and together with storage, drying is also essential for curbing the risk of aflatoxin, a family of toxins produced by certain fungi that are found on agricultural crops such as maize (corn), peanuts, cottonseed and tree nuts.

Drying can be done naturally with sun or shade or using mechanical dryers. Sun drying is labor-intensive, weather-dependent and vulnerable to losses incurred or contamination by dust, insects, birds and rodents. Mechanical drying tackles some of these issues; however, it is energy-intensive, and smallholder farmers still suffer from the limitations of high up-front and maintenance costs of dryers, adequate size availability and lack of knowledge regarding their use (Kumar and Kalita, 2017). For further coverage of dryers, see also the 2023 *Green Technology Book*.

Active solar dryers maximize the power of the sun with solar PV panels that provide an energy source used in evaporative cooling systems, and to power lights and charge cell phones. In developing countries, different factors may sometimes determine farmer preferences for solar dryers, not all related to food preservation. For example, the improved product hygiene provided by active solar dryers appealed to smallholder farmers in Nepal (Howe, 2019), whereas other farmers appreciate the reduced labor requirement (Jarman et al., 2023).

Threshing detaches grains from panicles manually, with animal power, or the use of mechanical threshers. Cleaning is performed after threshing to separate whole grains from broken grains and other materials like straw and sand. Winnowing is a common method in developing countries, whereby screening or sifting can also be done manually or mechanically. Insufficiently cleaned grains risk mold growth, insect infestation and unacceptable taste or color.

Milling or processing operations vary for different grains, and again can be performed manually or with milling machines. In rural areas, milling is accomplished manually by repeated pounding. Milling yields are dependent on the method, crop conditions and operator skills, and milling machines that are not well-maintained contribute to food loss. Studies have revealed that rice milling yields at small village level in several Asian countries were as low as 57 percent (compared to theoretical yields of 71 to 73 percent) due to grain loss caused by lack of maintenance, small scale, and poor calibration (Alavi, 2011). However, there is an economic rationale for farmers located in smaller farming communities to opt for small local milling facilities, despite potential efficiency trade-offs. Additionally, some flavor may be lost when processing certain crops, like rice, through larger mills.

Grain loss and waste is prevalent along the supply chain

Food loss during post-harvest is especially pronounced for grains, which account for 70 percent of all calories consumed globally (Gunasekera *et al*., 2017). McKinsey estimates that the value of lost grain may amount to USD 60 billion (McKinsey & Company, 2021). Reducing global post-harvest grain losses before retail by 75 percent could result in gains equivalent to approximately three times the cropland area of France. Southeast Asia, West Africa and South Asia would see the greatest potential land gains at 6.5 percent, 3.8 percent and 3.7 percent of the total cropland area of those regions, respectively (McKinsey & Company, 2021).

It is also important to recognize that grain losses occur at different points along the supply chain depending on the global region. In Thailand, the biggest waste occurs during handling and storage (19 percent), while in Peru the loss is due to drying in fields and the ensuing exposure to rodents and insects (Díaz-Valderrama *et al*., 2020). In the Arab region, 30 percent of cereal production is lost between production and consumption. One study estimated that 34 percent of the total wheat supply in Jordan is lost per year, amounting to more than USD 100 million annually (Khader *et al*., 2019). Strikingly, exposure during storage to pests, temperature fluctuations and moisture that causes mycotoxin formation ranges between a 1 percent loss in well-controlled environments to 40 percent loss for humid tropical areas cultivating maize (Kumar and Kalita, 2017).

Hermetic grain storage offers a very simple and environmentally friendly option to store grains in airtight containers to prevent spoilage and insect infestation. Options include airtight bags, cocoon storage using specialized containers, container storage using modified shipping containers with airtight seals, and bunker storage using underground facilities that are also sealed. Hermetic storage methods are decent options for smallholder farmers with limited access to modern technologies due to their low cost and complexity.

Grain drying systems are energy-intensive, but solutions abound

Grain drying systems are critical while often proving to be one of the most energy-intensive systems in larger farming operations (NYSERDA, 2024). Storing, aerating and transferring grains requires a significant amount of energy.

In developed countries, grain dryers are generally divided into batch and continuous flow dryers that are typically operated using propane or natural gas to heat air to high temperatures. Batch bin dryers are simple, requiring only a storage bin containing a perforated floor and a blower to transport heated air. Their major disadvantage is that the grain on the bottom is often overdried during efforts to dry grain on top, increasing energy use and reducing grain weight. Continuous flow dryers (also called crossflow, counter flow, concurrent flow and mixed flow) are named according to their airflow paths. Continuous flow mixed-flow dryers maintain airflow in both counter and concurrent directions and use about 40 percent less energy than crossflow dryers. To improve efficiency without investing in a whole new system, the dryer bins themselves can be adapted to higher efficiency using Shivvers systems, as covered in the technology solutions section.

Stirators are used in continuous flow bin dryers. They move grain vertically while a stirring device rotates around the bin, which elevates dry grain from near the bin floor, enabling higher moisture grain to replace it. *In-bin cooling* processes take grain from the dryer directly to the final storage bin, where it cools slowly, increasing dryer performance. *Dryeration* is a process that uses a grain's residual heat to remove moisture during cooling.

Moisture sensing controls maximize the energy savings potential of the overall system and its components, and automate drying processes including heater operation adjustments, fan operations, monitoring of the target transfer moisture conditions, grain removal process and in-bin cooling.

Geothermal is part of the solution

Geothermal heat energy can be used for drying fruits, vegetables, grains, meat and fish. Geothermal heat pumps, exploiting residual heat in shallow soils, can be used for electric and thermal-driven cold storage and refrigeration, and geothermal direct use (where hot geothermal fluids are directly used) can be employed for pasteurization, fermentation and evaporation. Geothermal electricity can power processing equipment (IRENA, 2022). Geothermal energy for cooling for cold storage and refrigeration works via absorption, where higher temperatures increase the efficiency of the process (Uwera et al., 2015). Absorption cycle equipment is particularly well-matched to geothermal energy since it uses heat to push the working fluid through the system; however, it should be noted that it is more apt for medium- to large-scale operations due to the higher capital costs (IRENA and FAO, 2021). Geothermal heat pumps also offer efficient heating and cooling solutions.

Renewables-based post-harvest technologies have limited uptake in developing countries

Agro-processing systems that are based on either standalone renewables or mini-grids can be cost-effective while reducing emissions, promoting decentralized processing infrastructure and decreasing the need for labor-intensive processing activities (IRENA and FAO, 2021). Electric-motor-driven mills are preferable to diesel-driven mills because they are easier to operate and require less maintenance, while decreasing the time and cost required to travel for fuel purchases (Power for All, 2020).

However, mini-grids that power post-harvest processes, including milling, oil-pressing and ice-making, are currently somewhat limited (IRENA, 2021). Solar milling technologies are still largely in the pilot phase. Mini-grid usage for milling has been slower in places like SSA, as diesel mills are less costly (Next Billion, 2020). Again, solutions on the market are often only appropriate for mid- to large-sized farms (Power for All, 2022).

Dairy processing achieves higher efficiency in the absence of heat

Dairy processing is one of the most energy-intensive sectors in the agrifood industry (Ladha-Sabur et al., 2019a). Electricity is generally used for refrigeration, pumps, control and separation, while thermal energy is employed for cleaning, evaporation and pasteurization (Xu and Flapper, 2011). Pasteurization can consume between 17 and 26 percent of the total energy in the system (Van Alfen, 2014), but with the right technology, up to 90 to 94 percent of this generated heat can be recovered (Ramirez et al., 2006).

Ultra-high temperature treatment and sterilization processes are more energy-intensive as higher temperatures are required. Nonthermal is a broad term for food processing techniques used in the absence of direct heat, which have been gaining ground in the food industry, as they reduce energy consumption, processing costs and waste while offering even better ways of preserving nutritional, taste and smell properties of foods than traditional heat-based methods (Cavalcanti et al., 2023). For milk, the nonthermal pulsed electric field (PEF) processing method is emerging as an alternative to thermal pasteurization to extend the shelf-life of heat-sensitive liquids at industrial scale. It uses short high-voltage pulses to disintegrate cells and deactivate microorganisms. High-pressure processing is a milk preservation method that uses cold high pressure instead of additives or heat to destroy pathogens.

Nonthermal processes based on membranes are also used for dairy, including reverse osmosis, microfiltration, ultrafiltration and nanofiltration, which accomplish sterilization from microorganisms using a microscopic filter or membrane to remove them (with these differing based on the pore size of the membranes). Because milk is mostly composed of water, reverse osmosis membranes remove water from cooled milk.

Technologies to improve the energy efficiency of dairy production also include vat wraps and plate coolers. Vat wraps are insulating materials typically made from substances like foam that improve efficiency by maintaining the temperature of milk during processing, providing up to 20 percent energy savings. Moreover, employing a heat recovery system reduces water heating costs by as much as 50 percent.

Due to the need to prevent spoilage, milk needs to be cooled quickly from a temperature of 37°C to 4°C. Plate coolers are composed of a series of thin stainless-steel plates arranged in a stack. Warm milk flows through channels between the plates, while cold water (or another cooling fluid) flows through adjacent channels on the opposite side of the plates. As the warm milk flows over the cold plates, heat is transferred from the milk to the cooling fluid, which reduces the temperature quickly, decreasing the demand for dairy cooler compressors and lowering the bacterial count in the milk. Pasteurization can also be accomplished with an innovative UV solution for opaque liquids that uses a filter technology to ensure that only the germicidal wavelengths reach the product.

Spray dryers employed to evaporate the liquid in milk using a stream of hot air utilize a great deal of energy, which can be optimized to increase efficiency, flexibility and speed using digital twins (virtual models of the system). And robotic milking systems offer enhanced efficiency, while solar-powered milk chillers and rapid milk chillers use the power of the sun in remote areas.

Cold chains are critical to the global food supply chain

A cold chain is a temperature-controlled supply chain which ensures that proper low temperatures are maintained throughout the product's journey. Securing the cold chain is fundamental at each stage to reduce losses, increase shelf life and prevent the loss of perishable harvested crops. Including industrial and domestic refrigeration, the cold chain accounts for 5 percent of global GHG food-system emissions, and this share of total emissions is slated to increase (Tubiello et al., 2021).

Producers in developing countries often store food in basic rooms instead of modern warehouses or cold rooms. Fruits and vegetables in Africa incur significant losses due to the lack of cold chain infrastructure, estimated at about 52 percent of production (Power for All, 2022). In addition to bolstering climate mitigation, the energy savings gleaned from improvements to cold storage facilities can lower expenses and shorten the payback period, enabling producers to sell agricultural goods at more competitive prices. Introducing low-emissions technologies can also provide jobs and decrease labor costs (WWF, 2021a).

Modern refrigeration technologies save energy and the ozone layer

Refrigeration has revolutionized food consumption and storage patterns. Extended food preservation has diversified diets, transformed shopping habits, and enabled global food trade alongside the evolution of the processed food industry. However, it has also exacerbated climate change through the emission of refrigerants and energy consumption. The refrigeration sector, including air conditioning, contributes roughly 17 percent of global electricity consumption, even exceeding 40 percent of total national electricity demand in some countries (Coulomb, 2021).

The refrigeration sector, including air conditioning, exceeds 40 percent of total national electricity demand in some countries

Fortunately, refrigeration technologies have evolved, and refrigerators and freezers are now much more energy efficient. Refrigerators are increasingly using advanced adaptive compressors that operate smoothly at varying speeds and maintain the ideal temperature more efficiently than traditional compressors. Improved insulation in refrigerators such as vacuum insulation panels and polyurethane foam reduce heat transfer. And of course, energy-efficient LED lighting can now be used instead of incandescent bulbs to consume less energy. Some refrigerators now contain convertible freezer compartments that can be altered to function as either refrigerators or freezers, enabling users to tailor temperature zones to specific needs. Advanced freezers use microprocessor temperature control and defrost sensors to optimize cooling and reduce energy consumption.

Blast freezing is an energy-intensive process, during which pallets of fresh produce are placed in blast freezers (large rooms), where very cold air is “blasted” through them, initiating the freezing process to enable safe storage and transport. Some innovative solutions are in the works targeting the energy intensity of this technique. One is the newly developed IcePoint system, discussed in the horizon technologies section, which is the first freeze point suppression system to utilize on-demand agile cooling and moisture control. This process creates a –40°C refrigerant at night by mixing ice with a freeze point suppressant such as salt, and then deploying the brine refrigerant during the day for required cooling and moisture control. The mixture is ultimately separated into water and freeze suppressant, while reusing both and continuing the cycle, and enabling the right amount of cooling exactly when needed.

Historically, many refrigerants, such as chlorofluorocarbons (CFCs) and halons, were found to be harmful to the ozone layer. These substances, when released into the atmosphere, would break down ozone molecules, contributing to ozone depletion. The Montreal Protocol, an international treaty established in 1987, has been highly effective in phasing out the production and use of ozone-depleting substances. This has led to the gradual replacement of harmful refrigerants with alternatives that have lower or no ozone-depleting potential.

Hydrochlorofluorocarbons (HCFCs), such as R22, have a lower ozone depletion potential compared to CFCs but still have some impact. HFCs like R134a and R404A do not deplete the ozone layer but have high GWP, contributing to climate change. Many countries are working to phase out HCFCs as well. It is essential to improve energy efficiency and to adopt refrigerants, including natural refrigerants, that have lower, or zero GHG impacts.

Refrigeration is discussed in Chapters 1 (Green energy solutions for climate action) and 4 (Green energy solutions for essential services), while off-grid refrigeration is also discussed in the rural households section above.

Cold chain logistics bolstered by plentiful innovation

Cold chain logistics encompass the storage and transport of temperature-sensitive goods throughout the supply chain to preserve the quality and safety of perishable food products. The global cold chain logistics market was slated to grow by more than 50 percent between 2021 and 2028 (The Economic Times, 2023). It relies on technologies such as specialized refrigeration, temperature control systems and monitoring devices, and cold storage facilities to ensure optimal conditions.

Major trends in energy-efficient innovations for warehouses and transportation include the adoption of phase-change materials, which absorb energy during phase transitions and maintain cool temperatures efficiently, increased investment in cold storage infrastructure, and standardized temperature control across the supply chain.

In addition to modern refrigeration systems, improved insulation, ventilation and humidity control have contributed to the required maintenance of precise conditions for perishable goods. Monitoring and tracking technologies are becoming more common, including IoT sensors and GPS to monitor temperatures and locations, and blockchain technologies offer the potential to provide a secure and decentralized transaction record to support the tracing of product origins and storage conditions.

Newly developed automatic polygon geofencing technology creates a virtual geographic boundary to display a destination and to inform others in the supply chain regarding delivery status. This helps to optimize routes. By creating virtual “fences” around specific geographic locations, vehicle movement can be tracked to maximize efficiency.

Electrified transport refrigeration units (eTRUs) deliver wins to food, climate, and even health

Vehicle electrification has created a buzz in the climate conversation, and related technological developments for logistics also warrant excitement. Food and other goods require temperature-controlled conditions along their journeys. TRUs are refrigerated truck trailers that serve this purpose and need a lot of energy. These usually run on diesel to maintain the cargo temperature, typically burning up to 3 liters of diesel per hour. eTRUs are alternatives to conventional diesel-powered TRUs, whereby the refrigeration system’s compressor is driven by an electric motor all or part of the time. eTRUs are not only more energy efficient, but also prevent particulate emissions and wasted heat, and lessen health risks to nearby residents posed by idling trucks and railcars near logistics hubs (Clean Cooling Collaborative, 2022).

In order to fully implement eTRUs, however, electricity infrastructure needs scaling up at idling and other non-transit locations, including truck stops, warehouses and ports to effect wide-scale implementation of eTRUs (Ndustrial, 2024). Some places are now well on their way: eTRUs in the United States received a helpful push from a California regulation enacted in late 2023 requiring carriers to begin electrifying 15 percent of their TRU fleets. This served as the impetus to fleet and facility owners to start decarbonizing the cold chain.

Food packaging for retail has been largely based on fossil-fuel plastics

Food packaging is essential to food retail. Currently, most food packaging is made from petroleum-based plastics. These are non-degradable and energy-intensive to produce, relying heavily on fossil fuels. Research toward the development of green or sustainable food packaging has gained momentum, especially under the added impetus of newly instituted plastic bans and other climate pledges. Green food packing connotes two meanings, one that it is non-polluting and harmless for humans, and the other that it is petroleum-derived polymer-free (Khalid and Arif, 2022). The alternative materials used are currently biomass-based, including cellulose and starch (Wang et al., 2023).

Nanocellulose has become the focus of new research due to its high specific surface area, biodegradability, material strength and design flexibility (Wang et al., 2023). Nanocellulose encompasses nanomaterials derived from cellulose, a structural polysaccharide found in the cell walls of plants which can be extracted and processed to create materials at the nanoscale that exhibit unique properties compared to their bulk counterparts. One technology highlighted in this chapter introduces nanocellulose from sustainable bio-based resources, mainly agricultural residues, that can be used in food retail packaging.

Fisheries and aquaculture need cold chain innovation too

Energy use differs among value chain stages for both fisheries and aquaculture. Post-harvest processing and distribution have relied on fossil fuels, electricity, and also wood for fish smoking (FAO, 2022b). Major disruption of cold chains during processing and storage are still occurring and incur a great loss of aquatic products (FAO, 2022b) due in part to inadequate cold storage facilities and inefficient transportation, with global estimates indicating that roughly 35 percent of catch is lost or wasted per year (WWF, 2021b). It's estimated that 10 to 20 percent fish catch losses can be prevented by providing fishermen with enough ice (IRENA and FAO, 2021).

The major technology types for fisheries cold storage include:

Ice flake machines are located at landing sites. Ice flakes can be used by fishermen and fish dealers, for transportation, and by retailers. Depending on location, solar or wind energy can power ice flake machines, which are easy to maintain. Drawbacks of the machines include limited storage time, and substantial power and water requirements for larger machines.

Solar-powered fridges and freezers keep products cold with low operating costs and can be used at landing sites or by individuals, and also for retail storage and processing. However, storage capacity is often limited for large catches. These can be expensive, as the use of batteries incurs costs, as does required maintenance.

Cooler boxes are used at sea and across the supply chain. They are offered in all sizes and can be used in conjunction with ice-making machines.

Cold storage rooms are temperature-controlled rooms that can be solar-powered and are located at landing sites, processing centers, and retailers.

Functional ice is produced by adding vinegar or citric acid to water before freezing, which slows the melting process and slows bacterial growth in fish. This technology, however, is at an early stage of development.

Importantly, inadequate regulatory frameworks and uneven market trends contribute to the issue in both developed and developing countries (WWF, 2021b). Improved processing practices can help, including investing in improved drying techniques and cold chain infrastructure, digital solutions and renewable energy across the board for cold storage and dryers. Solar PV systems can be used to power processing, refrigeration and cold storage appliances (FAO, 2022b).

Climate adaptation benefits from improved fisheries supply chains include improved nutritional and food security for coastal communities. Climate smart fisheries technologies can increase overall food safety and quality as well, since food handling during processing can also affect the microbial safety of the fish. Some smoking technologies, where used to preserve fish and enhance its flavor, can negatively impact its nutritional retention (WWF, 2021b).

Innovation examples

Energy-efficient and eco-friendly refrigeration for the aquaculture industry, Chile

Source: Getty Images/RusN

Starting in the 1970s, industrial-scale salmon aquaculture began to boom, and today Chile is the world's second largest producer of farmed salmon. Many fish farms have complex logistical infrastructure that supports export to foreign markets. The availability of hygienic refrigeration is crucial and historically, the industry standard was to use refrigerants that were harmful to the environment. But then Chile's Ministry of Environment partnered with the United Nations Industrial Development Programme (UNIDO) to launch a project at Marine Farm, an aquaculture company, to demonstrate the use of natural refrigerants. The three condensing units at Marine Farm, which can store 160 tons of fish per day, housed three condensing units using Freon gas (R22), a synthetic refrigerant with high GWP that damages the ozone layer. The facility also lacked energy efficiency due to its oversized units. A conversion project was launched, whereby ammonia was used to replace Freon in a solution designed by a local company called Sofrisur. At the project completion in late 2023, 10 secondary refrigerant evaporators were installed. The immediate benefit was reduced energy consumption of 10 percent by the facilities. Marine Farm also reduced emissions by 1.2 million kg of CO_2eq. Additionally, the use of natural refrigeration supports Chile's commitments to the Montreal Protocol, has improved food safety processes, and has become an industry example of the benefits of eco-friendly and energy-efficient technologies (UNIDO, 2024b).

Solar Freeze for refugee camps, Kenya

Source: Solar Freeze

The innovative Kenyan system called Solar Freeze™ supports smallholder farmers in dealing with post-harvest loss using a holistic approach that encompasses storage, transportation and market access. Solar Freeze produces portable solar-powered cold stores to help farmers avoid huge investments in storage space; a cold-chain distribution, logistics and refrigerated transport service with energy-efficient trucks that functions like an Uber service; and mobile access to the cold storage management system through an application and IoT platform. Kakuma Refugee Camp in Kenya is a settlement of 200,000 people from all over Africa where access to sustainable and affordable energy is limited. Solar Freeze is providing cooling for food and medicine alongside training for 100 people. Freezers are available using the affordable pay-as-you-go model for small shops that use them to store food and drinks, and health centers to store vaccines and treatments. Customers pay USD 1.20 per day, and eventually own their freezer outright after 18–24 months. In addition, in both farming areas and the refugee communities, Solar Freeze operates an initiative called “Each One Teach One” that trains young people aged 18–29 at no cost to install and maintain solar freezers and other solar-powered technologies. Upon completion of the training after 3–4 months, Solar Freeze recruits several trainees as short-term employees (Humanitarian Grand Challenge, 2020).

Technology solutions

Proven

Dairy processing: plate cooler
Paul Mueller

Source: Paul Mueller

The Accu-Therm® plate coolers, also known as plate heat exchangers, use the existing water supply to precool warm milk before it enters the milk cooler. This warmed water is then available for other uses. Precooling reduces the energy and time needed to reach necessary temperatures inside the bulk tank by up to 50 percent. The plate coolers are composed of stainless steel plates compressed onto a frame and separated by gaskets to create flow channels on opposite sides of each plate. Cool water flows down one flow channel while warm water flows up on the opposite side.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Dairy processing: pulsed electrified field (PEF) treatment
Elea

Source: Elea

PEF dairy treatment consists of passing milk between two electrodes separated by an insulator, and uses short pulses of high-voltage electricity. The electric field opens pores in the cell membranes and inactivates microorganisms. The Elea PEF Advantage™ Pipe system uses low temperatures to ensure that freshness and nutritional value are retained. The Elea PEF process can be applied to raw milk, cheese-making milk, whey and yoghurt drinks without losing any of their nutritional value, which enables the retention of health-promoting ingredients such as immunglobulines (IgG, IgA, IgE etc.) and lysozyme, and maintains its probiotic character.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Drying: seafood dryer and solar drying machine
Shuliy Machinery

Source: Getty Images/hanohiki

The seafood drying machine uses an air-energy heat pump that requires small amounts of electricity to absorb a large amount of heat energy to rapidly heat the drying room. It saves energy and ensures that no pollutants are emitted during the drying process. The drying machine can operate automatically once the parameters are determined through the intelligent control system, which helps to prevent overdrying or underdrying. It can dry both freshwater and marine fish. The small mobile solar drying machine is a different product available for small producers to dry vegetables, fruits, grains and meat.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: China
- Availability: China
- Contact: WIPO GREEN Database

Drying: continuous flow dryer system
Shivvers

Source: Getty Images/Vladimir Zapletin

Shivvers is a precision and automation control unit that automatically prevents over drying by using sensors and adjusting heat based on specifications, which helps maintain the drying system's operation within its most efficient range, preventing energy waste associated with inefficient drying conditions. When grain has reached the right transfer moisture level, the command center automatically transports the dried grain to storage; otherwise, it is kept in the drying zone until ready. The Shivvers system uses the *Counter-Flow Grain Drying Process* with a deeper grain depth of 91–243 cm instead of the commonly used 30–45 cm range, meaning that the air passes through a larger volume of grain before completion. It also uses lower temperatures while maintaining the versatility to dry a wide variety of crops. Automating the drying process by precisely controlling the temperature and airflow in the drying system ensures that the drying process is conducted at optimal conditions, reducing energy waste and improving efficiency.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: North America
- Contact: WIPO GREEN Database

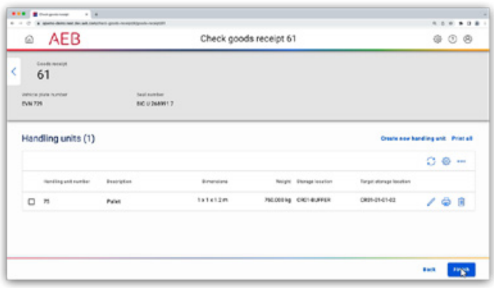
Drying: mechanical stirring system used in batch grain dryers
GSI

Source: Getty Images/ghornephoto

The StirAtor can cut drying time by 50 percent in low temperature bins, therefore reducing energy expenditure. It uses a spiral stirring pattern that enables the augers to spend more time stirring on the outside of the bin rather than the center of the bin, as half the grain is located in the outside third of the bin. Alongside the StirAtor, the Grain Flow and CalcuDri can convert the bin into an automatic in-bin drying system. The Grain Flow features an 8-inch (20 cm) discharge auger that pulls only the dried grain at the floor of the bin, improving efficiency. Using the StirAtor, the bin becomes a wet holding tank with a depth of up to 5 m, a continuous flow dryer and a dry and store unit. The CalcuDri maintains grain moisture while also controlling the system. The efficient removal of moisture and the uniform drying of the grain reduces the overall drying time and avoids over-drying, saving energy which would otherwise be wasted in reprocessing or correcting inconsistent drying.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cold storage: cold storage warehouse management software
AEB

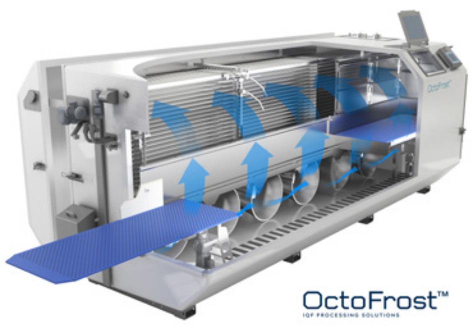


Source: AEB

The cold storage warehouse management software manages and optimizes cold storage facility operations. Through maintaining precise temperature controls and automatically adjusting settings based on actual needs, cooling systems can prevent overcooling and operate more efficiently without unnecessary energy consumption. Additionally, the software performs workflow automation of inventory rotation, helping to maximize the use of available space and reducing the need for excessive cooling capacity, thereby saving energy. It enables product traceability by storing batch numbers and supplier details and ensures accurate tracking and allocation of catch weight item handling (items that are priced according to the exact *weight* of the *item* delivered) throughout the supply chain.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cooling: individual quick-freezing (IQF) tunnel freezer
Octofrost



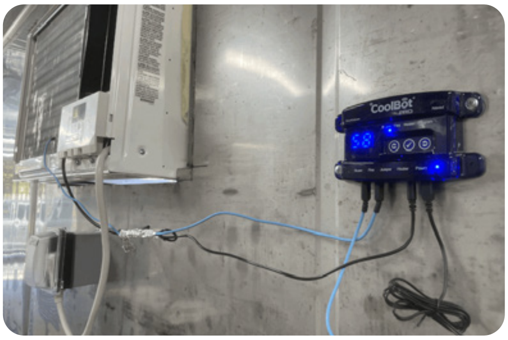
Source: Octofrost

An IQF tunnel freezer uses cold air to individually freeze individual pieces of food separately to preserve their freshness, shape, flavor and nutritional content. The OctoFrost IQF tunnel freezer's frequency converters that are installed on each fan allow the food processor to adjust fan speed according to the type of product, delivering up to 30 percent savings due to the decreased need for refrigeration to cool down the heat produced by the fans. Fan speeds do not need to exceed 75 to 85 percent, and for some products the speed does not exceed 30 percent, which enables increased energy efficiency. It is the smallest freezer available on the market and arrives ready-built and easily transported on a truck or container ship.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Sweden
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cold storage: walk-in cooler and mobile cooler

Store It Cold



Source: Store It Cold

The CoolBot is a patented digital temperature controller that enables users to create a low-cost walk-in cooler that saves energy by turning a standard air conditioning unit into a cooling machine that can maintain temperatures below 15.5°C. It does this by cycling the conditioner units on and off to avoid freeze-up so that they can cool a room far below the standard temperature. The CoolBot can also save up to 42 percent energy use compared to a conventional refrigeration system due to its use of only one 300 W fan, while a conventional refrigerator compressor may use three to five fans. The reduced air movement in a one-fan system can help keep crops fresher for longer. It can cool a room down to 1°C. The CoolBot Pro offers a mobile application for remote temperature adjustments, critical alerts, and data storage and reporting.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier

Dairy processing: UV treatment for opaque liquids
Lyras

Source: Lyras

UV light has inherent natural antibacterial properties that have commonly been used to disinfect transparent liquids such as drinking water. This technology uses UV to treat opaque liquids such as brine, whey and juice. The Raslysation™ Sirius offers a compact system to treat large quantities of liquid and features a patented filter technology to make sure that only the germicidal wavelengths reach the product. The Raslysation™ Castor is the world's largest UV unit for treatment of opaque liquids. It is modular, which allows it to be scaled up. The Raslysation™ Polaris is a compact air-cooled mobile standalone unit.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Denmark
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cold storage: tunnel freezer, non-pressure plate freezer and brine freezer for fish
Skaginn

Source: Getty Images/GI15702993

The freezing systems by Skaginn are energy-efficient and save time and labor. The tunnel freezer enables quick freezing with gentle handling and drip loss, ensuring that thawed products retain shape and texture. The non-pressure plate freezer uses up to 40 percent less energy than conventional blast freezers, is designed to plate freeze to retain product shape, and can freeze up to 100 tons in 24 hours. The automatic brine freezer can tolerate high salinity for crab and shrimp, for example, using a strong brine solution cooled to –17°C with a computer-controlled heat exchanger. Immersion freezing is very efficient due to the 100 percent heat transmission without thermal barriers, resulting in a rapid freezing time. It is also compact and can be installed in both onboard and onshore facilities.

- Contracting type: For sale
- Technology level: Medium

- Country of origin: Iceland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cold storage: e-cool truck (electric transport refrigeration unit, eTRU)
Carrier Transicold

Source: Carrier Transicold

The Supra e11 single-temperature electric truck refrigeration unit is part of the eCool™ series of products from Carrier Transicold. The Supra eCool electric unit covers 14- to 28-foot, Class 5 to 7 straight truck applications. The e11 unit provides comparable refrigeration performance to the diesel-powered Supra S10 unit. Designed to run off an electric power takeoff on a Battery Electric Vehicle or unique to California application on ICE (Internal Combustion Engine) trucks, units can run autonomously using Carrier's exclusive power pack. It uses maintenance-free electric evaporators and condenser fans, as well as a sealed electric compressor to reduce the need for maintenance. Additionally, it uses R-452A, a refrigerant with a GWP 45% lower than the traditional refrigerant used in transport applications. The Lynx Fleet™ telematics system conducts remote monitoring of temperature, location, battery charge, and operating performance.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cold storage: atmospheric monitoring and control sensor
PostHarvest

Source: onurdogel

Atmos is an advanced IoT atmospheric monitoring and control sensor that provides for accurate ethylene detection (ethylene being a plant hormone that affects fruit ripening and quality, so its monitoring enables detection of overripe or decaying produce), temperature and humidity. Using PostHarvest's Cloud Platform, all rooms can be monitored, and storage conditions can be set to the required specifications. The sensor then sends notifications when levels are too high. Using an open application programming interface (API), it is possible to use storage specifications to create room automations; for example, a door could be automated to open if ethylene levels reach a certain point.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Australia
- Availability: Worldwide
- Contact: WIPO GREEN Database

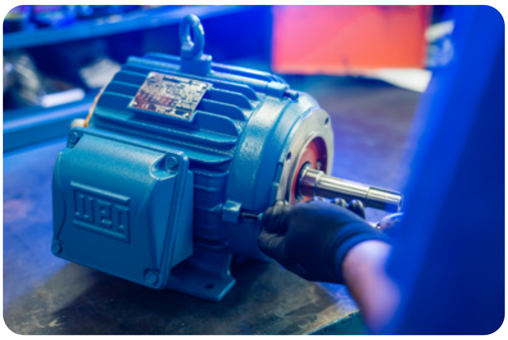
Cold storage: cold room (and milk chiller)
SelfChill

Source: SelfChill

The SelfChill Cold Room is a plug-and-play installation providing an autonomous, solar-powered cooling system that can be integrated into agricultural value chains to store fruits, vegetables, herbs and seeds at the required temperature and relative humidity. Due to its modularity, it can be tailored to meet specific needs. The SelfChill Milk Tank is a complete pre-configured plug-and-play milk cooling system that can cool up to 1,200 liters of milk per day. SelfChill technologies are all solar-powered and based on vapor compression heat pumps. They are offered as DC systems with thermal storage and AC systems for cold rooms and freezing rooms. Most cooling systems use natural refrigerants such as R290 and R600a with ultra-low GWP.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Africa, Latin America, Asia
- Contact: WIPO GREEN Database

Grain storage and processing: automated ventilation grain storage silo
WEG



Source: WEG

The WEG automation system for silo ventilation is an energy-efficient solution to ensure improved silo and grain storage management. It enables appropriate ventilation levels using electric motors and variable speed drives that allow the system to adjust to any kind of grain. The system provides the right aeration rate to maintain a homogenous temperature, saves up to 90 percent energy, enables mass humidity control, and avoids losses due to excessive drying. The technology uses thermometry to enable reduced fan speed and grain quality maintenance. The temperature variation causes fewer grain breaks, thereby producing better quality grain, and allows for precise control of the stored volume.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Brazil
- Availability: Worldwide
- Contact: WIPO GREEN Database

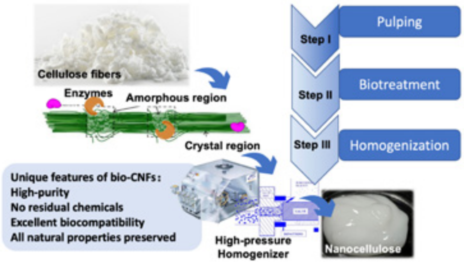
Milling: solar agro-processing machine
Agsol

Source: Agsol

The MicroMill is powered by solar, mini-grid, grid, or even e-bike to process cereal grains, pulses and tubers. It is 2.5 times more efficient than other small electric mills, providing 55 kg/h ±10 percent for fine flour and 250 kg/h for chicken feed. It's easy to swap screens in and out to produce fine flour or coarse grits for animal feed. The solar package includes a 600 Wh LFP battery, 48 V MPPT charge controller and 600 W of solar PV. Battery PV capacity can be adapted to meet customer requirements. Pay-as-you-go options are available.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Kenya
- Availability: Kenya
- Contact: WIPO GREEN Database

Food packaging: sustainable nanocellulose materials
NINGBO TANGJU New Materials Co. Ltd



Source: NINGBO TANGJU New Materials Co. Ltd

Cellulose nanomaterials (CNMs) are derived from sustainable processes and green resources and possess unique properties such as nanoscale dimension, high surface area, and biodegradability. Nanocellulose from sustainable resources is being used to replace petroleum-based materials for food packaging. Researchers have successfully extracted nanocellulose from local agricultural waste such as bagasse, wheat straw, apple stalks and corn cobs, and applied it to food packaging. Nanocellulose-based functional materials are also being widely utilized in various aspects of agricultural production. They can enhance biodegradable agricultural mulch and be used as a new type of agricultural chemical, including new pesticides, feed, slow-release fertilizers and soil water-retention agents. The sustainable development of agricultural resources using nanocellulose materials can limit agricultural pollution, and improve the quality and efficiency of agricultural production.

- Contracting type: For sale
- Technology level: High
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon

Cold storage: freeze point suppression cooling system
Rebound Technologies

Source: Rebound Technologies

Rebound's patented cooling system called IcePoint was developed with support from the National Science Foundation in the United States, with the aim of improving on vapor compression. Normal vapor compression moves heat by changing the pressure of a refrigerant, which requires energy-intensive compressors. IcePoint uses a highly efficient thermodynamic cycle called freeze point suppression that alters the refrigerant's chemical composition, enabling adaptability to fluctuating cooling demands. It can create a –40°C refrigerant at night by mixing ice with a freeze point suppressant such as salt and then deploying the brine refrigerant for cooling, after which the mixture is separated into water and freeze suppressant and reused in the cycle. This allows cooling to be applied in the exact amount needed at the appropriate time. Rebound Technologies, an advanced refrigeration equipment supplier, has commissioned the first full-scale commercial IcePoint system, now operational at Lineage Logistics' 115,000 ft2 cold storage and blast freezing facility in Greeley, Colorado.

- Contracting type: N/A
- Technology level: High
- Country of origin: United States
- Availability: United States
- Contact: WIPO GREEN Database

Cold storage: solar-powered ice block machine
AIREF

Source: AIREF

The ice block machine runs using solar power and R290 refrigerant, which is a preferred hydrocarbon alternative for more harmful fluorocarbon refrigerants with high GWPs that can destroy the ozone layer. The ice maker has a 1.2-ton capacity production, 12 horsepower, and a smart and fully automatic system. It is scalable and modular, ozone friendly.

- Contracting type: N/A
- Technology level: Medium
- Country of origin: Indonesia
- Availability: N/A
- Contact: WIPO GREEN Database

Grain storage and processing: pedal-powered thresher and blender
Maya Pedal

Source: Leonid Sorokin

Maya Pedal reconditions donated bikes from the United States and Canada and either sells them or recycles parts to create various types of *bicimáquinas* (bicycle machines). The *bicimáquinas* are adapted to fit a hand powered grinding mill or a corn thresher. The mill function has the capacity to mill 1.36 kg per minute of any type of grain with the most common use being for milling yellow maize, soybeans and coffee. The thresher is used post-harvest to degrain 1,200–1,500 kg per day, requiring only one person to operate the machine.

- Contracting type: For sale
- Technology level: Low
- Country of origin: Guatemala
- Availability: Guatemala
- Contact: WIPO GREEN Database

Heating: thermal pest control system for wooden pallets
BioAfriq Energy

Source: Getty Images/Baloncici

BioAfriq Energy is an established manufacturer of biomass pellet fuels, pure solar food dryers, and hybrid dryers which use both biofuel and solar energy. During 2024, the company successfully developed and applied a new low carbon heating system in collaboration with a food hygiene and cargo inspection company. The new system works by heating a truck container to high temperatures. It is capable of eliminating pests in wooden pallets and home items in one hour’s time. BioAfriq is now working on finalizing the model and introducing it to the market.

- Contracting type: Under development
- Technology level: Medium
- Country of origin: Kenya
- Availability: N/A
- Contact: WIPO GREEN Database

4. Green energy solutions for essential services

Supermarkets, healthcare facilities, and data centers, though serving different functions, all rely on continuous, reliable energy to operate efficiently. These sectors are highly energy-intensive, and their energy consumption is steadily increasing. They can no longer be overlooked in efforts to improve energy efficiency.

How can health care facilities, supermarkets and data centers manage their significant and growing energy use? And how can they overcome the challenges posed by limited access to green electricity? This chapter explores innovative solutions tailored for these essential services, highlighting the critical need for benchmarks and standards to better understand and mitigate their environmental impact.

Introduction

High-demand sectors in critical need of energy reliability and resilience

Supermarkets, health care facilities and data centers, despite serving vastly different purposes, share a critical commonality: they all demand reliable, uninterrupted energy to operate effectively. These sectors are energy-intensive, outstripping most other private, commercial and public building types (Gimeno-Frontera *et al.*, 2018; Delgado *et al.*, 2021.; McGain and Naylor, 2014).

Supermarkets, health care facilities and data centers share a critical commonality: they all demand reliable, uninterrupted energy to operate effectively

They also have strict requirements for maintaining temperature control, supporting essential equipment and ensuring the safety and well-being of their users or customers. Any disruption in power can have significant consequences, from spoiled food and compromised patient care to data loss and operational downtime.

This dependency on consistent energy supply also makes them prime candidates for clean energy solutions. Integrating renewable energy sources, enhancing energy efficiency and adopting advanced energy storage technologies can not only reduce their environmental impact but also bolster their resilience against power outages and fluctuations in energy costs.

Essential but energy-intensive sectors can no longer be overlooked

Another commonality for the sectors covered in this chapter is that their energy demand is growing. Supermarkets are trending toward smaller convenience stores – which can be about half as efficient as larger ones – and more frozen food, which demands more electricity for cooling (Kolokotroni et al., 2019). Hospital energy consumption is steadily increasing, driven in part by the increase in critical equipment and rapid adoption of advanced information technology (IT) (Suárez et al., 2022). And Google reported a 13 percent increase in greenhouse gas (GHG) emissions in 2023, primarily due to rising data center energy use and supply chain emissions (Google, 2024).

With limited renewable energy use in many regions and fossil fuels still maintaining an 82 percent share of global primary energy production (Energy Institute, 2024), a broader array of solutions is needed to drive the sustainable energy transition for these high-demand sectors. In this chapter, we delve into low-carbon energy solutions, often tailored for each service area.

Overcoming decarbonization challenges with decentralized energy supply

Decentralized energy systems, such as hybrid renewable energy systems incorporating solar photovoltaics (PVs) and batteries, are increasingly being adopted to provide clean and reliable energy in end-use sectors. For example, in Zimbabwe, over 400 health centers have installed solar arrays. Similarly, several supermarkets utilize rooftop solar panels and participate in micro-grids to stabilize their energy supply and reduce GHG emissions. Data centers, with their high energy demands, can benefit from modular and off-grid solutions like solar power, micro-grids and battery energy storage systems but are yet to do so on a large scale.

All these subsystems benefit from advances in intelligent energy management systems, which are essential for ensuring they work together efficiently and reliably, especially in critical situations like maintaining operations during extreme conditions such as natural disasters (Kyriakarakos and Dounis, 2020). The level of self-sufficiency achieved through renewable energy integration often hinges on effective energy storage. For example, in supermarkets, integrating PV plants can cover up to 20 percent of energy consumption without storage, but with appropriately sized battery storage systems, this figure can rise to 75 percent (Franco and Cillari, 2021).

Cooling and refrigeration shifting toward greener solutions

In addition to significant heating, cooling and ventilation needs, these essential services face unique challenges with regard to the need for cooling of food, hardware and medicine. Health care facilities also require higher ventilation standards. Cooling and ventilation is where much of the innovation is happening, with efficient medical freezers, subcritical CO_2 boosters and liquid cooling technologies, to name a few of the technologies described in the chapters.

> Simple and effective solutions like simply equipping supermarket cabinets with doors can sometimes offer the highest energy savings

New advances are further enabling better cooling efficiencies in hot and humid climates. Technologies that manage airflow and humidity in data centers and hospitals, for the benefit of heat dispersion and patient health, are becoming more sophisticated. However, simple and effective solutions like simply equipping supermarket cabinets with doors can sometimes offer the highest energy savings. Making use of natural elements, through free cooling that uses cold outdoor air or water bodies, is another promising trend that can help reduce demand for mechanical cooling.

Benchmarks and standards catching up

Energy efficiency standards and labeling schemes significantly impact the adoption of energy-efficient technologies. For instance, European Union (EU) minimum energy performance standards and energy labels reportedly increased the market share of efficient cold appliances by 15 to 38 percentage points (Schleich et al., 2021). Data centers, hospitals, as well as supermarkets, can now earn energy efficiency labels, for instance through Energy Star, by adopting energy-efficient products and practices.

However, more work is needed in terms of benchmarks, coordinated action and greater transparency to fully understand their energy footprint and evaluate the effectiveness of their climate investments. For health care facilities and supermarkets, they have only recently started their sustainability journeys. The energy consumption of data centers has been understood and assessed for longer, but the general lack of transparency by privately owned tech companies means real figures are hard to come by. These findings underscore the importance of policy measures, labeling schemes and public awareness in promoting low-carbon and energy-efficient technology adoption.

Energy-efficient supermarkets

Supermarkets are among the biggest energy consumers of all commercial building types. Grocery stores, wholesalers, convenience stores and other food retailers need energy for keeping produce fresh, illuminating their shops and controlling temperatures and humidity. By adopting low-carbon energy technologies, supermarkets and other food retailers can significantly reduce their climate impact and lower energy costs.

Technological developments and trends

Supermarkets’ unique energy challenge

Supermarkets have been growing rapidly in number, having emerged in the United States of America and Western Europe in the 1920s–40s, and in developing areas in the 1980s–90s (Lu and Reardon, 2018). Making use of economies of scale, they offer fresh and easy-to-prepare foods and save customers multiple trips to specialty shops. They also contribute to new supply chains and market arrangements, with repercussions for both large-scale food producers and small farmers growing perishable crops (das Nair et al., 2018). Innovative solutions have now enabled e-commerce to enter the food retail market, allowing consumers to browse and select food items online for delivery or pickup.

Supermarkets are among the biggest energy consumers of all commercial building types

With the vast number of daily visitors, supermarkets can be a place of influence, facilitating green diets and sustainable sourcing of food (Bauer et al., 2022). But supermarkets also take their toll on the environment, not least through food waste production, fugitive refrigerant emissions, excessive plastic packaging and energy consumption. The challenge of food waste in supermarkets has received global recognition and interest (Huang et al., 2021). In comparison, the high energy consumption of supermarkets, attributed mainly to the vast refrigeration needs (Karampour et al., 2016), has gone largely unnoticed. This is despite the fact that food retail stores can have 20 times higher global warming potential (GWP) per square meter than non-commercial buildings Gimeno-Frontera et al., 2018). Supermarkets are also among the most electricity-intensive types of commercial buildings (Khare et al., 2019).

While the supermarket industry has been growing, earlier data indicated that supermarkets in the United Kingdom accounted for about 3 percent of national electricity consumption (Tassou et al., 2011). This warrants a better understanding in terms of benchmarking the energy consumption of supermarkets, and standardizing energy efficiency measures across the many food retail chains across the world (see box 4.1). Several food retailers have now pledged carbon neutrality by various timeframes, and adoption of innovative energy technologies can help accelerate their energy transition.

Smaller supermarkets consume twice the energy of larger ones

In many countries, energy intensity in supermarkets has been reduced with the help of energy efficient technologies for lighting, refrigeration, and heating, ventilation and air conditioning (HVAC). A global trend that is hampering such progress is the growing number of smaller food stores such as convenience food shops, which also happen to have a higher energy intensity. In London, supermarkets of around 300 m2 have an energy intensity of 840–1200 kWh/m2 per year compared to larger supermarkets that average about 400 kWh/m2 annually (see box 4.1) (Kolokotroni *et al.*, 2019).

Another growing trend is frozen food, which performs particularly well during disruptions such as the pandemic and periods of economic turmoil. The higher the percentage of frozen food, the higher the total energy usage due to more demand for lower temperature refrigeration (Kolokotroni *et al.*, 2019.; Mylona *et al.*, 2017). On the somewhat positive side, excess heat from refrigeration and lighting systems means that supermarkets have lower heating needs. In fact, electricity needs for cooling and refrigeration can be on average 70 percent higher than the need for heating (Rosén and Borgqvist, 2015).

Box 4.1 Benchmarking and performance indicators for energy efficient supermarkets

In many countries, few food retailers own a majority of the grocery stores in the country. While these are not always managed centrally, there is a certain degree of standardization of the stores (Uhlig et al., 2021). This presents unique opportunities to also standardize energy efficiency measures. Initiatives related to benchmarking and development of energy indicators for supermarkets are therefore critical endeavors for the energy transition.

In the United States, the non-profit Ratio Institute has worked with more than 1,000 grocery stores and 20 grocery chains to benchmark their energy performance and identify store-level sustainability measures. While grocery stores within a chain try to contribute to the company's goals for energy efficiency and reduction in climate impact, most food retail companies do no benchmarking of store-level performance against an energy or sustainability standard. Benchmarking against a performance standard helps a food retailer with many locations be systematic and ensure accountability for a store's performance. A spectrum of high performers to low performers within a company's suite of stores can be realized and priorities can be determined to leverage opportunities for higher efficiency. Currently, efficiency measures are being performed in a random manner that limits alignment with company goals.

The International Energy Agency (IEA), under the IEA Heat Pumping Technologies (HPT) Annex 44 project, aimed to estimate the energy consumption of supermarkets around the world. While the size of the supermarket was found to be the best performance indicator for assessing energy consumption, other common indicators for supermarkets include refrigeration system type, installed refrigerating capacity and opening hours. In a survey of larger supermarkets in countries like Sweden and the Netherlands, the average energy intensity of larger stores was estimated to be approximately 400 kWh/m2 per year. It was also found that advances in refrigeration systems and lighting could enhance energy efficiency by up to 10 percent (Kolokotroni et al., 2019). Meanwhile, other estimates indicate a 10 to 50 percent energy-saving potential from lighting and refrigeration (Atzberger et al., 2015). With the low margins in food retailing, every percentage of energy cost saving has important financial implications.

Various other initiatives also seek to include food retailers in the energy transition. The SuperSmart European Project aims to increase uptake of energy efficient technologies in supermarkets. Under this initiative, a European label for eco-friendly supermarkets has resulted in guidelines and best practice measures for reducing total energy use by nearly half, through technologies such as intercoolers (internal gas coolers), heat recovery to water, destratification fans, as well as CO_2 refrigerators (Kolokotroni et al., 2019).

Refrigeration the biggest energy consumer

Refrigerator systems are energy-consuming and often dependent on refrigerants with a high GWP. The type of refrigeration system adopted by a supermarket has an important impact on energy consumption, considering they account for 35 to 50 percent of the total energy use (Karampour et al., 2016). The best available cooling equipment consumes 80 percent less electricity than comparable technology using outdated technology (U4E, 2024a). Even simple retrofits, such as installing low-E glass doors for refrigerators, can save up to 40 percent of energy consumption (Saengsikhiao and Taweekun, 2021).

Stand-alone plug-in cabinets, condensing units (with “split systems” connected to a remotely located condenser) and centralized systems using high-GWP refrigerants are common among supermarkets. While condensing units use more refrigerants, plug-in options often consume the most energy (CCAC, 2023a). A refrigeration technology which has gained in popularity in the last decade is the transcritical CO_2 booster system which uses natural CO_2 refrigerants. The technology is recognized for its potential to reduce refrigerant-based GHG emissions and generate at least 20 percent on energy cost savings (CCAC, 2023a).

Supermarket refrigeration technologies of the future

Between 2008 and 2020, the adoption of transcritical CO_2 refrigeration systems in Europe grew from 140 to 35,500 systems, with 55,000 reported in 2022. In Europe, transcritical CO_2 refrigeration systems have gained industry-wide acceptance, with over 18 percent of the food retail market having adopted the technology (Patenaude, 2022; ATMOsphere 2022). While they are not yet the norm in most other parts of the world, CO_2 refrigeration systems are spurred by policies promoting the use of natural refrigerants, including the Kigali Amendment which limits the use of hydrofluorocarbons (HFCs). Developed country investments since the 2010s have brought down production costs of the technology to nearly equal those of HFC systems, and enabled uptake in middle-income countries (CCAC, 2023a).

Between 2008 and 2020, the adoption of transcritical CO2 refrigeration systems in Europe grew from 140 to 35,500 systems, with 55,000 reported in 2022

While medium-sized supermarkets have been the main adopters of CO_2 refrigeration systems, a noticeable trend involves the development of units that are suitable for smaller stores (shecco, 2020). This will be relevant not least in countries with high population densities where smaller convenience stores are common. Another trend is multifunctional integrated systems providing combined refrigeration, heating and even air conditioning (Karampour et al., 2016). Self-contained cases of R290 (propane refrigerant, which has low GWP), subcritical CO_2 and R290 water-loop systems are other technologies expected to play a bigger role in the future (see list of technologies for details) (shecco, 2020).

Refrigeration systems in warmer climates

While transcritical CO_2 systems were previously considered unsuitable in warmer climates due to lower efficiencies, new innovations and cost competitiveness have allowed use of CO_2 refrigeration systems regardless of climate (UNEP Ozone Secretariat, 2015). Technological advances include cascade systems which use a combination of natural refrigerants in a setup that enables two or more refrigeration cycles to be combined to reach lower temperatures in a more efficient way.

Other efficiency-enhancing technologies which allow the use of transcritical CO_2 systems in warmer climates include ejectors and parallel compression, the latter which could enhance efficiency by more than 10 percent (Fritschi et al., 2016). These are expected to become standard features in transcritical systems (shecco, 2020).

Compared to regular transcritical CO_2 refrigeration systems, adiabatic refrigeration systems incorporate an additional cooling step to enhance efficiency, particularly in warmer climates. A study in Chile pointed to an adiabatic transcritical CO_2 refrigeration system being 44 percent more energy efficient than one using a conventional R507 HFC refrigeration solution (MoE Chile, 2018).

Efficient heat recovery and simple dehumidification techniques

In supermarkets, as in most energy-consuming sectors, a significant amount of energy is lost as waste heat. The use of heat recovery from refrigeration systems is gaining traction, but still remains underutilized despite great potential for energy and cost savings (van der Sluis, 2017). For instance, one supermarket in Denmark reportedly reduced their annual heating bill by nearly 90 percent by making use of heat recovery, highlighting a significant decarbonization potential across the sector (Danfoss, 2022). Several technology companies have now developed specialized heat recovery units that allow supermarkets to recover heat to warm the stores and provide hot water.

Another often overlooked efficiency measure relates to managing humidity. Humidity in supermarkets can lead to more frost formation on refrigeration coils in food display cabinets, which reduces their efficiency. Many supermarkets have not adopted solutions to dehumidify air. For those that have, dehumidification itself contributes to energy consumption, warranting a full analysis of net energy costs of the store.

Solutions can involve a combination of dehumidifiers, improved refrigeration design, anti-sweat glass doors, humidity sensors or the use of water-absorbing materials like silica gel that are incorporated in the ventilation systems (van der Sluis, 2017). Hot gas defrosting or electric defrosting can be equipped with precise controls that allow stores to reduce the frequency and energy consumption of defrost cycles.

However, sometimes the solution is far simpler. In fact, studies have shown that equipping display cabinets with doors to avoid frost formation on coils can offer energy savings of almost 40 percent, which is far greater compared to other dehumidification measures (Markusson and Ollas, 2013). Technology and service providers now offer solutions for retrofitting glass doors onto open display cases in supermarkets, to avoid changing the entire refrigerator.

Light-emitting diodes (LEDs), daylighting and automation

Lighting represents about 13 percent of electricity consumed in a supermarket or related establishment. Compared to other investments, lighting measures such as switching to LEDs is often considered a low-hanging fruit with potential to save up to 50 percent on lighting energy (Energy Star, 2008). LEDs can also be used in food display cases and cabinets. Today, LED tube lights can be fitted into conventional lighting armature fixtures making the switch easier.

Beyond switching to LEDs and training personnel in energy efficient behavior, energy consumption can be reduced further by installing motion and daylight sensors. Automated control systems can adapt lighting to occupancy rate and opening hours of the shops. Further, placement of photoelectric cells outside to measure light intensity enables shops to reduce indoor lighting when it is dark outside. This offers more comfortable lighting as the contrast is less harsh for consumers whose eyes have adjusted to the darkness outside. Combining daylighting with artificial lighting and suitable control systems such as dimmers also helps enable a more cost-effective and efficient lighting level.

On-site energy production for food retailers

While energy conservation and efficiency measures are a priority, supermarkets and food retailers have the option of producing their own clean energy to further mitigate energy-related GHG emissions. The profitability of such initiatives is higher for larger supermarkets and is largely dependent on the price of electricity. On-site electricity production can be particularly suitable for supermarkets as they have predictable energy consumption patterns, with the only variance being whether the store is open or closed. Supermarkets also often have large parking facilities and ample space for rooftop solar.

Solar, off-site wind and geothermal energy are all options for provision of electricity, heating and cooling. However, given the excess heat generated from refrigeration and lighting systems, technologies for on-site heat production are often of low interest (Rosén and Borgqvist, 2015). Supermarkets can also participate in or develop micro-grids to combine renewable energy sources with battery storage for increased energy security and resilience. On the simpler end, solar-powered food storage units are replacing diesel generators in several urban markets around the world to enable retailers and wholesalers to avoid food loss.

Automation and monitoring systems

In modern building management, various technologies can be seamlessly integrated into building systems to achieve greater energy efficiency. Using smart meters, supermarkets can track electricity consumption at regular intervals throughout the day or in real time, enabling them to identify opportunities for optimization. Integrating such meters with building management systems can enable automated demand response programs, allowing utilities and building systems to communicate to dynamically manage electricity demand during periods. This also allows adjustment of energy-intensive activities based on peak and off-peak periods, price signals or grid conditions. Beyond energy savings, this promotes grid stability and reliability. Automation is in fact among the most sought-after technologies for supermarkets to adopt (box 4.2).

Calculation and comparisons of energy consumption is also useful for identifying the right refrigeration system. Off-the-shelf simulation tools are available to integrate load profiles and weather data to compare the performance of different refrigeration systems and configurations. Other innovations enable multiple appliances in supermarkets to be monitored and managed through an internet of things (IoT)-based solution that collect data from appliances. Supermarket kitchen equipment such as vent hoods equipped with sensors can save energy by detecting when the stove is in use, to avoid sucking out dry air throughout the day.

Box 4.2 Supermarket readiness to adopt new technologies

Supermarkets are surprisingly keen on adopting new technologies, as evident from a 2023 market report that surveyed more than 130 grocery industry professionals. While climate technologies were not specifically addressed, all respondents indicated that technology will be at least somewhat important for the future of retail, and expressed an intention to invest in the year to follow. Peer recommendations and existing vendors are prioritized, indicating a challenge for climate tech startups to introduce their products to the sector. In fact, 58 percent suggested that industry peers and networking are the main resources when looking for technologies. The adoption of most new technologies is driven by chain retailers. Further, the most sought-after technologies are those that enhance operational efficiencies through for instance automation, which often goes hand-in-hand with energy efficiency (Supermarket News Intelligence, 2023).

Innovation examples

Energy-efficient refrigeration systems in Jordan

Source: UNIDO

A supermarket in Jordan, with the support of the United Nations Industrial Development Organization (UNIDO) and the Ministry of Environment in Jordan, installed a transcritical CO_2 refrigeration system to demonstrate the feasibility of such systems in high temperature environments. The Al Salam military supermarket in Amman was the first in its region to install this technology in 2018, using a system supplied by Italian manufacturer Enex Srl. In addition to avoiding climate-hazardous refrigerants, the CO_2 refrigeration system was more energy efficient than the previously used conventional system using HFCH-22 refrigerant. A state-of-the-art ejector technology was integrated to ensure high efficiency during warm summer months. Also known as a jet pump, the ejector is a device that can use energy in a high-pressure refrigerant to compress a low-pressure refrigerant, increasing overall efficiency (UNIDO, 2024a).

Solar at South Africa’s largest retailer

Source: Shoprite Holdings

The Shoprite Group, South Africa’s largest retailer with over 2,900 stores in 11 African countries, is making use of solar energy to cut operational costs. Given that South Africa’s energy grid is predominantly coal-powered, the installation of solar systems at on-site and off-site locations offers a good option for low-carbon energy supply. In 2022, solar systems had been installed at over 60 sites in South Africa and beyond, with a total installed capacity of 26.6 MW (Shoprite, 2022).

Technology solutions

Proven

Energy efficiency: retrofitting refrigerator doors
Koolmax Group

Source: Getty Images/Михаил Руденко

The simple switch from open to closed refrigerator cases at supermarkets have shown to have a tremendous impact on energy efficiency. Rather than replacing the entire system, technology and service providers can be identified to retrofit doors onto existing display cabinets. Koolmax Group offers several designs of double glazed hinged or sliding doors that can be retrofitted onto existing cabinets.

- Contracting type: For sale
- Technology level: Low
- Country of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: low-E glass doors
Loreco System

Source: Getty Images/Hitra

Low-E glass doors can enhance energy efficiency in supermarkets as they reduce heat transfer, helping to maintain cold temperatures inside refrigeration cabinets. This special type of glass has a coating that blocks infrared and ultraviolet light while letting in visible light, which keeps the temperature more stable and results in lower energy costs. Additionally, these doors are less prone to condensation, avoiding moisture build-up and making them easier to maintain.

- Contracting type: For sale
- Technology level: Low
- Country of origin: Spain
- Availability: Spain
- Contact: WIPO GREEN Database

Energy efficiency: transcritical CO2 refrigeration
SCM Frigo

Source: Getty Images/alacatr

SCM Frigo, an Italian manufacturer that specializes in refrigeration technologies based on the natural refrigerant CO_2 has recently introduced a new line of transcritical CO_2 booster systems for commercial use. The technology can be adapted with optional heat recovery as well as energy meters, and works in all climates due to a dynamic vapor injection technology which helps handle gases that typically weaken transcritical refrigeration systems.

- Contracting type: For sale
- Technology level: High
- Country of origin: Italy
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: transcritical CO2 refrigeration
Arneg Andina

Source: Arneg

Arneg offers different kinds of transcritical CO_2 refrigeration systems for grocery stores of all sizes: the Globo, Globo+, Mini Booster, Booster and Booster XL. The standard systems are suitable for all climates, while those with an adiabatic post-cooler are designed for hotter climates. The other systems, either having a parallel compressor or a parallel ejector and compressor, optimize energy performance through different mechanics to address varying needs for reducing energy use. The systems also come with optional accessories for recovering waste heat or producing cold water to use in other applications in the store, such as in the HVAC system.

- Contracting type: For sale
- Technology level: High
- Country of origin: Colombia
- Availability: Latin America
- Contact: WIPO GREEN Database

Energy efficiency: compact transcritical CO2 system for smaller supermarkets
Advansor

Source: Advansor

For smaller supermarkets with limited space, Advansor offers a line of compact transcritical CO_2 refrigeration system units. They are the Value Pack (VP), VP Light, VP II and the Minibooster. At their upper ranges, these systems deliver medium temperature cooling capacities between 45 kW and 136 kW. Additionally, all systems come with optional accessories allowing for functions such as waste heat recovery.

- Contracting type: For sale
- Technology level: High
- Country of origin: Denmark
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: destratification fans
Airius

Source: Airius

Conventional heating and cooling systems can lead to an uneven temperature distribution in supermarkets and stores, leading to warm air rising to the ceiling and cooler air settling at surface level – so-called stratification. This exerts extra pressure on the heating and cooling systems, leading to unnecessary losses. Destratification fans support air circulation in stores, providing a more consistent temperature and saving in HVAC energy costs. Company Airius provides a wide range of fans, with a specific series relevant for grocery stores.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy supply: solar-powered cold storage units
ColdHubs

Source: ColdHub

Solar-powered cold storage units are critical for avoiding food waste in many markets and farms. The technology is particularly relevant in rural regions in developing countries where temperatures soar high, and off-grid locations create challenging conditions for food retailers. However, urban markets can also benefit from adopting the technology to store food and reduce waste.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Nigeria
- Availability: Nigeria
- Contact: WIPO GREEN Database

Energy efficiency: adiabatic subcooler for supermarket refrigeration systems
MITA Cooling Technologies

Source: MITA Cooling Technologies

To boost the efficiency of CO_2 or natural refrigerant systems, MITA Cooling Technologies offers patented adiabatic subcoolers. These subcoolers can be installed in supermarket to increase efficiency without major system changes. They are plug-and-play solutions that are added downstream of the condenser or gas cooler in CO_2 chillers. In addition to energy savings, the coolers include functions such as a software for calculating return on investment as well as a compact, modular design with simple maintenance.

- Contracting type: For sale
- Technology level: High
- Country of origin: Italy
- Availability: Italy
- Contact: WIPO GREEN Database

Energy efficiency: daylighting in supermarkets
Sundowner Skylights

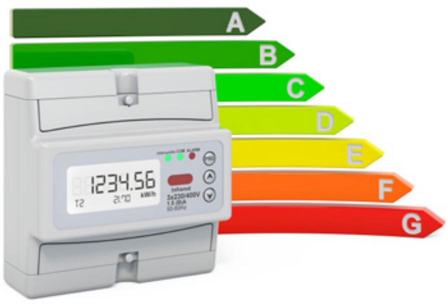
Source: Getty Images/beekeepx

Supermarkets can reduce their energy use and costs by installing light-capturing domes on their roofs. The Tube Skylights from Sundowner Skylights funnel sunlight directly into the indoor environment through these domes. They come with a range of diffusers to adjust for desired intensity, a built-in lamp for nighttime illumination, and an optional attachable ring to turn the light off. The skylights are compatible with a wide selection of roof types, including corrugated iron or cement tiles.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: South Africa
- Availability: South Africa
- Contact: WIPO GREEN Database

Frontier

Energy efficiency: simulation tool for refrigeration systems
IPU



Source: Getty Images/AlexLMX

Pack Calculation Pro is a simulation tool for calculating and comparing the yearly consumption of refrigeration systems and heat pumps. The tools use load profiles and weather data to compare the performance of different refrigeration systems and their configurations.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Denmark
- Availability: Denmark
- Contact: WIPO GREEN Database

Energy efficiency: real-time monitoring of energy consumption
Memoco

Source: Getty Images/MartinPrescott

Memoco's Energy Box has been designed to reduce energy costs in the retail sector, by giving energy operators an insight into real-time energy consumption in the shops via a web interface. The Box is also provided via a leasing agreement where the cost is recovered through the energy and cost savings made by the store.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Belgium
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: wireless sensors for supermarket temperature monitoring
Ruuvi

Source: Ruuvi

RuuviTag is a wireless thermometer designed for use in grocery stores and supermarkets. It allows users to monitor temperature, manage cooling and heating systems, receive alerts and review past temperature data. The device supports remote monitoring through the Ruuvi Gateway and Cloud service, providing flexibility in overseeing temperature conditions.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Finland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: integrated refrigeration, air conditioning and heating unit for supermarkets
Daikin

Source: Daiki

Daikin's Conveni-Pack system is an innovative solution tailored for supermarkets, combining refrigeration, cooling, heating and ventilation into one compact unit. Utilizing CO_2 as a natural refrigerant with a GWP of just 1, the system is highly energy-efficient and environmentally friendly. Its CO_2-specific swing compressor boosts energy efficiency by 5 to 15 percent and extends the compressor's lifespan. The Conveni-Pack is flexible in installation, space-saving and operates quietly, making it suitable for supermarket environments.

- Contracting type: For sale
- Technology level: High
- Country of origin: Japan
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: heat recovery from refrigeration installations
Danfoss A/S

Source: Getty Images/Sheikoevgeniya

Heat is typically a by-product of refrigeration processes. By recovering this heat, supermarkets can reduce their CO_2 footprint and grid-energy consumption. Danfoss offers the Heat Recovery Unit, a combined CO_2 refrigeration and water heating system that captures waste heat from the cooling process to meet the supermarket's space and water heating needs. Excess heat can also be sold to the local district heating system.

- Contracting type: For sale/service
- Technology level: High
- Country of origin: Denmark
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: actively cooled refrigerated and frozen containers for last-mile delivery
Phononic

Source: Phononic

Phononic has developed actively cooled and temperature-sensitive tote freezers and refrigerators which use CO_2 as a natural refrigerant. The totes use wireless contact charging and real-time temperature insights, enabling better transportation of perishable goods for grocery stores that have adopted e-commerce. For instance, data can be used to manage demand-based energy savings by only cooling or freezing the number of customer orders needed rather than an entire cooler or transport truck.

- Contracting type: For sale
- Technology level: High
- Country of origin: United States
- Availability: Puerto Rico, United States
- Contact: WIPO GREEN Database

Energy efficiency: ultra-low superheat module for supermarket refrigeration system
Advansor

Source: Advansor

Advansor's Ultra-Low Superheat Module enhances supermarkets' refrigeration efficiency by allowing the cooling units to operate at higher temperatures without causing them to overflow with refrigerant, using less energy. The module includes three main components: a suction accumulator, an internal heat exchanger, and an optional ejector. The suction accumulator captures any returning liquid from the units and separates it from the gas. The internal heat exchanger then evaporates and superheats the gas and liquid CO_2 from the accumulator, while also cooling the liquid line. This leads to energy savings of up to 30 percent with a two-year payback time.

- Contracting type: For sale
- Technology level: High
- Country of origin: Denmark
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: demand control kitchen ventilation
Melink Corporation

Source: Melink Corporation

Kitchen hood fans typically waste energy by operating either at full capacity or not at all, and they also expel air that has already been heated or cooled at a cost. Demand-control kitchen ventilation systems address this inefficiency by retrofitting hood fans with advanced controls that automatically adjust the fan speed based on the cooking activity. This technology lowers energy bills, creates a more comfortable environment for staff and customers, and reduces the need for “make-up air” the fresh air that replaces the exhausted air.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon

Energy efficiency: integrated IoT-based data monitoring and management for supermarkets
Tietoevry

Source: Tietoevr

Tietoevry is a Finnish IT software and service company that has piloted a solution to harness the power of data for energy efficiency in a supermarket. In collaboration with retailer REWE Austria, Tietoevry transformed a store in Austria into an energy-efficient “Supermarket of the Future” by leveraging data integration. The project focused on gathering data from various store appliances, which were previously unconnected, to optimize energy use and maintenance processes. Tietoevry developed an IoT-based solution that collects and analyzes the data, presented through a user-friendly dashboard on Microsoft’s Azure platform. This system not only simplified store management but also reduced energy and maintenance costs by up to 25 percent.

- Contracting type: For service
- Technology level: High

- Country of origin: Finland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: Smart energy management tool for supermarket distribution centers

Star Refrigeration

Source: Star Refrigeratio

Star Refrigeration and the UK's largest supermarket chain, Tesco, joined forces in trialing the Ethos system, an AI-driven monitoring and performance optimization system, at eight of Tesco's supermarket distribution centers for 21 months. This achieved an average cut of 10% in energy use, corresponding to a total of 4 GWh of energy savings and an 835 tonne reduction in CO_2 emissions. The Ethos system gathers and analyzes data from heating and cooling equipment to generate a cloud-based digital twin, which provides managers with detailed insights on system performance, inefficiencies, trends, as well as recommended corrective measures coupled with estimated financial and CO_2 savings. The continuous monitoring and resulting insights also help with maximizing the operational lifetimes of Tesco's refrigeration plants, further minimizing costs.

- Contracting type: For service
- Technology level: High
- Country of origin: United Kingdom
- Availability: United Kingdom
- Contact: WIPO GREEN Database

Energy efficiency: Quantum computing in grocery optimization

D-Wave Quantum Inc.

Source: D-Wave Quantum Inc

In grocery retail, quantum computers can help minimize waste and carbon footprint by optimizing tasks like product placement, efficient resource use, and delivery of perishable goods. D-Wave is a quantum computing company offering a full-stack technology solution, including systems, cloud services, development tools, and professional services to benefit business and society. They help businesses identify and solve problems that benefit from hybrid quantum technologies, providing online training, professional services, and access to the Leap quantum cloud. Save-On-Foods, a leading grocery retailer in Western Canada, is piloting innovative grocery optimization solutions in their business by leveraging D-Wave hybrid quantum algorithms. A key optimization task is now being completed in just 2 minutes each week—a task that previously took 25 hours. D-Wave is exploring quantum computing applications in various fields, including optimization problems relevant to energy management and refrigeration systems.

- Contracting type: Under development
- Technology level: High
- Country of origin: Canada
- Availability: N/A
- Contact: WIPO GREEN Database

Energy efficiency: Device for energy-efficient refrigeration cabinets
Aerofoil Energy

Source: Getty Images/Andrii Atanov

Aerofoil Energy is a technology company supplying energy solutions to grocery retailers worldwide by transforming the performance of display refrigeration, reducing energy consumption and associated emissions. Jetseal is Aerofoil Energy's latest innovation in green-retrofit technology, designed to enhance the energy efficiency of refrigerated cabinets with doors. After thorough research, Aerofoil Energy identified why these cabinets often underperform in energy savings and developed Jetseal to tackle a key issue: warm air leakage through door gaps. Retailers implementing Jetseal in their refrigerated cabinets can anticipate a return on investment in under a year. This technology works by harnessing the fridge's own cold air flow to effectively block warm air from entering through the door gaps, thereby creating a more efficient thermal barrier. Currently undergoing trials with several international grocery chains across the USA and Europe, Jetseal delivers an additional 15-25% energy savings. It is entirely passive and maintenance-free, and replaces door wiper seals for better merchandising and hygiene. It is quick and easy to install, even during store operating hours.

- Contracting type: Under development
- Technology level: High
- Country of origin: United Kingdom
- Availability: N/A
- Contact: WIPO GREEN Database

Green energy solutions for health care facilities

Health care facilities play a vital role in patient care. While health-care delivery remains a priority, there is growing awareness of the environmental and climate impact of the facilities' essential functions like heating, cooling, lighting and waste management. These functions determine health outcomes beyond the facility level. At the same time, the always-on requirements of health care facilities heighten their vulnerability to extreme weather events which can disrupt health care services and damage infrastructure. This requires resilient energy infrastructure and back-up systems to safeguard health and protect lives.

Technological developments and trends

The health care sector's carbon footprint

The health care sector, constituting 10 percent of the world's gross domestic product, emits a significant amount of GHGs. If the global health care sector were a country, it would be the fifth-largest carbon emitter (Karliner *et al.*, 2019.; Leal Filho *et al.*, 2024). Emissions are produced during various activities of the sector, including product manufacturing and transport, daily operations and waste management. See box 4.3 for more information on health care spending and emissions.

If the global health care sector were a country, it would be the fifth-largest carbon emitter

Emissions from health care facilities themselves represent approximately 30 percent of the global health care sector's total carbon emissions. The other 70 percent are outside of the scope of this chapter and relate to emissions from the health-care supply chain, including production of pharmaceuticals, hospital equipment, textiles and food (Karliner et al., 2019).[1] While there are numerous building design principles that enable lower energy use for health care facilities, this chapter will focus on reducing carbon impact during their operational phase, through integration of renewable energy sources and use of energy-efficient technologies.

Hospitals have high energy-use intensity

Compared to other commercial building types such as schools and offices, hospitals have nearly three times higher energy-use intensity. More than half of the energy consumption is spent on HVAC (Delgado et al., 2021; McGain and Naylor, 2014). Lighting and energy-hungry medical machinery and IT equipment are another key area to decarbonize (Pichler et al., 2019), with medical equipment accounting for up to 20 to 30 percent of hospital's electricity consumption (McGain and Naylor, 2014).

Box 4.3 Strong correlation between health care spending and climate impact

Geographically, more than half of the sector's emissions stem from three regions alone: the United States, China and the European Union. While comparisons between countries are often uncertain, it is relevant to note that this regional imbalance remains consistent for per capita emissions; the US health sector produces 57 times more emissions per person than does India. However, there is a strong correlation between the amount of health care spending and the emissions from the sector, marking the important linkage between global sustainability goals such as universal health coverage and climate targets (Karliner et al., 2019).

Global initiatives for green hospitals

Public buildings can be forerunners in the energy transition. We are already aware of the very damaging impacts of climate change on human health across the world, with for instance 37 percent of heat-related deaths being attributed to climate change (Vicedo-Cabrera *et al.*, 2021). It is therefore within the very mandate of the health care sector to not only provide care to the victims of climate change impact, but to engage fully in the low-carbon energy transition to prevent further harm.

1 Supply chain emissions are highly relevant and important to address, but for the sake of narrowing down the target group we have chosen to focus on the energy transition within health care facilities themselves.

Localized application of technology and innovation play a vital role in the energy transition of a hospital

In the European Union it will soon be mandatory for all but the smallest hospitals to disclose information on their energy and resource use through annual sustainability reports, and global organizations such as Healthcare Without Harm (HHWH) work directly with hospitals to reduce their negative impact on the environment. At COP26, the World Health Organization (WHO) launched the Alliance for Transformative Action on Climate and Health (ATACH) to build climate-resilient and sustainable health systems. While the climate footprint of a hospital is highly influenced by the emission intensity of the energy system in that country (Pichler et al., 2019), localized application of technology and innovation still play a vital role in the energy transition.

Air quality and humidity a primary concern in hospitals

Maintained and properly designed ventilation systems are critical in hospitals, given the risk of hospital-acquired infections and the direct relationship between certain air pollutants and health problems (Delgado et al., 2021). Often, the design of such systems is determined by stringent standards and guidelines such as minimum ventilation rates proposed by the WHO (Rahman et al., 2021). Systems must also be able to adapt ventilation settings to various rooms for critical care patients, operating rooms, physical therapy rooms and other procedures (Delgado et al., 2021). But technological advances have enabled better use of energy without compromising patient care.

Debate persists regarding the optimal humidity levels in hospitals, and their connection to airborne viruses. Several technologies offer efficient solutions for maintaining both high and low humidity levels. For instance, to avoid high humidity levels, a double heat pipe heat exchanger system is recommended over conventional heat exchangers. This not only reduces the risk of fungal growth but also reduces energy consumption (Ghani et al., 2018).

Adaptive and demand-controlled ventilation

Hospital ventilation is often left running continuously, including within unoccupied areas of the hospital overnight (McGain and Naylor, 2014). An HVAC solution which can help minimize ventilation's energy consumption is adaptive variable air volume (VAV) systems. Traditional VAV systems installed in hospital rooms often operate at a constant air volume. Adaptive VAV control systems adjust the volume of airflow to different zones or areas depending on the heating or cooling needs, thereby enhancing energy efficiency. The adjustment is based on parameters such as occupancy level or temperature variations.

Box 4.4 Enabling natural ventilation

Natural ventilation in health care facilities, building on principles such as the stack effect or wind-driven ventilation, offers a connection to the natural environment for patients and saves energy on mechanical ventilation. There is a concern that natural ventilation would be insufficient, or that non-filtered outside air would include contaminants (Delgado et al., 2021). However, studies have also shown that naturally ventilated hospital wards can in fact achieve even higher ventilation rates than for mechanical ventilation, but that the airflow patterns and pressure differences may be harder to control (Qian et al., 2010). For times when natural ventilation rates are low or outside temperatures are unfavorable, natural ventilation could be combined with mechanical ventilation. Advanced hybrid ventilation systems include intelligent controls to manage thermal comfort and energy consumption. Ventilation air can also be pre-cooled through earth tubes or thermal labyrinth technologies.

Ventilation can also be further optimized in real time. Demand-controlled ventilation adjusts ventilation rates based on real-time demand and makes use of sensors to monitor factors such as CO_2 levels, humidity or occupancy level. Further energy savings could be made by retrieving heat or coolness from exhaust air and transferring it to incoming fresh air, through energy recovery ventilation systems, or by making use of natural ventilation (box 4.4).

Heating and cooling consume half of hospitals energy

Improving air conditioning systems is often the most direct and effective way to save energy in health care facilities (Ji and Qu, 2019). Refrigeration and air conditioning can account for about 40 percent of hospital's total electricity consumption (Rahman et al., 2021). Efficient air conditioners only use half as much energy as the average ones on the market, meaning that the mitigation potential is significant. Traditionally, hospitals have often relied on a combination of chillers and boilers that are dependent on on-site fossil fuel combustion. Heat pump systems run on electricity and tend to be more energy-efficient than conventional heating and cooling. Heat pumps are key technologies in the energy transition with a potential to significantly reduce hospital's energy cost.

The integration between heat pumps and solar energy, such as a solar PV or solar thermal heat pump system, has great potential to save both energy and enable renewable energy integration (Rahman et al., 2021). In addition to electricity, the solar PV panels produce heat that can be absorbed by heat collectors and reused for heating and cooling purposes. Some hospitals opt for ground source heat pumps (also called geothermal heat pumps), such as the Queen's Medical Centre in the United Kingdom. While expensive up-front, the technology is expected to reduce the hospital's GHG emissions by 30 percent by replacing a gas-fired heating system (Phipps, 2023).

Innovations such as solar absorption chillers, air curtains and variable refrigerant flow (VRF) systems – which circulate only the minimum amount of refrigerant needed during a single heating or cooling period – are also gaining acceptance in the health care market. While VRF systems are helpful in controlling the temperature for individual spaces and are useful for smaller health care facilities, chillers can be more advantageous for larger hospitals (LG, 2022). Another innovation involves making use of ice; capturing waste cold and embracing thermal storage methods like ice or snow "thermal batteries" in order to provide cooling. Carbon emissions can be mitigated by creating ice during low load times, and using the ice for cooling during peak energy load times (where usually more carbon-intensive fuels are used) (K-CEP, 2018).

Optimizing medical freezers and laboratory refrigerators

Health care facilities rely on laboratory fridges and medical freezers to store samples, medicines and vaccines. Medical deep freezers, or ultra-low temperature (ULT) freezers that go as low as minus 80 degrees Celsius, are particularly energy-consuming, especially as they age. Their market expanded substantially due to the enormous vaccine storage need brought on by the COVID-19 pandemic (Udroiu et al., 2022).

Advances in refrigeration technology for health care facilities means more energy-saving alternatives are available on the market today. Energy-efficient cascade refrigeration systems, better cooling processors, air circulation systems and advanced microprocessor controls for temperature monitoring all contribute to reducing the energy footprint in this area. Furthermore, old freezer models generate more heat to the surrounding room. Replacing them therefore has the bonus of reducing the need for AC, resulting in further energy savings.

Addressing the challenge of 24/7 lighting needs

Health care facilities often require round-the-clock lighting, 365 days a year. Each area of a hospital has its own lighting design needs and requirements with regard to intensity and color. Commonly used fluorescent light tubes are not energy efficient, and also contain traces of mercury. LEDs can reduce energy usage by up to 70 percent (Aghajari and Chen, 2023) and for certain functions, such as surgical lighting fixtures, LED lighting has now become the industry standard (PAHO, 2020). Technological developments have led to a diverse range of products and features.

One development is the ability to integrate LEDs with building automation systems. Sensors and IoT integration for adaptive and automated lighting controls are starting to become increasingly relevant for accommodating various lighting needs at different points of the day. Also called luminaire level lighting controls, such data-supported and connected lighting products are gaining in popularity in the health care space (Lorenzi, 2022). LED light fixtures can even adapt to a patient's care schedule.

Such adaptive lighting settings may have joint benefits with regard to energy savings, patient care and staff productivity if designed effectively. For instance, rooms may often be more brightly lit than necessary. Studies suggest that very low illuminance (5–60 lx) warm lighting is ideal for night-time conditions in patient rooms and that moderate illuminance (60–300 lx) with high intensity in the red spectrum is more suitable for non-patient areas at night. This so that night shift workers' circadian rhythms (determining our sleep–wake cycles) are not interrupted, enabling them to remain alert (Delgado et al., 2021).

Possibilities for daylighting, meaning the use of natural light, often depend on the design and positioning of the building and rooms. In addition to reducing electrical lighting needs and save energy, daylighting can have important benefits for patient recovery due to its ability to regulate circadian rhythms. In fact, patients located in rooms with greater exposure to daylight are likely to recover more quickly and with less medication (Park et al., 2018).

Technology can help enhance or optimize the impact of daylighting while saving energy. Adaptive glazing technology or window treatment such as low-E films help control glare and excessive solar heat gain, consequently regulating energy use for cooling (Sadek and Mahrous, 2018). In new buildings, fiber-optic cables can be installed to channel sunlight into spaces which would normally not receive natural light. However, in terms of energy-efficiency, such solutions should be compared with LED options which are cheaper and easier to install.

Energy-efficient medical equipment

Energy-efficiency is perhaps not considered a priority when designing medical equipment and machinery for patient monitoring, diagnostics and X-rays. Yet, there have been some important technological advances. This is significant, as medical imaging equipment alone accounts for 5 percent of health care facilities' total energy use. Magnetic resonance imaging (MRI) units, in particular, offer an opportunity for significant energy savings as they are highly energy consuming and up to 40 percent of their energy is consumed when they are not being used during nights and weekends (DOE, 2023).

MRI units are highly energy consuming and up to 40 percent of their energy is consumed when they are not being used during nights and weekends

Innovative MRI units are now on the market using intelligent magnet technology, built-in sleep mode and reduced scan times that contribute to energy conservation. Remaining measures like replacing cathode ray tube monitors with liquid crystal display monitors that use less energy may be small in impact but add up in numbers. Adopting energy-efficient medical equipment is crucial, as it may also be the determining factor for whether health care facilities can rely completely on solar energy or not.

Managing energy consumed by plugged-in devices

A surprising amount of energy can be saved by avoiding electricity "leaks" in machines and appliances and optimizing their use. Plug loads, meaning energy that is consumed by equipment in stand-by mode that is plugged into an outlet, consume a significant portion of energy in hospitals. The expected load can be difficult to predict and manage, sometimes leading to oversized electrical circuits and poorly designed HVAC systems.

New technology areas like learning behavior algorithms and automatic load detection could result in more efficient electricity delivery and use, but further work is needed to scale such solutions on the market (Trenbath and Doherty, 2019). Meanwhile, more can be done about leaks and standby electricity use. Standby electricity consumption can account to up to 90 percent of total energy consumption of medical equipment (Jensen and Petersen, 2011).

Smart power strips with automatic shutoff functions are commonplace alternatives to at least help avoid phantom leaks from plugged-in devices. However, such measures need to be implemented in a way that does not jeopardize the health and safety of patients, as some devices cannot easily be turned off in a hospital environment due to complicated recalibration settings.

Decentralization enables energy security and renewable energy integration

In order for energy to be decarbonized and used efficiently, it must first be made available. But in fact, close to 1 billion people in low- and lower middle-income countries are served by health care facilities without electricity access or with unreliable electricity. In sub-Saharan Africa, only half of hospitals have access to reliable electricity (WHO, 2023). Technologies that support decentralized energy generation can address both energy access and energy security needs.

Close to 1 billion people in low- and lower middle-income countries are served by health care facilities without electricity access or with unreliable electricity

The main cause of power outages in the electric grid are extreme weather events and natural disasters (Ali et al., 2023). Decentralized energy and back-up systems have always been crucial for hospitals, as they rely on a steady power generation for many critical care-giving functions. Technologies that strengthen energy security are particularly needed in countries experiencing frequent extreme weather events, aging infrastructure, power outages and other disturbances.

Traditionally, on-site energy and back-up systems have been based on fossil fuels. Diesel generators connected to the utility electric grid are less expensive up-front and are the most common form of back-up energy in hospitals. However, where the integration of renewable energy in the grid is slow, several hospitals are moving toward hybrid renewable energy systems to improve the quality and reduce the energy cost of power supply. Advances in solar PVs, batteries and modularity make such systems easier and more affordable for hospitals to adopt (SEforALL, 2024). For instance, in Zimbabwe, more than 400 health centers have installed solar arrays through a United Nations Development Programme (UNDP) initiative, and in South Africa the private health system Netcare provides 10 MW of power through solar panels (Karliner et al., 2019).

Mini-grids and cogeneration

Among mini-grid options, the trend appears to favor hybrid mini-grids over solar mini-grids (SEforALL, 2024). New-generation mini-grid systems are often solar hybrid systems with smart meters and remote monitoring systems. A number of facilities have also adopted on-site cogeneration, or combined heat and power (CHP) plants, which are seen as an effective way to convert energy. Usually driven by gas turbines, systems can also be designed to integrate grid-connected PV, biomass and batteries (Peirow et al., 2022).

Technological advances have further enabled the combination of fuel cells and CHP systems, which can be particularly relevant for reducing emissions in countries that rely on coal-fired power (Olabi et al., 2020). CHP plants capture waste heat from electricity generation and use it to generate steam for heating and cooling. While they have high capital costs and must be configured to enable back-up capabilities, cogeneration can have reasonable payback times and is particularly ideal for hospitals which require continuous electricity and heat (Johnson, 2010).

Innovation examples

The impact of LED replacements in hospitals

Source: Getty Images/EvgeniyShkolenko

Upgrading from compact fluorescent lamps (CFLs) to LEDs in hospitals presents significant energy-saving opportunities. St. Anthony Hospital (Gig Harbor, Washington, United States) replaced 1,262 CFLs with LED lamps, resulting in a more than 50 percent reduction in energy usage. The LED replacements fit into existing CFL sockets, maintained compatibility with electronic ballasts, and improved lighting quality with consistent color temperature and better rendering of saturated colors. The hospital's calculated return on investment was 26.3 percent, with an estimated annual energy savings of 131,279 kWh and USD 10,424 in cost savings. With a utility rebate, the project achieved a simple payback period of less than three years (Pacific Northwest National Laboratory, 2015).

Energy-saving measures at Egyptian hospital reduced energy consumption by 20 percent

Source: Shefaa Al-Orman Oncology Hospital

The Shefaa Al-Orman Oncology Hospital in Egypt, as a member of the Global Green and Healthy Hospitals (GGHH) initiative, has implemented an ambitious energy efficiency program. In addition to staff awareness raising and training measures, the hospital invested in a number of technological solutions to reduce energy consumption. Changes in equipment included the installation of timers to operate fan coil units more efficiently, scheduling HVAC systems via a building management system, switch to LED lighting, standardization of temperature settings and incorporation of photocell sensors for external lighting. In total, the measures resulted in energy savings amounting to approximately 20 percent, operational cost savings of more than USD 20,000 and a reduction of more than 260 metric tonnes of CO_2 emission in a six-month period between 2022 and 2023 (GGHH, 2023).

Autoclave water and energy recovery at Somerset hospital in Cape Town

Source: Getty Images/MykolaSenyuk

Autoclaves are used by hospitals to produce steam from potable water; water which eventually ends up as waste. As the water remains both clean and hot throughout the process, there are significant opportunities for reusing it. An autoclave typically uses about 200 liters of water per cycle, which is eventually discharged as waste at about 40°C. The Somerset Hospital in Cape Town, South Africa installed a heat pump to address this challenge. Clean water is captured through a so-called "Jo-Jo tank" and cooled using a water-to-water heat pump. The cooled water is then pumped back to the autoclave. This installation has resulted in not only water savings but the production of 6,000 liters daily of domestic hot water from waste heat from the autoclaves. Cost savings have amounted to approximately USD 15,750 per year, with a two-year payback period. Roll-out to nearby hospitals is currently underway.

Technology solutions

Proven

Space heating and cooling: biomass boilers in hospitals
Lasian

Source: Getty Images/imantsu

Biomass boilers have been adopted by several hospitals as a more low-carbon alternative to conventional fossil fuel-based heating systems. These boilers burn organic materials such as wood pellets, wood chips or other biological waste products to generate heat. Lasian offers a range of domestic and industrial biomass boilers of varying sizes that work with wood pellets, firewood and even olive pits and almond shells, which have a low ash content.

– Contracting type: For sale
– Technology level: Medium
– Country of origin: Spain
– Availability: European Union
– Contact: WIPO GREEN Database

Space heating and cooling: condensing boilers in hospitals

AERCO

Source: Getty Images/imantsu

Boilers are required in hospitals for various heating needs such as sterilization, laundry and heating of buildings. As the majority of hospital boilers rely on fossil fuels, alternatives that integrate renewable energy as well as reduce energy consumption are crucial for the energy transition. Condensing boilers are a boiler type that are designed to be more efficient by capturing and reusing heat that would otherwise be lost through a heat exchanger. AERCO's Benchmark condensing boilers also feature a patented combustion technology that continuously monitors boiling conditions and automatically adjusts combustion processes to maintain ideal oxygen levels and improve system efficiency.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Space heating and cooling: automatic blowdown controls

Trilan Energy

Source: Getty Images/surasak petchang

Large health care facilities may need industrial steam boilers to cater to their various needs. In a boiler, so-called blowdown can control the build-up of solids in boiler water, protecting the boiler's surface and improving heat transfer. Often, blowdown is not optimized, which leads to unnecessary energy loss. Trilan Energy provides installation of automatic blowdown controls in industrial steam boilers to continuously monitor boiler water conductivity and ensure that the blowdown rate is appropriate.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: India
- Availability: Worldwide
- Contact: WIPO GREEN Database

Space heating and cooling: air pre-heater for boiler combustion air

Thermodyne

Source: Getty Images/Dmytro Kudnietsov

Thermodyne supplies air pre-heaters which can be used to pre-heat air before it is supplied to the boiler for fuel combustion. This increases combustion temperatures, which leads to more complete and efficient fuel combustion and lower emissions. The heat exchanger heats the incoming combustion air using heat recovered from the boiler's fuel gases.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: India
- Availability: India
- Contact: WIPO GREEN Database

Lighting: LED surgical lighting

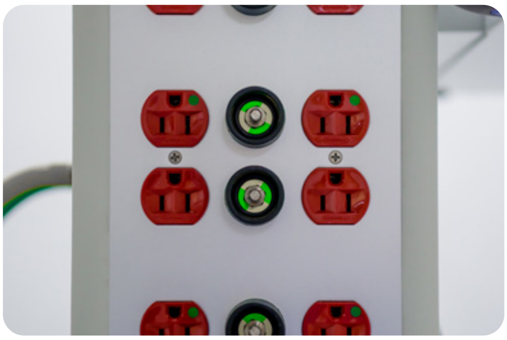
STERIS

Source: Getty Images/MDV Edwards

Operating rooms require bright lighting with minimal heat loss for both comfort and practicality, making LED surgical lighting systems and headlamps suitable as they can emit intense white light while emitting low amounts of heat. STERIS's new lighting system, the HarmonyAIR G-series, uses 70 percent less energy in comparison to previous LED technologies, with a heat-to-light ratio of 3.4.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Machines and appliances: medical grade power strips
Leviton



Source: Getty Images/Elis-Blanca

For powering medical equipment in health care facilities, medical grade power strips may be required. Levinton provides such power strips featuring Inform™ Technology – LED indicators which enable real-time monitoring of the load imposed by connected devices, for protection against excess power draw and for compliance with safety regulations. The power strips are also available with surge protection which protects any connected device from damaging voltage spikes.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Machines and appliances: energy-efficient medical freezers
Meling Biomedical

Source: Meling Biomedica

The ULT freezers from Meling Biomedical can reach down to –181°C and work with dual compressors to ensure stability in case one would fail. This makes them suitable for medical and lab applications where freezers that can hold stable conditions over a wide range of temperatures are required. These freezers cool with an energy-saving auto-cascade system, using two different refrigerants and dual compressors to reach low temperatures quickly.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Machines and appliances: energy-efficient autoclaves
Consolidated Sterilizer Systems

Source: Getty Images/grafvision

Autoclaves utilize steam and variations in pressure to disinfect equipment for health care facilities. The medical autoclaves from Consolidated Sterilizer Systems come with several energy- and water-saving features, including software to schedule startup and shutdown, and automatic temperature regulation between cycles. Energy is saved both during the autoclave's use phase and because of minimized heat losses to the surrounding environment.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Machines and appliances: energy-saving mini cold storage unit
Ningbo Juxin ULT-Low Temperature Technology Co., Ltd.

Source: Ningbo Juxin ULT-Low Temperature Technology Co., Ltd.

The Ruibao Platinum Portable ULT Cold Chain Box leverages advanced military-grade Stirling refrigeration technology, functioning as a compact and mobile mini cold storage unit. Designed for versatility, this product is ideal for a range of applications, including ULT storage and transport for laboratories, pharmaceutical cold chain logistics, biological sample preservation and transport and life sciences cold chain operations. Key features of the Ruibao Platinum Cold Chain Box include its broad temperature range compatibility, precise temperature control, high energy efficiency, and a lightweight, compact design.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Frontier

Space heating and cooling: temperature monitoring sensors for hospitals
E-Control Systems

Source: Getty Images/hxdbzxy

E-control Systems offers temperature monitoring and data management solutions designed specifically for hospitals. The system uses wireless sensors placed in key areas to continuously collect data on temperature, humidity and pressure. The data are analyzed in real time, allowing for immediate alerts if a reading falls outside acceptable ranges. In addition to enabling energy savings by avoiding excess heating and cooling, the solution helps hospitals maintain optimal storage conditions for temperature-sensitive items.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: United States
- Contact: WIPO GREEN Database

Space heating and cooling: solar absorption chiller for hospitals, data centers and shopping malls
Hope Deepblue Air Conditioning Manufacture Corp., Ltd.

Source: Getty Images/Auttawit Jindaloung

In the context of air-conditioning and cooling, solar absorption refers to the use of captured solar heat using solar panels or collectors. The heat is then used to power a cooling cycle which drives a chemical process to create a cooling effect, resulting in chilled water which can be used to cool air or other spaces in buildings. Hope Deepblue Air Conditioning Manufacture Corp., Ltd. supplies a solar absorption chiller particularly suitable for hospitals, data centers and shopping malls.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Space heating and cooling: antimicrobial cooling towers

Delta Cooling Towers, Inc.

Source: Getty Images/primeimages

A cooling tower is a large structure used to cool down water by bringing it into contact with air. The cooled fluid is then reused to lower temperatures in for instance HVAC systems. Delta Cooling Towers, Inc. has developed an innovative cooling tower for hospitals that combines cooling with antimicrobial features, as they come with shells made of anti-microbial high-density polyethylene resin to inhibit bacterial growth. The design of the tower also reduces risk of *Legionella* bacteria colonization.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: United States
- Availability: United States
- Contact: WIPO GREEN Database

Lighting: intelligent lighting in hospitals

XAL

Source: Getty Images/izusek

In health care facilities, lighting is a major energy consumer. Advanced and intelligent lighting systems can enable smarter use of lighting by making sure it is only used when and where it is needed the most. XAL provides sensor-controlled lighting technology for hospitals that can lower energy costs by adjusting brightness based on room occupancy and activity levels. IoT-sensors can be further integrated to allow for analysis of indoor climate in order to connect with and optimize ventilation and air-conditioning use.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Austria
- Availability: Worldwide
- Contact: WIPO GREEN Database

Machines and appliances: energy-efficient MRI machines
GE Healthcare Technologies, Inc.

Source: Getty Images/nimon_t

MRI scanners require helium, a non-renewable resource, to cool the magnet to suitable working temperatures. GE Healthcare Technologies has developed the SIGNA™ 3T MRI scanner, which, compared to its predecessors, is stated to require 67 percent less helium and features a magnet that is 1.4 times more efficient. This increased efficiency translates into potential energy savings due to the reduced time required for scanning. Furthermore, the company offers retrofitting options for their scanners, enabling material savings through initiatives such as the SIGNA™ Continuum™ program.

- Contracting type: For sale
- Technology level: High
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy supply and storage: internet portal for monitoring of renewable energy integration
SMA Solar Technology

Source: SMA Solar Technology

Integrating solar and wind energy systems in hospitals is possible, but relies on a number of enabling technologies. For instance, the energy system may need to be monitored to understand its performance. The sunny WebBox is such a product that enables energy system monitoring, remote diagnostics, data storage and visualization. A large display unit with data of interest can be installed in the hospital foyer for the general public interested in knowing the amount of energy generated and carbon emissions avoided to date. While not reserved for hospitals, the Khayelitsha hospital in South Africa is an example of a hospital which has installed the system.

- Contracting type: For sale
- Technology level: Medium
- Country of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon

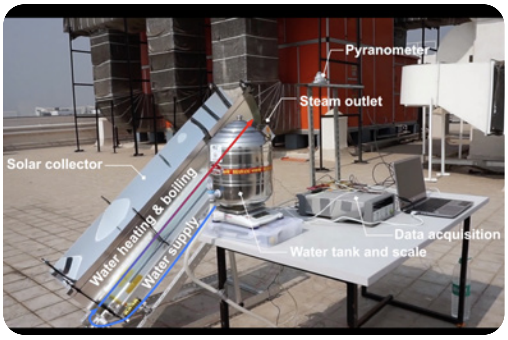
Energy supply and storage: hydrogen back-up for hospitals
EODev

Source: EODe

The GEH2® hydrogen genset, developed by EODev, provides a solution for continuous or back-up decarbonized electricity production. It delivers 100 kVa of clean energy with zero emissions of CO_2, NOx or fine particles, making it ideal for urban settings, hospitals and construction sites. The genset operates with low noise, no odors and immediate startup, and the thermal energy produced can be used for heating. While hydrogen storage is managed separately by the customer, distributors and partners assists in defining appropriate storage and supply solutions according to regulations.

- Contracting type: For sale
- Technology level: High
- Country of origin: France
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy supply and storage: solar-powered sterilization of medical equipment
Massachusetts Institute of Technology (MIT) and Indian Institute of Technology (IIT) Bombay

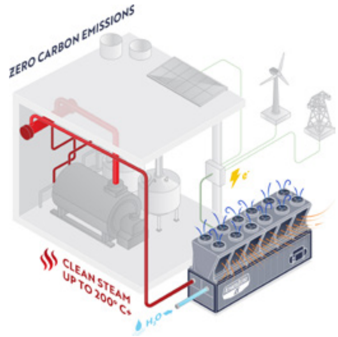


Source: Zhao et al. (2020) (https://doi.org/10.1016/j.joule.2020.10.007)

The use of solar thermal energy for autoclaves is not new and has been used since the 1970s (Ituna-Yudonago et al., 2021). In recent years, more innovators have been trying to find new and cost-effective designs suitable for rural health care purposes. Among them are researchers from MIT and IIT Bombay, who developed a novel solar-powered system that sterilizes medical tools, making it particularly valuable for regions lacking reliable energy sources. The system uses a portable solar energy collector and a transparent, thermally insulating aerogel to generate high-temperature, high-pressure steam, which drives a small-clinic autoclave. Unlike conventional solar-powered sterilization systems, this innovative design is entirely passive, with no moving parts, and offers high energy efficiency. While not commercialized yet, the system's simplicity, modularity and potential for low-cost mass production could make it an ideal solution for sterilizing medical equipment in remote areas.

- Contracting type: Under development
- Technology level: High
- Country of origin: United States and India
- Availability: N/A
- Contact: WIPO GREEN Database

Space heating and cooling: air-sourced electric boiler for decarbonized steam
AtmosZero



Source: AtmosZer

The Boiler 2.0 is a new alternative to combustion and electric resistive boilers with zero on-site emissions. It is a modular and drop-in heat pump solution, utilizing the heat in ambient air and electricity to generate up to 200°C steamwith a cascaded vapor compression cycle. The process has an efficiency of more than 100%, meaning that the output in heat energy is greater than the input of electrical energy. This contrasts with combustion boilers, which operate at lower efficiencies and emit pollutants that reduce local air quality. The Boiler 2.0 can be used in various applications and industries, with examples such as pasteurization in food processing, distillation in chemicals, or sterilization and heating in healthcare facilities. A 650-kW thermal installation will be tested at an American brewery in Q1 2025.

- Contracting type: Under development
- Technology level: High
- Country of origin: United States
- Availability: N/A
- Contact: WIPO GREEN Database

Energy smart data centers

Data centers, the backbone of our digital lives, are notorious for their substantial energy consumption and environmental impact. This chapter explores innovative climate solutions aimed at managing data centers’ power consumption, cooling and operations to mitigate their climate change impact.

Technological developments and trends

Data centers – climate friend or foe?

Whenever we scroll social media, send an email or use ChatGPT, servers in a data center are working behind the scenes to store and process the data. From small corners in an office building to hyperscale data centers, thousands of racks of equipment are in constant need of electricity and cooling. As artificial intelligence (AI), the gaming industry, the metaverse and other digital sectors expand, the demand for data is increasing. And as more and more servers must be cooled, the substantial water and energy consumption of data centers has become a serious concern (see box 4.5).

As more and more servers must be cooled, the substantial water and energy consumption of data centers has become a serious concern

In China, regulators have mandated the adoption of innovative energy-saving technologies and use of renewable energy sources for data centers (Ni et al., 2024). In the European Union, new energy and sustainability reporting requirements have recently been introduced for data centers (IEA, 2023c). And in the United States, lawmakers in several states have recently proposed more stringent requirements in terms of carbon emissions (Piedmont Environmental Council, 2024; ; Rogoway 2023)).

While AI is an important driver behind data centers' growing energy demand, it also offers promising new thermal cooling solutions for data centers that are ready to integrate AI into their own operations (Siemens, 2023). Google has reportedly reduced energy consumption for cooling at one of its data centers by 40 percent, using AI algorithms and machine learning (see innovation example). Data and AI are also integral to many modern climate solutions, enabling advancements in precision farming, weather forecasting, industry 4.0 and digitalization of the energy sector.

At the same time, the applicability of AI is broad, meaning it can contribute to driving up emissions in several ways. For instance, by enabling more fossil fuel exploration, or by simplifying the design of targeted digital ads toward consumers that ultimately increase consumption. The combined effect of such activities is not yet well researched, and as such the net climate impact of AI and data usage on climate change is largely uncertain (Kaack *et al*., 2020).

What we do know is that data and AI use is here to stay. Since 2010, the global number of internet users has more than doubled (IEA, 2023c). Technological innovations can help manage demand for data and support data centers in their energy transition. This chapter explores how; from on-site renewable energy generation to the adoption of energy-saving technologies and processes such as efficient cooling systems, server virtualization and power management measures.

Location of data centers impacts energy consumption

The energy demand from data centers is highly uneven across regions and countries. In Ireland, data centers are expected to consume nearly a third of the nation's electricity by 2028 (EirGrid). However, Ireland is also considered Europe's data center capital, hosting more than 80 data centers with another 50 underway. Globally, there are currently more than 8,000 data centers, with about 33 percent of these located in the United States, 16 percent in Europe and nearly 10 percent in China (IEA, 2024c).

Data centers risk causing grid congestion or impacting the availability of connection points for other users such as renewable energy parks

The number of data centers is relatively small in Africa. But grid and internet expansion is expected to cause the regional data center market to double in the next two years alone, presenting an opportunity to implement climate-smart and resilient solutions from the start (ADCA, 2024).

The geographical location of data centers plays an important role for their energy consumption and climate impact, with the local energy mix being a key determinant. Countries with a cool climate and secure supply of green electricity such as Canada and the Nordic countries are attracting cloud computing centers and hyperscale facilities, with major companies such as Google, Meta and Amazon having established facilities there in recent years (Payton, 2023). Varying prices on green electricity between countries is another important draw. Areas like Spain or California are similarly gaining traction for installation of data centers due to favorable electricity prices driven by their substantial renewable energy production capacities.

Moreover, the local climate plays an important role. Maintaining hardware and servers within recommended temperature and humidity guidelines is essential to avoid overheating and damage. Data centers in warm countries require more energy for cooling, which is why even locations such as the Arctic have become the subject of interest. The location also has an impact on the type of cooling technology used at a data center, with certain cooling techniques demanding specific geographical conditions such as cold outside temperatures or access to a lake, river or sea (see sections on cooling below).

Box 4.5 Energy and water consumption of data centers

A common assessment is that data centers and transmission networks account for 2 to 3 percent of global electricity consumption (Istrate et al., 2024; ; IEA, 2023c). The IEA also estimates that by 2026, electricity consumption from data centers, AI and the cryptocurrency sector could double, becoming roughly equivalent to the total electricity consumption of Japan(IEA, 2023c)..

Electricity demand in data centers is mainly driven by the servers and cooling systems, which each account for 40 percent of electricity use. The remaining 20 percent comes from other associated equipment such as storage devices and communication equipment (IEA, 2024c). To put the energy consumption of data into further context: a video on YouTube achieving viral success can consume the same amount of energy as heating thousands of homes (Mazzucato, 2024).

Water use is another challenge. An estimated 700,000 liters of water were potentially used to cool the machines that trained ChatGPT-3 at Microsoft’s data facilities, and total global demand for AI may be accountable for up to 6.6 billion cubic meters of water withdrawal in 2027. However, resource consumption numbers from data centers are often uncertain, owing to the secrecy of private companies that operate them (Li et al., 2023).

Finally, it is relevant to note that the location of data centers in turn can have an impact on grid efficiency and renewable energy deployment. As major energy consumers, data centers risk causing grid congestion or impacting the availability of connection points for other users such as renewable energy parks. However, smart planning can mitigate this challenge. Strong collaboration with electricity transmission system operators can enhance grid optimization and stability, by for instance co-locating data centers in nodes with high renewable energy production, allowing the centers to draw from these installations instead.

Energy-efficient hardware and software

Energy-efficient hardware and software can help data centers significantly reduce their power demand, as IT equipment such as servers, storage devices and networking equipment accounts for a significant amount of the energy consumption (Li et al., 2023). Standards and green labels such as the ASHRAE standards and the ENERGY STAR® label can guide data center operators in identifying IT equipment and servers that meet maximum operating temperatures and energy efficiency standards. In the European Union, a voluntary European Code of Conduct for Energy Efficiency Centres (Joint Research Centre et al., 2024) sets ambitious standards for companies willing to participate, but in the rest of the world efficiency measures are largely unregulated.

In addition to the hardware itself, IT accessories that can enable higher efficiencies and reduce energy loss include couplings, insulation and high-efficiency cable connectors designed to ensure a smooth flow of electricity and secure connections between cables.

Identifying energy-efficient software is more challenging, but forecasting and measurement tools for such purposes are being developed, and approximations can be drawn based on the power draw from hardware to achieve results. Writing more lean software codes and avoiding overly complicated codes are examples of energy-saving practices. Once methods for measuring power consumption of software are in place, programming language can be adapted to develop more energy-efficient software (Aalborg University, 2022). Software can also play a more active role in energy optimization, by enabling dynamic power management in data centers and making it easier to identify and analyze energy consumption in real time.

Furthermore, significant energy could be saved through advanced power semiconductors and other innovations that help enable high data processing performance. New materials such as gallium nitride (GaN) are being explored in semiconductors to increase efficiency and power density in data centers (White, 2023).

Virtualization and load balancing enhances both energy efficiency and climate resilience

A data center runs on multiple hardware and server configurations. Virtualization is a technology that allows data centers to create virtual versions of these physical resources. These virtual versions (or “virtual machines”) can then run on a single machine, optimizing their use and enhancing efficiency. A so-called virtual machine monitor (VMM) then acts as the operating system, which can also help manage power use and facilitate an efficient allocation of hardware resources.

By going further and allowing each virtual machine to manage its own energy management strategy, and by using a system for managing computer resources (or a virtualization infrastructure provider) , significant power can be saved. Such a system can save up to 27 percent energy and run programs that require a lot of processing power up to 32 percent faster compared to standard settings in a VMM (Katal et al., 2023).

Another practice that can enhance efficiency is load balancing, involving optimization of workload between data centers. This balancing of load on servers helps improve the performance of data centers and minimize energy use and processing time in cloud systems (Udayasankaran and Thangaraj, 2023).

In the context of climate adaptation, both virtualization and load balancing can contribute to enhancing data centers’ resilience. In addition to the remote management opportunities, virtualization simplifies the process of moving and replicating virtual machines, enabling more efficient recovery processes after disasters and extreme weather events. Load balancing, on the other hand, allows data centers to distribute workloads across multiple servers and locations. In the event of extreme weather affecting one location, workloads can be dynamically shifted to unaffected data centers.

Greening back-up generators, or avoiding them altogether

Many data centers are dependent on back-up generators, often run on fossil fuels such as diesel, to guarantee consistent power supply. Fossil-free back-up alternatives and battery-based systems are still limited but are becoming more common, with innovative sources such as hydrogen being explored. The advantage of a battery-based system is that compared to diesel generators they can avoid startup times and don’t need to sit idle when there are no power outages, but could potentially be used as assets to strengthen the electric grid by banking renewable power and balancing variability (Kava, 2020).

Hydrogen-powered fuel cell generators are currently being developed by energy companies in collaboration with data centers. To date, a number of demonstration units have been piloted to test the technology. However, this often uses hydrogen made from natural gas and not green renewable hydrogen (Calma, 2022). Given the substantial global demand for green hydrogen, and with most large-scale electrolyzer plants already having entered into long-term agreements with their end-users, the production of green hydrogen would need to accelerate significantly to make this an option for data centers. And while hydrogen fuel cells are promising, they are still in the early stages of adoption.

From air cooling to liquid cooling

Today, the sheer size of data centers means standard air conditioning systems are no longer sufficient. Instead, conventional data centers frequently use computer room air handlers or computer room air conditioning units to cool down hardware. Implementing control systems that take factors such as cooling load and air temperature into account can help optimize the cooling system in real time. Many of these units now have the option to connect their control systems and run together to work more efficiently.

In addition to air conditioners, more specialized cooling technologies are needed for the hottest most power-hungry components of data centers. A typical shift in the sector can be seen in terms of moving from air cooling to liquid cooling which generally provides more efficient cooling (Joint Research Centre et al., 2024). Liquids such as water have a much higher heat capacity compared to air, and are more adequate for cooling servers (Koronen et al., 2020). The technology is not new, and several different systems of liquid cooling technology have been developed, with various types of liquids and cooling techniques. These are for example:

Immersion liquid cooling: this cooling technology has gained in popularity. It cools by submerging equipment directly in coolant, which makes heat transfer more efficient. The coolant has high thermal conductivity and stable temperatures, reducing energy use, noise and the need for fans. This technology is ideal for large data centers, supercomputing and research institutions needing high cooling efficiency and energy savings. It’s particularly useful in cold, high-altitude areas with limited space and in data centers near offices and residential areas due to its low noise (Li et al., 2020). A more recent innovation, two-phase immersion cooling, relies on the phase change of a liquid (between boiling and condensing) and offers even higher heat transfer efficiency due to the latent heat of vaporization. However, it can be more complex to design.

Cold-plate liquid cooling: direct-to-chip cooling refers to liquid coolant being delivered directly via tubes to cold plates directly on chip surfaces. This method provides more targeted cooling for high-performance components, resulting in better thermal management. Pipes connect liquid to cooling plates on the computer’s high-power parts, while other parts are still cooled by air. This method is more efficient, quieter and cheaper than using air alone (Li et al., 2020).

Spray cooling: this also involves direct contact with liquid, similar to immersion cooling, but here the dielectric liquid is sprayed directly onto the hottest parts of the servers. The servers are kept at an inclination to allow the liquid to then flow down and be collected in a small tank at the bottom, filtrated and fed through a heat exchanger. Being a more recent innovation, spray cooling is not as common as immersion and cold-plate liquid cooling (Li et al., 2023), but offers the advantage of more targeted cooling. Table 4.1 shows a breakdown of the estimated energy consumption of various components in a data center, with a comparison between an air-cooled and a spray-cooled data center, highlighting significant energy savings for spray cooling.

Table 4.1 Estimated energy consumption between air-cooled and spray-cooled data centers

Data center energy consumption breakdown	Air cooling (kW)	Air cooling (%)	Spray cooling (kW)	Spray cooling (%)
IT load	1 000	59	1 000	80
Electrical losses	71	4	71	6
Lighting, other elect.	33	2	33	3
Compressor based cooling unit	259	15	-	-
Cooling tower fan	74	4	56	5
Condenser water pump	-	-	53	4
Coolant spray pump	-	-	29	2
Air management and other cooling accessories	251	15	-	-
Vapor condenser fan	-	-	10	1
Total	1 687	100	1 252	100

Source: Kandasamy et al. (2022).

Free cooling technology makes use of the natural elements

The need for enhanced efficiency has led to the development of adiabatic and free cooling technology for data centers. By making use of naturally available air and water, free cooling can replace part or all of data centers mechanical cooling needs. This necessitates locating the data center in a cold climate or close to a body of water that can act as a cooling source (Koronen *et al.*, 2020).

Adiabatic cooling – or evaporative cooling – uses the process of water evaporation to cool the air, where warm air is passed over water-soaked pads or misted with water, reducing the air temperature before it is circulated through the data center. This method is particularly energy-efficient and effective in regions with low humidity. However, while this may save on energy it is very water-consuming. As an attempt to overcome this challenge, pilot demonstrations in recent years have even tested underwater data centers that use sea water as a natural cooling source (Warren, 2018; (Bowen) 2023. There is also a growing interest in free cooling based on air cooling, particularly in colder climates. This simply involves bringing in fresh outside air into the data center to provide cooling, unless the outside air is too warm, in which case a mechanical cooling system takes over.

Geothermal cooling has been around for a while but its use in data centers is limited due to geographic constraints. These systems cool data centers by using the ground as a heat sink, operating a closed-loop piping system filled with water or coolant which transfers heat to underground wells.

Managing airflow

While the choice of cooling technology is central, various design measures can help enhance the airflow within the data center. Good airflow means operators can avoid unnecessarily low cooling temperatures or excessive air volumes, and further enhances cooling efficiency. The purpose is to circulate only the necessary amount of air to remove heat generated by the IT equipment. For instance, solid doors can be replaced with perforated doors where needed to ensure better cooling airflow.

Other measures help contain and separate cold air from heated return air, for instance by enclosing either the hot or cold aisles, installing curtains or using blanking plates in areas where there is no equipment to reduce hot air recirculating through gaps in the cabinet. In one specific case, designing closed aisles to deliver cold air to IT equipment reduced the cooling energy consumption by nearly 60 percent (Li *et al*., 2023).

During early stages of designing a data center, computational fluid dynamics can contribute to optimizing airflow design. Further, using thermography and computer modelling to create images of hot and cool zones in a data center, ideal positioning of equipment can be found to help optimize cooling (Joint Research Centre *et al*., 2024).

Waste heat recovery in data centers

Data centers are more often equipped with heat pumps to enable efficient heat recovery. This is partly spurred by the current shift from air cooling to liquid cooling in data centers, which has opened up better heat-capturing possibilities. Captured waste heat can have many uses, including being reused to heat nearby buildings and pools or feeding into district heating networks. For instance, a data center in Switzerland warms a nearby swimming pool, another one in Paris sends waste heat to a neighboring science lab, and a Danish data center in Odense is being designed to recover heat for a local community. The most efficient ways of reusing waste heat in data centers are for the heating supply in nearby buildings directly after pre-heating, and for supplementing district heating networks (Yuan *et al*., 2023). As heat doesn't travel well, various innovations are now focused on enhancing the efficiency of waste heat recovery. This involves innovations such as developing materials that can soak up water vapor and release heat more efficiently.

Innovation examples

Data center heat recovery for local community

Source: Getty Images/alacatr

Stockholm Data Parks is a pioneering initiative in Sweden that effectively utilizes waste heat from data centers to meet the heating needs of thousands of residential apartments. This project, a collaboration between the City of Stockholm, Stockholm Exergi (district heating and cooling provider), Ellevio (power grid operator), and Stokab (dark fiber provider), demonstrates the economic and environmental feasibility of repurposing excess heat from data centers for direct building and community heating. When data centers set up operations within Stockholm Data Parks, Stockholm Exergi captures the waste heat, which would otherwise be vented away, and channels it into the district heating system. This recovered heat is then used to provide heating for residential and commercial spaces (Stockholm Exergi, 2024).

Energy efficient data center in Germany

Source: F. Löchner

A good example of an energy-efficient data center is the Super MUC-NG in the Leibniz Supercomputing Center (LRZ) at the Bavarian Academy of Science and Humanities in Garching, Germany. The data center utilizes direct warm-water cooling (40°C–45°C) and waste heat is captured to heat about 40,000 m2 of office space. Waste heat is also used for generating cold water through adsorption chillers, which in turn is used in heat exchangers to capture heat from other IT equipment in the data center. As the innovative cooling system means the data center can operate with reduced mechanical cooling and without the need for fans, cooling power consumption is reduced, saving around 30 percent of energy. The racks are insulated to reduce radiation to the environment given the high supported water temperatures (ASHRAE, 2021).

Technology solutions

Proven

Energy efficiency: efficient uninterrupted power supply (UPS) system for data centers
ABB

Source: ABB

UPS systems maintain power to data centers in the event of a utility power disruption. They typically rely on batteries as a back-up power source and are part of a data center's electrical distribution system. As electrical distribution system losses can account for 10 to 12 percent of the total energy consumed by the data center, the right UPS system can help data centers save energy. For instance, ABB's UPS system provides a highly efficient power supply, reducing the usual power losses. The UPS system provides continuous power of up to 24 kW, suitable for data centers, while protecting loads and reducing downtime to enhance efficiency.

- Contracting type: For sale
- Technology level: High
- Country of origin: Sweden & Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: data center energy monitoring

ABB

Source: ABB

ABB Ability™ is a cloud-based connectivity platform that provides remote data collection for energy and asset monitoring. Those data are then analyzed and accessible on a fully integrated ABB platform. The data, refreshed every 30 seconds, are rolled into a preconfigured dashboard for data centers where users can find all the information about their operation. This includes data points for power usage effectiveness, input and output power, energy trends, peak power and so on. In addition to producing reports and analyses, the system provides insights that enable smarter (and even automated) energy consumption decision-making.

- Contracting type: For sale
- Technology level: High
- Country of origin: Sweden & Switzerland
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: automated storage tiering (AST) for energy-efficient storage in data centers

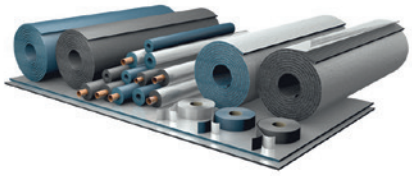
DataCore Software

Source: Getty Images/Ole_CNX

AST is a software management feature that can help data centers save energy on storage. It dynamically moves data between different disk types and back-up levels to meet capacity, performance and cost requirements. Their SANsymphony system improves this process by adding features that reduce duplicate data and compress files, continuously analyzing data access patterns to optimize both speed and storage space. This system ensures that critical data perform well while keeping storage usage low for less active files, making it an effective solution for data center efficiency.

- Contracting type: For service
- Technology level: High
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: thermal insulation for data centers
Armacell



Source: Armacell

Insulation in data centers (for piping, HVAC, chilled water etc.) is essential for maintaining stable temperatures and optimizing energy efficiency. It helps minimize heat exchange with the external environment, reduces the workload on cooling systems and lowers overall energy consumption. Effective insulation also supports consistent operational conditions. Armacell specializes in comprehensive thermal insulation solutions for large-scale engineering projects, with portfolio packages designed particularly for data centers.

- Contracting type: For sale
- Technology level: Low
- Country of origin: Luxembourg
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cooling: air-cooled free cooling chiller for data centers
Vertiv

Source: Getty Images/baibaz

Free cooling for data centers refers to a method where outside air is used to cool IT equipment instead of traditional mechanical cooling systems. This approach leverages naturally lower temperatures of cold outside air to reduce energy consumption. The Vertiv™ Liebert® HPC-S is a turnkey cooling solution designed for small and medium-sized data centers with a cooling capacity ranging from 80 to 500 kW. It utilizes refrigerants with a low GWP and features enhanced free cooling capabilities, significantly reducing electricity consumption from mechanical cooling.

- Contracting type: For sale
- Technology level: High
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cooling: single-phase immersion cooling for data centers
Engineered Fluids

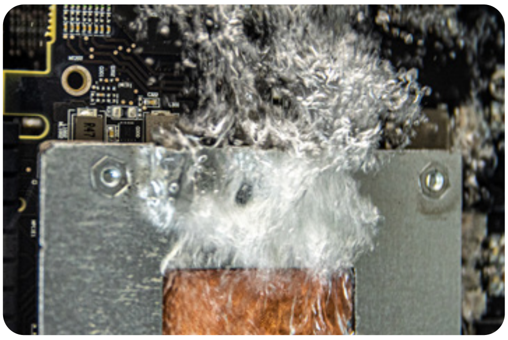
Source: Engineered Fluids

Immersion cooling is a technique used to cool computer servers in data centers by submerging them in a special liquid. This liquid is non-conductive, meaning it won't cause electrical disruptions. As the servers run and generate heat, the liquid absorbs the heat and carries it away, keeping the servers cool. This method is very efficient, reducing the need for air conditioning and saving energy. Engineered Fluids provides single-phase immersion cooling. Here, the liquid remains in a single liquid state, as opposed to double-phase immersion where the coolant boils and vaporizes at it absorbs heat, only to condense and turned to liquid again.

– Contracting type: For sale
– Technology level: High
– Country of origin: United States
– Availability: Worldwide
– Contact: WIPO GREEN Database

Frontier

Cooling: two-phase immersion cooling for data centers
Opteon



Source: Opteon

Opteon's solution for data center cooling leverages two-phase immersion cooling technology, using their Opteon™ 2P50 dielectric fluid. This approach significantly enhances energy efficiency, reducing cooling energy use by over 90 percent compared to traditional air cooling methods, according to the technology provider. The process involves immersing servers and electronics in tanks of dielectric fluid, which absorbs heat, vaporizes and then condenses, allowing for effective heat removal. Opteon™ 2P50 is chemically stable, safe with no flammability risks and compatible with most server materials. It also supports sustainability with zero ozone depletion potential and low global warming potential.

– Contracting type: For sale
– Technology level: High
– Country of origin: Australia

- Availability: Worldwide
- Contact: WIPO GREEN Database

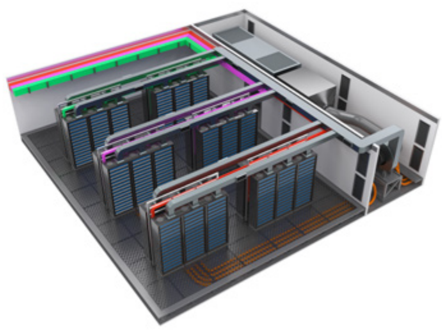
Cooling: direct-to-chip cooling for data centers
Asetek

Source: Asetek

Direct-to-chip cooling is a method used to cool computer servers in data centers. Instead of using air to cool the whole room, this method involves placing cooling plates directly on the computer chips. These plates carry a liquid coolant that absorbs heat from the chips and then moves it away. This method is more efficient and keeps the servers from overheating. Asatek's direct-to-chip cooling technology makes use of an integrated pump and cold plate design for cooling high-power components within servers.

- Contracting type: For sale
- Technology level: High
- Country of origin: Denmark
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: efficient modular edge data centers
Edge Centres



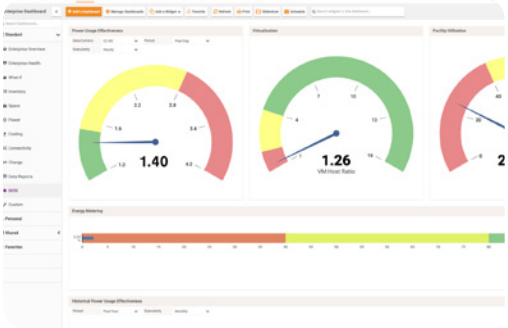
Source: Getty Images/wir0man

Edge Centres is developing a global network of modular and edge data centers strategically positioned across Asia-Pacific, North America, and other regions. These "Edge Pods" deliver ultra-low-latency connectivity and computational resources directly to end-users. They fill connectivity gaps left by centralized hyperscale data centers, particularly in rural and underserved areas where reliable coverage is lacking. The modular data centers include features such as solar energy, free cooling and custom sun shielding, while aiming to reach a power usage effectiveness (PUE) of 1.1 during peak load operations aiming for a PUE target of 1.1 during peak load operations, compared to the effectiveness of data centers of around 1.5–1.8.

- Contracting type: For sale
- Technology level: High

- Country of origin: Australia
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: energy management system for data centers
Sunbird DCIM

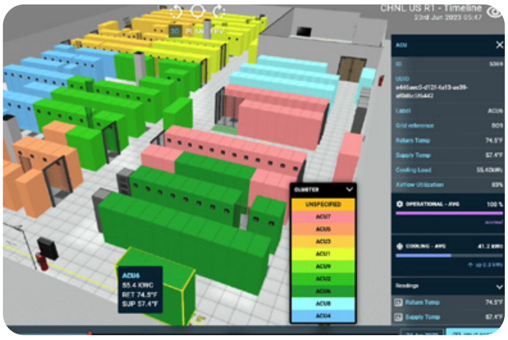


Source: Sunbird DCIM

Sunbird DCIM utilizes a patented electronic dashboard to visualize temperature sensor data within data center rooms, facilitating better management of temperature increases and cooling settings. The technology automates data collection from buildings and IT equipment from multiple data centers and tracks the PUE in real time. Users can promptly assess the impact of energy efficiency measures, compare yearly PUE metrics internally and against industry benchmarks, and identify and deactivate energy-wasting servers.

- Contracting type: For sale
- Technology level: High
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: AI-driven data center optimization software
EkkoSense



Source: EkkoSense

Ekkosense provides an AI-driven software for optimizing various functions within a data center, such as cooling and waste heat minimization. Their product EkkoSoft Critical is a thermal management solution that can gather highly granular cooling, power and space data for more informed decision-making. It uses digital twins and 3D visualization to interpret complex data and highlight anomalies within the data center, and leverages AI and machine learning to translate the data points into actionable insights. For a more comprehensive assessment of the data centers operations, the product EkkoSense Digital Twin generates a broader real-time visualization and suggested recommendations on airflow and cooling.

- Contracting type: For sale
- Technology level: High

- Country of origin: United Kingdom
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: data-reducing software for data centers

Pure Storage

Source: Getty Images/Veit Störmer

Pure Storage® Purity Reduce is a software that employs various techniques to save space in data center storage systems, which can contribute to significant energy savings. First, it identifies and removes repetitive patterns in data to reduce the amount that needs to be processed further. Next, it uses a high-speed process to find and store only unique blocks of data, which helps save space on the flash storage. Then, it uses various data compression algorithms to maximize space savings. Lastly, it efficiently handles copies of data, using metadata to create instant, space-efficient copies for tasks like back-ups and data replication.

- Contracting type: For sale
- Technology level: High
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cooling: heat recovery solution for data centers

Qarnot

Source: Qarnot

Qalway by Qarnot uses waste heat from computer servers to heat new and existing buildings and supply domestic hot water efficiently. Their digital heater and boiler convert server heat into usable energy, creating a circular economy where computer heat becomes a resource. Qalway solutions are adaptable for social housing, property development, local authorities, swimming pools and various types of residential, commercial and institutional buildings.

- Contracting type: For sale
- Technology level: High
- Country of origin: France

- Availability: Worldwide
- Contact: WIPO GREEN Database

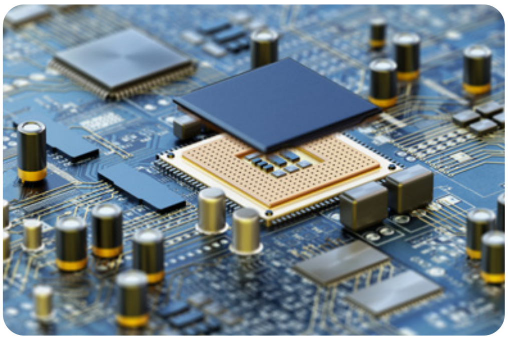
Cooling: spray liquid cooling with heat recovery for data centers
AIRSYS

Source: AIRSYS

AIRSYS' patented cooling system, LiquidRack, is the world's first spray liquid cooling solution that offers 100 percent heat recovery, capturing waste heat as usable hot water. The technology features information and communication technology for precise temperature control, and sprays fluid directly onto central processing units to eliminate uneven temperatures and remove heat faster.

- Contracting type: For sale
- Technology level: High
- Country of origin: United States
- Availability: Worldwide
- Contact: WIPO GREEN Database

Energy efficiency: GaN power transistors for data centers
Infineon Technologies

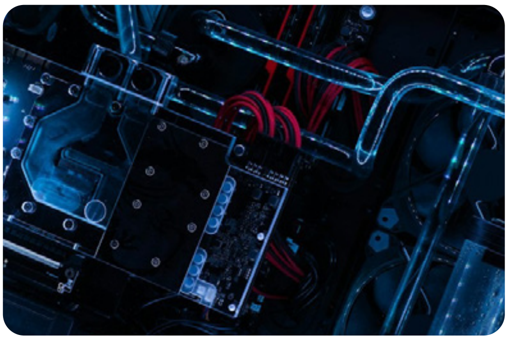


Source: Getty Images/adventtr

Infineon Technologies has developed new GaN transistors which can significantly improve energy consumption and reduce heat generation of data centers, compared to traditional silicon-based components. GaN semiconductor material is known for its superior electrical properties compared to silicon. It enables faster switching speeds, higher conductivity and better overall performance in electronic components. Infineon's GaN devices, which can handle high voltages from 40 V to 700 V, are designed for a wide range of applications, including data centers.

- Contracting type: For sale
- Technology level: High
- Country of origin: Germany
- Availability: Worldwide
- Contact: WIPO GREEN Database

Cooling: two-phase cold plate liquid cooling
Xiangyang Guangre Environmental Protection Technology Co., Ltd.



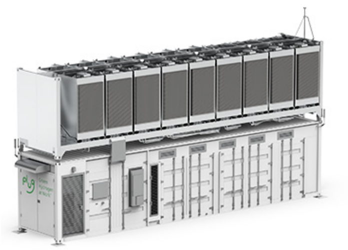
Source: Xiangyang Guangre Environmental Protection Technology Co., Ltd.

The pump-driven two-phase cold plate liquid cooling technology utilizes fixed-point refrigerant phase change cooling and heat dissipation, specifically designed for high-power devices such as server chips. This system effectively circulates coolant to cool low-power components on the server motherboard. By eliminating the need for central or precision air conditioning systems, this technology significantly reduces energy consumption by 60 to 80 percent and lowers the annual PUE value to below 1.15. The technology can manage heat dissipation temperatures exceeding 45°C, making it suitable for heat recovery and recycling applications.

- Contracting type: For service
- Technology level: High
- Country of origin: China
- Availability: Worldwide
- Contact: WIPO GREEN Database

Horizon

Hydrogen fuel cell back-up generators for data centers
Plug Power



Source: Plug Power

Plug Power has developed a hydrogen fuel cell system that serves as a zero-emission back-up power source for data centers. This innovative system, housed in 40-foot-long shipping containers, recently demonstrated its capability by delivering 3 MW of power – enough to support critical data center operations during power outages without relying on traditional diesel generators. Plug Power's GenSure fuel cells support mission-critical applications and emergency power needs but also contribute to reducing the environmental impact of data centers. With the prototype testing complete and concept proven, Plug is focused on rolling out an optimized commercial version of such high-power stationary fuel cell systems.

- Contracting type: Service
- Technology level: High
- Country of origin: United States

- Availability: N/A
- Contact: WIPO GREEN Database

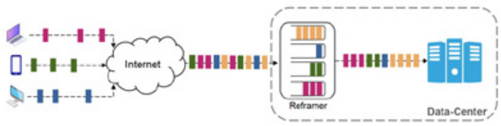
Energy efficiency: ultra-low power chips for extended device lifespan
SureCore

Source: SureCore

SureCore is developing solutions to address the power consumption of data centers. The company creates energy-efficient chips for devices that use AI, machine learning and IoT, and that need to be on all the time. Their goal is to extend device battery life from days or weeks to months or years. They are redesigning memory components (static random-access memory) and system-on-chip designs to significantly reduce power consumption, even at very low voltages. This innovation helps devices run longer on a single charge, enhancing efficiency. For data centers, these advancements are important as they can significantly reduce overall energy usage and operational costs.

- Contracting type: For sale
- Technology level: High
- Country of origin: United Kingdom
- Availability: N/A
- Contact: WIPO GREEN Database

Energy efficiency: tool for enhancing processing speeds in data centers
KTH



Source: KTH

Researchers at the Royal Institute of Technology and Ericsson have jointly developed a software called Reframer that demonstrates a potential to reduce the energy consumption in data centers by 50%. The accomplishment is made possible by the Reframer first delaying incoming traffic by 10-100 milliseconds, during which it inspects the individual data packets and sorts them into queues of similar flows. This reordering of packets allows for enhanced processing speeds of up to 86%, resulting in the lowered energy consumption. The Reframer source code and experimental data is publicly available for further testing and development.

- Contracting type: Under development
- Technology level: High

- Country of origin: Sweden
- Availability: N/A
- Contact: WIPO GREEN Database

Energy efficiency: Silicon-embedded liquid cooling for high-power chips
JetCool

Source: JetCool

JetCool's patented microconvective liquid cooling technology meets the requirements of AI infrastructures, where chips can consume upwards of 1,000W or more. The single-phase, direct-to-chip cooling solution has effectively been applied through their SmartPlate product, reportedly reducing total IT power consumption by an average of 15%. The company is now developing the SmartSilicon, where the microconvective cooling technology has been integrated into the chip substrate to provide direct on-chip cooling. The company regards SmartSilicon to be on track to handle chips consuming 3500W+.

- Contracting type: Under development
- Technology level: High
- Country of origin: United States
- Availability: N/A
- Contact: WIPO GREEN Database

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Energy is at the forefront of WIPO's third edition of the *Green Technology Book.* This volume showcases a range of significant energy technology innovations across key sectors of society, including households and communities in both urban and rural areas, as well as essential services provided by supermarkets, healthcare facilities and data centers.

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