

Green Technology Book

Energy
solutions for
climate change

Executive
Summary



© WIPO, 2024 /  Attribution 4.0
International (CC BY 4.0)

The CC license does not apply to non-WIPO
content in this publication.

Cover: Getty Images / Jaakko Heikkilä, Anze
Furlan/psgtproductions, marvinh

WIPO Reference 1080/24-ExSum/EN
[DOI:10.34667/tind.58488](https://doi.org/10.34667/tind.58488)

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 CO₂ 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 underserved 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 CO₂ 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.

Energy is at the forefront of the third edition of the *Green Technology Book*. This Executive Summary provides the background to the solutions for climate change showcased in the full report, which presents 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.