HIGH-LEVEL DIALOGUE ON ENERGY

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THEME REPORT ON INNOVATION, TECHNOLOGY AND DATA

TOWARDS THE ACHIEVEMENT OF SDG 7 AND NET-ZERO EMISSIONS

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Food and Agriculture Organization of the United Nations	Food and Agriculture Organization (FAO)
UN-HABITAT FOR A BETTER URBAN FUTURE	UN-Habitat
UNIDO UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION	United Nation Industrial Development Organization (UNIDO)

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PREFACE

Energy can create transformational opportunities. For the 759 million people in the world who lack access to electricity, the introduction of clean energy solutions can bring vital services such as improved healthcare, better education and affordable broadband, creating new jobs, livelihoods and sustainable economic value to reduce poverty. In regions such as sub-Saharan Africa where half of secondary schools and a quarter of health facilities have no power, clean energy access will help save lives, and offer opportunities for prosperity at a transformative scale.

An energy revolution based on renewables and energy efficiency is urgently needed not just to accelerate economic progress and development, but also to slash emissions that are rapidly warming our planet. The energy sector today, dominated by fossil fuels, accounts for 73 per cent of human-caused greenhouse gas emissions. Global CO_2e emissions must be halved by 2030 to avoid an increasing frequency and severity of dangerous and unprecedented weather extremes, including heatwaves, devastating floods and droughts, risks to food and water security, population displacement, and loss of lives and livelihoods.

As governments start to define a pathway out of the COVID-19 crisis, we must now ensure that all countries have the chance to be part of an energy transition that seizes the opportunity to significantly improve the wellbeing of people, and planet.

This will not be an easy task. To ensure a just transition, we must support countries and communities to adapt to a green economy through social protection and new skills, ensuring all who need to be are equipped to take advantage of the 30 million new green jobs expected by 2030.

To generate the vital momentum needed for this transition, the UN Secretary-General is convening the High-Level Dialogue on Energy in September 2021, the first such meeting in 40 years. The landmark event will offer a global stage for countries to attract new investments and forge new impact focused partnerships to drive forward this energy revolution.

As a foundation for informed deliberations, five Technical Working Groups were established on the five key themes of the High-level Dialogue: (1) Energy Access, (2) Energy Transitions, (3) Enabling SDGs through Inclusive, Just Energy Transitions, (4) Innovation, Technology and Data, and (5) Finance and Investment. These Technical Working Groups brought together leading experts on these subjects from across the world to identify key recommendations for a global roadmap towards the achievement of SDG7 and the climate objectives of the Paris Agreement.

This proposed roadmap illuminates a way forward for how the world can achieve a sustainable energy future that leaves no one behind. We hope that it will help to inspire the actions needed to get there.

Mr. Liu Zhenmin
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UNDP Administrator and Co-chair of the Dialogue and UN-Energy

Ms. Damilola Ogunbiyi
Special Representative of the UN Secretary-General for Sustainable Sustainable Energy for All and Co-Chair of Dialogue and UN-Energy

FOREWORD

To achieve universal energy access by 2030 and net-zero emissions by 2050 while building back better in the aftermath of the current global COVID-19 pandemic, we must recognise the key role of modern energy and its pivotal role in climate action. Yet, significant policy, technology, finance and social challenges to energy innovation, technology development and deployment and better data persist as we attempt to navigate a path to these objectives.

Within this context, the following report was developed by the 4th Technical Working Group on the theme of "Innovation, Technology and Data" as part of the preparations for the United Nations High Level Dialogue on Energy. It is the result of three meetings of the 36 Technical Working Group Members, and was guided by three co-leads, namely the Food and Agricultural Organization of the United Nations (FAO), the United Nations Human Settlements Programme (UN-Habitat) and the United Nations Industrial Development Organization (UNIDO).

The report highlights that we need to make use of energy innovation, technology development and deployment, as well as improve data collection and use to achieve universal energy access by 2030 and net-zero emissions by 2050.

Innovation is a dynamic process, which results from complex interactions influenced by multiple actors and institutions at different levels that include governments, the private sector, academia, civil society and end-users. Innovation has played a key role in enabling progress towards the SDG 7 targets and the Paris Agreement, but major technology, policy, financial and social innovations are still needed in all aspects of the energy system, especially in the end-use sectors of transport, industry, food and buildings.

High quality, reliable data are a prerequisite for making evidence-based decisions and planning, monitoring trends, and tracking progress toward policy goals, including meeting SDG 7 targets. Accelerating action on energy innovations for effectively developing inclusive energy policy, planning and systems requires better systems of data collection and application. These should be open, reliable, complete and address the digital divide.

FAO, UN-Habitat and UNIDO would like to thank all Working Group Members for their inputs to this report. Whilst this body of work has underscored that the challenge before us is significant, it has also demonstrated that the solutions are within our grasp We are convinced it will contribute towards an action-oriented SDG 7 roadmap to 2030 in support of the 2030 Agenda for Sustainable Development and the Paris Agreement on Climate Change.

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CONTENTS

1 PRIORITY RECOMMENDATIONS

This report aims to align international action on energy innovation, technology development and deployment, and data collection and use with the achievement of SDG 7 by 2030 and net-zero carbon emissions by 2050. The report provides an overview of the present status of energy innovation; it proposes actionable recommendations with priority results and action areas; and it assesses the catalytic impacts that such actions can have.

Innovation is a dynamic series of processes: it results from complex, interconnected systems influenced by multiple actors and institutions at different levels, including governments, the private sector, academia, civil society, and end users. Innovation is not just about technology, but also about policy and planning, and the finance, business and social domains.

Better systems of data collection and application that are open, reliable, and complete are necessary to accelerate the effective development of inclusive energy policy, planning, and systems. Digitalization and Industry 4.0 technologies can also act as enablers for transformational change.

There are significant and persistent policy, technology, finance-related, and social challenges to energy innovation, technology development and deployment, and data improvement. Existing technologies are under-deployed, and approximately half of the technologies necessary to meet the 2050 target are still in the early stages of development and demonstration.

Energy innovations present positive transformational potentials for achieving universal energy access and for net-zero emissions: innovations should follow four key principles:

- **Set an ambitious vision**: Align innovation, policy, finance, and action with the achievement of SDG 7 targets by 2030 and net-zero emissions by 2050;
- **Integrate sustainability**: Ensure that social, economic, and environmental sustainability are considered in the design, implementation, and monitoring of energy innovations;
- **Act locally**: Ensure that innovations are customized to the local context so that energy innovations fulfil the needs and aspirations of local stakeholders and end users; and
- **Leave no one behind**: A diversity of needs, based on geography, gender, equity, age, and marginalized populations should be considered, and issues such as the digital divide, affordability, and capacity development should be addressed.

With these principles in mind, five key recommendations are presented:

RECOMMENDATION 1

Align energy innovation governance and international cooperation with meeting the targets for 2030 and 2050

National and local energy-innovation governance and international cooperation around mission-oriented policies and strategies must be strengthened. This process should be informed by evidence and science-based targets, and backed by long-term predictable funding and financing that drive 'homegrown' innovation; and it should be guided by the principles of a just transition.

RECOMMENDATION 2

Expand the supply of energy innovation that addresses key gaps

To increase the supply of clean energy innovation, international cooperation and national commitments in partnership with the private sector need to be enhanced. Expanded innovation should be based on targeted, sustained, outcome-based funding for research, design, development, and demonstration that is proportional to the challenge at hand and sets solid milestones for scaled-up commercial adoption.

RECOMMENDATION 3

Increase the demand for clean and sustainable energy technologies and innovation

Demand for clean and sustainable energy technologies and innovation through market-oriented policies, harmonized international standards, and carbon pricing mechanisms needs to be accelerated. This will enable infrastructure, fiscal incentives, access to finance, regional and local green value chain development, and commitments to public and private procurement of clean energy technologies.

RECOMMENDATION 4

Leverage digitalization for innovation, while addressing the digital divide

An inclusive and integrated enabling environment should be developed for innovation that can leverage digitalization for financial and social innovation into new business models that not only improve affordability, reliability, and accessibility to clean energy technologies, but also strengthen capacity and knowledge around digital technologies to address the digital divide.

RECOMMENDATION 5

Improve the collection, management, and application of data and data systems

Enhance data systems and energy-planning workflows and analytics: (i) to better inform energy policies, planning, and regulations; direct investment decisions and monitoring, evaluation, and reporting in order to address disparities; and (ii) to effectively manage synergies and trade-offs in energy access, technologies, and security among vulnerable and marginalized communities.

If all stakeholders adopt and act urgently on these recommendations, in tandem with the recommendations of the other technical working groups, the catalytic impact is expected to be a rate of energy innovation consistent with achieving SDG 7 by 2030 and net-zero emissions by 2050: this will also create jobs, economic growth, and a more inclusive energy sector in terms of both the needs and the participation of women, youth, and marginalized groups.

2 RESULTS AND ACTIONS MATRIX

PRIORITY RESULTS	PRIORITY ACTION AREAS	STAKEHOLDER ACTIONS			
		Public	Private	Civil Society	International organizations
Priority Result 1 Energy innovation governance, cooperation, and capacity are aligned with the 2030 and 2050 targets.	1.1 Implement, and monitor mission-oriented energy innovation visions and ecosystems. This will ensure policy coherence by aligning the objectives and impacts of energy innovation with binding commitments (to SDGs and in NDCs).	Develop, implement, and monitor visions and energy innovation ecosystems in a participatory manner	Actively engage in the development, implementation and monitoring of energy innovation visions and ecosystems.	Actively engage in, and provide support for, the development of energy innovation visions and ecosystems.	Facilitate international cooperation and development assistance to countries through open data knowledge sharing platforms and peer-to-peer learning.
	1.2 Adopt existing or develop international technical standards and quality-control requirements. Harmonize these with energy supply and demand policies and regulations at the national level.	Adopt internationally harmonized technical standards and quality-control requirements, and/or develop national ones.	Apply international or national technical standards and quality-control requirements.	Support localization of international standards and the development of national standards.	Develop and/or support the adoption of international or national standards and quality- control requirements; and facilitate access of developing and least-developed countries to state-of-the-art quality and testing infrastructure.
	1.3 Strengthen local and national ecosystems to support 'homegrown' energy innovations and green value chains.	Develop national policies, regulations, local and national coordination mechanisms and institutional arrangements; this will support homegrown energy innovations and bring together stakeholders from the public and private sectors, academia, and civil society, on both the energy supply and demand sides.	Invest in local RD&D. Support local technical capacity building. Partner with governments and universities to develop local innovations and homegrown technologies.	Mobilize women, communities, youth, and vulnerable groups to shape and lead local energy innovation. Support connectivity between different actors.	Develop a comprehensive global assessment of energy innovation programmes to learn from collective experience and establish best practices. Facilitate international cooperation and technical assistance to countries with nascent capabilities to build homegrown energy innovation capabilities, develop an understanding of the concept of inclusiveness, and be able to connect to global ecosystems.

PRIORITY RESULTS	PRIORITY ACTION AREAS	STAKEHOLDER ACTIONS			
		Public	Private	Civil Society	International organizations
	1.4 Develop programs that provide opportunities and build capacity among professionals, including youth and women. Programs will be on the supply and demand sides of energy innovation and of data collection and monitoring.	In partnership with the private sector, academia, and civil society, develop national programs for young professionals and women related to the supply and demand sides of energy innovations. Promote and finance inclusive energy incubators and start-up centres.	Provide opportunities for young professionals to work in energy innovation programs in partnership with government and civil society. Develop programmes that address the gender gap, in order to enhance the engagement of women in the energy sector and their career advancement within it.	Support the development of energy innovation programs targeting young professionals and women in partnerships with government and the private sector.	Facilitate international cooperation and quality standards for curricula development and certification and accreditation schemes. Enable access to affordable, high quality professional qualifications for low-income earners and disadvantaged groups (e.g. women and youth). Facilitate South–South technology transfer.
	1.5 Foster multi-sector partnerships for energy technology innovation and enable cooperation through open access policies, best practices, and knowledge exchange.	Champion open access policies and facilitate the establishment of multi-sector energy innovation partnerships.	Participate in and support global and multi-sector energy innovation partnerships.	Participate in global, national, and local multi-sector energy innovation partnerships.	Facilitate inter-governmental and global multi-sector energy innovation partnerships.
Priority Result 2 The rate of technology research, development, and demonstration is increased to be consistent with meeting the 2030 and 2050 targets.	2.1 Implement sector- specific commercial-scale pilot and demonstration projects that takes into account user benefits, especially those for women and vulnerable groups.	Facilitate the development of pilots and demonstration projects at the national and local levels. Create partnerships with the private sector and academia around commercialization pathways.	Support pilot and demonstration projects. Create partnerships with government and academia around development and commercialization pathways.	Participate in pilot and demonstration projects, both as a beneficiary and in decision-making. Create partnerships between academia, the private sector, and government around commercialization pathways.	Facilitate international cooperation and a level playing field for all countries to participate in technology development and benefits. Facilitate the removal of technical and trade barriers, as well as barriers to accessibility. Support the diffusion and scale-up of successful pilot schemes and demonstrations, in addition to evaluation support in this regard.
	2.2 Strengthen commitment to predictable, sustained, outcome-based funding in RD&D and invest in portfolios of key technologies and innovations to accelerate early-stage development to commercialization. Strengthen energy system reliability, resilience, and/or security.	Develop enabling policies and institutions for home-grown RD&D and the development of energy innovations that include all key actors along value chains. Establish mechanisms for evaluating progress on innovation policy outcomes, making data available to researchers and adjusting programmes accordingly.	Provide financial support and/or implement home-grown RD&D.	Provide local and regional input on needs and risk assessment.	Facilitate cross-border cooperation, public–private collaboration, and sector- specific consensus, particularly for sectors of a global nature (such as aviation, cement, iron and steel) that cannot be transformed through national policy alone.

PRIORITY RESULTS	PRIORITY ACTION AREAS	STAKEHOLDER ACTIONS			
		Public	Private	Civil Society	International organizations
	2.3 Approve the creation of the International Energy Innovation Fund to address the lack of financial resources for localized energy innovations in developing countries.	Approve the creation of the International Energy Innovation Fund. Establish an Energy Innovation Fund to encourage the development of homegrown solutions to energy needs.	Provide financial support to the International Energy Innovation Fund.	Provide input on local and national energy innovation funding needs.	Champion and facilitate inter-governmental support for the establishment of an International Energy Innovation Fund.
	2.4 Increase research and education opportunities directed at energy innovation for women, youth, and marginalized groups in science, technology, and innovation (STI).	Develop and/or enhance education and research programs that support women, youth, and marginalized groups in STI.	Create positions, internships, and support programmes (e.g., mentoring, capacity-building programmes) for women, youth, and marginalized groups in STI.	Create positions and internships for women, youth, and marginalized groups in STI. Enhance awareness of the need for and benefits of involving women, youth, and marginalized groups.	Facilitate and enhance global opportunities for women, youth, and marginalized groups in STI.
	2.5 Ensure that international and national systems are in place for open communication and knowledge dissemination among the research community and the public of knowledge created from publicly funded RD&D.	Participate in and support global and multi-sector energy innovation partnerships.	Participate in and support global and multi-sector energy innovation partnerships.	Participate in global, national and local multi-sector energy innovation partnerships.	Facilitate global and multi-sector energy innovation knowledge-sharing partnerships.
Priority Result 3 Drastic stimulation of demand for and development of infrastructure for clean energy innovation to ensure economies of scale in line with meeting the 2030 and 2050 targets.	3.1 Support the development of international, regional, and national markets through internationally harmonized standards, financial facilities, pricing mechanisms, and awareness-raising.	Adopt national measures to support national markets.	Apply national and international measures in support of market development.	Raise awareness on market development measures.	Facilitate cooperation and international coordination of measures to develop sustainable energy innovation in regional, national, and international markets.
	3.2 Increase funding for clean energy technologies and innovation by committing to the procurement of clean energy technologies and greening supply chains.	Develop/implement green energy public procurement plans.	Develop/implement green private procurement plans and green supply chains.	Actively engage in developing, promoting, and ensuring the broad application of demand-side measures.	Develop international standards that provide technical assistance to governments and the private sector in developing-green procurement plans and green supply chains.
	3.3 Mainstream inclusive energy-innovation policy, planning, and development of enabling infrastructure to provide increased accessibility and affordability at national and sub-national levels.	Develop energy- innovation policies that are predictable and flexible. Ensure planning is inclusive, taking into account the needs of women and vulnerable groups.	Ensure planning is inclusive, taking into account the needs of women and vulnerable groups.	Mobilize communities to incorporate local knowledge into energy innovation policy and planning.	Facilitate North–South and South–South cooperation and technical assistance to countries that are sustainable and inclusive.

PRIORITY RESULTS	PRIORITY ACTION AREAS	STAKEHOLDER ACTIONS			
		Public	Private	Civil Society	International organizations
	3.4 Require energy suppliers to integrate costs, activities, and partnerships related to productive use of energy (PUE) into their project designs and/or business models.	Embed PUE in the development of policies and programmes dedicated to energy innovation and facilitate access to high-risk, early-stage financing for innovators and entrepreneurs.	Drive innovations around PUE to increase the commercial viability of energy-supply systems, while triggering local economic growth in the target communities.	Advocate implementation of their PUE to governments, private sector, and international organizations. Mobilize the community to increase social acceptance around innovation approaches for PUE.	Provide technical assistance to support governments and the private sector to develop clean energy supply plans that integrate PUE. Facilitate international pooling of resources for high-risk, early- stage financing for innovators and entrepreneurs. Facilitate data-access and sharing for clean energy supply.
	3.5 Make energy tariffs accessible to energy users, particularly in developing countries, taking into account women, youth, and marginalized groups.	Develop smart subsidies, at least at the beginning of clean energy deployment, and in developing countries in particular. Develop Public-Private Partnerships (PPPs) to include tariff subsidies.	Develop joint solutions with energy end users and governments. Develop Public-Private Partnerships (PPPs).	Participate in the development of solutions to make energy tariffs affordable.	Support the development of multi-stakeholder solutions to make energy tariffs affordable.
Priority Result 4 Significantly increased access to, and adoption of, clean energy digital solutions and innovation by all.	4.1 Invest in the development of adequate digital infrastructure supported by digital transformation roadmaps for energy and across sectors.	Ensure policies and regulations are flexible to accommodate new technologies and innovations, with consideration for system-wide benefits. Develop capacity and facilitate cross-department collaboration on digitalization.	Develop pilot projects and monitor the impact of digitalization and Industry 4.0 technologies on energy demand.	Advocate to governments and the private sector the needs of women, youth, and marginalized groups, and provide input on these issues.	Provide technical assistance to governments and the private sector in supporting the adoption of sustainable digital solutions and innovation for energy systems.
	4.2 Strengthen local access and capacity with targeted support to address the skills gap in digital literacy through curriculum development, training, and reskilling programs and paying particular attention to women, youth, and marginalized groups.	Support existing or create new national collaborative mechanisms aimed at bridging the digital divide. Develop partnerships with academia and the private sector that support training and skills development.	Support existing and/or develop new national collaborative mechanisms aimed at bridging the digital divide.	Support development of programs that aim to bridge the digital divide, as well as participation in them.	Facilitate and support existing international and/or national development of collaborative mechanisms that aim to bridge the digital divide and/or support new ones.
	4.3 Increase international and interdisciplinary collaboration and dialogue among stakeholders at global and national level to bridge the digital divide and enhance system resilience against cyber-security risks.	Organize and support interdisciplinary collaboration and dialogue between energy-innovation stakeholder groups on cyber-security risks.	Participate in and support interdisciplinary cooperation and dialogue between energy-innovation stakeholder groups on cyber-security risks.	Participate in interdisciplinary cooperation and dialogue between energy innovation stakeholder groups on cyber-security risks.	Participate in and support interdisciplinary cooperation and dialogue between energy-innovation stakeholder groups on cyber-security risks.

		STAKEHOLDER ACTIONS			
PRIORITY RESULTS	PRIORITY ACTION AREAS	Public	Private	Civil Society	International organizations
Priority Result 5 Substantial increase in the availability, reliability, validity, and completeness of open data and enhanced workflows for planning, deployment, and accessibility of clean-energy and energy-efficiency technologies and solutions.	5.1 Improve data architecture, interoperability, and management to drive meaningful and sustainable innovations by leveraging international standards to enhance data quality and security.	Develop high quality data architecture, management, and governance for clean energy and energy efficiency innovations.	Support the development of high-quality data architecture, management and governance for clean- energy and energy- efficiency innovations.	Provide community input on data architecture and management.	Support the establishment of a new global open-source centre for collecting traditional and emerging types of data. Facilitate the development of international standards, guidelines, and capacities for the adoption of good-quality and interoperable data architecture, management, and governance for clean-energy and energy-efficiency innovations.
	5.2 Leverage data and evidence towards the scaling up of energy innovations through the use of Industry 4.0 (i.e., big data, artificial intelligence, internet of things) technologies, and national and global data platforms.	Make adequate use of Industry 4.0 technologies and data platforms in data generation for planning energy innovations.	Combine data with Industry 4.0 solutions to support energy planning and operational efficiencies.	Advocate for inclusive application of data and Industry 4.0 technologies in the design of energy policies, planning, business models, and innovation.	Facilitate cross-country cooperation in the use of Industry 4.0 technologies and data platforms in planning energy innovations. Support countries in ensuring that data systems are safe, transparent, are non-discriminatory, and respect privacy.
	5.3 Invest in multi-sectoral approaches to data collection, sharing, and monitoring in a disaggregated form by making use of digital technologies, innovations and better integration of available data to take account of local contexts, site-specific information, relevant identity groups, and spatial elements.	Include disaggregated data in the design of energy innovations, policies, and programs, while respecting the need to anonymize the personal data of citizens/users.	Include disaggregated data in the design of energy innovations.	Participate in disaggregated data collection, where appropriate. Support accountability and transparency measures in the collection and application of data.	Facilitate the adoption of common and comparable methodologies for collecting data in a disaggregated form and for the integration of available data on energy- innovation policies and programs. Support accountability and transparency measures in the collection and application of data.
	5.4 Ensure data on energy innovations and workflows are made publicly available with consideration for data sensitivity.	Develop rules and modalities to make data on energy innovations publicly available. Adopt and develop standards and planning principles to enhance accountability.	Where possible (confidentiality clause) make data on energy innovations available to the public.	Consult publicly available data where appropriate.	Support platforms, processes, and policies to make energy innovation data publicly available. Support the development and adoption of standards to enhance accountability.

Note: Energy innovation pathways are not linear; different emphasis is needed on different aspects of innovation (e.g. supply, demand, knowledge) along the way. It is therefore difficult to set time-bound and quantitative milestones for actions to achieve results related to the recommendations mentioned above. As an example, the IEA publication, *Tracking clean energy innovation: A framework for using indicators to inform policy* (2020) proposes a series of metrics with possible ways to measure progress, but without setting any time-bound or quantitative target in that respect. The same rationale has been followed in developing the result and action matrix presented in the rest of this report.

3 GOAL

This report aims to outline recommendations that will align international action on energy innovation, technology development and deployment, and data collection and use, with the achievement of universal energy access by 2030 and net-zero emissions by 2050. As innovation, technology, and data is a cross-cutting theme of the High-Level Dialogue on Energy, this report complements and builds on the in-depth analysis provided by thematic papers on energy access, the energy transition, ensuring a just transition, and energy finance.

To achieve energy access for all and to avoid the severe social, economic, and environmental consequences of climate change that have been projected, a radical acceleration in clean and sustainable energy innovation is imperative. The scope and scale of action necessary is nothing short of a global 'moonshot' that will require unprecedented international cooperation between governments, the private sector, academia, civil society, and citizens. Innovation in policy and planning, technology, business models, finance, and collaboration that is actively inclusive of women, youth, and marginalized communities will be needed in order to foster new clean and sustainable energy solutions and to progress those currently available.

While feasible pathways to meet both targets have been modelled, significant social, economic, and technical barriers persist. Under currently planned policy scenarios, countries are not on track to achieving SDG 7, nor are they aligned to hold global temperature rise to 1.5°C above pre-industrial levels. Deployment of renewable energy has grown over the last decade thanks to innovations in technology and decreasing costs but this deployment is not on pace for meeting 2030 targets. Likewise, half of the emission reductions needed in 2050 require technologies that have not yet reached market, many of which are only in the early stages of development.

The need for investment in research, development, and deployment is urgent. In some key sectors, such as steel, cement, and plastics, there is only a single investment cycle between now and 2050; this means that innovation timelines need to be aligned now with net-zero emission targets and avoid the risk of 'locked-in' emissions from either investing in existing technologies or making only incremental innovations. This challenge has been further complicated by the COVID-19 pandemic, where critical investments in innovation and technology have understandably competed with the immediate social and economic needs brought on by the crisis.

International cooperation and support for developing countries are critical for ensuring countries receive the technical assistance and funding for energy innovations that they need. The growth and application of carbon-intensive technologies and processes in developing and emerging economies risks locking these countries into pathways that are inconsistent with meeting net-zero emissions. The growing digital divide also exacerbates existing inequalities and acts as a barrier to achieving energy access and ensuring that the energy transition is inclusive. Gaps in data and data application have also inhibited deployment of existing clean and sustainable technology solutions that increase energy access.

Immediate action must be taken to develop an international innovation system that is mission-oriented towards addressing these challenges and is supported by investment that is equally ambitious and strategically aligned to place countries on a trajectory to achieving SDG 7 by 2030 and net-zero emissions by 2050, at the same time, leaving no one behind.

4 CONTEXT

The energy sector has historically experienced relatively long incubation periods for mainstreaming innovations because of low private investment in research and development (R&D) and long asset lifetime. In the last decade, innovation in the energy sector has been driven by the convergence of technologies along three trends: decarbonization, decentralization, and digitalization. This convergence has in part contributed to the technologies required to meet the SDG 7 targets and net-zero emissions; all these technologies are known and exist, but are at varying stages of readiness for adoption and deployment.

To meet the targets, energy innovation should not be considered strictly in terms of developing new technologies. In the case of achieving the SDG 7 targets, including energy access for all (7.1), the technologies to extend grids or provide energy services through the use of individual electricity generation systems or decentralized mini grids already exist. Meeting universal access to energy and clean cooking by 2030 requires innovation in policy, finance, and business models enabled by better data collection and application. So, too, do increased deployment of renewables (7.2) and gains in energy efficiency (7.3), where technology solutions have become increasingly available and affordable.

There are different pathways to achieving the goals, each with its own set of trade-offs. The Special Report on Global Warming of 1.5°C of the Intergovernmental Panel on Climate Change (IPCC) models 90 individual scenarios that have a 50% chance of achieving net-zero emissions by 2100, 18 of which achieve a net-zero energy sector and industrial processes by 2050 through a combination of new and existing technologies.[1] In scenarios where warming is kept to 1.5°C with no or limited temperature overshoot, rapid and pronounced system change is necessary, with social, business, and technological innovations contributing to lower energy demand and rapid decarbonization of the energy system through enhanced energy efficiency and rapid electrification of end-use sectors.

Scenarios that are aligned with net-zero emissions by mid-century rely more heavily on the rapid deployment and scale-up of proven clean and sustainable energy technologies and solutions (i.e., wind, solar, storage, energy-efficiency measures, electrification). These same scenarios rely less on technologies that are in the early stages of development (i.e., carbon capture, utilization, and storage, and carbon dioxide removal technologies). The trade-off in delaying rapid deployment of proven technologies is increased reliance on early-stage technologies that carry their own set of risks and uncertainty, which include potentially higher abatement costs and challenges with respect to reaching maturity and scalability in line with net-zero by 2050.

In addition to those in the IPCC report, pathways consistent with meeting net-zero by 2050 have recently been developed by organizations such as the Energy Transition Commission (ETC), International Energy Agency (IEA), and International Renewable Energy Agency (IRENA).[2, 3, 4]

Broadly, the overall combination of strategies necessary can be divided into three main action areas:

1. Improve material efficiency to minimize embodied energy

Material efficiency measures are particularly promising for energy-intensive materials such as steel, cement, steel, plastic, and aluminium, with some estimates suggesting that circular economy strategies could help reduce emissions in heavy industrial sectors by 40%. Economic development has historically been coupled with an increased demand for materials for buildings, infrastructure, and goods and services, and this has contributed to growth in energy demand and CO_2 emissions from material production throughout value chains. Opportunities for material efficiency are present across all stages of a product's life-cycle, from design and fabrication, to use and end of life. Improving material efficiency by adopting circular economy principles can contribute to reducing the demand for inputs (raw materials, transport of raw materials) and, in turn, contribute to emission reductions and decrease the need to deploy other emission mitigation options.

2. Increase energy efficiency to reduce energy demand

Energy efficiency represents more than 40% of the emissions abatement needed by 2040. According to the IEA Efficient World Scenario, cost-effective technologies currently in existence are sufficient to double global energy efficiency by 2040. Innovative solutions in energy technology and digitalization are likely to further boost efficiency improvements.

However, due consideration should be given to trade-offs in achieving energy efficiency, in particular in productive sectors; for instance, energy savings should not be made in agriculture if they lead to reduced production or worsen the quality of food products. The performance of energy efficiency in productive use sectors should thus be assessed taking into consideration the amount and quality of products (i.e., via an indicator of changes in energy use/changes in amount of output).

3. Apply clean and sustainable energy technologies and solutions to decarbonize energy supply

Direct electrification, supported by grid interconnection and rapid deployment of solar, wind, and other renewables, is the primary route to decarbonization of energy supply. This is due to its availability, affordability, and energy-efficiency in technically feasible applications.[6] Innovations that improve grid flexibility, reliability, and resiliency will also be key to advancing future energy systems in this area.

Where electrification is not technically feasible or cost-effective, it is still technically feasible to decarbonize all sectors of the economy through a combination of direct electrification and other technologies.

Hydrogen and hydrogen fuels are anticipated to be key for the decarbonization of heavy trucks, aviation, and shipping, as well as for chemical and steel production. These technologies are clean insofar as the gas/fuels are produced using renewable energy. Significant investment in the sector is necessary to move the technology beyond the demonstration and prototype stage, to address the hurdles in transporting hydrogen (through ground transportation or pipeline infrastructure), to reduce costs of electrolysers, increase production, and achieve economies of scale.

Sustainable bioenergy is versatile and technological readiness is present across much of its value chain. Primarily, it can be used to make transport fuels and generate power and heat when coupled with carbon capture utilization and storage (CCUS).

CCUS technologies can reduce the emissions of fossil-fired plants both in power generation and industry. CCUS can also provide negative emissions when combined with sustainable bioenergy production and permanent storage of CO_2; over the longer term, the CO_2 captured could be utilized to produce synthetic fuels to replace fossil fuels.

TABLE 1. ACTION AREAS AND STRATEGIES

Action area	Strategies (indicative, not exhaustive)
1. Improve material efficiency	1.1 At product design stage • Lightweight products, optimize design, and reduce over-design • Design for use, long life, and reuse • Design out fossil-fuel-based inputs 1.2 At product-fabrication stage • Reduce losses and over-use of materials when manufacturing materials/ products and in construction 1.3 At product use stage • Increase life-time extension and repair • Intensify use 1.4 At end of life • Remanufacture, repurpose, and reuse • Recycle
2. Increase energy efficiency	2.1 Build net-zero energy, water, waste, and net-zero carbon buildings 2.2 Develop district heating and cooling systems where possible 2.3 Apply renewables to space and water heating and cooling 2.4 Retrofit homes and buildings 2.5 Apply digital technologies to make buildings/homes 'smart' and improve energy data monitoring 2.6 Increase energy efficiency performance of products and services 2.7 Improve manufacturing/industrial processes through energy management systems 2.8 Electrify transport and green logistics 2.9 Reduce vehicle distance travelled and modal shifts
3. Decarbonize energy supply	3.1 Deploy renewable energy and storage 3.2 Increase electrification where possible 3.3 Where electrification is not feasible, use one of the following: • Green hydrogen and hydrogen fuels • Sustainable bioenergy • Carbon capture storage and utilization • Other clean energy solutions

To leverage the full potential of decarbonization in these areas and strategies while achieving energy access for all, a holistic approach that embraces systems thinking and considers the entire energy value chain is necessary. Intersecting these strategies are opportunities for innovation in policy and planning, technology, finance, and social innovation, including new governance and business models. Digitalization and Industry 4.0 technologies (i.e., block chain, big data and analytics, artificial intelligence) can act as cross-cutting enablers for system transformation.

As an illustrative example, the demand for batteries is anticipated to grow in the coming decades, driven largely by electrification of the transport sector and the storage needs of a decarbonized grid supported by a large share of variable renewable energy. System-wide innovation that includes collaboration among governments and the private sector, researchers, and local communities is necessary to responsibly and sustainably meet the growth in battery demand and address the environmental, social, and economic risks that may arise.

At the design phase, critical decisions are made, often along with trade-offs that impact a battery's performance, costs, recyclability, and overall material efficiency. The chemistry of a battery, the mining, processing, and transport of raw materials and location of manufacturing, all have a bearing on its embodied energy. The energy efficiency of the production process and the source of energy supply impact the demand for energy and the carbon intensity of the manufacturing process.

Policy, technology, financial, and social innovation and data are now briefly discussed in turn.

4.1. Policy innovation

Achieving universal access and net-zero emissions requires policies and targets that rapidly deploy available technologies and encourage widespread adoption of new technologies over the present decade. In tandem, policy measures must also be adopted that enable major innovations in technologies that are at the demonstration or prototype stage of development and are key to emission reductions between 2030 and 2050.

Innovation is an uncertain, dynamic series of processes—the result of a complex, interconnected system influenced by multiple actors and institutions at different levels.[7] The traditional thinking of a linear model of innovation through research, development, demonstration, and deployment (RDD&D) has evolved to a systems approach that is driven by 'supply push' and 'demand pull' activities shaped by governments, the private sector, and civil society. Also critical for effective energy innovation systems is knowledge management to ensure that new innovations flow to users and to the development of new products. Another crucial area to foster is socio-political support for new technologies and solutions to increase the chances of innovations being adopted by users and decision makers, and to reduce potential tension between innovation and social preferences.[8] Sample indicators for tracking progress of different policy levers can be found in Appendix 1.

TABLE 2. TYPES OF INNOVATION POLICY LEVERS

Enhance innovation supply	Enhance supply and demand	Enhance innovation demand	Facilitate knowledge management	Foster socio-political support
• Direct investment in R&D • Fiscal incentives for R&D • Training and skills • Cluster policy • Innovation network policies • Policies to support collaboration	• Pre-commercial procurement • Innovation-inducement prizes • Standards • Regulation • Technology foresight	• Private demand for innovation • Public and private procurement policies • Behavioural insights	• Intellectual property regime • Open access publication requirements • International cooperation	• Consultations with industry, civil society and other pressure groups • Opinion surveys • Transparent innovation policy processes

Source: Based on Edler & Fagerberg[9]. IEA (2020) *Energy Technology Perspective: Special Report on Clean Energy Innovation*[10]

Innovations in technology have generally required decades to progress from invention, to breakthrough, to diffusion, and then finally to achieving significant market share, particularly in the energy sector. Each stage requires research and innovation and has its own set of feed-back loops and dead-ends as a result of 'learning by searching' and 'learning-by-doing'.

Evidence-based policy that sets science-based targets and is supported by sector-specific roadmaps are critical for realistically aligning energy innovation policy with meeting goals. Unfortunately, the assessment 2020 Emissions Gap Report of the United Nations Environment Programme of the implementation of countries' Nationally Determined Contributions (NDCs) found that the vast majority of countries are not on track to realistically contribute to targets of 1.5°C or 2°C by the end of the century and often fall short on action that goes beyond renewable energy and energy efficiency measures.[11] These national commitments are not only important for guiding government innovation policy and investment, but also for helping drive innovation in the private sector by providing signals of where market demand for certain innovations may be in the future.

To address the historic rate of innovation and meet 'wicked' societal challenges (such as climate change, curing cancer, and healthy oceans), mission-oriented innovation policy (MIP) approaches have been proposed as methods for accelerating the directionality of innovation towards achievement of highly ambitious targets. MIPs are systemic public policies that aim to deploy transformative-based innovation policy.[12] Rather than focusing on pushing innovation, MIPs place the emphasis on addressing societal challenges through coordinating the innovation efforts of a large set of actors by engaging them in the formulation and development of well-defined objectives.[13] Recent examples of the MIP approach being adopted include the European Commission's newly launched Horizon Europe research and innovation programme, which includes the goal of 100 climate neutral cities by 2030.[14]

International collaboration between public and/or private organizations can further accelerate the diffusion of knowledge, reduce risks, bring efficiencies to efforts, and leverage R&D investments for maximum impact by pooling resources.[15] In some sectors, international cooperation around standards and policy are critical to create markets for key energy technologies and innovations that are highly dependent on global markets (i.e., green steel and green cement). Development of international and national standards and harmonization between them can further drive demand for new technologies. Multilateral relaxation of intellectual property regimes can also increase the rate of diffusion of technology and innovation.

There already exist many multilateral, regional and bilateral initiatives, and forums with binding or voluntary commitments that can drive innovation in energy and use of specific technologies. Mission Innovation (MI), formed on the side-lines of COP21 in 2015, is one global initiative focused on accelerating global energy innovation through a programmatic approach that targets key clean-energy technology areas. Alongside MI, the Clean Energy Ministerial is an example of a forum that builds global coalitions around clean energy goals and innovation. See the thematic report of Work Group 2 of the High-Level Dialogue on Energy, which covers the energy transition, for a list of other ongoing initiatives.

Policies must also be in place to support people to develop the local capacity, knowledge, and skills necessary for local innovation and to meet the anticipated growth in research and jobs in the clean energy sector. Measures that support reskilling or job matching are also necessary for those impacted by job losses in the transition. In particular, it is critical to develop policies that are inclusive of women, youth, and marginalized groups—groups that have historically been underrepresented in science, technology, and innovation, as well as in energy policy and planning related to energy.

4.2. Technology innovation

Approximately half of the technologies necessary to meet the target of net-zero emissions by 2050 are still at early stages of development and demonstration; significant energy technology innovation is necessary in key technologies over the next decade to stay on track to meeting this target. In this report, the definition of energy technology innovation used by the International Energy Agency (IEA) is adopted, in which energy technology innovation expressed as 'the process of generating ideas for new products or production processes and guiding their development all the way from the lab to their mainstream diffusion into the market'.[16]

International cooperation and national policy in research, design, development, and demonstration (RDD&D) is critical to ensuring that key milestones are reached for certain clean energy innovations to become commercially available. Creating partnerships with the private sector and universities early in the process can also help to accelerate the rate at which energy technology innovations make it to market. Developing a portfolio of RDD&D around key technology areas can help focus efforts towards reaching the milestones set. A broader overview of technology innovation needs and indicative milestones for achieving them can be found in Appendix 2.

It is important to fund basic research, as it can be hard to predict where the next breakthroughs will come from. However, innovations in specific technologies have significant potential to accelerate advances across multiple low-carbon value chains due to the spillovers of knowledge and applications if linkages are leveraged.[17] The IEA, in its Special Report on Clean Energy Innovation, has identified key technology areas for prioritization based on their potential for knowledge and application spillovers for low-carbon value chains:

- Electrochemistry: modular cells for converting between electricity and chemicals
- CO_2 capture: process to separate CO_2 from industrial and power-sector emissions from air
- Heating and cooling: efficient and flexible designs for electrification
- Catalysis: more efficient industrial processes for converting biomass CO_2 to products
- Light-weighting: Use of lighter materials and their integration into wind energy
- Digital: Integration of data and communication to make energy systems flexible and efficient

This is not an exhaustive list, but covers the type of solutions that hold the most promise for advancing value chains involving electrification, hydrogen, hydrogen-based fuel, bioenergy, and CCUS.

Other technologies that have potential for knowledge spillovers are scientifically complex. They include small modular nuclear reactors and small-LED technologies with high-efficiency motors and flexible or building-integrated solar PV.

A brief overview of the status of technology and innovation across sectors is now provided.

4.2.1 ELECTRICITY FOR THE LAST MILE

Renewable energy systems–based mini-grid and off-grid solutions for addressing electricity access are available but will require innovation in business models to be profitable and affordable for consumers.[18] Innovations include using smart inverters to modularly increase grid capacity, bulk procurement of components to reduce installation costs, and tariff reductions to spur end-use consumption to profitable levels for suppliers.[19] Ensuring access to electricity by 2030 in underserved regions, especially in rural areas, will also require increased and sustained public investment to catalyse private capital and also homegrown innovation that is responsive to the specific needs of end users and consumers in underserved regions/markets.[20]

Likewise, clean cooking solutions are widely available, but they are not on track for adoption by 2030. Emphasis has been on deploying cookstoves based on their efficiency rather than on promoting access to cleaner fuels.[21] A lack of integrated value-chain approaches, marketing-enabling conditions, and poor institutional frameworks act as barriers to scale-up and replicating best practices.

4.2.2 POWER SYSTEMS

Decarbonizing power systems and meeting SDG 7 targets is technically feasible and can be enabled by decreasing costs in renewable energy technologies and storage. Globally, these costs in many places are lower than total costs of new coal or gas plants and increasingly below the marginal costs of existing thermal power plants.

The main challenges to technology innovation in the power sector are the scaling up of deployment of renewables for power generation and the system-wide innovation necessary to leverage the convergence of multiple technologies that can improve grid flexibility and increase the penetration of distributed variable renewable energies. Solutions include building networks of Ultra High Voltage (UHV) backbone grids and smart grids to form an interconnected platform capable of realizing the large-scale of renewable energy, electricity transmission and affordable energy for all. These solutions also support the maintenance of the grid reliability of a low-inertia, inverter-dominated system and the reduction of grid costs, while addressing projected growth in energy demand. IRENA has identified 30 emerging innovations in technologies, business models, market design, and system operations that support the adoption of variable renewable energies into power systems.

4.2.3 END-USE SECTORS

Achieving zero emissions in industry will be difficult, especially for heavy industry which accounts for 18% of global CO_2 emissions and 25% of energy demand.[24] Deep decarbonization requires three complementary innovations: (i) demand management through material efficiency and adoption of circular economy principles (recycling, reuse, product design for circularity, and extended product-life time); (ii) energy efficiency improvements through advanced production techniques and the application of digital technologies that can contribute to short-term emission reductions; and (iii) the application of decarbonization technologies (electrification, green hydrogen, and hydrogen-based fuels, sustainable bioenergy, CCUS, etc.) across sectors based on cost-effectiveness and local resources.[25]

Technologies needed in industry to drastically reduce emissions are at an early stage of development. In particular, technologies that provide high-temperature heat are needed, as in many cases this cannot be addressed by electricity using commercial technologies or by reducing process emissions from the chemical reactions inherent in industrial feedstocks.[26] Low-carbon options to achieve this include: (i) biomass and biofuel combustion; (ii) hydrogen combustion; (iii) electrical heating; (iv) nuclear heat production; and v) post-combustion carbon capture. Each option currently poses limitations or challenges to commercial deployment. Industry equipment needs are also expensive and long-lived (blast furnaces and cement kilns operate for 40 years, slowing deployment of new technologies). Industrial materials are also highly price-sensitive due to being traded on global markets.

The transport sector also has significant technology challenges to decarbonization, especially with respect to long-haul freight, shipping, and aviation. Rising incomes and population growth in developing countries could drive up transport needs, increasing the sector's decarbonization challenge. Electric vehicles (EVs) are expected to become cost-competitive with internal combustion engine (ICE) vehicles by the mid-2020s, thanks to innovation in battery technologies that reduce cost and improve range. EVs provide a unique opportunity for sector coupling between the energy and transport sector, as innovations in Vehicle-to-X electric vehicle (EV) technologies are allowing EV batteries to provide grid services when vehicles are not in use, with the potential to increase grid flexibility and support the penetration of variable renewable energy.

EVs are also increasingly being deployed in the Global South. For instance, E-rickshaws currently comprise 83% of the Indian electric vehicle market.[27] However, in many countries, the sector requires continued development of an enabling environment for mass adoption (i.e., charging infrastructure, lower upfront costs).

Decarbonization in heavy-duty trucking, shipping, and aviation is more challenging than in light-duty vehicles because of the formers' energy and power-density requirements. Technically viable alternative fuel technologies (hydrogen, biofuels) are not advanced yet and their initial costs are not competitive with oil-based fuels.[28]

Buildings account for a third of global final energy consumption, creating direct and indirect emissions from electricity and commercial heat. Energy demand for heating and cooling is rising due to growth in air-conditioner ownership and more frequent extreme weather events, with space-cooling demand anticipated to grow by 300% in emerging and developing countries by 2050.[29] To meet the goals of the Paris Agreement, buildings across the globe will be required to improve their energy intensity by 30–50% per square metre.[30]

Innovation needs for buildings depend on the local climate, building type, local energy systems, and availability of technology and building materials. Buildings have four main areas of innovation: building design and performance (energy-efficiency measures, minimizing demand, construction materials); advanced building technologies (integrating renewables, electric heat pumps, energy storage to balance demand); systems and integration (smart solutions that improve flexibility and integrate with larger energy systems, district heating and cooling networks); and cross-cutting innovation (new business models, knowledge, and skills).[31] Barriers to technology adoption in buildings include the continued operation of fossil fuel-based assets, a dearth of effective energy-efficiency policy and enforcement regimes in many regions, and high transaction costs in the adoption environment: these all dampen the flow of investments into technology solutions.[32]

Food systems use about 30% of global available energy, mostly in the form of fossil fuels beyond the farm gate,[33] which represent about 30% of greenhouse gas emissions from food systems.[34] At the same time, energy poverty affects food systems in many developing countries and emerging economies, resulting in significant food losses and reduced income for food chain actors.

There is an increasing interest from governments, private-sector companies, and international institutions in implementing clean energy solutions in food systems. The food sector can produce renewable energy—for instance, from food chain residues and solar panels in agricultural fields.

Energy systems used in food value chains can also support other sectors. Examples are: allowing the pumping of good quality water; powering of local clinics; and supporting families, especially women, through livelihood-generating activities. This synergy between energy for food and health applies also to clean cookstoves, where interesting innovations that combine cooking with other functions like lighting or device-charging result in more value for money and thus have improved adoption rates (e.g., in India).[35]

Finally, combining renewable energy systems with end uses, as seen in integrated food-energy systems, can reduce possible competition between the use of land for energy and other purposes.[36]

Co-locating renewable energy systems can reduce their land footprint and deliver significant investment and operating savings.[37] Moreover, co-locating large-scale intermittent renewables like solar with energy storage has several benefits, from future proofing schemes and optimizing sites to making behind-the-meter solutions more attractive.

4.2.4 ENABLING TECHNOLOGIES AND APPROACHES

Across sectors, digitalization is converging with two other trends: decentralization and electrification. In tandem with these trends, artificial intelligence, big data, and distributed ledger technologies, such as block-chain, are contributing to a grid that is flexible and able to integrate a larger share of variable renewable energy at reduced costs.[38] Digital technologies are also enabling innovative new business models that support last-mile energy access, such as pay-as-you-go solar business models. Combined with remote sensing, digital technologies can also help to assess the energy profile of energy consumers in a cost-effective way. End-use sectors are also adopting Industry 4.0 technologies with potential transformative technologies that are close to deployment, such as autonomous vehicles, intelligent home systems, and machine learning.[39]

While digitalization presents many opportunities for achieving the SDG targets and the net-zero goal, it is not without risks. Data centres and crypto currency mining are contributing to a growth in energy demand that needs to be managed. Digitalization makes energy systems more vulnerable to cyber-attacks, and some areas in cities, for example, still lack the basic infrastructure to enable any engagement with digital technologies. This affects different groups in different places, but most often the poor and vulnerable are disproportionately affected.

Consumer concerns about privacy and data ownership must be addressed, especially given the projected growth in connected devices and appliances. Ensuring data can be aggregated and anonymized is critical for improving energy systems, understanding load profiles, and reducing costs for individual consumers. Digitalization also impacts jobs and skills in the different energy sectors, presenting job opportunities in certain areas and losses in others. It is critical for governments to manage the transition to guarantee that no one is left behind.

Standards related to energy innovations can help overcome interoperability and implementation challenges. Furthermore, standards are instrumental for overcoming the silo approach to technological innovation, developing a common language for innovation that enables progress to be made on a collective basis, and to elevate best practices that can benefit all the stakeholders involved.

The climate change impacts of enabling technologies can be important. For instance, the information and communications technology (ICT) sector currently accounts for about 2% of global emissions, and under worst case scenarios, potentially increasing to 23% by 2030 as a result of growth in energy demand.[40] At the same time, ICTs and digital technologies can enable up to a 20% reduction in global CO_2 emissions by 2030 when applied to five sectors: mobility, manufacturing, agriculture, energy, and buildings.[41]

4.2.5 CONVENTIONAL FUELS

Although pathways consistent with net-zero emissions by 2050 project a substantial decrease in the demand for oil and gas and indicate that no additional new investment is necessary in the sector, innovation can help reduce emissions from existing assets. Within the energy sector, methane emissions—the second-largest cause of global warming—come from oil, natural gas, coal, and bioenergy. Further innovation is necessary to better understand emission levels, detect and repair leaks more consistently, and reduce emission mitigation costs.

Efforts are also needed to increase the capture rate of CCUS power plants. Currently operating plants capture only 90% of the CO_2 from the flue gas, and measures must be taken to close the last 10%.[42] Innovation is also necessary to improve the cost-competitiveness of retrofits to existing plants.

4.3. Financial innovation

Innovative financing mechanisms have been developed and implemented in the distributed renewable energy and clean cooking space, although further innovation will be necessary to meet SDG 7 targets. The high cost of investment often represents a major challenge in transitioning to clean energy systems and access, both for the energy supplier and the energy user. Conventional financing solutions have proven their limitations in addressing challenges of the energy transition, particularly for the poor.

From the energy supplier side, there are obstacles to ensuring sufficient and regular energy demand that can be paid for. Frequent additional hurdles in rural areas often result in limited and scattered demand, with users often unable to afford paying the rate that would cover the operational costs of energy suppliers.[43] To address this, financial innovations have been introduced including guarantees, blended concessional finance, results-based financing (RBF), securitization and currency risk instruments, and enterprise challenge funds.

Digital technologies and remote sensing are also helping energy suppliers to better assess demand.[44] Other solutions for suppliers include aggregating demand, for instance, through bulk procurement,[45] or grouping energy consumers, such as in the farm blocks programme in Zambia (also see COOPEM case study in Appendix 3).[46]

From the energy-user side, ensuring adequate access to sustainable modern energy for all requires that energy costs and energy appliances be made more affordable. Pay-as-you-go (PAYGo) has demonstrated itself to be a promising and innovative financing solution for addressing energy costs. Thanks to widespread mobile money and coverage by the Global System for Mobile (GSM) Communications, the PAYGo solar business model allows end-customers to finance their small-scale systems with the PAYGo company, which typically holds the consumer debt on its own balance sheet.[47] However, a major barrier to PAYGo's scaling up relates to capital constraints on the energy supplier's side for product financing: handling credit and liquidity issues. Innovative finance to address this includes sourcing funds from crowdfunding and combining PAYGo with micro-financing.

Another key area for financial innovations for the productive use of energy is improved affordability of renewable energy appliances. Many models exist, such as including RE appliances in vendors' energy packages (as in Nepal),[48] developing rent-to-own schemes (as in Uganda),[49] or making such appliances competitive with fossil fuel ones (as with solar grain mills in Tanzania).[50]

Financial innovation is also critical for achieving net-zero emissions by 2050. Financing innovations in this area include carbon markets and climate crediting mechanism (e.g., the Clean Development Mechanism, which puts a price on carbon to internalize the environmental and social costs of carbon pollution and permit trading; green bonds; debt for nature swaps; disaster risk insurance schemes; impact investment; environmental trust funds, and payments for ecosystem services (PES). Where funds for innovation are limited, governments can explore coordinating their procurement across different ministries and departments.

Financial institutions and companies are also looking at measures to drive decarbonization. Banks, development institutions, and other credit institutions are also requiring the disclosure of environmental, social, and government (ESG) risks. Many energy companies are also coalescing around the Task Force on Climate-related Financial Disclosures (TCFD) and the Sustainability Accounting Standard Board's (SASB) reporting frameworks.

4.4. Social innovation

Clean energy transition and access to energy cannot be achieved by relying solely on technological and financial innovations. The uptake and use of these innovations will require new ways of organizing and governing energy supply and demand and recognizing the sociological dimensions of clean energy. It is envisaged that different groups in different places will be able to lead, shape, and engage (or not) with clean energy based on their gender, socio-economic status, age, where they live, the skills they have, and so forth.

Due consideration must therefore be given to the socio-economic and cultural context in which energy innovations occur to fully ensure that all groups can equally lead, participate in, and benefit from them. This requires the relevant energy producer and user groups to be sufficiently empowered to undertake these tasks, for energy infrastructure to be connected and integrated across cities and regions, and for stakeholders to be suitably engaged in government and private sector energy initiatives. A focus on the socio-culture and spatial elements will help ensure that this innovation is 'homegrown'.

Despite the absence of a unique definition on the features common to social innovation projects in the energy sector, there is increasing consensus as to what they entail: they emerge bottom-up; contribute to civic empowerment and improved collaboration; boost low-carbon energy transition; and adapt to local context and strive for the general well-being of society.[51] Some of the most often-cited advantages of social innovations in energy development include enhanced acceptance of renewable energy systems (in particular, on-shore wind energy, e.g., in Germany),[52] increased affordability of energy (e.g., in Sweden),[53] citizen participation in decision- and policymaking to ensure more effectiveness and coherence, and improved communication leading to attitude change (e.g., in Tajikistan).[54]

Experience shows that successful social innovations, including those relating to energy, often require a history of successful bottom-up governance and multi-sector partnerships. This applies particularly to community energy, a type of social innovation that is present in the Global North (in particular Europe), which is gaining momentum elsewhere in the world. Community energy does, however, limit the possibility to scale social energy innovations and it also complicates government support, as it has to be tailor-made. However, energy communities have recently addressed these challenges through partnering with local governments and the private sector. Partnerships between the different actors in the energy chain allow each of the actors, regardless of their size and geographical location, to receive and share information that is necessary to develop their own renewable energy projects. This is all the more beneficial when innovation allows for new solutions that guarantee more accessible and less expensive energy.[55]

The advent of various renewable energy sources and the IOT is transforming energy consumers into energy prosumers, namely, people who consume, as well as produce energy to give it back to the grid. This is creating opportunities for new business models that are consumer-centred. Technological innovations can also enable social innovations such as peer-to-peer trading enabled through blockchain, and the participation in local energy collective structures. However, it is important to ensure that digital rights and access are given due consideration when exploring these options.

Education on energy innovation is also crucial to facilitating its acceptance and the deployment of existing and new technologies. Education can target all levels, but emphasis should be placed on future young professionals, researchers, and entrepreneurs, with a focus on supporting women. Combined technology and social innovations have recently occurred in the education sector in rural areas, addressing both the digital divide and energy access challenges. This has been the case with the UNESCO-supported Avicenna Virtual Campus Network (AVCN), which developed a Mobile Avicenna Virtual Classroom (MAVC), working in places without grid electricity and internet in Burkina Faso, Chad, Libya, Morocco, and Sudan.[56]

Some initiatives, like the KOKO bioethanol cookstoves programme in Nairobi, Kenya, combine technical, financial, and social innovations (see case study in Appendix 3).

4.5. Data availability and data systems

High quality, reliable data are a prerequisite for making evidence-based decisions and also for planning, monitoring trends, and tracking progress toward policy goals, including meeting SDG 7 targets. For example, reliable statistics on energy production and demand provide a robust starting point for energy planning. Data systems need to be improved to address data gaps and tackle the problems of underserved communities. They must, however, be sensitive and nuanced in terms of capturing the range of stakeholders involved in energy ecosystems, including beneficiaries that fall into vulnerable categories or who live in remote or informal parts of cities and countries.

In line with the above, the policy of open access data- and knowledge-sharing in the energy sector should be considered a priority. Open access data, tailored information, products, and tools will boost efforts in the energy sector, by providing a knowledge sharing network for the less developed regions and countries, to help leave no one behind.

Innovations such as smart metering, big data, artificial intelligence, and the IOT can be used to generate new data, and to improve energy analytics and forecasting for renewables, while also driving greater energy efficiency. While the need for new data is critical, better use of existing data for planning and design also needs to be achieved. GIS data, real-time Google maps, meteorological, and climate data can be used to inform sectoral development plans, energy planning for smart cities, and energy planning to improve energy-access planning and monitoring.

Appropriate open data management is critical and forms a foundation for further innovation. For example, goals have been developed to enable good governance with respect to data, analysis, and stakeholder engagement. The so-called U4RIA goals allow the process of policy analysis, as well as public engagement (which builds on that data), to become increasingly accountable.[57]

As the energy sector is continuously moving towards new cleaner energy technologies and improved e-communications and data mechanisms, integrating the needs and participation of women and men remains critical. Data based on gender-constructed stereotypes are already aggregated in the fields of smart metering, energy data collection, and technology-adoption methods. Caution is required to ensure that artificial intelligence does not amplify gender inequality.[58, 59]

Some risks of unintentional bias stem from the fact that most algorithms used to train machines are created by men. Whether unconscious or deliberate, such biases seep into AI artefacts and need to be addressed through systematic interventions. Further research and advocacy for gender equality throughout the entire cycle of designing, testing, and deployment of AI applications are needed to ensure that AI remains inclusive and that each gender can equally lead, participate in, and benefit from it.

5 CHALLENGES

Scaling up the application of innovations, technology, and data present structural and specific challenges. Broadly speaking, clean energy technology innovation and deployment endeavours are taking place in a transitioning energy system; here the rules of the game that are influencing the selection of innovations and adoption environments have not evolved fast enough to overcome the favourable conditions for incumbent technology regimes (i.e., fossil-based energy systems).

Historically, tension and resistance have always been part of the emergence of a new technology regime. They are compounded by the unique challenge facing zero-carbon technologies and innovation, such as cost premium (not internalized by the incumbent), economies of scale, vested interests, and long-term capital, as well as all types of market distortions favouring the incumbents. Moreover, in general, there is a lack of awareness regarding the possible social and environmental costs associated with technological advancements and innovations.

It should also be noted that not all technology contexts are the same, with innovation challenges being unevenly distributed across geographies. This section therefore assesses some of the key cross-cutting challenges specific to the need to foster technology and innovation systems so that progress can be achieved on SDG 7 by 2030 and net zero by 2050.

5.1. Achieving the 2030 targets: challenges in broadening technology adoption

From the context section we can clearly see promising progress being made across a broad range of technologies to deliver on the SDG 7 targets, coupled with enabling innovations in finance, business models, and institutions. However, most of these remain in isolated pockets and geographies, and/or the pace of change is insufficient. Significant challenges remain in broadening the adoption of technology in line with achieving energy access by 2030 while rapidly increasing the deployment of renewables and the gains in energy efficiency required to meet net-zero emissions by 2050.

Distorted incentives that favour fossil fuel consumption and production remain an obstacle to renewable energy markets. Global subsidies for fossil-fuel consumption reached USD 400 billion in 2018—a 30% increase over the previous year and double the estimated total for renewable power generation.[60] While some countries are phasing out existing fossil-fuel production and infrastructure, in many countries, investment continues for new fossil-fuel production and related infrastructure, both for use domestically and abroad. Private bank funding for, at times, inefficient fossil fuel projects has grown annually since the signing of the Paris Agreement in 2015, totalling USD 2.7 trillion between 2016 and 2019.[61] The true cost of fossil fuels to society is estimated at USD 5.2 trillion, inclusive of negative externalities (air pollution, traffic congestion, and the effects of climate change).[62] Fossil fuel systems and infrastructure are often inefficient and pose additional challenges in the form of stranded assets. Cumulative stranded assets between 2015 and 2050 across the buildings, industry, power-generation and upstream sector have been estimated at USD 10 trillion— with these costs potentially doubling by 2030 for all sectors if policy action is delayed.[63]

Competitive auctions that support access to energy have favoured larger multinational energy companies collaborating together rather than smaller actors, including community-led groups. The larger energy companies focus on urban areas that have the ability to pay for the energy they generate rather than underserved regions, which are prone to energy poverty. To support the deployment of renewable energy systems, countries tend to switch from a feed-in tariff (FiT) policy to competitive auctions and tender mechanisms, and to focus on deploying large-scale centralized projects. Decentralized energy systems have lagged behind as the major means of powering the last mile. According to the Renewables 2020 Global Status Report, the number and diversity of local investors has declined since the shift to auctions, while installations have become concentrated geographically.[64]

A lack of knowledge and confidence in low-emission solutions along with gaps in capacity and skills pose challenges for the deployment of existing clean-energy technologies and for fostering innovation. Tracking progress against the SDG 7 and SDG 13 targets is also difficult for some countries where national capacity is absent. These challenges are further exacerbated in some contexts by a lack of awareness regarding energy-related issues and the impacts of climate change, resulting in limited engagement on these issues.

Limited availability of the necessary financing and investment for energy access also continues to be a barrier. According to the Renewables 2020 Global Status Report, an estimated USD 51 billion is required annually to achieve universal electricity access in 20 high-impact countries by 2030 using Distributed Renewables for Energy Access (DREA); however, around only USD 36 billion was invested in 2017. Global investment in renewable energy capacity has seen a steady increase since 2010, reaching an estimated USD 300 billion in 2019, with only 5% of the global amount invested in Africa, where 82% of people live without energy access. Investment in the DREA sector is beginning to decline, with capital flows to off-grid electricity systems dropping 20% from the USD 395 million raised in 2018, to USD 311 million in 2019.

The lack of information and data also remains a barrier to de-risking and optimizing investments in clean energy solutions, particularly in productive use sectors. This represents a major barrier to accelerating progress on clean energy access in many developing countries, including small islands. Grid infrastructure data, local technology costs, renewable resource assessments, and land-use information, are often unavailable.[65] Finding appropriate planning tools is also difficult, given the lack of data and the need, in these contexts, to consider latent unmet energy demand and energy access.[66] The inability to model energy needs or foster inter-sector linkages also slows down the deployment of allocated resources. The resolution of current climate models is still too coarse to accurately capture climate change and extreme-event impacts locally and across interdependent systems (i.e., changes in demand, wind and solar outputs, pipeline and grid infrastructure, etc.).[67] Better data can also help to make decisions more transparent, investments less risky, and development easier to monitor so that new learnings can be captured and future plans designed. At the same time, the available digital and remote sensing technologies, and the related assessment approaches that address this challenge, are under-used.

Data privacy and protection of data use from misuse by data companies and agencies also remains a risk as application of digital technologies within the energy sector grows. Protection needs to be in place for cities, public utilities, and countries to reduce exposure of infrastructure systems to cyber-attacks, and also to reduce the risk of not being able to reach poorer and vulnerable groups in cities and regions.

5.2. Technology and innovation for achieving net-zero by 2050: challenges with technology development and demonstration

Achieving net-zero by 2050 will require innovation cycles in clean energy technology development that significantly outpace recent successes. Under the International Energy Agency's "Faster Innovation Case", technologies that are at the laboratory or small prototype stage would have to be commercialized in ten years on average: this kind of rapid progress has only been seen with LEDs, which require low levels of capital expenditure and, being compact, can be mass-produced.[68] To realize their potential as solutions by 2050, direct electrification, hydrogen and hydrogen derived-fuels, and CCUS need to be developed rapidly in a wide range of technologies at different levels of maturity and at different points in their value chain. The COVID-19 crisis has the potential to slow down the pace of innovation, reduce R&D spending, and maintain attention on long-term climate goals.

Policies, regulations, and financial incentives across sectors are not always aligned with the promotion and adoption of clean energy technologies and, in many cases, favour incumbent technologies. Key technologies, such as green steel, lack the global markets necessary to create demand and to achieve the economies of scale required for them to be deployed at scale. Sector-focused international cooperation between governments and the private sector is necessary to develop these markets and nurture these technologies towards adoption at scale. Opportunities for innovation through sector-coupling are also often overlooked due to silo approaches to energy policy and planning.

Lack of confidence amongst policymakers, companies, and investors about what possibilities are on offer is discouraging the kind of action on policy and investment that is needed for faster technology development and adoption. The inherent risks and uncertainties associated with new technologies impede the policy and investment decisions that would encourage demonstration and early adoption. This challenge is exacerbated by the limited understanding of the risks associated with new technologies on the part of financial institutions and investors, which creates additional barriers to investing in new technologies.

Limited resources for research, development, and demonstration (RD&D) increase the risk that key technologies, needed for decarbonization and that are only at the early stages of development and commercialization, will not reach scale within the necessary time horizons. Sustained, long-term targeted investment from the public and private sector is needed but continues to fall short. Investment in clean energy technology RD&D has grown in recent years since 2017 to approximately USD 30.8 billion annually, with most additional funding targeting low-carbon energy technologies.[69] This funding falls considerably short of the estimated USD 100 billion annual public investment required to meet targets. Private sector R&D spending has increased by an estimated 40% since 2010, with an IEA sample of companies in the energy technology sectors increasing annual spending by approximately 5% in 2019 — a total of USD 92.4 billion. However, compared with the public sector, the majority of R&D spending is dedicated to incremental improvements to existing technologies as well as product development.

Barriers to international collaboration on RD&D also hinder efforts to align innovation efforts with targets. Examples include the transaction costs of collaboration, restrictions on intellectual property, lack of pooled funding to derisk RD&D investments, and concerns around competitiveness.[70] Some countries also lack the institutional capacity and resources to manage multiple bilateral collaborations. While recent shifts towards non-binding, voluntary, and short-term collaborative structures have enabled flexibility, they can also put at risk essential long-term and multilateral RD&D.

A lack of diversity in the energy sector workforce needs to be addressed. Studies have shown that companies with more women on their board are more likely to proactively invest in renewable energy and reduce carbon emissions across the value chain, and countries with higher female parliamentary representation are more likely to seek to reduce their carbon dioxide emissions.

Developing countries need to enhance their science, technology and innovation (STI) capabilities and apply their entrepreneurial potential to leverage opportunities, while creating response capacity for facing anticipated challenges.[71] This includes enhancing the STI capabilities of women, youth and marginalised groups that have been historically underrepresented in this area.[72]

Weak demand signals from governments and/or the market for clean energy technologies hinders the deployment of existing and emerging technologies. Government policy has played an important role in the growth of renewable technologies and continues to be critical in overcoming economic, institutional, and technical barriers. However, many countries have not committed to net-zero emissions by mid-century. Significant progress has been made globally, with nearly all countries having renewable energy support policies in place. However, the level of ambition varies and often focuses only on the power sector. The number of countries with mandates for renewable heat and for renewable energy support in transport and industry is still small.[73]

Despite progress, the digital divide remains a challenge and hampers the wide deployment of technological and financial innovations. Access to the internet is nowadays considered key for the progress of society, and many technological and financial innovations rely on steady, high-speed fixed internet connections. However, to date, almost half the world population is still offline.[74] This is particularly the case for many developing countries that lack adequate digital infrastructure and where, for most people, internet costs are prohibitive.

6 RECOMMENDATIONS

Innovation has played a key role in enabling progress towards the SDG 7 targets, with innovations in power generation technologies having considerably reduced costs, accelerated the uptake of renewable energy, and offered opportunities to engage and empower poor and vulnerable groups and communities to be part of renewable energy ecosystems. The overall progress towards achieving the 2030 Sustainable Development Goals and the longer-term 2050 Paris Agreement targets has been limited to date. Major innovation is still needed in all aspects of the energy system. The most pressing innovation needs are now in the end-use sectors of transport, industry, food, and buildings. Emerging technologies such as the digitalization of grid services, battery storage, smart charging for electric vehicles, wider utilization of mini-grids, and others, will be key enablers.

Delivering energy innovation will require increased and focused action that is better coordinated across national governments, international initiatives, and the private sector. As innovation does not follow a linear pathway from product to market, there is a need to move towards a systemic approach to innovation that takes into account innovations in systems, processes, market design, business models, and socio-cultural contexts.

The requirement for clear frameworks to ensure the participation of all key stakeholders in clean energy ecosystems, in the design and operation of the energy system, and in ensuring sustainability in the implementation of energy innovations, should, however, be noted.

It is of crucial importance to ensure that energy innovations, from both the supply and demand sides and related enabling technologies, are implemented in a sustainable manner. To secure acceptance of energy innovations, their sustainability needs to be guaranteed early on. Confidence in the sustainability of energy innovations will also be helpful in buoying up public confidence and helping to accelerate the upscaling of new energy innovations: unwanted impacts creating distrust are better avoided. Ensuring that energy innovation is sustainable, can also help to clear pathways towards CO_2 neutrality, in line with recent important commitments to that end by major stakeholder groups.

To meet these targets and realize the positive transformational opportunities presented by the energy transition, energy innovations should follow four key principles:

- Set an ambitious vision: Align innovation, policy, finance, and action with achieving SDG 7 targets by 2030 and net-zero emissions by 2050;
- Integrate sustainability: Ensure that social, economic, and environmental sustainability are considered in the design, implementation, and monitoring of energy innovations;
- Act locally: Ensure that innovations are customized to the local context to ensure that energy innovations fulfil the needs and aspirations of local stakeholders and end users; and
- Leave no one behind: Consider a diversity of needs based on geography, gender, equity, age, and marginalized populations; also address issues such as the digital divide, affordability, and capacity development.

The recommendations outlined in this section aim to address specific challenges and opportunities identified in the previous sections.

RECOMMENDATION 1

Align energy innovation governance and international cooperation with meeting the targets for 2030 and 2050.

Strengthen national and local energy innovation governance and international cooperation around mission-oriented policies and strategies: these must be informed by evidence and science-based targets, as well as backed by long-term predictable funding and financing that drive 'homegrown' innovation, and guided by the principles of a just transition.

Priority Result 1: *Energy innovation governance, cooperation, and capacity are aligned with the 2030 and 2050 targets.*

Governments need to set a clear direction for energy innovation using mission-oriented policies that include evidence and science-based targets, and are based on goals that are ambitious, measurable, time-bound, and align with achieving energy access by 2030 and net-zero in 2050. Targets and goals should be co-developed with all stakeholders from government, the private sector, academia, and energy users, with clear responsibilities being allocated to each of these groups. COVID-19 economic recovery packages should be developed to leverage synergies with energy innovation policies where possible.

Measures should also be adopted that strengthen national and local ecosystems to accept energy innovations in support of meeting these targets, and to facilitate 'homegrown' and contextualized innovation. Programmes and opportunities that support building the capacity of energy professionals and entrepreneurs, including as part of a just transition, should be created or enhanced, especially for youth, women, and marginalized groups.

The global targets cannot be reached without international cooperation and multi-sectoral partnerships. North–South, North–North, South–South and triangular cooperation is necessary to foster energy innovation and enable technology transfer. Countries should promote open-access policies in this area to accelerate the diffusion of best practices and know-how.

PRIORITY ACTION AREAS:

- 1.1 Develop, implement, and monitor mission-oriented energy innovation visions and ecosystems in line with meeting the 2030 and 2050 targets and ensure policy coherence by aligning the objectives and impacts of energy innovation with binding commitments (to SDGs and in NDCs);
- 1.2 Adopt existing international technical standards and quality-control requirements or develop new ones, and harmonize these with energy supply and demand policies and regulations at the national level;
- 1.3 Strengthen local and national ecosystems to support 'homegrown' energy innovations and green value chains;
- 1.4 Develop programs that provide opportunities and build the capacity of professionals, including youth and women, both on the supply and demand side of energy innovation, and in data collection and monitoring; and
- 1.5 Foster multi-sector partnerships for energy technology innovation and enable cooperation through open- access policies, best practices, and knowledge exchange.

RECOMMENDATION 2

Expand the supply of energy innovation that addresses key gaps

Enhance international cooperation and national commitments in partnership with the private sector to expand the supply of clean energy innovation through targeted, sustained, outcome-based funding in research, design, development, and demonstration that is proportional to the challenge and which sets solid milestones for scaled-up commercial adoption.

Priority Result 2: *Rate of technology research, development, and demonstration is increased to be consistent with meeting the 2030 and 2050 targets.*

Countries should develop portfolios of prioritized, clean- and sustainable-energy technology innovations based on national and local needs: these should be supported by proportional and matching outcome-based funding that is necessary for them to meet the milestones on the way to achieving the 2030 and 2050 targets. Sector-specific commercial-scale pilot and demonstration projects should be developed with the early involvement of the private sector. Designed to optimize user benefits, these will help overcome barriers and expedite innovation.

An International Energy Innovation Fund within the UN system should be established to assess the gaps in developing country financial resources for localized energy innovation and to mitigate the chance of underinvestment due to the competing funding priorities that have emerged as a result of COVID-19. Research and education opportunities for women, youth, and marginalized groups in science, technology, and innovation (STI) targeting energy innovation should also be developed or enhanced to promote inclusiveness, and these groups should be represented and participate in actions to meet both targets.

Global collaboration and international and national systems for knowledge dissemination among researchers and the public are also critical for ensuring the rapid diffusion of new knowledge and innovations. Communication of the results of publicly funded RD&D is also important for highlighting results and building continued support for public investment.

PRIORITY ACTION AREAS:

- 2.1 Implement sector-specific commercial-scale pilot and demonstration projects with consideration for user benefits, in particular for women and vulnerable groups;
- 2.2 Strengthen commitment to predictable, sustained, outcome-based funding in RD&D and invest in portfolios of key technologies and innovations to accelerate early-stage development to commercialization. Strengthen energy system reliability, resilience, and/or security;
- 2.3 Approve the creation of the International Energy Innovation Fund to address the lack of financial resources for localized energy innovations in developing countries;
- 2.4 Increase research and education opportunities directed at energy innovation for women, youth, and marginalized groups in science, technology, and innovation (STI); and
- 2.5 Ensure that international and national systems are in place for open communication and knowledge dissemination among the research community and the general public of knowledge created from publicly funded RD&D.

RECOMMENDATION 3

Increase the demand for clean and sustainable energy technologies and innovation

Accelerate demand for clean and sustainable energy technologies and innovation through market-oriented policies, harmonized international standards, carbon pricing mechanisms, enabling infrastructure, fiscal incentives, and access to finance, regional and local green value chain development and commitments to public and private procurement of clean energy technologies.

Priority Result 3: *Drastic stimulation of demand for infrastructure for clean energy innovation and the development of it to ensure economies of scale in line with meeting the 2030 and 2050 targets*.

To accelerate the adoption of energy innovations and to upscale them, action is needed to create certainty in the demand for new technologies: at the same time measures are needed that reduce initially higher costs for emerging technologies that have not yet realized economies of scale. In sectors where demand and price are highly dependent on international markets, countries must collaborate to create new international markets. This is particularly the case in the aforementioned "hard-to-abate" sectors, where green steel and green cement will likely need to be coordinated internationally and regionally, and possible measures taken, such as the development and harmonization of international standards, pricing mechanisms, and financing facilities.

Public and private procurement are powerful tools for driving demand for emerging technologies and increasing innovation budgets. Governments at all levels purchase enormous amounts of cement, fuel, and steel. Policy and incentives such as tax credits and loan guarantees that target the private sector and citizens can also stimulate demand for new technologies. Governments also have tremendous influence in building the enabling infrastructure that supports bringing new and existing technologies to market, such as transmission lines and utility storage for wind and solar, charging infrastructure for electric vehicles, and pipelines for hydrogen.

Mainstreaming inclusive energy policy, and planning and infrastructure development are also critical for ensuring accessibility and affordability for all members of society. Energy developers need to 'think outside the 'energy box', by designing energy services around the productive use of energy (PUE), and not just concentrate on energy supply. Regulations and energy tariffs also need to be made accessible to energy users.

PRIORITY ACTION AREAS:

- 3.1 Support the development of international, regional, and national markets through international harmonized standards, financial facilities, pricing mechanisms, and awareness-raising;
- 3.2 Increase funding for clean energy technologies and for innovation by committing to the procurement of clean energy technologies and greening supply chains;
- 3.3 Mainstream inclusive energy innovation policy, planning, and development of enabling infrastructure for increased accessibility and affordability at national and sub-national levels;
- 3.4 Require energy suppliers to integrate costs and activities and to pursue partnerships related to productive use of energy (PUE) into their project designs and/or business models; and
- 3.5 Make energy tariffs accessible to energy users, in particular in developing countries, taking into account women, youth, and marginalized groups.

RECOMMENDATION 4

Leverage digitalization for innovation while addressing the digital divide

Develop an inclusive and integrated enabling environment for innovation to leverage digitalization for financial and social innovation into new business models that improve affordability, reliability, and accessibility to clean energy technologies, while strengthening capacity and knowledge around digital technologies to address the digital divide.

Priority Result 4: *Significantly increased adoption and access of clean energy–based digital solutions and innovations.*

The convergence of digitalization on energy systems has enormous implications and potential to enhance the speed and rate of broadening of technology adoption, innovation, and data for the clean energy transition. This convergence has enabled new delivery models of energy services at reduced costs through financing and business model innovation, improved energy-use efficiency, and enhanced demand-side management. It has helped capture new data that support better decision making in energy planning and policy and for delivering energy to unserved markets.

A three-pronged approach is necessary to leverage this potential: first, in countries with inadequate ICT infrastructure, further support is needed to boost investment in a sound digital infrastructure combined with digital transformation road-mapping across sectors, including the energy sector.

Second, in all countries, the skills gap in digital literacy and technologies needs to be addressed through curricula development, training and reskilling programs. The integration needs to take place in both formal tertiary education and vocational training. This should be further supported through global and national collaborative mechanisms aimed to bridge the digital divide, such as the Giga Connect initiative.[75]

Finally, the higher integration of digital technologies into energy systems is not without risks. Interdisciplinary collaboration and dialogue are necessary amongst all stakeholders in energy innovation to address legitimate concerns related to cyber-security in energy systems and infrastructure.

PRIORITY ACTION AREAS:

- 4.1 Invest in the development of adequate digital infrastructure supported by digital transformation roadmaps for energy and across sectors;
- 4.2 Strengthen local access and capacity with targeted support for skills gaps in digital literacy through curricula development, training and reskilling programs, with particular attention given to women, youth, and marginalized groups; and
- 4.3 Increase international and interdisciplinary collaboration and dialogue among stakeholders at the global and national levels to bridge the digital divide and enhance system resilience against cyber-security risks.

RECOMMENDATION 5

Improve the collection, management, and application of data and data systems

Enhance data systems and energy-planning workflows and analytics to better inform energy policies, planning, and regulations, direct investment decisions, and monitoring, evaluation, and reporting. This aims to address disparities and to effectively manage synergies and trade-offs in energy access, technologies, and security amongst vulnerable and marginalized communities.

Priority Result 5: *Substantial increase in the availability, reliability, validity, and completeness of open data and enhanced workflows for planning, deployment, and accessibility of clean energy and energy-efficiency technologies and solutions.*

Accelerating access to and the deployment of clean energy in line with meeting net-zero targets will not be possible without high-quality, robust, and reliable data. Key data and appropriate application tools continue to be a gap for many developing countries and small island states in deploying renewable energy and enhancing the resilience of their energy systems. Existing data are often not collected in a disaggregated form, which acts as a barrier to inclusive energy policy and planning. Transparency in planning workflows and how data are used is critical for both ensuring respect for user privacy and accountability in energy planning.

International standards for data architecture, interoperability, and management should be adopted in order to enhance the security and quality of energy data. Data also need to be leveraged to support the scale-up of energy innovation by applying Industry 4.0 technologies. To address gaps in data and to better inform inclusive options in policy and planning, investments should be made to support collection, sharing, and monitoring of data in a disaggregated form and digital technologies and innovation that facilitate data integration. Measures should also be adopted that promote open data, protect user privacy, and encourage transparency, where possible, regarding how data are collected and used.

PRIORITY ACTION AREAS:

- 5.1 Improve data architecture, interoperability, and management to drive meaningful innovations by leveraging international standards to enhance data quality and security;
- 5.2 Leverage data and evidence towards the scaling up of energy innovations through the use of Industry 4.0 technologies (i.e., big data, artificial intelligence, internet of things) and national and global data platforms;
- 5.3. Invest in multi-sectoral approaches to data collection, sharing, and monitoring in a disaggregated form by making use of digital technologies, innovations and better integration of available data to take account of local contexts, site-specific information, relevant identity groups, and spatial elements. Author, check, meaning wasn't clear.
- 5.4 Ensure data on energy innovations and workflows are made publicly available, taking into account the need for data sensitivity.

7 IMPACTS

The adequate and swift implementation of the above-mentioned recommendations and action plan would accelerate the applications of technology, innovation, and data with respect to meeting the SDG7 targets for 2030 and reaching the net-zero emissions goal for 2050 in the following ways:

Scale up technology adoption and innovation diffusion, particularly in lagging sectors and regions by removing adoption barriers. As outlined earlier, these barriers cut across a number of factors, for example: data gaps; market distortion and cost premiums; weak supply chains; capacities and skills. The action plan outlined here aims to tackle these barriers at different levels of influence from local to global.

Accelerate throughput of innovation and technology solutions towards achieving net-zero emissions by 2050. This would be in line with recent commitments to this goal by 61% of countries, 9% of states and regions in the largest-emitting countries, 13% of cities with a 500,000+ population, and at least one fifth of the world's 2,000 largest public companies. Globally, this represents at least 61% of GHG emissions, 68% of gross domestic product (GDP), and 56% of population.[76] The action plan targets key factors that aim to strengthen local and national energy innovation systems, call for a significant increase in financing for RD&D, and strengthen international cooperation and coordination for transformational change in the hard-to-abate sectors.

Enhance knowledge sharing and 'learning by doing' to accelerate the pace of the energy transition. On the one hand, this means that early-stage clean energy technologies will likely need to contribute almost half of the emissions reductions required to set the world on the ambitious path to net zero. On the other hand, the action plan would further deliver visible impacts on the specific innovation needs of developing and emerging countries. As highlighted earlier, a large amount of future energy growth will come from developing and emerging economies with different economic, technological, and geographical contexts. Energy services and technology performance needs are often very different from those in developed economies. We should see increased innovation throughput across technology, financial, and social innovation to address specific needs such as clean cooking and off-grid electricity access.

Shift the focus towards the specific needs of end users. Provide enhanced support to the clean energy transition across all major energy-use sectors, including building, industry, food, and transport. This will leverage the enabling role of energy in the implementation of several SDGs. In the particular case of productive uses of energy, as demonstrated by examples from the food sector, supporting energy service innovation at the intersection with end-use sectors can, in some cases, lead to more viable business models and affordable service delivery.

Mobilize public, private-sector, and civil society support for a transformational innovation paradigm. A rapid rise in investment is needed in the power sector alone, with more than USD 1.6 trillion needed per year to be on track for net-zero emissions by 2050.[77] The action plan on social innovation calls for transparent dialogue regarding trade-offs and will be catalytic in garnering public support for increased investments in the energy transition.

Finally, the action plan calls for better international collaboration on science, technology, and innovation (STI) with respect to energy. This aligns with the three pillars for collaboration proposed by the UN: build country capacity, boost international flows, and broker coalitions—providing a framework for measuring progress. These measures would also support the increased participation of women, youth, and marginalized groups that have traditionally been underrepresented in energy innovation.

8 APPENDIXES

APPENDIX 1: INDICATORS

There is no single indicator for tracking progress in energy innovation. Thus, a broad set of indicators has to be tracked, that would also capture ideas, products, and approaches from outside the energy sector. Such indicators should also accommodate the fact that energy-innovation pathways are not linear, with emphasis being needed on different aspects (e.g., supply, demand, knowledge management, socio-political support) at different times along the way.

IEA proposes a suite of metrics developed by governments and companies to help governments answer and monitor the following questions:

- Are the resources devoted to energy innovation increasing?
- Is the allocation of resources aligned with strategic priorities?
- What/where are the weaknesses in the energy innovation system?
- How does the country or region compare with international peers?
- Are inputs translated into outputs that support policy objectives?
- Which combinations of policies have the highest impact?

Sample metrics for different energy innovation policy levers proposed by THE IEA are presented in Table 3. A more comprehensive list can be found in the 2020 Tracking Clean Energy Innovation report of the IEE.78

This report also suggests options for tracking progress to inform policy and set benchmarks internationally. It proposes insights into tracking strategies based on the evidence available. This includes indicators that reflect synergies among innovations in clean energy and SDG indicators related to their end-use sectors; it particularly highlights the productive use of energy and the need to be conscious of the way different groups and locations are engaged in clean energy ecosystems—or not engaged. Other suggested indicators would measure the implementation of innovative good practices in clean energy end-use sectors—both quantitatively and qualitatively. For example, the amount of food produced using innovative good practices, the amount clean energy used in the food sector, and an assessment of the quality of the implementation of those practices. An example regarding the food sector is presented in Table 4 below.

TABLE 3. SAMPLE INDICATORS FOR ENERGY INNOVATION POLICY LEVERS

Energy innovation metric	Possible use cases for tracking metrics
Resource push metrics	
• Public funding for energy RD&D, technology area breakdown • Public gross expenditure on R&D	• Track levels of public support for RD&D • Reveal technology priorities and identify areas that may be underserved • Set priorities to guide innovation activities
• Public spending on higher education in programmes relevant to clean energy • Number of public institutions involved in energy R&D • Availability and qualification of human capital for energy innovation	• Track availability of human capital for energy R&D • Assess ability to train, attract, hire, and retain talent • Benchmark relative importance of science, technology, and engineering programmes
• Private energy R&D spending, technology area breakdown • Number of private companies involved in energy innovation • Foreign direct investment (FDI) in energy innovation activities and infrastructure	• Track levels of private support for R&D • Reveal corporate and investor preferences • Set priorities to guide innovation activities
• Existence of energy technology needs assessments (TNAs) and energy R&D strategies • Durability of energy R&D roadmaps and policies • Variety of stakeholders signing off on energy-technology roadmaps	• Identify technology-innovation gaps • Set priorities to guide innovation activities
Market pull metrics	
• Public spending in early deployment and diffusion • Number of publicly funded demonstration projects with private-sector co-financing • Private spending in early deployment of emerging energy technologies • FDI in emerging technology deployment activities	• Mobilize public resources to develop demonstration, late-stage R&D, and early market diffusion • Identify and target emerging energy technologies with public procurement or subsidy programmes • Assess ability to mobilize private-sector capabilities
• Diversification of innovation activities on the part of incumbents • Number and nature of new energy products on market	• Assess market shares for emerging technologies and the existence and size of niche markets over time • Measure improvements in selected emerging technologies over time
• Existence of standards and other market mechanisms to pull product development • Existence and level of carbon-pricing mechanisms	• Assess the existence and effectiveness of existing incentive-constraint mechanisms • Seek to provide consistent market signals and incentives with medium- to long-term visibility

Energy innovation metric	Possible use cases for tracking metrics
• Access to finance for energy entrepreneurs • Prospects for start-ups that benefit from public funding	• Examine the health of access to finance for energy, entrepreneurs, and innovative small and medium-sized enterprises (SMEs)
• Trade balances in energy technologies (imports, exports, and balance)	• Measure the long-term outcome of energy innovation programmes launched in the past • Set priorities for future energy-innovation activities
Knowledge management metrics	
• Share of energy sector in scientific output volumes • Number and share of publications or patents related to priority energy technology areas	• Identify strengths, weaknesses, and revealed preferences or priorities in domestic knowledge-creation capabilities • Track the success of energy-innovation policies
• Collaboration: number of domestic partnerships in energy R&D and demonstration programmes • Collaboration: number of international partnerships (bilateral, regional, and global) in energy RD&D	• Assess the ability to disseminate knowledge among relevant innovation stakeholders • Promote collaborative work and multilateral RD&D activities, including with academia and industry • Promote open access to new knowledge
Socio-political support metrics	
• Existence of and support for energy technology roadmaps • Existence and credibility of long-term clean energy transition targets and objectives • Effectiveness of government institutions in introducing energy innovation mechanisms • Existence of independent monitoring and evaluation mechanisms for R&D programmes and policies	• Provide long-term signalling and expectations to the innovation system • Ensure policy signals and programmes are credible, consistent, and durable • Ensure transparency and open access to results from public energy innovation programmes • Publish results of energy R&D activities and policies
• Public spending on fossil fuels relative to clean energy technologies • Public opinion • Number of major companies with environmental statements	• Assess public readiness for technological change and clean energy transitions • Evaluate support for clean energy transitions and individual technologies

TABLE 4. SAMPLE INDICATORS FOR ENERGY INNOVATION POLICY LEVERS

Targets	Indicators	Data source & comments
RE: Significant increase (maybe 25%) by 2030) in number of food chains with RE – Ref SDG 7.2. links to SDG2.3 & 2.4.	Adapted SDG 7.2 indicator RE share in food chain energy consumption	Survey or selected samples + number of new RE projects from ministries of agriculture or energy + maybe a trend indication indirectly through FAOSTATS
Efficiency: Significant increase (maybe by 25%) of food chains with double energy efficiency innovations – Ref SDG 7.3. links to SDG 2.3 & 2.4	Adapted from SDG 7.3. indicator: share of food chains with energy efficiency	Same as above but more difficult to find information than for RE + maybe a trend indication indirectly through FAOSTATS
Energy efficiency: Improved efficiency of wood fuel use for cooking	Change in amount of improved cookstoves	Information on relevant projects from the ministries of energy, forestry or cooperation
RE and Energy Efficiency	Indirectly, through share of energy in reduction of GHG emissions from food chains	Likely difficult —maybe sampling. Moreover, FAO statistics only give information regarding land use; hence energy for machinery used in production stage

APPENDIX 2: EXAMPLES OF TECHNOLOGY INNOVATION NEEDS

The listed technologies have high potential in terms of emission reduction and describe necessary innovations to be expected in the near, intermediate, and longer term. Market viability, compatibility with other elements of the energy system, and consumer value are also considered. Assuming all RD&D activities are implemented concurrently, initial commercialization is targeted in the specified timeframe.

The table below has been adopted from the Mission Innovation publication, Mission Innovation Beyond 2020: Challenges and Opportunities.[79]

The analysis is based on the following sources: Breakthrough Energy - http://www.b-t.energy/landscape/; IEA innovation gaps analysis- https://www.iea.org/topics/innovation/innovationgaps/; IRENA. 2019. Innovation landscape for a renewable-powered future; Energy Transitions Commission. 2018. Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century, and several technology roadmaps.

TABLE 5. TECHNOLOGY INNOVATION NEEDS AND MILESTONES

Technology	Near Term (2025)	Intermediate Term (2035)	Longer Term (2050)
Energy storage/ batteries	• System design to improve cost/performance/weight of batteries • Increased power and energy density, high cycle life • Deployment of High-Power EV Charging Stations • Next generation power electronics • Physical and cybersecurity • Hybrid energy storage systems	• Emergence of new battery chemistries • Wireless charging • Battery or fuel cells for short distance aviation and shipping • Longer-term storage, including thermal storage, capacitors, compressed air, fuel pumps, flywheels, molten salt, pumped hydro and power-to-X	• Seasonal, environmentally friendly, high-density, low-cost thermal energy storage
Hydrogen	• Improved plant efficiencies and asset life • Solid oxide fuel cells and electrolysis cells to reach industrial scale • Progress on hydrogen capable pipeline materials and operating pressures, reduction of storage tanks costs • Higher efficiency compression technologies • H2 fuelling demonstrations, • Hydrogen-capable heat appliances e.g. boilers • High-efficiency electrolysis (targeting capex USD 250/kw)	• Improved cost/performance of low- or zero-carbon H2 production pathways • Progress of chemical looping, methane cracking, biomass gasification, solar fuels • System design for H2 distribution infrastructure for integrated transportation and industry applications • Hydrogen in steel and chemical production • Hydrogen and ammonia in shipping	• Utilization approaches for high energy intensity manufacturing
Alternative fuels	• Improved cellulosic conversion technology • High-efficiency bioelectricity generation • Biomass in iron and steel industry • Biokerosene or alternative biojet fuels • Increasing sustainable feedstock supply	• Improved biochemical, electrochemical and thermo-chemical conversion pathways of biomass • Synthetic fuels (H2 + CO_2) – Power-to-gas / Power-to-Liquids • Algae harvesting	• Affordable low-carbon drop-in fuels • Sunlight-to-fuels

Technology	Near Term (2025)	Intermediate Term (2035)	Longer Term (2050)
Electrification	• Interoperability standards • Common modelling framework • Non-traditional contingency planning • Cybersecurity, assure system trust	• Integrated grid architecture across voltage- levels • Innovative control approaches, technologies to visualize data and enable faster controls • Automated and distributed decision-making • Material innovations including wide • bandgap semiconductors • Internet of Things (IoT)	• DC grids • Non-synchronized grids • Electric Cement Kilns and electric furnaces
Materials	• Chemical recycling of plastics • Using timber or pozzolan-based concrete as a substitute for Portland cement; • Phase-change material for thermal storage	• High-value bioproducts and input to chemicals • Lightweight, strong materials with low-cost manufacturing • Improved sorbents and solvents for direct air capture of CO_2	• Low-carbon cement and concrete chemistries • Novel materials for construction
Smart cities	• Thin insulating material s for deep retrofit • Flexible power management systems • Improved sensors and controls • Thermal storage • Technology-enabled urban planning and design • Hybrid heat pumps	• High-efficiency electric heating systems (heat pumps) • Tunable PV systems (e.g., PV windows) • Wireless sensors and controls	
Carbon management	• Second-generation CCUS pilot plants • CCUS retrofit demonstration • Improved post-combustion capture • CO_2 storage infrastructure • Demonstration of sequestration in alternative geologic media • Testing of large-scale biological sequestration • Direct air capture demonstration	• Industrial CCUS applications (e.g., cement, steel) • Natural gas CCS, methane cracking • Fuel cell carbon capture • Sub-surface CO_2 management at gigaton scale • Demonstration of large-scale (gigaton) biological sequestration	• Efficient, low-cost, large-scale CO_2 removal (e.g., direct air capture)

APPENDIX 3: CASE STUDIES

CASE STUDY 1

KOKO and Vivo Energy partnership for ethanol clean cookstove distribution in in Nairobi, Kenya - Combining technological, financial and social innovations

Problem Statement
Lack access to affordable clean cookstoves in Nairobi.

Solution
Koko bioethanol cookstoves made accessible and affordable through technological, financial, and social innovations.

Lessons Learned
Combining technological, financial, and social energy solutions through strategic partnerships can significantly strengthen the affordability and accessibility of clean energy products. Often policies and regulations hinder the implementation of innovations.

Relevant material
Dalberg (2018). Scaling up clean cooking in urban Kenya with LPG & Bio-ethanol A market and policy analysis, June 2018. https://southsouthnorth.org/wp-content/uploads/2018/11/Scaling-up-clean-cooking-in-urban-Kenya-with-LPG-and-Bio-ethanol.pdf

Koko (2021). Technology for Life in the world's fastest growing cities - An Overview - Presentation during the GBEP 2021 Bioenergy Week. http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2021_events/Online_Bioenergy_Week/PPTs_17_March/Liquid_Biofuels/17_March_liquid_AGNEW_KOKOnetworks.pdf

CASE STUDY 2

Linking energy supply and affordability of energy appliance in food chains: The PowerGen mini grid project in Tanzania

Problem Statement
Renewable energy appliances are often costlier to run than fossil fuel ones.

Solution
Improve the performance of RE appliances to make them competitive with fossil fuel ones.

Lessons Learned
Energy developers need to think outside the energy box and take better account of the affordability of customers' energy needs. In this particular case, the due consideration given to improving the performance of solar grain mills compared to fossil-fuel ones made them more cost-effective in terms of the value of food products for money spent on energy. This, in turn, improved their business case vis-a-vis food chain actors and led to wider adoption.

Relevant material
Next Billion (2020). Milling on Mini-Grids: How Africa’s Largest Crop Could Go Diesel-Free. https://nextbillion.net/milling-on-mini-grids-africa-maize/

CASE STUDY 3

Implementation of Recommendation ITU-T L.1381 'Smart energy solutions for data centres' in China

Problem Statement
Energy consumption of data centres is growing exponentially, especially in China.

Solution
Use guidance provided by the international standard ITU-T L.1381 to improve energy efficiency of data centres.

Lessons learned
There is indeed an urgent need to focus on the energy aspect of technology itself. As a result, the power usage effectiveness of a data centre in this case is reduced to 1.15 and the annual electricity expense is also reduced by 12.2%. 4.91 million kWh of electricity with 2215 tce/a of energy being saved every year, reducing carbon dioxide emissions by 4724 tons.

Relevant material
Implementation of Recommendation ITU-T L.1381: https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=14305

CASE STUDY 4

Brazil Building Energy Efficient code and energy performance labelling scheme

Problem Statement
Addressing energy wastage in buildings by introducing energy performance, rating systems, and labelling programs for residential, commercial, and public buildings.

Solution:
Following the energy crisis, the Brazilian Government adopted regulations for energy efficiency labelling of commercial, service, and public buildings, and also residential buildings. The energy performance labelling of federal public buildings is mandatory, while that of other buildings is voluntary.

Lessons learned:
The introduction of the building energy code and regulation has had a great impact on energy saving and conservation in the building sector. Building developers are more conscious of the importance of energy, adopting energy-saving measures and applying environmentally friendly building design principles. With energy performance and labelling schemes, users can make sound decisions when selecting their buildings and appliances. The introduction of building energy codes has really improved energy efficiency in buildings. This is valid for other countries that have done the same. Adoption of the energy efficiency building code is a major step toward decarbonization; however, actual implementation of the code could save 42% of energy, depending on the building type.

Relevant material:
Building energy efficiency: Review of Brazilian and Portuguese regulations. Available online at: https://www.academia.edu/22600650/BUILDING_ENERGY_EFFICIENCY_REVIEW_OF_BRAZILIAN_AND_PORTUGUESE_REGULATIONS

An international survey of building energy codes and their implementation. Meredydd Evans, Volha Roshchanka, Peter Graham. https://www.osti.gov/pages/servlets/purl/1341745

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