IRENA
International Renewable Energy Agency

INNOVATION LANDSCAPE FOR SUSTAINABLE DEVELOPMENT POWERED BY RENEWABLES

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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Wallonie

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FOREWORD

Francesco La Camera

Director-General

International Renewable Energy Agency

The world has reached a defining moment in the global energy transition. We have the technology and knowledge to transform our energy systems in ways that will improve people's lives considerably; yet, more than 650 million people still lack access to electricity worldwide and countless more face unreliable supplies that constrain their aspirations and limit their opportunities. The energy transition represents an opportunity to deliver reliable and affordable energy for all, whilst also creating local jobs, building healthier communities and driving sustainable development.

For the energy transition to succeed, it must be relevant to people's everyday lives; beyond climate targets, it must deliver tangible benefits – energy security and affordability, economic opportunity, improved public health and education, enhanced agricultural productivity, and ecosystem preservation.

Building on previous reports mapping innovation in grid integration and the smart electrification of end uses, this third Innovation landscape report explores how renewable energy innovations can serve as catalysts for sustainable development that aligns with countries' own priorities, visions and needs. It provides policy makers with a comprehensive innovation toolbox containing 40 innovations addressing: grid modernisation and decentralised solutions, accelerating energy access and inclusive local development.

The technologies exist; the business models have been proven. What we need now is the collective commitment to deploy them in ways that honour local priorities, empower communities, create economic opportunities and deliver tangible improvements in daily life. This report provides a practical innovation toolbox that policy makers, innovators, development partners, investors and other stakeholders may use to bring about that transformation, as we work together to achieve a just global energy transition.

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ABBREVIATIONS

AC	alternating current
AI	artificial intelligence
CAPP	Central African Power Pool
CO_2	carbon dioxide
COMELEC	Maghreb Electricity Committee
CSP	concentrated solar power
DC	direct current
DER	distributed energy resource
DLR	dynamic line rating
DRE	decentralised renewable energy
EAPP	Eastern Africa Power Pool
ECOWAS	Economic Community of West African States
EUR	Euro
EV	electric vehicle
GDP	gross domestic product
GW	gigawatt
GWH	gigawatt hour
IBRS	inverter-based resources
ICT	information and communications technology
IOT	Internet of Things
IRENA	International Renewable Energy Agency
KES	Kenyan shilling
KV	kilovolt
KW	kilowatt
KWH	kilowatt hour
LDES	long-duration energy storage
LI-ION	lithium-ion
MW	megawatt
MWH	megawatt hour
P2P	peer-to-peer
PAYGO	pay as you go
PHS	pumped hydropower storage
PPA	power purchase agreement
PV	photovoltaic
RPS	renewable portfolio standards
SAPP	Southern African Power Pool
SCADA	Supervisory control and data acquisition
SDG	Sustainable Development Goal
STATCOM	STATic synchronous COMpensator
TWH	terawatt hour
USD	United States dollar
VAT	value-added tax
VPL	virtual power line
VRE	variable renewable energy
WAMS	Wide area monitoring system
WAPP	West African Power Pool

EXECUTIVE SUMMARY

The global energy transition presents enormous opportunities to transform and modernise energy systems around the world. All regions have much to gain from this transition, making it possible to create resilient and affordable low-carbon energy systems and to provide universal access to electricity. The development of renewables can be a catalyst for ensuring an equitable energy transition for all, as well as fostering sustainable development, in particular in emerging markets and developing economies.

The technologies to make it happen exist today. Yet 666 million people still live without access to electricity, and many more suffer from unreliable power that stifles economic opportunity. Universal energy access remains a challenge in many countries, while others have weak, islanded, or poorly interconnected grids, introducing energy security challenges. The combination of declining costs for renewables and the decentralised nature of many innovative renewable solutions puts universal access to electricity within reach and can also increase the resilience of power systems.

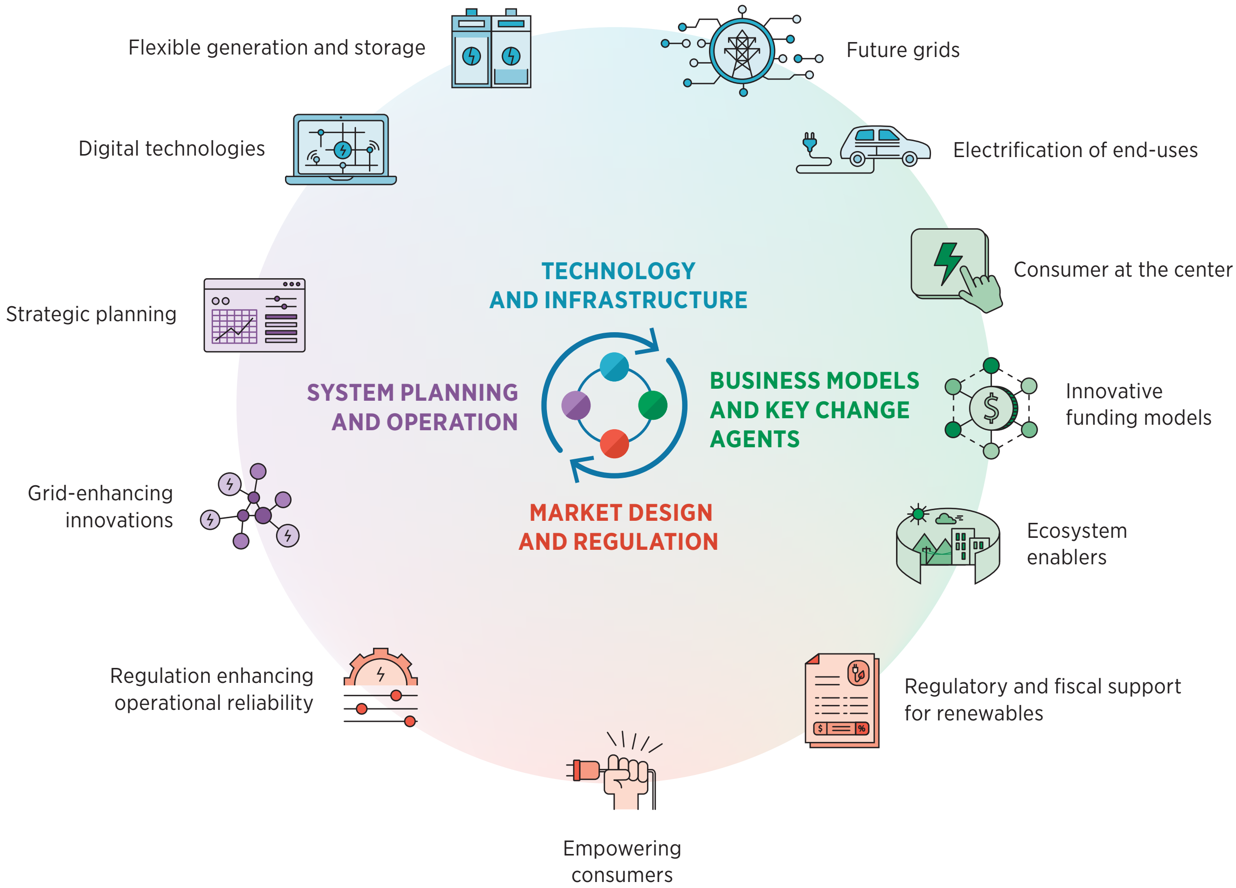
The question is not whether we can transform our energy systems – it is whether we will seize the moment to do so in a holistically beneficial way, leaving no-one behind. Therefore, the energy transition is not only about access to or availability of technology, but also about prioritising solutions that deliver sustainable development and contribute to social justice.

Innovation is systemic

Through technological advances, supportive government policies and economies of scale, solar and wind generation technologies have become the cheapest source of electricity in most regions. This includes developing countries, where they are no longer a luxury but a cost-competitive solution to close the access gap and to power economic development. However, technology alone will not deliver the transformation we need. The transformation happens when technological innovation is woven together with innovation in policy, regulation, market design, system operation and planning, and business models.

Innovation in the energy transition must be approached from a systemic perspective, as real implementable solutions emerge from matching and maximising synergies between various innovations across multiple components of the power system. This is called systemic innovation (Figure S1).

FIGURE S1 | Systemic innovation



"One-size-fits-none" solution

A "one-size-fits-all" solution for the future of energy systems does not exist. Optimal strategies and implementation of innovations will vary by a countries' circumstances, as they need to account for system-specific attributes; including the technical and economic aspects of a given power system, end-use sectors in the economy, resources available, and social and cultural dimensions.

Countries have different technical starting points for renewable energy deployment and grid integration. Policy makers must prioritise innovations based on impact potential and feasibility in their specific contexts, aligned to their overall objectives, and ensuring that the transition is inclusive.

Renewable energy innovations driving sustainable development

Innovations are reshaping the energy landscape in unexpected ways:

Energy communities in Colombia, Kenya, Malaysia and the United Republic of Tanzania, where residents collectively own and benefit from local renewable projects

Virtual power lines in Chile using batteries to unlock renewable resources without building costly transmission infrastructure

Productive uses of energy in Senegal transforming rural livelihoods through solar-powered milk preservation

Agrivoltaics in The Gambia and Mali where solar panels simultaneously generate electricity and protect crops from heat stress

Regional power pools in West Africa enabling 15 countries to share renewable resources across borders

Dynamic line rating in Malaysia that increased transmission capacity 10-50% simply by monitoring real-time weather conditions

Battery swapping stations in Rwanda and Uganda where e-motorcycle taxi drivers can exchange depleted batteries in minutes, eliminating range anxiety and making electric mobility accessible without expensive charging infrastructure

Pay-as-you-go business models that have brought affordable electricity and enabled access for more than 500 000 people in Liberia and Sierra Leone

Time-of-use tariffs in six West African countries that incentivise consumers to shift demand away from peak periods, reducing the need for costly back-up generation while keeping electricity affordable

Strategic electrification planning in Kenya and Rwanda that balanced grid extension with off-grid solutions, achieving electricity access rates of 78% and 75% respectively – up from single digits just 15 years ago

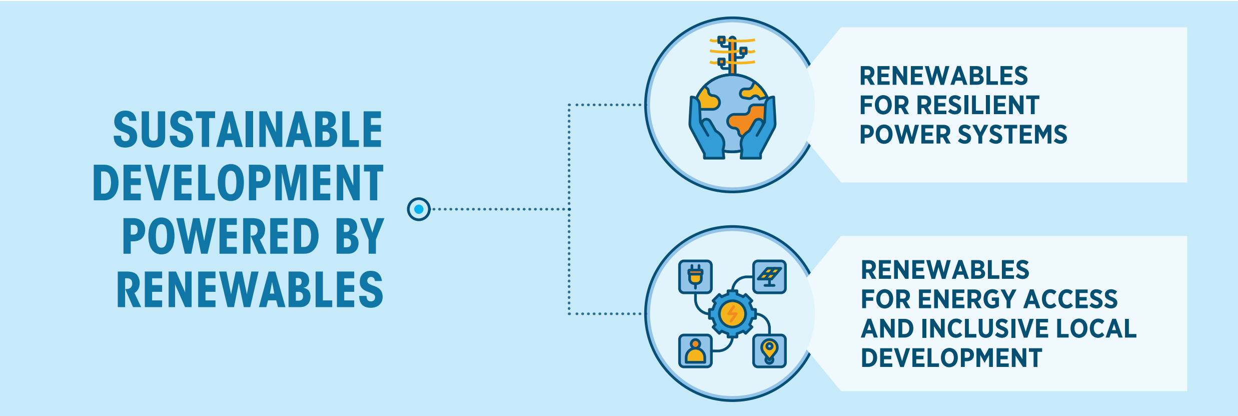
Corporate renewable sourcing in India where companies like Tata Motors have committed to 100% renewable electricity by 2030, driving 33.2 gigawatts of corporate renewable capacity and proving that businesses can be powerful allies in the transition

Green hydrogen initiatives in Mauritania and Namibia that could transform countries with vast solar and wind resources into major exporters while creating thousands of local jobs and building domestic green steel industries

This report maps the innovation landscape for sustainable development powered by renewables in a systemic way, encompassing innovations in technology, business models, regulation and market design, and system operation and planning. The landscape identifies 40 innovations that policy makers can strategically combine to build solutions for two urgent goals:

I. **Building resilient power systems** that can integrate high shares of renewables and withstand extreme climate events.

II. **Expanding energy access and driving inclusive local development** through decentralised productive uses.



The innovation toolbox

Recognising the various objectives that policy makers have in the energy transition, this report introduces a comprehensive innovation toolbox for formulating tailored, context-specific solutions. Taken together, these innovations can foster sustainable and socially inclusive growth powered by renewables, by building solutions with renewables for resiliency, and promoting energy access and local development.

Systemic innovation is at the core of the toolboxes – meaning that real, implementable solutions require not only technological innovation, but also innovation in business models, regulation and market design, and system planning and operation. Innovations are not siloed but instead should address the interconnected aspects of change, such as aligning technical advancements with supportive regulations and operations, and facilitating scalable business models.

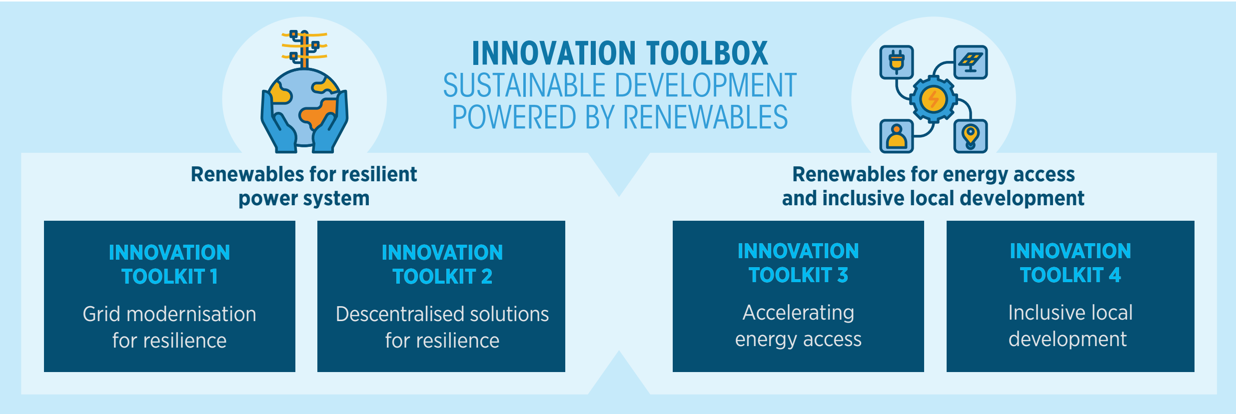
The innovation toolbox includes 40 innovations (Table S1) and represents a cohesive framework that enables the design of tailored solutions reflecting the unique technical, economic and socio-cultural needs of different circumstances in the countries, regions and communities.

TABLE S1 | The innovation toolbox for sustainable development powered by renewables

TECHNOLOGY AND INFRASTRUCTURE	BUSINESS MODELS AND KEY CHANGE AGENTS	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION
Flexible generation and storage	**Consumer at the centre**	**Regulatory and fiscal support for renewable energy deployment**	**Grid-enhancing innovations**
• **1** Increased flexibility from existing generation assets • **2** Large-scale batteries • **3** Small-scale batteries • **4** Long-duration energy storage	• **13** Energy community • **14** Decentralised productive uses of electricity • **15** Peer-to-peer trading • **16** Aggregators • **17** Storage as a service	• **25** Development-linked fiscal instruments • **26** Renewable energy auctions with socio-economic requirements • **27** Renewable portfolio standards	• **34** Storage as virtual power lines • **35** Dynamic line rating • **36** Installing innovative compensation devices on the grid • **37** Enhanced forecasting of variable renewable generation
Digital technologies	**Innovative funding models**	**Empowering consumers**	**Strategic planning**
• **5** Monitoring systems • **6** Smart and autonomous systems	• **18** Pay as you go (PAYGO) • **19** Crowdfunding and financial bundling for electricity access • **20** Corporate renewable sourcing	• **28** Time-of-use tariffs • **29** Innovative pricing for prosumers • **30** Regulation for mini-grids	• **38** Electricity losses reduction • **39** Planning for harmonised grid and off-grid developments • **40** Planning for regional interconnections
Electrification of end uses and energy efficiency	**Ecosystem enablers**	**Regulation enhancing operational reliability**	
• **7** Energy-efficient appliances • **8** Electric vehicles • **9** Green hydrogen • **10** Renewables-based electrification of heating, cooling and cooking	• **21** Key change agents to support renewables-based development programmes • **22** Powering a sustainable health and education ecosystem • **23** Renewable energy synergies for modernised railway infrastructures • **24** Renewable energy for resilient agriculture and farming systems	• **31** Regional integration • **32** Innovative ancillary services • **33** Grid connection codes	
Future grids			
• **11** Renewable mini-grids • **12** Supergrids – green corridors			

Implementation guidelines: Four strategic toolkits

The 40 innovations in this toolbox are not meant to overwhelm – they are designed to empower. To make them actionable, they are organised in **four strategic toolkits**, each addressing a distinct policy objective, serving as a guide for policy makers. The toolkits complement each other and are not exclusive. Top-down solutions (Toolkit 1: Grid Modernisation) complement bottom-up solutions (Toolkit 2: Decentralised Solutions) for achieving resilient power systems. Creating local value and development (Toolkit 4: Inclusive Local Development) must go hand in hand with solutions that provide energy access (Toolkit 3: Accelerating Energy Access).



TOOLKIT 1: Grid Modernisation for Resilience

How do you strengthen weak grids to handle more renewables? This toolkit combines innovations such as dynamic line rating, enhanced forecasting, storage as virtual power lines and innovative ancillary services. These solutions help policy makers modernise existing infrastructure without always requiring massive new investments, often achieving considerable capacity increases through smarter operations.

TOOLKIT 2: Decentralised Solutions for Resilience

What if the grid cannot reach everyone reliably? This toolkit embraces distributed energy solutions, such as renewable mini-grids, small-scale batteries, smart autonomous systems and community ownership models. It shows how bottom-up approaches can complement centralised grids, providing reliable power where it is needed most.

TOOLKIT 3: Accelerating Energy Access

How do you reach the people still living without electricity? This toolkit focuses on innovations that make energy access affordable and achievable: from pay-as-you-go financing and peer-to-peer trading to streamlined mini-grid regulations and harmonised planning between grid extension and off-grid solutions.

TOOLKIT 4: Inclusive Local Development

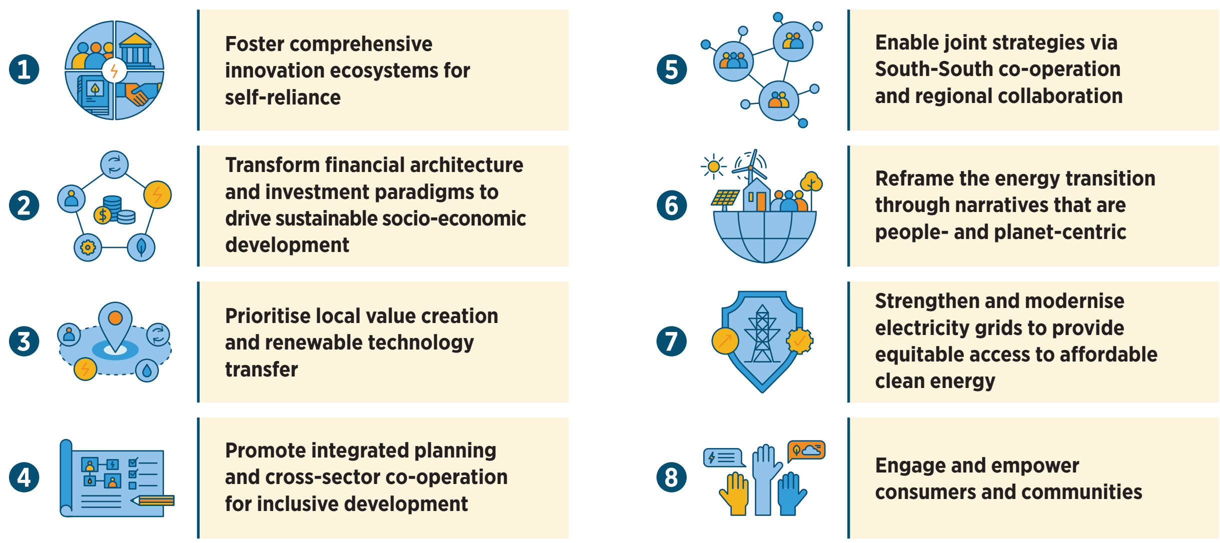
How do you move beyond basic access to energy that transforms lives? This toolkit goes further, combining renewable electricity with productive uses, such as electric cooking, agricultural applications, powering health and education facilities, and community-led initiatives. These innovations turn energy from a basic service into a catalyst for economic growth, job creation and genuine empowerment.

Eight strategic priorities to enable action

Barriers to the adoption of innovative renewable energy solutions must be systematically addressed through a holistic approach. Action is needed at every level, from multilateral institutions and regional forums to national governments and local communities. A truly just energy transition also requires prioritising inclusion and fairness, ensuring that the benefits of renewable energy reach all segments of society, especially vulnerable and marginalised groups.

To create an enabling environment where innovations can flourish and deliver transformative impact, the International Renewable Energy Agency (IRENA) identifies eight strategic priorities.[1] These priorities establish the conducive conditions – spanning policy, finance, skills, capacity and institutional frameworks – necessary for countries to successfully deploy and scale innovative renewable energy solutions.

STRATEGIC PRIORITIES FOR ENABLING SUSTAINABLE DEVELOPMENT POWERED BY RENEWABLES



1. **Foster comprehensive innovation ecosystems for self-reliance** by investing in people, skills and institutions – beyond just imported technology – building the domestic capabilities essential for long-term sustainable development.

2. **Transform financial architecture and investment paradigms to drive sustainable socio-economic development**, by shifting from profit-driven to impact-driven models that value sustainable development. While global investment in the energy transition reached USD 2.4 trillion in 2024, vast regional disparities persist: Sub-Saharan Africa captured about 2.3%, Latin America and the Caribbean received around 5%, and countries representing half the world's population secured only 10% of this financing. Closing these gaps requires more than mobilising capital – it demands reforming multilateral development banks to lower the cost of capital, enabling local currency financing, addressing structural inequities in capital flows and prioritising local value creation over import dependency.

[1] *Based mainly on discussions during IRENA Innovation Week 2025: https://innovationweek.irena.org.*

3. **Prioritise local value creation and renewable technology transfer** by building domestic supply chains, processing critical minerals locally and fostering indigenous manufacturing capacity to reduce dependency and strengthen economic resilience.

4. **Promote integrated planning and cross-sector co-operation for inclusive development**, engaging communities and end users from the outset and breaking down silos between energy, agriculture, transport and industry to create holistic solutions that serve multiple development objectives.

5. **Enable joint strategies via South-South co-operation and regional collaboration**, leveraging shared challenges and complementary resources to accelerate learning, reduce costs and build collective capacity.

6. **Reframe the energy transition through narratives that centre people and planet**, by moving beyond climate action alone to emphasise energy security, economic opportunity, community empowerment, and the intrinsic value of protecting nature and ecosystems, reflecting both contemporary sustainability thinking and indigenous wisdom.

7. **Strengthen and modernise electricity grids to provide equitable access to affordable clean energy**, recognising that grid modernisation is fundamentally about ensuring access and that no community is left behind.

8. **Engage and empower consumers and communities**, by moving beyond top-down approaches to genuinely participatory processes that centre local knowledge, needs and decision making in energy transition planning and implementation.

THE TOOLS ARE READY. THE MOMENT DEMANDS ACTION.

This report is divided into five major sections. The first section is an introduction to the tremendous opportunities that renewables can bring to sustainable growth, and to the need to accelerate the global energy transition. It explains how renewables can contribute to energy access and beyond, as well as contribute to increased system resilience and reliability. It also introduces the need for a systemic innovation approach, the innovation toolbox and the toolkits that guide policy makers in formulating tailored solutions. The next four major sections describe in detail the innovations in each of the four dimensions, explaining the benefits of each and providing examples of implementation.

The report ends with a section on recommendations, where eight strategic priorities to create the enabling conditions for renewable innovations to thrive and drive sustainable growth are outlined.

01 INTRODUCTION: RENEWABLES FOR SUSTAINABLE DEVELOPMENT

The global transition towards sustainable energy systems is gaining speed, driven by both the continuing drop in renewable energy costs and improvements in performance, and expedited by globally agreed goals such as the commitment to triple global renewable power capacity made at the 2023 United Nations Climate Change Conference (COP28), Sustainable Development Goal 7 (SDG 7) and the Paris Agreement. The energy transition presents enormous opportunities to transform and modernise energy systems across the globe. All regions have much to gain from this transition, making it possible to create resilient and affordable low-carbon energy systems and provide universal access to electricity. The energy transition with renewables can be a catalyst for sustainable development, if the right policies and priorities are in place.

The energy transition not only offers an affordable pathway to preventing the potentially catastrophic impacts of climate change, it also brings myriad benefits. It could spur more sustainable and inclusive economic development, raise living standards and improve livelihoods, reduce pollution and disease burdens, and make communities more resilient in the face of increasing climate change impacts. That is especially true for emerging markets and developing economies, which are the first and most impacted by climate change (World Bank, 2025a; World Economic Forum, 2023).

Globally, the power sector is leading the energy transition as costs for renewable electricity technologies have declined over the past decade, making them the most competitive technology in most regions. Universal energy access is still a challenge in many countries, while others have weak, islanded, or poorly interconnected grids, introducing energy security challenges. The combination of declining costs for renewables and the decentralised nature of many innovative renewable energy solutions puts universal access to electricity within reach and can also increase the resilience of power systems.

Digital technologies offer powerful opportunities to accelerate this transformation. Digitalisation can facilitate locally tailored, reliable and efficient energy services – from smart mini-grids to innovative payment systems for energy access. Similarly, the electrification of end-use sectors not only supports decarbonisation but can also stimulate local economies by creating new opportunities for clean energy use in transport, heating, cooling, cooking and productive applications.

The IRENA innovation toolboxes aim to support policy makers in the energy transition by mapping the key innovations that can be used to build implementable solutions. A "one-size-fits-all" solution does not exist. Optimal strategies and implementation of innovations will vary by countries' circumstances and by policy makers' needs to account for system-specific attributes, including the technical and economic aspects of given energy systems, end-use sectors, and social and cultural dimensions. Policy makers must prioritise innovations based on impact potential and feasibility in their specific contexts.

The innovation toolboxes aim at enabling policy makers to pick and choose the innovations that are most suited for their environment to form tailored solutions. Four innovation toolboxes have been released, one included in the "IRENA Innovation Landscape for a renewable-powered future" and three included in the "IRENA Innovation Landscape for smart electrification", as follows:

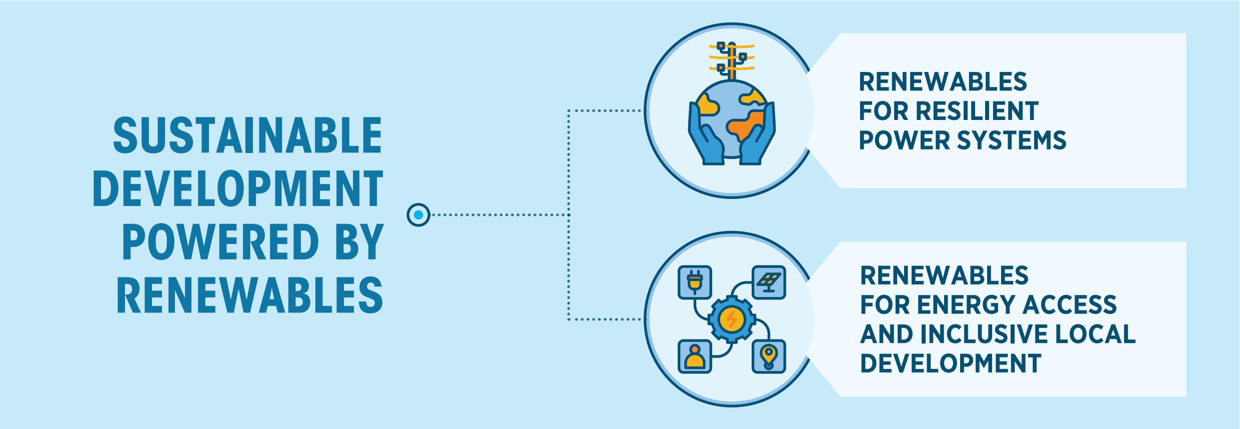
- Innovation toolbox for increasing flexibility to integrate high shares of variable renewable energy in the power system
- Innovation toolbox for smart electrification of the mobility sector
- Innovation toolbox for smart electrification of the heating and cooling sectors
- Innovation toolbox for smart production of green hydrogen.

This report offers another comprehensive innovation toolbox for formulating solutions that can create **sustainable and socially inclusive development powered by renewable solutions that enhance resilience, deliver energy access and support development.**

The innovation toolbox provides a map of 40 innovations for policy makers to build solutions for two urgent goals:

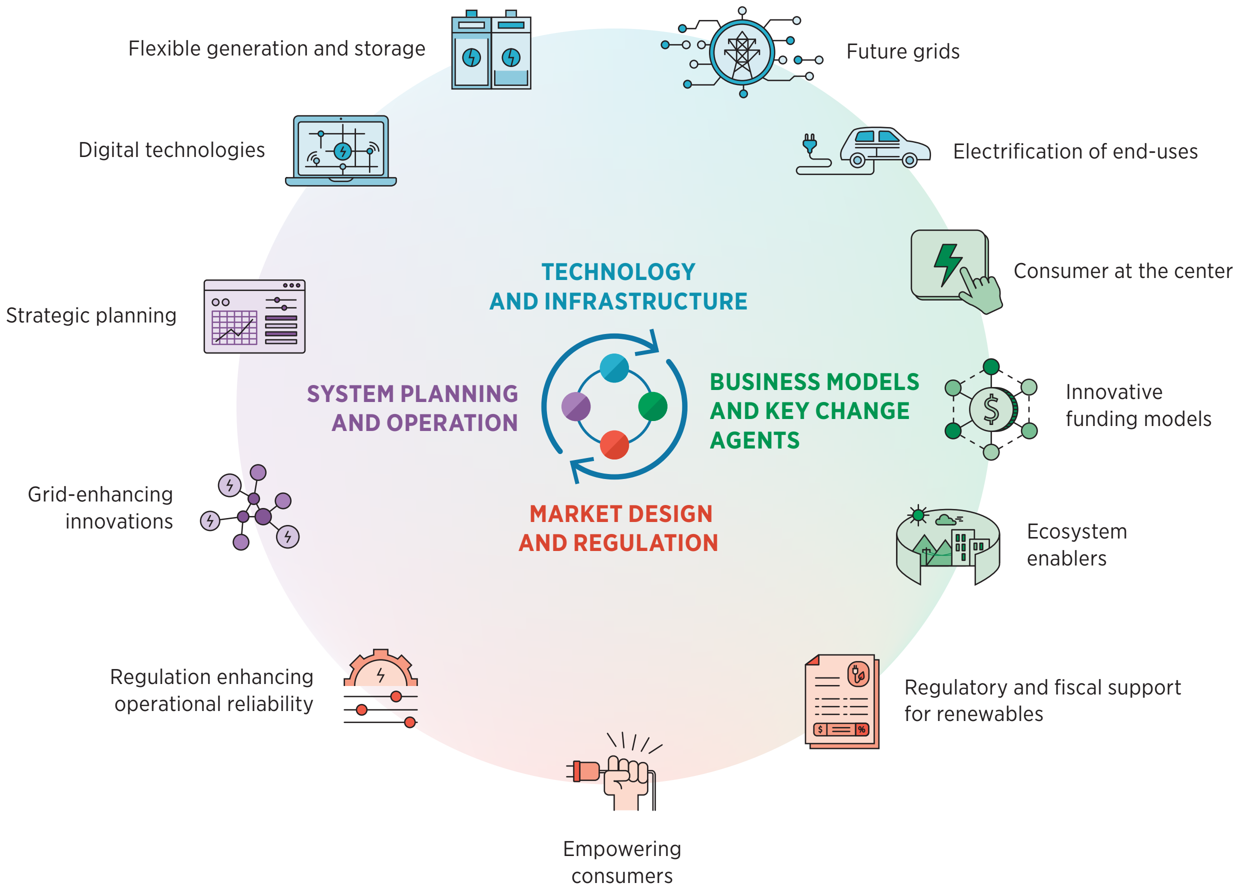
I. **Building resilient power systems** that can integrate high shares of renewables and withstand extreme climate events.

II. **Expanding energy access and driving inclusive local development** through decentralised productive uses.



Systemic innovation is at the core of the toolboxes – meaning that real, implementable solutions require not only technological innovation, but also innovation in business models, regulation and market design, and system planning and operation. Innovations are not siloed but instead should address the interconnected aspects of change, such as aligning technical advancements with supportive regulations and operations and scalable business models. Systemic innovation is essential to achieving the structural transformation of the energy sector (Figure 1).

FIGURE 1 | Systemic innovation



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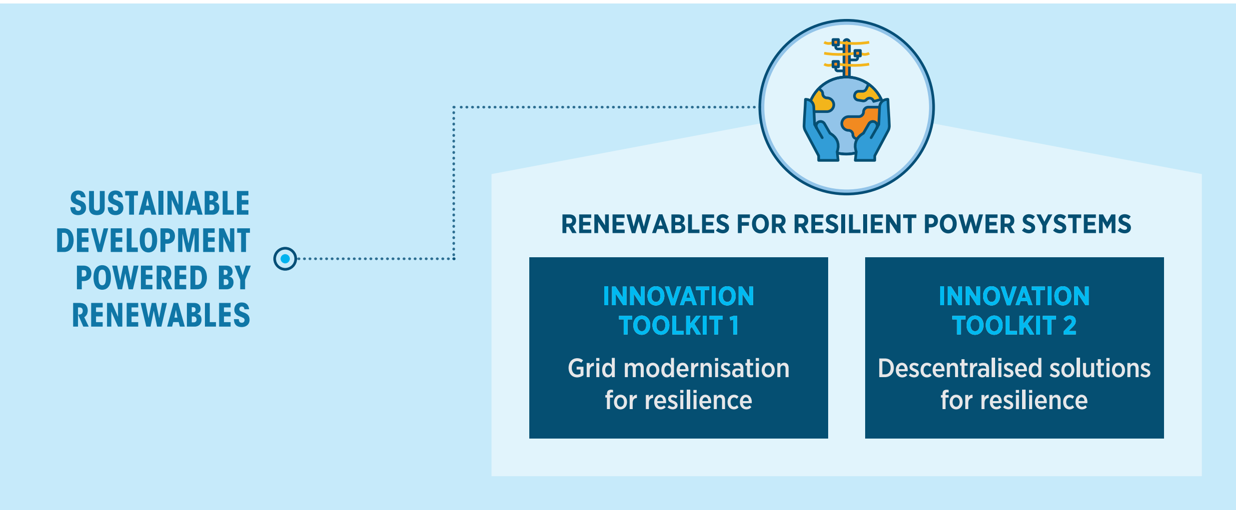
1.1 Renewables for resilient power systems

Many regions and communities experience weak or unstable electricity grids that limit economic growth and social development, particularly in emerging markets and developing economies. Traditional grid extension or reinforcement alone is often slow and costly and becomes quickly insufficient due to growing demand. Innovative alternative solutions can play a critical role in improving both the reliability of supply and the overall resiliency of these systems.

The energy transition imperative accelerates deployment of renewable electricity generation, largely coming from wind and solar photovoltaics (PV). However, their output varies greatly depending on wind speed (for wind turbines), solar irradiation and cloud cover (for solar) and other weather conditions. Integrating large amounts of variable renewable energy (VRE) into energy systems brings new reliability challenges. VRE can be location constrained, and renewable energy projects are usually developed where the resources are available, needing new grid capacities to transport the power where the demand is. The variable nature of wind and solar generation requires increased flexibility[2] along the entire electricity system chain, including supply, transmission, distribution and demand-side flexibility. These challenges are exacerbated in developing countries, where compounded by their ageing and weak grids, frequent outages result in unreliable power supply. This has adverse social and economic consequences.

Within the innovation toolbox, two toolkits are designed to support building resilience in power systems. Grid modernisation and decentralised solutions go hand in hand to increase power system resilience.



[2] *IRENA (2018a) defines flexibility as the "capability of a power system to cope with the variability and uncertainty that VRE generation introduces into the system in different time scales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers".*

TOOLKIT 1: Grid Modernisation for Resilience

This toolkit aims to strengthen weak grids to integrate more renewables. Challenges often include rising demand, unreliable access, under-investment, weak planning, outdated infrastructure and limited skilled labour. The rapid growth of distributed renewables such as rooftop PV adds complexity for grid operators. A major challenge is the lack of investment, often stemming from, among others, a lack of planning, insufficient policy and regulation, and ageing infrastructure that needs replacement, not just expansion.

This toolbox includes innovations such as dynamic line rating, enhanced forecasting, storage as virtual power lines and innovative ancillary services. These solutions help policy makers modernise existing infrastructure without always requiring massive new investments, often achieving considerable capacity increases through smarter operations.

Ultimately, grid modernisation is not just about technology but also about social justice and ensuring that no one is left behind.

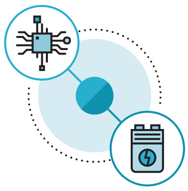
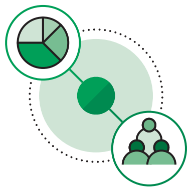
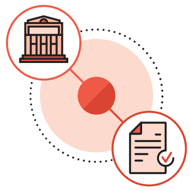
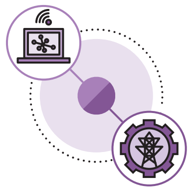
TOOLKIT 2: Decentralised Solutions for Resilience

This toolkit proposes distributed energy solutions to build resilience. It shows how bottom-up approaches can complement centralised grids, providing reliable power where it is needed most.

Such solutions include renewable mini-grids, small-scale batteries, smart autonomous systems and community ownership models.

Decentralised renewable energy systems provide flexible and modular capacity additions that can stabilise supply in weak-grid areas. These systems can operate autonomously when the main grid fails, while also integrating back into the grid when it is available. Coupled with battery storage, renewables smooth out fluctuations and ensure continuity of power for critical services such as hospitals, schools and small businesses. In this way, distributed renewable energy acts as a buffer against outages and voltage drops that are common in fragile grid systems.

Furthermore, climate risks, such as extreme weather events, pose additional challenges for grids in emerging markets and developing economies, but renewables paired with smart grid technologies and storage can help build adaptive systems that withstand shocks. A reliable grid can also integrate high shares of renewable energy, contributing to diversifying energy sources and reducing the risks associated with over-reliance on fossil fuels and their price volatility. Solutions that electrify end-use sectors, such as transport, heating, agriculture, *etc.* further decrease the dependency on fossil fuels and vulnerability in the face of climate change.

INNOVATION TOOLKIT 1
GRID MODERNISATION FOR RESILIENCE

TECHNOLOGY AND INFRASTRUCTURE	BUSINESS MODELS AND KEY CHANGE AGENTS	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION
• Increased flexibility from existing generation assets • Large-scale batteries • Long-duration energy storage • Monitoring systems • Energy-efficient appliances • Supergrids – green corridors	• Storage as a service • Corporate renewable sourcing	• Development-linked fiscal instruments • Renewable energy auctions with socio-economic requirements • Renewable portfolio standards • Time-of-use tariffs • Regional integration • Innovative ancillary services • Grid connection codes	• Storage as virtual power lines • Dynamic line rating • Installing innovative compensation devices on the grid • Enhanced forecasting of variable renewable generation • Electricity losses reduction • Planning for regional interconnections

INNOVATION TOOLKIT 2
DECENTRALISED SOLUTIONS FOR RESILIENCE

TECHNOLOGY AND INFRASTRUCTURE	BUSINESS MODELS AND KEY CHANGE AGENTS	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION
• Small-scale batteries • Monitoring systems • Smart and autonomous systems • Renewable mini-grids • Electric vehicles • Renewables-based electrification of heating, cooling and cooking	• Aggregators • Crowdfunding and financial bundling for electricity access • Key change agents to support renewables-based development programmes • Powering a sustainable health and education ecosystem • Renewable energy synergies for modernised railway infrastructures • Renewable energy for resilient agriculture and farming systems	• Development-linked fiscal instruments • Innovative pricing for prosumers • Regulation for mini-grids • Grid connection codes	• Planning for harmonised grid and off-grid developments

1.2 Renewables for energy access and inclusive local development

Despite huge progress in access to modern energy over the past decades, 666 million of the world's people still lack access to electricity. Access deficits have been shrinking in Eastern Asia and Southeastern Asia, as well as in Central Asia and Southern Asia – thanks largely to policy measures and rising incomes. However, in Sub-Saharan Africa, the number of people lacking access continues to grow at a rate of 14 million people yearly, with gains in access outpaced by rapid population growth. Energy access remains low in many parts of Sub-Saharan Africa, with some 565 million people in the region still lacking access to electricity in 2023, representing 85% of the global population without electricity access (IEA *et al.*, 2025).

At the same time, Africa had only a total of 20 gigawatts (GW) of solar capacity installed in 2025, and only 9 GW of wind, which together represented less than 10% of the region's total installed electricity generating capacity (IRENA, 2024a; Jowett, 2025).

All of this makes Sub-Saharan Africa home to the world's largest population without access to modern and clean energy. Beyond electricity access, the affordability and reliability of electricity supply and higher-quality fuels are major issues across the continent. This comes at a significant economic cost, hindering the development of local industries and the delivery of crucial public services, including education and health care. Historically, even fossil fuel-exporting countries in the region have continued to experience large energy access deficits, especially in rural areas (IEA *et al.*, 2024).

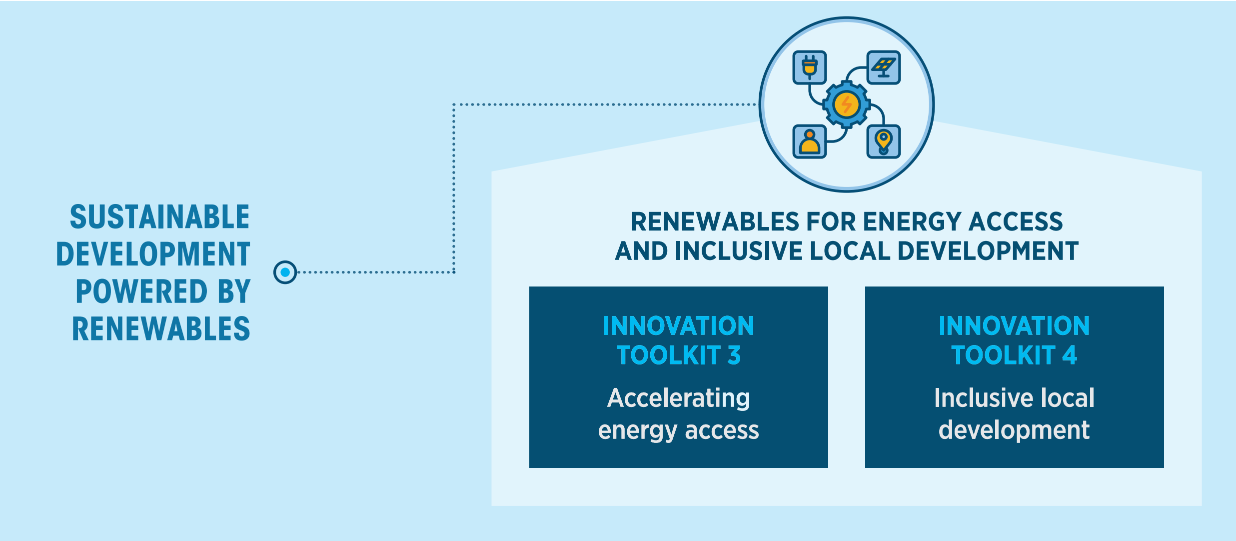
The success of the energy transition will, therefore, depend on the extent to which modern energy systems include those last-mile and most remote communities, as well as public facilities (such as health care and education), and encourage productive use activities (such as agriculture).

Achieving this will necessitate targeted policies that not only expand infrastructure but also actively foster demand for productive uses, thereby creating sustainable economic ecosystems in newly electrified areas.

The decentralised nature of many innovative renewable solutions can put universal access to electricity within reach, complementing the centralised grid connections with off-grid energy solutions. Off-grid solutions focused on decentralised renewable energy, such as solar PV mini-grids coupled with batteries, can provide reliable power in areas that are not connected to the central grid, lack energy access and are particularly vulnerable to climate risks.

However, it is important to go beyond providing basic residential electricity access to supporting productive uses of energy in areas such as agriculture, commerce and industries that are vital for sustainable development and job creation. In the period 2010-2021, 63% (USD 1.2 billion) of off-grid renewable energy investment in Sub-Saharan Africa was directed to residential energy uses – that is, to provide basic energy access to households in remote areas (IRENA, 2024b).

Within the innovation toolbox, two toolkits are designed to support accelerating energy access and inclusive local development. These toolkits are strongly interconnected: reliable energy access enables productive applications, while these productive uses in turn generate the demand and revenue that make energy systems economically sustainable, creating a mutually reinforcing cycle where access unlocks opportunity for local development.



TOOLKIT 3: Accelerating Energy Access

This toolkit focuses on innovations that make energy access affordable and achievable: from pay-as-you-go financing and peer-to-peer trading to streamlined mini-grid regulations and harmonised planning between grid extension and off-grid solutions.

TOOLKIT 4: Inclusive Local Development

This toolkit goes further, combining renewable electricity with productive uses, such as electric cooking, agricultural applications, powering health and education facilities, and community-led initiatives. These innovations turn energy from a basic service into a catalyst for economic development, job creation and genuine empowerment.

Prioritising productive uses is economically vital as it generates local income streams, enhances the financial viability of off-grid projects, and creates a virtuous cycle of demand and development, making electrification efforts more sustainable in the long term.

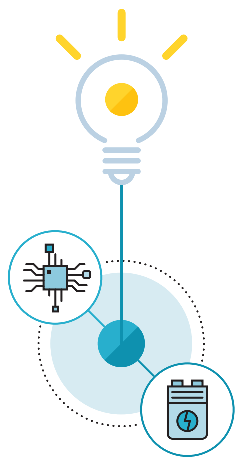
TECHNOLOGY AND INFRASTRUCTURE	BUSINESS MODELS AND KEY CHANGE AGENTS	MARKET DESIGN AND REGULATION	SYSTEM PLANNING AND OPERATION
INNOVATION TOOLKIT 3 — ACCELERATING ENERGY ACCESS			
• Small-scale batteries • Monitoring systems • Smart and autonomous systems • Renewable mini-grids • Energy-efficient appliances	• Pay as you go (PAYGO) • Peer-to-peer trading • Crowdfunding and financial bundling for energy access	• Regulation for mini-grids	• Planning for harmonised grid and off-grid developments
INNOVATION TOOLKIT 4 — INCLUSIVE LOCAL DEVELOPMENT			
• Electric vehicles • Renewables-based electrification of heating, cooling and cooking	• Energy community • Decentralised productive uses of electricity • Key change agents to support renewables-based development programmes • Powering a sustainable health and education ecosystem • Renewable energy for resilient agriculture and farming systems	• Development-linked fiscal instruments • Renewable energy auctions with socio-economic requirements	

02 TECHNOLOGY AND INFRASTRUCTURE

Innovation often starts with technology and infrastructure. The renewable energy generation technologies need to be complemented with other innovations to guarantee a reliable supply of electricity based on renewable energy and economically efficient operation of the system. This becomes increasingly relevant with the trend of increased electrification of end uses.

As shown in Figure 2, twelve such innovations are emerging as key, and they fall into four main categories: flexible generation and storage that make it possible to better balance supply and demand; digital technologies; technologies that allow electricity to power many new uses; and new grid systems for renewable electricity.

FIGURE 2 | Innovations in technology and infrastructure



TECHNOLOGY AND INFRASTRUCTURE

Flexible generation and storage	**1** Increased flexibility from existing generation assests
	2 Large-scale batteries
	3 Small-scale batteries
	4 Long-duration energy storage
Digital technologies	**5** Monitoring system
	6 Smart and autonomous systems
Electrification of end uses and energy efficiency	**7** Energy-efficient appliances
	8 Electric vehicles
	9 Green hydrogen
	10 Renewables-based electrification of heating, cooling and cooking
Future grids	**11** Renewable mini-grids
	12 Supergrids – green corridors

2.1 Flexible generation and storage

Innovations in flexible generation and storage can help balance supply and demand in the process, allowing the integration of high shares of renewables. Four key enabling technologies are providing promising solutions to balance supply and demand in power systems: technological improvements in flexibility for existing assets and in large- and small-scale batteries, and long-duration energy storage.

Innovation 1

INCREASED FLEXIBILITY FROM EXISTING GENERATION ASSETS

In many developing countries, where conventional thermal power plants still represent a large share of the generation mix and are unlikely to be decommissioned in the near term, innovations to increase flexibility from existing assets are particularly relevant. In cases where conventional thermal power plants are not decommissioned before their end of life, they can provide operational flexibility to reduce curtailment of renewable generation in the short to medium term. While conventional power plants are dispatchable and can adjust their output, they have limitations on how flexibly they can operate. They may be required to operate frequently at low loads, leading to lower efficiency and to higher operational and maintenance costs. This is due to limits on their minimum loading, start-up costs and times, ramping capabilities, and minimum and maximum up times, *etc.*

Greater flexibility from existing thermal power plants can be achieved through process improvements, increased automation and retrofitting certain plant components (IRENA, 2019a). Retrofitting these generators, depending on their age and design, includes improved operational practices, retrofitting machines with updated technologies, modernising control systems and using software to increase the rates at which the plants can ramp up and down. Such improvements can also reduce the start-up times, costs, and length of downtimes for the plants (Figure 3), therefore allowing greater integration of VRE.

Deployment of different flexibility solutions is often carried out in parallel and depends on the individual circumstances and investment needs. Smaller investments in retrofitting existing thermal power plants can help avoid larger investments in other flexibility options in the short or medium term until affordable solutions are available. The decision to retrofit should be based on a thorough techno-economic analysis comparing the life-cycle costs and flexibility gains against alternative solutions such as new storage or demand response programmes, especially considering the remaining operational life. Also, completing this innovation with innovations in regulation and business models is essential to ensure that the investments are recovered and that the extra flexibility is remunerated.

FIGURE 3 | Enhanced flexibility of conventional power plants

Shorter start-up time and lower start-up costs	• With shorter start-up times, the plant can quickly reach full load. • Rapid start-up significantly improves the operational flexibility of a plant. • Costs associated with the start-ups include more frequent maintenance and additional fuel consumption.
Lower minimum load and improved part-load efficiency	• Operating thermal plants at lower loads increases the bandwith of their operation, increasing flexibility. • Most thermal power plants experience a drastic reduction in their fuel eficiency at low loads, and therefore improving this is an important element of increasing flexibility.
Higher ramp rate	• The rate at which a plant can change its net power during operation is defined as the ramp rate. With higher ramp rates, the plant can quickly alter its production in line with system needs.
Shorter minimum uptime and runtime	• Reducing the minimum time that the plant must be kept running after start-up, or remain closed after shutdown, allows a plant to react more rapidly.

Source: (IRENA, 2019a).

Countries that include hydropower generation in their energy mix can harness the flexibility potential of the hydropower generators. Hydropower plants are inherently flexible, but small upgrades and introducing digital technologies can increase their flexibility even further. Table 2 shows the flexibility services that each type of hydropower plant can provide (IRENA, 2023a)

TABLE 2 | Power-related services of hydropower

				HYDROPOWER PLANT TYPE		
				RoR	**Reservoir**	**PSH**
Power generation				🟢	🟢	🟢
Balancing			Positive	🔴	🟢	🟢
			Negative	🔴	🔴	🟢
Ancillary services	**Frequency regulation**	Primary	Positive	🔴	🟢	🟢
			Negative	🔴	🔴	🟢
		Secondary	Positive	🔴	🟢	🟢
			Negative	🔴	🔴	🟢
		Tertiary	Positive	🟢	🟢	🟢
			Negative	🟢	🔴	🟢
	Non-frequency regulation	Voltage support		🟢	🟢	🟢
		Active power-loss compensation		🟢	🟢	🟢
		Black start		🟢	🟢	🟢

Source: (IRENA, 2019a).

Notes: The green circles indicate that a plant can provide this service while the red circles indicate it cannot. Positive balancing refers to the ability to supply the correct amount of electricity to the grid to meet fluctuations in demand. Negative balancing would imply consuming electricity to counter oversupply. Positive frequency regulation refers to the act of feeding energy to the grid in order to increase the system frequency and level out frequency deviations. Negative regulation requires consuming energy from the grid. PSH = pumped storage hydropower; RoR = run-of-river.

Hydropower assets can benefit greatly from improvements aimed at increasing their own flexibility, and consequently, the overall system flexibility. This can be done in different ways, for example (IRENA, 2023a)

- **Plant redesign:** This includes the addition of storage facilities by installing pumps, reversible pump turbines or batteries. This option requires civil works, new equipment and, in some cases, a reinforced grid connection.
- **Equipment upgrades:** Older facilities can benefit from modern equipment that can increase their efficiency, capacity and operating range. This option requires civil works, new equipment and/or, in some cases, a reinforced grid connection.
- **"Smarter" plants:** More flexibility is possible with advanced digital control technology, creating a "smart" hydropower plant (Corà *et al.*, 2019; Dahle, 2019; Poel and Oliveira, 2018). Technology has advanced considerably in the last decade, and new sensory and testing capabilities from turbine manufacturers have resulted in software that can make operations more efficient and controllable and expand the operating range of hydropower plants. Digitalisation could improve data availability, facilitate better decision making, and improve the resolution and capabilities of plant controls. The digitalisation of operations can enable plants to enhance the range and efficiency of their operations, reduce operation and maintenance costs, and extend their lifetimes. This option does not require civil works or major equipment changes.

It is also possible to harness synergies between hydropower and solar PV by installing floating photovoltaic panels on hydro reservoirs. The reservoir surface provides a large area for the installation of the solar panels, and the panels reduce the evaporation rate and increase the hydropower output. The cooling effects of evaporation and wind ventilation can reduce the thermal co-efficient and can yield better results as compared to PV systems on land. PV modules provide shading and can reduce evaporation, which contributes to significant water loss in reservoirs. Estimates show that covering less than 1% of the surface area of some reservoirs in Africa with solar PV could increase output by 58% (Gonzalez Sanchez *et al.*, 2021; Kakoulaki *et al.*, 2023).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SUMMARY TABLE: Increased flexibility from existing generation assets

INNOVATION READINESS LEVEL		LOW HIGH
BENEFITS	Affordability	LOW HIGH Increasing the usage rate of existing plants defers the need for other back-up solutions.
	Energy access	LOW HIGH
	Power system resilience	LOW HIGH More flexibility increases the systems' capacity to withstand unplanned events.
	Energy security	LOW HIGH Increasing the operational range of existing plants improves the security of supply. This is especially the case for hydropower with varying heads due to reduced flows.
	Sustainable development	LOW HIGH Serves as a flexibility provider for integration of more renewable electricity but is still not a clean flexibility source.
IMPLEMENTATION	Implementation cost	LOW HIGH Less costly than building grid infrastructures.
	Prerequisites	A clear framework to reward the additional flexibility provided is also necessary.
	Stakeholders responsible for implementation	Transmission system operator, utilities, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		China, India, Indonesia

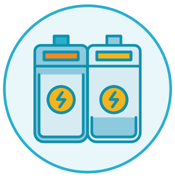
Innovation 2

LARGE-SCALE BATTERIES

Large-scale batteries (or utility-scale batteries) are storage facilities typically with a capacity ranging between a few megawatt hours (MWh) to hundreds of MWh, installed in front of the meter, and operated to strategically manage imbalances between supply and demand at the distribution or transmission voltage level or to power generation assets. Batteries can be lithium ion (Li-ion), lead acid, sodium sulphur, metal air or flow batteries. Li-ion batteries have dominated utility-scale markets in recent years due to a sharp decline in costs associated with the growing demand for electric vehicles (EVs).

Batteries store electricity when generation exceeds demand and then provide additional supply when demand is high or supply is low. As a result, they can both reduce the curtailment of wind and solar generation during periods of surplus generation and reduce the investments in generation capacity and grid infrastructure that would otherwise be needed to meet demand peaks. The ability of utility-scale batteries to meet the evening peaks in demand has the added benefit of reducing the need for fossil fuels (especially thermal back-up generation). The batteries also can help reduce grid congestion, boost the economic value of solar and wind electricity generation, and improve the resilience of the system during unplanned or extreme events. They can be located next to renewable resources, close to sub-stations supplying large load centres, or installed as individual battery systems. Figure 4 summarises the key services that large-scale batteries offer (IRENA, 2019b)

FIGURE 4 | Services provided by utility-scale batteries



SERVICES OFFERED BY UTILITY-SCALE BATTERIES

SYSTEM OPERATION	• Frequency regulation • Flexible ramping • Black start services
INVESTMENT DEFERRAL	• Energy shifting and capacity investment deferral • Transmission and distribution congestion relief
SOLAR PV AND WIND GENERATORS	• Reduced renewable energy curtailment • Capacity firming
MINI-GRIDS	• Reduced reliance on diesel generators

Source: (IRENA, 2019b).

Adding spinning reserve in the West African Power Pool with batteries

The Regional Electricity Access and Battery Energy Storage Technology (BEST) Project aims to build new transmission lines and transformers to provide electricity access to 235 000 households in Côte d'Ivoire, Mali, Mauritania, Niger and Senegal (World Bank, 2021). The project will include 205 MWh of battery storage, helping to enable the integration of up to a planned 400 megawatts (MW) of solar power plants and providing crucial frequency control to the West African Power Pool (WAPP). The battery storage system is estimated to provide nearly 50% of the total spinning reserve approved by the regional Electric Regulatory Authority of the Economic Community of West African States (ECOWAS).

Batteries and solar in Africa

In November 2023, the South African utility, Eskom, switched on the largest battery storage system in Africa, 20 MW of Li-ion batteries in Western Cape province. The system supplies enough to power entire towns, such as Howick, for up to five hours. The utility plans to build an additional 144 MW of battery storage, along with 60 MW of solar generation, which will enable South Africa to reach its target for net zero greenhouse gas emissions by 2050 and make the grid much more resilient to outages (ESKOM, 2023; Murray, 2022). Overall, the total capacity of battery storage systems across Africa could reach 4.8 GW by 2030 if there are supportive regulations and business models (USAID, 2022). Similar projects are planned in other countries as well. For example, Botswana's first utility-scale battery energy storage system with 50 MW output and 200 MWh storage capacity is planned next to the country's first large-scale solar PV plant. In Mozambique, the first-ever solar-plus-storage plant became operational in 2023 (Heynes, 2024).

Batteries and solar in Chile

Faced with an uncertain supply of natural gas from Argentina and strong opposition to coal plants, Chile has made substantial investments in renewable energy. By 2023, solar generation alone provided 20% of the country's electricity, up from less than 1% in 2013. Combined with wind and hydropower, renewables accounted for 63.3% of Chile's electricity mix in 2023 (Hedley, 2023). To integrate all this VRE into the energy system, Chile is adopting energy storage systems. As of 2025, 3 GW of energy storage projects were in various stages of project implementation, and another 15 GW were at the environmental permitting stage (Luis Ini, 2025). Battery energy storage system capacities in Chile reached 523 MW in 2024. The storage facilities include the first deployment of a Li-ion battery bank with a run-of-river hydropower plant, which stores energy during low demand and delivers around five hours of electricity when demand is high.

SUMMARY TABLE: Large-scale batteries

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Reduces VRE curtailment, but high upfront investment costs.
	Energy access	LOW – HIGH Opportunity to satisfy end users by adapting the generation to the demand profiles.
	Power system resilience	LOW – HIGH Large-scale storage is an efficient centralised option for ensuring power quality and reliability through different services it can cover, such as frequency response, frequency regulation and black start.
	Energy security	LOW – HIGH Provides more secure balancing process in the short to medium term. Shifts the demand for power but does not constitute a new primary source of electricity.
	Sustainable development	LOW – HIGH Allows more green electricity.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH High upfront costs, but important expectations of future cost decrease.
	Prerequisites	Clear regulation on the role of utility-scale batteries and the type of services they can provide, and how to be remunerated.
	Stakeholders responsible for implementation	Transmission and distribution system operators, utilities, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		West African countries (Côte d'Ivoire, Mali, Mauritania, Niger and Senegal), South Africa

Innovation 3
SMALL-SCALE BATTERIES

Small-scale batteries are stationary battery storage systems installed at the locations of commercial, industrial and residential consumers. They are also called behind-the-meter batteries because they sit between the utility's supply meter and the consumer demand. They range in size from 3 kilowatt hours (kWh) to 5 MWh and are typically installed with rooftop PV systems.

Small-scale batteries offer several key services (Figure 5), including back-up power for consumers, reduced energy costs, replacements for diesel generators and uninterrupted quality power for industrial customers. They can even be combined into virtual power plants, supporting the operation of the power grid by providing electricity during demand peaks and offering frequency support. In rural areas in developing countries, where diesel fuel deliveries can be disrupted, batteries added to renewable generation ensure more reliable and resilient electricity supplies (Elgqvist, 2021). However, unlocking the full value of these diverse services, including their aggregation into virtual power plants, critically depends on the deployment of smart inverters, sophisticated energy management systems and reliable communication networks that enable dynamic control and co-ordination.

FIGURE 5 | Services provided by behind-the-meter batteries

SERVICES OFFERED BY BEHIND-THE-METER BATTERIES

ELECTRICITY CONSUMERS	• Increased self-consumption • Back-up power • Savings on electricity bills • Demand charge reduction
SYSTEM OPERATION	• Frequency regulation • Network investment deferral • Peak capacity investment deferral
MINI-GRIDS	• Replacing diesel generators • Back-up power • Smoothening of variable renewable energy

Source: (IRENA, 2019c).

Behind-the-meter batteries may be challenging to adopt in countries that have high average costs of capital. However, incentives such as low-interest loans and tax credits can help encourage adoption. Utilities could also work in tandem with consumers to share the operation of behind-the-meter services in a mutually beneficial manner.

Solar mini-grids that include small batteries hold great potential to boost energy access – powering households, key social services such as health centres and schools, and businesses, driving economic growth. Modelling from the United Nations Development Programme estimates that mini-grids will be the lowest-cost approach to bring electricity to 265 million people in 21 countries in Africa by the year 2030 (Africa Minigrids Program, 2024).

SUMMARY TABLE: Small-scale batteries

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Can reduce peak loads for end users and increase security of supply, but has high upfront investment costs.
	Energy access	LOW – HIGH Can facilitate the development of off-grid solutions.
	Power system resilience	LOW – HIGH Increases the resilience at the end-user level and can improve it for the grid if adequate demand response mechanisms are established.
	Energy security	LOW – HIGH Provides more secure balancing process in the short to medium term. Shifts the demand for power but does not constitute a new primary source of electricity.
	Sustainable development	LOW – HIGH Allows integration of higher shares of renewables in the grid.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH High upfront costs, with expectations of cost decrease. Supportive policies that facilitate access to consumer finance, such as on-bill financing, dedicated green loan programmes, or pay-as-you-go models, to mitigate the barrier of high upfront costs for end users and stimulate market development.
	Prerequisites	Regulator and distribution systems operators to support the connection of distributed small-scale batteries to the power grid.
	Stakeholders responsible for implementation	Transmission and distribution systems operators, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Kenya, Mali, Tanzania, other countries in Africa, Southeast Asia

Innovation 4

LONG-DURATION ENERGY STORAGE

Long-duration energy storage (LDES) refers to storage systems that can provide electricity for extended durations of, for example, 10 hours or more. They can store excess energy generation during periods of low demand and allow for balancing of supply and demand when the demand is high or when VRE generation is low. LDES can improve system resilience and reduce the use of fossil fuel-based peaking power plants. Examples of LDES include pumped hydropower storage (PHS), compressed air energy storage systems (CAES), thermal energy storage and hydrogen.

Pumped hydropower storage uses two reservoirs at different elevations. It pumps water uphill during low-demand, low-price periods and releases it downhill through turbines to generate electricity when demand and prices are higher. Like batteries, PHS can balance the grid, provide inertia support, shift supply to match demand, and provide ancillary services such as fast ramping, capacity reserves and black start. Moreover, PHS offers relatively low-cost LDES.

However, PHS has major geographical constraints. PHS-suitable sites are limited due to water access requirements and to locations with adequate elevation differences between the reservoirs. Impacts on local communities and the environment should also be accounted for.

Thermal energy storage converts electric energy from the grid into thermal energy that is stored in inexpensive materials. Such systems can store energy from hours to weeks before converting it back to electrical energy or discharging the thermal energy directly. Thermal energy storage accumulates heat (or cooling) over hours, days, weeks or months. Storage is of three fundamental types:

- Sensible storage of heat and cooling uses a liquid or solid storage medium with high heat capacity – for example, water or rock.
- Latent storage uses the phase change of a material to absorb or release energy.
- Thermo-chemical storage stores energy as either the heat of a reversible chemical reaction or sorption process.

World's largest pumped hydropower storage commissioned in China

China is a global leader in pumped hydropower storage with the completion of the 3.6 GW Fengning Pumped Storage Power Station in Hebei province. This is the world's largest facility of its kind, finalised in August 2024. When the reservoir is fully ch arged, the power station can deliver up to 40 gigawatt hours (GWh) of electricity over 10.8 hours. The project commenced in 2013 and was built in two phases, each phase adding six 300 MW reversible pump-turbine units. In total, China has more than 200 GW of PHS projects under construction or approved and is on track to exceed its 2030 target of 120 GW, potentially reaching 130 GW. The revised Energy Law of January 2025 supports the orderly expansion of PHS, underscoring the country's dominance in the sector and ambition to carbon neutrality (IHA, 2024).

SUMMARY TABLE: Long-duration energy storage

INNOVATION READINESS LEVEL		LOW — HIGH Most technology is mature (except hydrogen storage).
BENEFITS	**Affordability**	LOW — HIGH Reduces VRE curtailment but has high upfront investment costs.
	Energy access	LOW — HIGH Opportunity to satisfy end users by adapting the generation to the demand profiles.
	Power system resilience	LOW — HIGH
	Energy security	LOW — HIGH
	Sustainable development	LOW — HIGH
IMPLEMENTATION	**Implementation cost**	LOW — HIGH
	Prerequisites	Clear regulation on the role of long-duration storage and the type of services it can provide, and how to be remunerated.
	Stakeholders responsible for implementation	Transmission and distribution system operators, utilities, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		China, India, South Africa

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2.2 Digital technologies

Digitalisation is defined as the integration of digital technologies into the planning, operation and management of power systems. This includes the use of sensors, smart meters, communication networks, data platforms and automation tools to improve grid reliability, efficiency, flexibility and customer engagement. Digitalisation makes it possible to monitor, predict, optimise and automate operations across entire power systems (IRENA, 2025a).

Digitalisation is a broad concept that is not limited to a mere substitution of analogue components and techniques by digital ones. Instead, it extends to a wide and evolving range of applications that leverage computational capabilities to enable automation and smart systems. Consequently, digitalisation is not a closed-end task, but a transformational process that takes advantage of innovations in information technologies for adding value to the system where these are applied (IRENA, 2025a).

Digital technologies can support the operation of energy systems with complex and diverse assets through approaches such as optimised forecasting, operation and maintenance. This is expected to lead to efficiency gains, while supporting energy security with enhanced reliability and resiliency.

The growing importance of digitalisation is associated with increasing the decentralisation and electrification of end-use sectors. Decentralisation is led by the increased deployment of small power generators, mainly rooftop PV, connected to the distribution grid. Electrification of transport and buildings (heating and cooling) involves large quantities of new loads, such as EVs, heat pumps and electric boilers. All these new assets on the supply and demand sides are adding complexity to the power sector, making monitoring, management and control crucial for the success of the energy transition (IRENA, 2019d).

Power systems have many variables that reflect the state of the systems, such as electricity flows, frequencies and voltages. Monitoring and quickly acting on the information about each of these variables can enable system operators and generators to adjust imbalances between supply and demand, maintain the current frequency and voltage at stable levels, anticipate and prevent problems, reduce costs, and create more reliable and resilient systems. Such data monitoring and analysis become even more critical as power systems integrate higher shares of VRE.

In many regions, however, power grids typically lack advanced data monitoring and control systems, which may result in frequent grid outages, among other issues. A reliability index called the System Average Interruption Frequency Index (SAIFI), which charts the average number of service interruptions experienced by a customer (World Bank, n.d.), starkly illustrates the size of the problem. SAIFI is a ratio of the total number of customer interruptions to the total number of customers served, calculated on a yearly or monthly basis. According to the World Bank, the median SAIFI for the world in 2019 was 2.23. For West African countries on average, it was more than an order of magnitude higher at 27.5, and for a few, it exceeded 50 or even 200 (Niger). The SAIFI was around 4.5 for South America and around 2.7 for South-East Asia (World Bank, 2025a).

To improve reliability, grid modernisation and optimisation are key. Motivation drivers for grid modernisation differ by country to country, and more generally from developed and developing economies. These primarily include system efficiency improvements, enabling new products, services, optimizing system utilisation and utilization improvements (W-T. Paul Wang, 2014) .

Data collection, data management and monitoring are the first steps in digitalising the power system and increasing the visibility of congestion on the grids. Introducing the digital electricity meter (smart meter) is important to enable the collection of energy usage data in an energy system. More advanced digital technologies, such as the Internet of Things (IoT) and artificial intelligence (AI), can increase automation and transform grids into smart grids, enabling increased optimisation of system operations.

Realising the full potential of digitalisation necessitates significant investment in foundational elements such as robust and secure communication networks, interoperable data management platforms, and clear regulatory frameworks governing data access, sharing and cybersecurity. These can be substantial undertakings.

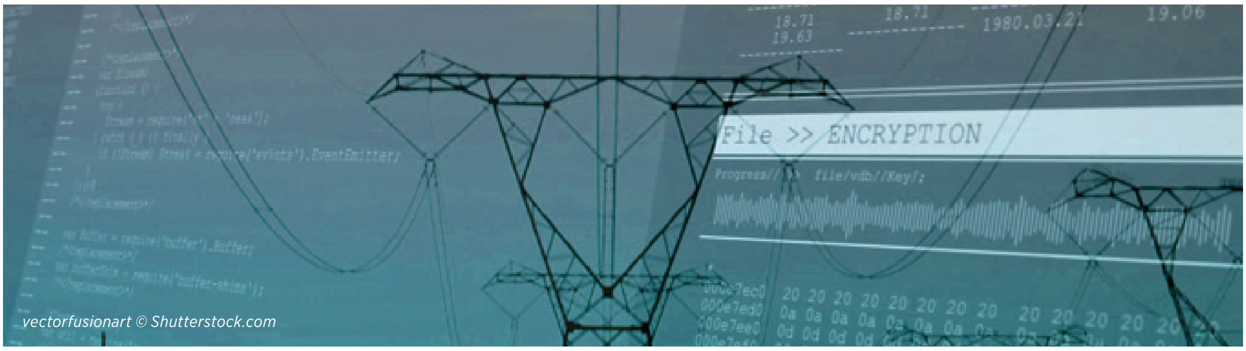
Cyberattacks on smart meters and other devices can cause significant economic losses (Kumar *et al.*, 2019). Combatting cybersecurity risks and maintaining confidence in the power system will require trusted and secure industry standards and skilled technical staff. The European Smart Metering Industry Group (ESMIG) has been promoting technical requirements and certification (Thales Group, 2022) as well as shared best practices (D’Souza, 2021). Similar standards need to be applied throughout the world to enable more digitalised energy systems.

Key concrete steps that policy makers can take to enable the roll-out of digital technologies and to harness the benefits of digitalisation in the power systems are:

- **Accelerate digital infrastructure roll-out and ensure interoperability and proper data governance.** Ensure access to digital infrastructure such as smart meters and digital platforms. Support digitalisation efforts across the technology layer (smart meters, telemetry, sensors), the data layer (with a focus on interoperability of data) and the regulatory layer (to enable innovative business models and system integration). Addressing the lack of interoperability includes establishing clear data governance, protection and regulation frameworks for data owners when digital solutions are deployed.
- **Empower energy consumers and foster their engagement in the energy transition through digital tools and skill-building initiatives.** This can be achieved through launching initiatives that enable consumers to become active participants (“prosumers”) and to raise their energy and digital skills. Other key steps are funding hands-on training at the intersection of the digital and energy sectors and supporting upskilling (where expertise is urgently needed).
- **Unlock finance in smart grid technologies.** There is a recognised lack of investment in smart grid technology. Development banks and funds can specifically invest in data networks, cloud platforms, and edge computing nodes in the Global South, treating digital grids as essential climate infrastructure akin to poles and wires.

- **Address and mitigate the risks associated with digitalisation, notably cybersecurity vulnerabilities**. Policy makers must manage inherent risks such as cyber vulnerabilities, particularly in critical infrastructure. Specific measures are needed to reduce the energy used by digital solutions, such as implementing reporting obligations, energy labels and minimum energy performance standards for data centres.

This report discusses two innovations that can support the modernisation of existing grids with digital technologies: monitoring systems, and smart and autonomous systems.



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Innovation 5

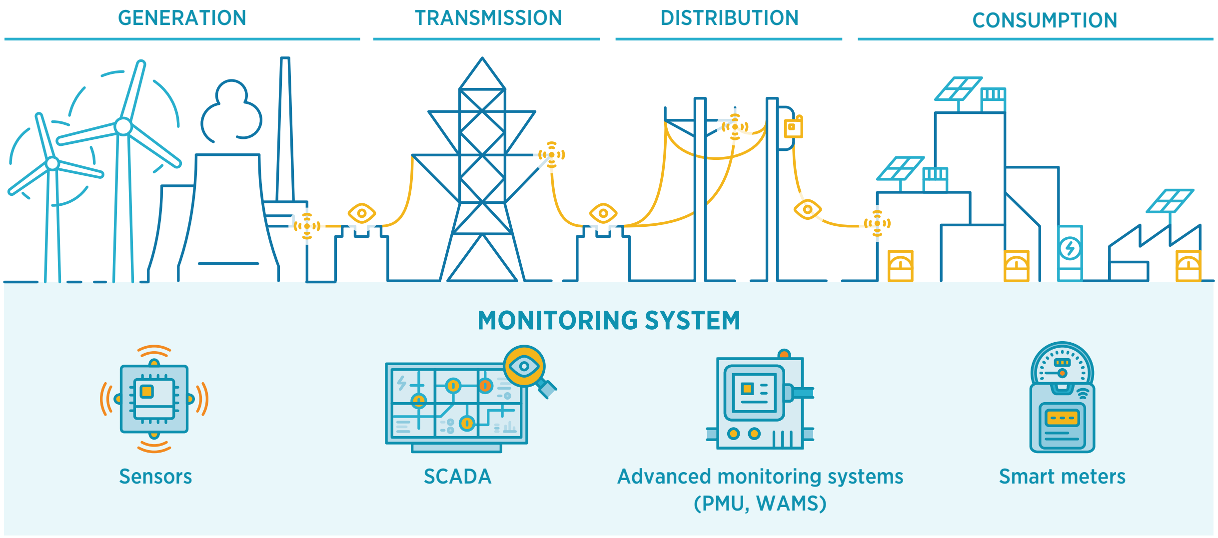
MONITORING SYSTEMS

Monitoring is the foundational layer of power system digitalisation. Monitoring encompasses the acquisition, transmission, and handling of data across the entire energy supply chain, from generation systems and transmission to distribution networks and end users. This includes real-time and historical data on electrical parameters, asset conditions, environmental factors and user behaviour (IRENA and AfDB, 2022).

Monitoring systems comprise several digital technologies (Figure 6):

- **Sensors:** These are the primary data acquisition tools, measuring physical and environmental parameters such as voltage, current, temperature, vibration and humidity. Advanced sensors, including nanoscale and AI-enhanced variants, enable high-resolution, context-aware monitoring.
- **Smart meters:** Installed at consumer endpoints, smart meters provide granular consumption data and support two-way communication with utilities. They form the backbone of Advanced metering infrastructure (AMI), enabling demand-side insights and flexible pricing schemes.
- **SCADA systems:** Supervisory control and data acquisition (SCADA) systems integrate field devices, communication networks and central processors to monitor and control grid operations. They are essential for real-time situational awareness and remote asset management.
- **Advanced monitoring systems:** Phasor measurement units (PMUs) and wide area monitoring systems (WAMS) are technologies that provide synchronised, high-frequency measurements across large grid areas, enhancing visibility and enabling fast response to disturbances.

FIGURE 6 | Overview of monitoring systems



SCADA

Supervisory control and data acquisition (SCADA) systems can increase visibility on the grid. SCADA is a system of different hardware and software elements that come together to enable a plant or facility operator to supervise and control processes. SCADA implementation of power system improves the overall efficiency of the system for optimising, supervising, and controlling the generation, transmission and distribution systems. SCADA functions in the power system network offer greater system reliability and stability for integrated grid operation.

A typical SCADA system includes (AllumiaX, 2024):

- sensors that measure and collect data from various locations
- conversion units that receive and interpret data
- programmable logic controllers that allow localised control
- remote terminal units, which are electronic devices that transmit information from the sensors to the SCADA system
- a communication network that provides a channel for the flow of data
- a central processing unit or hub for the entire system
- a remote communication server, which acquires and stores data.

SCADA systems for power grids measure voltage, temperature, current, humidity and other parameters at many remote locations. They also control automated switches and circuit actuators at different points of the network. For power plants, these systems can continuously monitor the speed and frequency of electrical machines, the amount of active and reactive power, the condition of boilers and turbines, and the status of circuit breakers, protective relays and other safety equipment. In addition, they can do load dispatch planning and load scheduling.

For transmission networks, SCADA systems monitor and control circuit parameters, relay functioning, voltages, and transformer tap changing, helping to manage service restoration after outages and re-routing for maintenance. For power distribution systems, they can reduce disruptions and the amount of manual labour needed by quickly locating faults and responding rapidly. These capabilities make them key enablers for integrating high shares of VRE.

SCADA systems also are the primary building blocks on which more advanced data analysis and control systems can be developed. For example, energy management systems (EMS) and distribution management systems (DMS) use data from SCADA systems and remote terminal units (RTUs) to optimise the operation of power systems, increase reliability and improve security.

SCADA systems have been adopted in most countries, but many are still in their infancy. Manual operation of the grid contributes to the high number and duration of grid disturbances leading to power outages.

Advanced monitoring systems

Advanced monitoring systems allow greater integration of data types or sources, such as advanced meters, phasor measurement units (measuring current and voltage at different locations), and even real-time weather information, to improve grid system operations and decisions. Advanced monitoring systems make it possible to create wide area monitoring Systems (WAMS) that provide holistic and geographically detailed pictures of the current state of critical systems elements, thus improving so-called grid situational awareness.

The expected benefits of an advanced monitoring system include better anticipating weather events that may cause problems on the grid, identifying the precise locations of those problems and taking more optimised corrective measures. The systems can also anticipate surges in demand from changing weather patterns, further improve the management of grids equipped with SCADA/EMS and SCADA/DMS systems, and improve the integration of national transmission systems and the sharing of data and knowledge among operators. In addition, they can help with commercial and financial monitoring, customer or utility accountability, and technical performance, helping grid operators analyse risks and set limits.

SCADA implementation in Nigeria

Nigeria is the largest power system in West Africa, generating 36.4 terawatt hours (TWh) of electricity in 2021 (Statista, 2022). But it has suffered from repeated outages and other failures, due in part to insufficient engineering expertise within the Nigerian power company and reliance on a proprietary system that was difficult to integrate with software and hardware from other vendors. In 2024, the Nigerian government introduced an advanced SCADA system aimed at improving efficiency, reliability and sustainability. Key features include real-time monitoring and control and integration with existing critical infrastructure. The country has achieved more than 3 000 kilometres of fibreoptic cables, SCADA equipment at 100 transmission sub-stations and training of technical staff. The introduction of the SCADA system aligns with Nigeria's objectives of achieving energy security and expanding electricity access for all. The government sees this development as a vital part of its strategic efforts to modernise power infrastructure and implement smart grids .

Enabling synchronisation in West Africa via the Information and Coordination Centre (ICC)

After nearly two decades of effort led by the Economic Community of West African States (ECOWAS), 12 West African countries (Benin, Burkina Faso, Côte d'Ivoire, Ghana, Guinea, Liberia, Mali, Mauritania, Senegal, Sierra Leone, The Gambia and Togo) reached a major milestone by uniting their national power grids in 2023. These grids are now synchronised thanks to a new dedicated SCADA, with the ICC of the West African Power Pool (WAPP) operating as the central entity to facilitate co-ordination and information exchange among its member states. The technology helps create a regional energy market, enabling the exchange of cleaner, more cost-effective energy across borders. The system greatly reduces reliance on expensive, polluting sources and increases access to reliable electricity for people and businesses (Power Africa, n.d.).

Wide Area Monitoring System (WAMS) in India

India's grid is one of the world's largest synchronised grids, connecting five regional grids with each other. The complexity of the grid, enhanced by the inclusion of market mechanisms, creates challenges to the system operator. After severe blackouts affected 620 million people across 22 Indian states in 2012, the Power Grid Corporation of India Limited (PGCIL) determined that a key reason for the outages was the lack of real-time dynamic grid data. Although increased communication infrastructure allows SCADA to provide an overview of the steady state of the system with updates of 4-15 seconds, system dynamics under fractions of seconds are needed to derive corrective actions. SCADA systems alone cannot typically provide this information because of delays in communications between remote terminal units (RTUs) and control centres. To improve situational awareness and visualisation of the system, India implemented synchrophasors or phasor measurement units (PMUs) with high sampling rates, which could provide time synchronised data very fast. Collectively, this WAMS collects measurements of current, voltage, and frequency and synchronises this using the Global Positioning System (GPS) every microsecond. Under this "Unified Real Time Dynamic State Measurement" project, 1 700 PMUs installed at 34 control centres and 356 sub-stations across India will collect data 25 times per second (Gupta, 2018; Vedachalam, 2022). WAMS provide sub-second data to the operator for enhanced decision making on how to operate the grid efficiently and reliably.

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SUMMARY TABLE: Monitoring systems

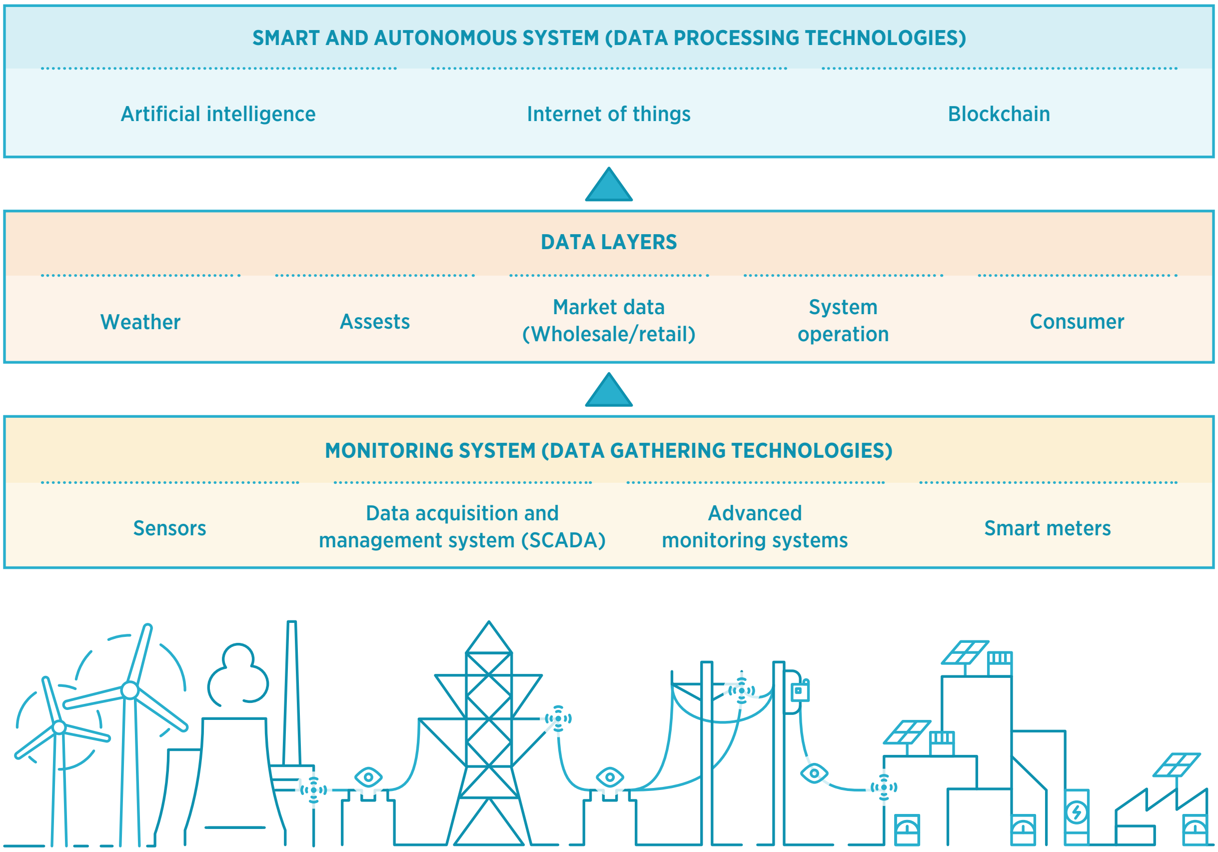
INNOVATION READINESS LEVEL		LOW HIGH
BENEFITS	**Affordability**	LOW HIGH Improves the ability to pilot the power system in a cost-effective manner. However, SCADA has a high upfront cost.
	Energy access	LOW HIGH
	Power system resilience	LOW HIGH A data acquisition system is a prerequisite to improve the resilience of the system. Contributions by coupling grid data with climate or other data source to increase the situational awareness.
	Energy security	LOW HIGH From collecting valuable data on the status of the system. Contributes more to short-term balancing than to security of supply.
	Sustainable development	LOW HIGH
IMPLEMENTATION	**Implementation cost**	LOW HIGH A specific infrastructure with high upfront costs (sensors, meters, database).
	Prerequisites	Staff training. Exploitation plan to ensure that the value of the data collected will be used to define Key Performance Indicators. Support from the regulator and from the transmission and distribution system operators is needed to valorise the economic value of this additional level of data integration.
	Stakeholders responsible for implementation	Transmission and distribution system operators, equipment manufacturers, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Brazil, China, Côte d'Ivoire, Ghana, India, Nigeria, South Africa

Innovation 6

SMART AND AUTONOMOUS SYSTEMS

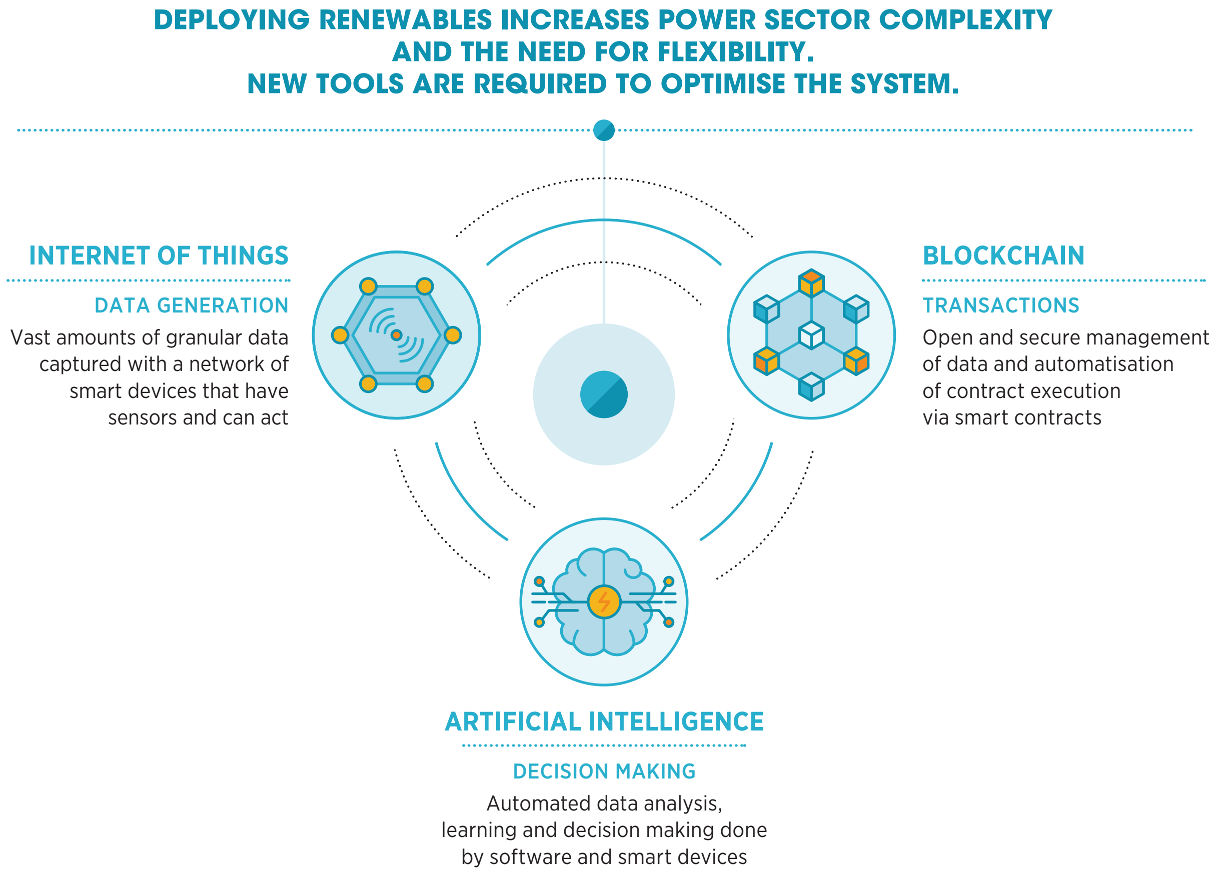
Small appliances equipped with sensors, smart meters, SCADA and advanced monitoring systems bring new levels of data and information. When combining all this new data with data processing technologies, such as the Internet of Things (IoT), AI, and blockchain, it enables a variety of new cases that turn the power system into a smart and autonomous system. Figure 7 illustrates the architecture of such a system.

FIGURE 7 | Architecture of digitalisation



Three specific digital technologies can have a great impact on smart and autonomous systems: 1) the IoT, 2) AI and big data, and 3) blockchain. While none of these are silver bullets, they reinforce each other as part of a toolbox of digital solutions needed to optimise the operations of an increasingly complex power system based on renewable energy (Figure 8).

FIGURE 8 | Digital technologies



Source: (IRENA, 2019d).

Internet of Things (IoT) technology has the potential to increase the flexibility and responsiveness of the smart assets connected to the grid, as well as the visibility of these assets for the system operator. By connecting energy suppliers, consumers, and grid infrastructure, IoT technology aims to facilitate the operation of complex systems and to open new commercial possibilities by enabling clients to further monetise the value created by their assets by providing different services through demand-side management.

Artificial intelligence (AI) refers to systems that, in response to data observed, collected, and analysed, change behaviour without being explicitly programmed. At its core, AI is a series of systems that act intelligently, using complex algorithms to recognise patterns, draw inferences and support decision-making processes through their own cognitive judgement, the way people do. AI can support with decision-making processes, with a variety of applications in power systems (IRENA, 2019e).

AI is envisioned to contribute greatly to power sector transformation, from improved VRE and demand fore casting to optimisation of preventive asset maintenance and enhanced grid stability and reliability. However, massive electricity demand from data centres can involve operational challenges for weakly interconnected power systems. In the case of Ireland, where data centres consume more than a fifth of the national electricity demand, there is a need for appropriate regulatory efforts and innovative approaches, such as the ones precisely promised by AI, to guarantee system stability.

Effective development and deployment of AI solutions also demand significant computational infrastructure, access to large, high-quality datasets, and the availability of specialised human capital in data science and AI engineering, which can present considerable barriers. Currently AI is largely fed with data from the Global North, which means that it will deliver biased solutions that are not always appropriate for developing country contexts.

Blockchain is a technology enabling a new world of decentralised communication and co-ordination, by building the infrastructure to allow peers to safely, cheaply and quickly connect with each other without a centralised intermediary, with applications in peer-to-peer electricity trading in particular (IRENA, 2019f).

Widespread digitalisation does, however, require a robust, interoperable and secure information infrastructure to allow data sharing and to reduce cybersecurity risks (Reidenbach *et al.*, 2022). This includes the need for data centres and standards. The infrastructure requirements make it especially challenging to achieve ubiquitous digitalisation in developing countries, although the low penetration of existing systems means that they also have the opportunity to leapfrog to more innovative solutions.

Smart grid development in Mexico

In 2013, Mexico began to transform its vertically integrated power system, dominated by a state-owned monopoly, into a deregulated sector with a competitive spot market and a more reliable modernised grid (Binz *et al.*, 2019). Mexico installed nearly 4 million smart meters (representing 8% of all meters) by 2022. The penetration rate of electricity meters is forecast to increase from around 8.5% in 2023 to nearly 22% in 2029 (Jones, 2024). Those meters are being used to collect data, manage bills, reduce maintenance needs and improve reliability. However, the Mexican example shows that digitalisation is only part of the solution, since the power system still suffers from stability and reliability issues because of rising demand.

SUMMARY TABLE: Smart and autonomous systems

INNOVATION READINESS LEVEL		LOW / HIGH
BENEFITS	**Affordability**	LOW / HIGH
	Energy access	LOW / HIGH
	Power system resilience	LOW / HIGH
	Energy security	LOW / HIGH Contributes more to short-term balancing than to security of supply.
	Sustainable development	LOW / HIGH Can facilitate the penetration of VRE sources.
IMPLEMENTATION	**Implementation cost**	LOW / HIGH Higher upfront costs for the sensors and the database infrastructure.
	Prerequisites	Regulation that enables extracting the economic value of this additional level of data integration. Digitalisation requires very strong and skilled human capital to deal with the associated privacy and security issues. Increased electricity demand from data centres needs to be taken into account and covered with renewable electricity. National digital transformation strategies are needed that explicitly integrate the energy sector, ensuring policy coherence, targeted investments, and resource allocation for building foundational digital infrastructure and fostering digital literacy across relevant institutions and the workforce.
	Stakeholders responsible for implementation	System operators, information and communications technology (ICT) industry, energy regulatory agency, consumers.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Egypt, India, Mexico, South Africa, Zimbabwe

2.3 Electrification of end uses and energy efficiency

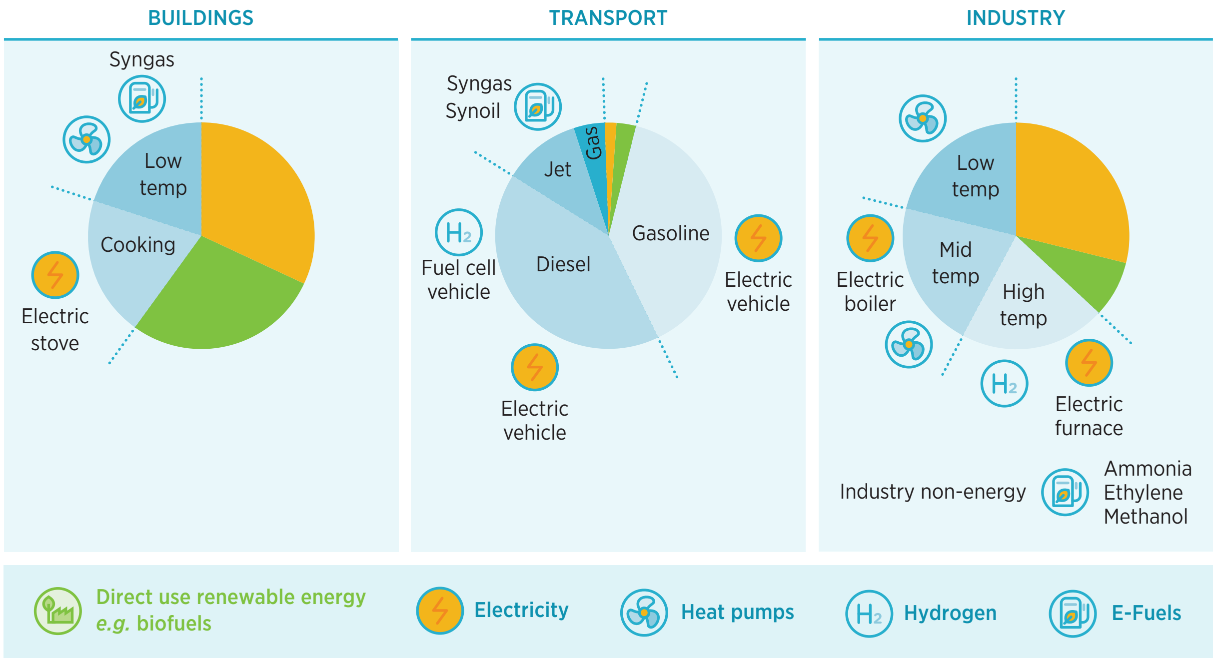
Electrification of end-use sectors is another innovation trend, with the aim of decarbonising end-use energy sectors and with a great impact on the power system.

Under IRENA's 1.5°C Scenario, the share of direct electricity in total final energy consumption must increase from 22% in 2020 to 29% by 2030 and 51% by 2050; this can be achieved with tremendous growth in electric-powered technologies, many of which are already available (IRENA, 2023b). They include EVs and heat pumps, which can provide heat for buildings and many industrial processes. In addition, end-use sectors that are difficult to electrify directly can be decarbonised using "green" hydrogen produced by electricity generated from renewable energy, also known as indirect electrification.

The electrification of end-use sectors, which reflects the shift towards electricity as a key energy carrier, combined with renewable electricity generation and increased energy efficiency, is crucial for a successful energy transition (IRENA, 2023c).

Figure 9 shows the major electrification options by end-use sector. The electrification of end-use sectors is not solely driven by decarbonisation targets; it can also support development, decrease air pollution and noise pollution (especially from transport sector) and reduce health issues caused by traditional cooking options in developing countries.

FIGURE 9 | Major electrification options by end-use sector



Source: (IRENA, 2022a).

This section focuses on four key end-use areas of innovation: energy-efficient appliances, electric vehicles, green hydrogen, and renewables-based electrification of other end uses (heating, cooling and cooking).

Innovation 7

ENERGY-EFFICIENT APPLIANCES

Electrification is a powerful strategy to decarbonise and improve overall energy efficiency, but it needs to be accompanied by greater efficiency of electric devices.

Energy efficiency helps to reduce the load, making it easier to meet electricity demand using existing infrastructure and minimising investments needed in new infrastructure. More efficient refrigerators, freezers, heating and cooling systems, lighting, and other appliances also reduce the needed capacity (and thus cost) of associated solar PV panels, making solar home systems or solar mini-grids more viable and affordable in areas lacking or with unreliable energy access.

Switching to appliances such as heat pumps, which are three to four times more efficient than conventional technologies, requires removing inefficient appliances from the market, implementing strategies and policies to surmount the barrier of higher upfront costs, and creating an effective supply chain. Key policy tools for achieving this include the establishment and enforcement of stringent minimum energy performance standards (MEPS) to remove the least efficient products from the market, coupled with clear and informative energy labelling programmes that empower consumers to make informed purchasing decisions.

One potentially effective strategy would be combining end-use efficiency policies with power system expansion plans. Governments could also rapidly adopt some technologies themselves, such as by installing more efficient public lighting systems.

Benefits of energy efficiency programmes in several African countries

After a series of droughts in the 1980s and 1990s that stressed energy supplies, Ghana implemented Appliance Standards and Labelling initiatives (CEESD, 2020; Cold Link Africa, 2021) that set minimum efficiency standards for refrigerators, air conditioners and lighting. Those measures saved 8.3 TWh of electricity and USD 832 million in electricity bills and reduced carbon dioxide (CO_2) emissions by 4.6 million tonnes between 2007 and 2020 (Tamakloe, 2022). Many other African countries have similar requirements for electric appliances. The innovative next step is to explicitly combine efficiency improvements with the roll-out of renewables to lower overall system costs and reduce evening peaks. For example, Uganda's Energy Efficiency Roadmap (Can *et al.*, 2017) found that end-use efficiency improvements would cut forecasted electricity demand in 2030 by 31%, greatly reducing energy bills and investment costs while helping to stimulate electricity access.

Energy efficiency in India

Through the Bureau of Energy Efficiency (BEE), India launched its Standards and Labelling (S&L) scheme in 2006 to promote energy efficiency in home appliances. This was aimed at providing consumers with information on the energy- and cost-saving potential of products. A "star label" was introduced to detail the efficiency of 21 equipment or appliance types (*e.g.* lighting, refrigerators, air conditioners). The BEE conducted awareness-raising workshops, seminars, outreach programmes and capacity building initiatives, which involved four crucial stakeholders: end users, retailers, manufacturers, and testing and servicing professionals.

To promote the deployment of energy-efficient compact fluorescent lamps (CFLs) to replace incandescent bulbs, two energy-efficient lighting programmes were launched: Bachat Lamp Yojana (BLY) and Unnat Jyoti by Affordable LEDs for All (UJALA). The BLY programme, launched in 2009, distributed CFLs at a modest price of INR 15 (USD 0.17) to households in exchange for incandescent bulbs. In 2014, this was replaced by the UJALA scheme, wherein LED lighting was distributed to end users at 40% discounted prices, without subsidies (UNFCCC, 2023).

SUMMARY TABLE: Energy-efficient appliances

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Beneficial because of the amount of avoided energy losses. Many efficiency improvement measures have a short pay-back time. Yet access to capital is an important barrier.
	Energy access	LOW – HIGH Improves energy access by reducing the amount of electricity needed to deliver end-use services.
	Power system resilience	LOW – HIGH Can contribute to a resilient power system by reducing the peak load.
	Energy security	LOW – HIGH Reduces the amount of primary energy needed to satisfy the demand.
	Sustainable development	LOW – HIGH Favourable to the penetration of VRE sources by reducing the need for new thermal plants to match the growth rate of the electricity demand.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH Moderate in general but upfront cost for less affluent households.
	Prerequisites	Support from policy makers. Access to upfront capital for technology upgrades. Clear regulation and standards with efficient controls. Awareness and availability of efficient appliances.
	Stakeholders responsible for implementation	Energy regulatory agency, dedicated energy efficiency agency, non-governmental organisations for awareness raising.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Algeria, Egypt, Ghana, Kenya, Morocco, Nigeria, Rwanda, Senegal, South Africa, Uganda

Innovation 8
ELECTRIC VEHICLES

Electric vehicles can dramatically reduce greenhouse gas emissions from the transport sector. EVs bring additional benefits such as less air pollution (and thus improved health), less noise, lower maintenance costs, and the potential for decentralised energy storage and valuable grid services. Plug-in electric vehicles can power homes or commercial establishments, inject power back into the grid to help meet peak demands, and adjust charging rates to help power system managers balance supply and demand, reducing the need for investments in generation and grids. In developing countries, EV batteries could be especially important in providing back-up power during extreme weather events, increasing power system resilience.

Electric two- and three-wheelers are particularly important in many developing economies, where this transport mode is predominant. The market for electric two- and three-wheelers has grown significantly with the launch of many models of e-scooters, e-bikes, three-wheel cargo bikes, e-motorcycles and auto rickshaws (tuk-tuks). Particular focus has been placed on improving mileage, charging time, battery management systems and connectivity, and increasing durability and ride comfort.

However, rapid adoption of EVs in developing countries is challenging because of high upfront costs, the lack of charging networks and potential impacts on electricity grids. Given these challenges, the most effective current strategies may be measures such as investing in EVs for public transport (buses) and fleets (such as taxis), in addition to promoting electric two- and three-wheelers. In India, 60% to 70% of all sales of new vehicles are expected to be electric two-wheelers by 2030 (McKinsey & Company, 2023).

Furthermore, emerging markets and developing economies can explore opportunities for local manufacturing or assembly of electric two- and three-wheelers and associated charging components, which can help reduce costs, create local value, generate local employment and allow for product designs that are better tailored to specific local conditions and user needs.

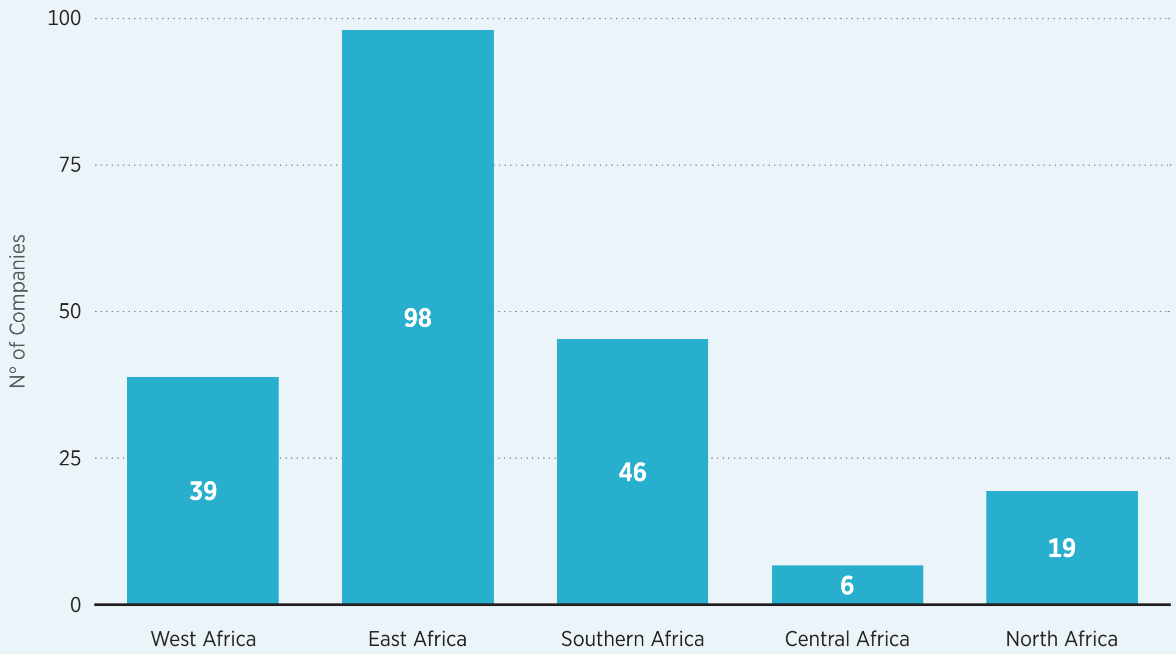
Promising electro-mobility developments in Africa

Several countries in Africa have promising enterprises for electro-mobility (Figure 10). In Ghana, after the rapid entry of independent power producers into the electricity market led to excess generation capacity (Direction générale du Trésor, 2020), the country launched a "Drive Electric Initiative" in 2019 to use the excess electricity and reduce CO_2 emissions. The initiative has led to plans for an electric bus system in Accra (UNEP, 2023), new businesses that rent EVs – such as Solar Taxi (Climate-Chance, 2022) and Accraine Ghana (Orient Energy Review, 2020) – and 200 EV charging stations country-wide (IRENA and AfDB, 2022).

Rwanda plans to deploy more than 50 000 electric two-wheeled taxis (e-motos) in the capital city of Kigali (Mitigation Action, 2024). The start-up company Ampersand sees a potential market of 600 000 electric motorbikes in Kigali alone, as well as large markets in Kenya and Uganda (AfricaNews, 2024). Ethiopia (Ethiopian Business Review, 2022), Seychelles and South Africa (ESI-Africa, 2022) have begun testing electric public transport buses.

In 2020, Kenya submitted its Nationally Determined Contribution (NDC) to reduce its emissions 32% by 2030. In addition to reducing emissions, it is envisaged that Kenya's transport sector can help reduce the current curtailment of renewable generation, which averages more than 1 357 MWh of curtailed power daily. This could help charge around 7 000 electric buses or 200 000 electric motorcycles. In 2023, Kenya developed the National Electric Mobility Policy (e-Mobility Policy) to enable the growth and adoption of EVs. This includes developing an integrated and comprehensive policy, legal and regulatory framework, to promote local manufacturing and assembly, enhance EV infrastructure capacity, and improve fiscal and socio-economic measures to accelerate uptake (Ministry of Roads and Transport, 2024).

FIGURE 10 | Electric mobility companies in Africa (as of August 2025)



Source: (Africa E-Mobility Alliance, 2025).

SUMMARY TABLE: Electric vehicles

INNOVATION READINESS LEVEL		LOW — HIGH
BENEFITS	**Affordability**	LOW — HIGH High vehicle costs and less developed second-hand market.
	Energy access	LOW — HIGH Does not contribute to improved energy access.
	Power system resilience	LOW — HIGH Can contribute to resilience in a vehicle-to-grid charging/discharging mode. Needs smart charging strategies. Can be used for increased resilience but not as the main solution.
	Energy security	LOW — HIGH Reduces oil dependency. Creates more dependency on a well-functioning power system.
	Sustainable development	LOW — HIGH Enables the transition to a low-carbon transport system. Favourable for the penetration of VRE sources with smart charging strategies.
IMPLEMENTATION	**Implementation cost**	LOW — HIGH High upfront implementation cost due to the cost of the vehicle and the need for a dense network of charging stations.
	Prerequisites	A comprehensive package of targeted consumer incentives (*e.g.* purchase subsidies, tax exemptions, registration fee waivers) and non-fiscal support measures (*e.g.* development of public charging infrastructure, preferential parking/charging access, and awareness campaigns) to overcome the initial high cost barrier and accelerate market uptake, particularly for individual consumers and small businesses. Suitable business model to install the charging infrastructure. Clear standards and regulatory updates because of the co-existence of multiple types of vehicles and manufacturers. Consideration of the impact of charging infrastructure on the local distribution grid, including technical analysis of charging station siting with respect to the grid, high traffic and population density, *etc.* Consideration of end-of-life management of battery strategies: use as stationary batteries for the grid, and recycling.
	Stakeholders responsible for implementation	Energy regulatory agency, transport ministry and authorities, non-governmental organisations for awareness raising, EV manufacturers, governments.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Egypt, Ghana, Kenya, Morocco, Rwanda, South Africa, Uganda

Innovation 9

GREEN HYDROGEN

Green hydrogen is produced by splitting water into oxygen and hydrogen using renewable electricity through the process of electrolysis. The hydrogen can then be used as a fuel, as a feedstock for chemicals and other substances, or as an energy storage medium (IRENA, 2020a).

For end uses that cannot be easily powered directly by electricity – such as some industrial processes, shipping and aviation – green hydrogen offers an effective decarbonisation option (IRENA, 2019c). It can also provide valuable long-term energy storage, enabling it to play a pivotal role in stabilising energy grids that rely on solar and wind power and are affected by seasonality.

Green hydrogen that is produced when renewable inputs are readily available, to be consumed when energy demand is highest, may provide a solution for large-scale, long-duration energy storage needed across extended periods. Flexible electrolysers may also support power system resilience in variable, highly renewable power systems (IRENA, 2025b).

While offering significant decarbonisation potential, it is crucial to acknowledge the inherent energy conversion losses during electrolysis and any subsequent reconversion to electricity or other energy forms. These impact the overall round-trip efficiency of electrolysis and often render it a more costly pathway compared to direct electrification where technically and economically feasible.

Many countries in the Global South possess considerable renewable resources and could produce large amounts of green hydrogen using electrolysers located near solar or wind facilities. As a result, many of these countries could become major producers of green hydrogen for future anticipated global hydrogen markets (Green Hydrogen Organisation, n.d.). More important, however, is the potential for green hydrogen production to spark a transformation within developing countries themselves by driving industrial development and fostering innovation.

Many of these countries are not locked into high investments in extensive fossil-fuelled industrial assets. Their emissions from hard-to-abate sectors are limited for now, but as industrialisation progresses they must leapfrog into renewable energy-powered solutions for industries. Green hydrogen production and use could fuel economic development and the rise of new home-grown industries, create jobs, and enhance pathways to energy independence, while also accelerating decarbonisation, particularly in hard-to-abate industries such as steel and chemicals (UNIDO *et al.*, 2024).

However, there are multiple barriers to scaling up electrolysers and hydrogen transport, such as high costs, uncertain future demand, and lack of technical and commercial standards (IRENA, 2021a).

Green hydrogen in Africa

The Africa Green Hydrogen Alliance (AGHA) was formed by six leading African countries – Egypt, Kenya, Mauritania, Morocco, Namibia and South Africa – to intensify collaboration and development of green hydrogen projects in Africa. Its objective is to develop public and regulatory policy, capacity building, financing and certification needs to mobilise green hydrogen production for domestic use and export. Green hydrogen, produced using the high potential for wind and solar in these countries, has the potential to increase their gross domestic products (GDPs) by 2050. It would also enable production of green ammonia for meeting export as well as domestic demand in hard-to-abate sectors (Africa Green Hydrogen Alliance, 2022).

Mauritania has set an ambitious goal of being Africa's leading producer and exporter of green hydrogen and green ammonia. In 2024, the country adopted a green hydrogen law/code defining a new legal framework aimed at bolstering private investment, with a strong focus on green hydrogen development. Key aspects of the code include exemption from value-added tax (VAT) and export tax for green hydrogen projects, reduction of import customs duties, progressive corporate income tax, *etc*. (Green Hydrogen Organisation, 2025a, 2025b). Three projects have been identified for implementation. Project Aman is projected to produce 1.7 million tonnes of green hydrogen and 10 million tonnes of green ammonia from renewable capacities of 30 GW (18 GW wind and 12 GW solar) that will generate 110 TWh of electricity per year. In addition, feasibility studies have been completed for Project Nour (Chariot Energy Group, 2024), which plans to use 10 GW of electrolyser capacity (powered by solar and offshore wind) to make green hydrogen for a domestic steel industry and green ammonia for export (apofeed, 2023; Powers, 2023; Wood, 2024). Finally, the state-backed Green Steel MOU with ArcelorMittal aims to produce 2.5 million tonnes of green steel per year (Reed, 2022).

Namibia has launched a green hydrogen strategy aimed at supporting the country's goal of achieving net zero emissions by 2050. The joint venture Cleanergy Namibia aims to produce green hydrogen from solar energy for use in trucks, locomotives, mining equipment and ships through a public refuelling station featuring a 5 MW capacity electrolyser and 5 MWh of battery storage (Chandak, 2023). The project plans to develop a hydrogen academy to develop local expertise in hydrogen production (Cleanergy Solutions Namibia, 2025). In Kenya, the Kenya Nut Company near Nairobi says it will be the first farm in the world to produce its own "green" fertiliser (*i.e.* green ammonia), using solar energy (Yale School of the Environment, 2023). In South Africa, the platinum producer Anglo American has developed the world's largest hydrogen-powered mining haul truck and plans to replace its diesel fleet with the hydrogen vehicles. It installed a 3.5 MW electrolyser to make the green hydrogen (Mining Review Africa, 2023).

Hydrogen development in ASEAN countries

To reduce carbon emissions and ensure energy supply, the member states of the Association of Southeast Asian Nations (ASEAN) have sought hydrogen and ammonia as solutions to transform their fossil fuel-based energy systems, including the industry, transport and power sectors. Several hydrogen projects (including green hydrogen) are under consideration or being developed, with plans to be operational in the late 2020s. Indonesia, Malaysia and Singapore are among the ASEAN member states that have released national hydrogen strategies, reflecting their own priorities and circumstances. Indonesia's strategy focuses on developing a domestic green hydrogen ecosystem by expanding demand in the industrial, transport, and power generation sectors, while aiming to establish the country as a leading global hydrogen export hub (Green Hydrogen Organisation, 2025c). Malaysia aims to transform into a regional hydrogen leader by 2050, leveraging its renewable energy resources to accelerate decarbonisation, generate economic growth and export hydrogen (Ministry of Science Technology and Innovation Malaysia, 2023). Singapore is promoting various green hydrogen applications in all energy sectors, aiming for hydrogen to supply up to half of the country's power needs by 2050 and to play an important role in industry decarbonisation (Ministry of Trade and Industry Singapore, 2025).

SUMMARY TABLE: Green hydrogen

INNOVATION READINESS LEVEL		LOW — HIGH	
BENEFITS	**Affordability**	LOW — HIGH	
	Energy access	LOW — HIGH	
	Power system resilience	LOW — HIGH	May contribute to a resilient power system if flexible operation of the electrolyser is leveraged to provide grid balancing (on-demand load following or load shedding) or ancillary services to the system operator.
	Energy security	LOW — HIGH	Reduces fossil fuel dependency. The novelty of the hydrogen economy can introduce new supply chain risks.
	Sustainable development	LOW — HIGH	Enables the transition to low-carbon industry and transport sectors (shipping, aviation).
IMPLEMENTATION	**Implementation cost**	LOW — HIGH	New investments are needed for the electrolysers and for the hydrogen transport infrastructure.
	Prerequisites		The development of comprehensive national hydrogen strategies that clearly define priority domestic use cases, realistic production targets, and the strategic role of green hydrogen in the energy transition, all supported by rigorous techno-economic assessments and integrated resource planning as a foundational element for coherent and sustainable development of ahydrogen economy. Training for a skilled local workforce to safely operate the hydrogen production and distribution system. Trusted long-term off-taker contracts in case of development motivated by export to developed countries. Certification schemes to specify the type or grade of hydrogen. Construction of the hydrogen transport infrastructure and water availability.
	Stakeholders responsible for implementation		Energy regulatory agency, electrolyser manufacturers, hydrogen-using industrial sectors, governments.
JURISDICTIONS WHERE IT IS IMPLEMENTED			Egypt, Kenya, Mauritania, Morocco, Namibia, South Africa

Innovation 10

RENEWABLES-BASED ELECTRIFICATION OF HEATING, COOLING AND COOKING

Renewable electricity can be used to power end uses, especially heating and cooling in buildings (via heat pumps), cooking (via electric cooking appliances) and industrial processes (by using heat pumps or electric boilers). Around a third of the global population uses open fires or inefficient stoves fuelled by kerosene, biomass, and coal, which generates air pollution. Household air pollution was responsible for an estimated 3.2 million deaths in 2020 (WHO, 2024).

Electrification of end uses offers numerous advantages and benefits (IRENA, 2021b), including greater overall energy efficiency (given the high efficiencies of electric appliances such as heat pumps) and providing flexibility to the power grid, improving its reliability and reducing curtailment of VRE.

Clean cooking solutions, such as electric stoves, can improve air quality and health (especially by replacing wood, charcoal and fossil fuels), reduce deforestation and empower women. Women are the most impacted by implementation of clean cooking solutions, as they are usually responsible for the time-intensive tasks of collecting fuel and cooking. They are exposed to unsafe stoves and insecure environments and experience drudgery associated with the use of firewood and charcoal. Women can invest in the clean cooking sector and be involved in designing, producing and distributing clean technologies. Adoption of clean cooking shifts finances and improves time spent on income generation or leisure.

Although clean cooking technologies are available in developing countries, barriers to adoption include a lack of awareness of the cost savings from switching to electric cookers, high upfront costs, high electricity (operating) costs), lack of access to capital, lack of supportive regulations and unreliable electricity grids (World Bank, 2025b). Electric cooking solutions may also face social barriers. Overcoming social barriers and ensuring sustained adoption beyond initial distribution often requires the development of culturally appropriate and user-centric clean cooking solutions, coupled with delivery models that consider local cooking practices, affordability and accessibility of electricity.

Power-to-heat reduces wind power curtailment in China

In some Chinese provinces, up to 30% of available wind power has had to be curtailed[3] (cet.energy, 2022) because of the need to run existing coal-fired combined heat-and-power (CHP) plants in northern China near their full capacity in winter (Zhang *et al.*, 2021). A proposed pilot project in West Inner Mongolia would address this problem by using the excess wind power to supply heat to a local district heating system using 50 MW of electric boilers (IRENA, 2017a). In addition, China's Clean Winter Heating in the Northern Regions programme aims to replace coal with electricity and natural gas, which studies show can cut sulphur dioxide air pollution by around 20.4% (Xue and Larsen, 2025).

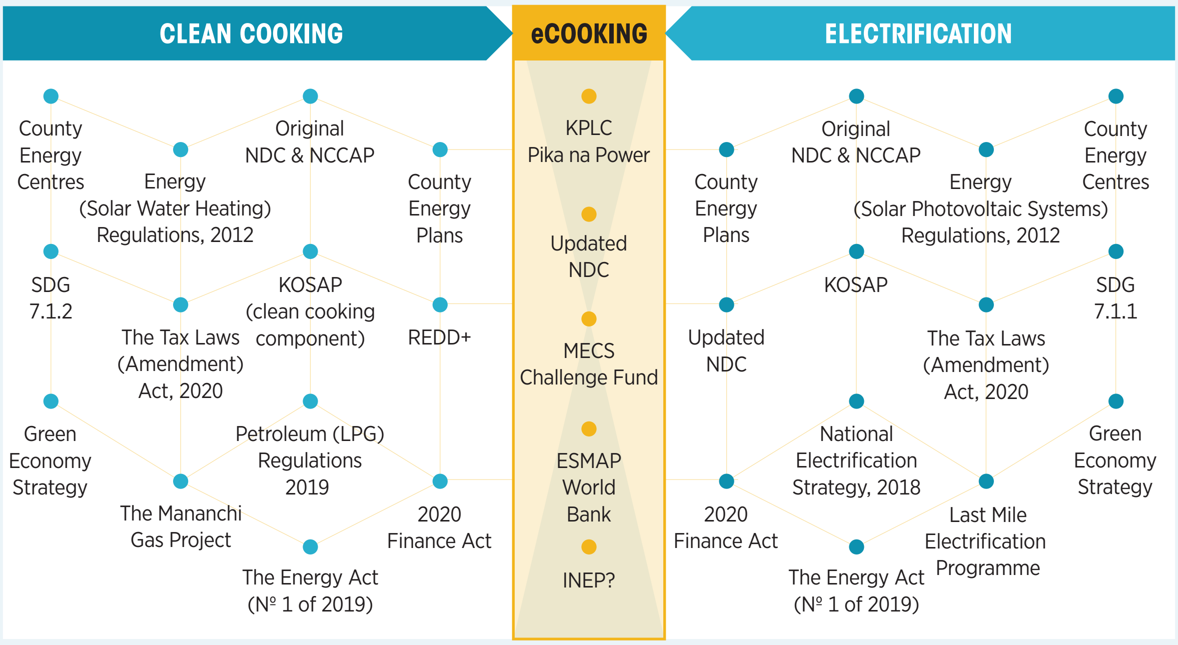
[3] Recent estimates show a decrease from 12% to 3.1% at the country level in China between 2017 and 2021, but the rate in West Inner Mongolia remains high at 8.9% in 2021.

Another promising option for providing district heating is solar thermal energy storage using molten salt. This technology is already in use in countries such as Denmark, where large-scale solar collectors provide heat for residential and commercial buildings. A promising complementary technology is seasonal thermal energy storage using molten salt, which enables excess solar heat collected in the summer to be stored and used during the winter. This approach is being piloted in China, offering potential for broader application in future low-carbon district heating networks.

Kenya is a front runner in electric cooking in Africa

The Kenya National Electric Cooking Strategy, launched in October 2024, lays the foundation for a sustainable eCooking marketplace in the next five years (Figure 11). Kenya Power and Lighting Company (KPLC) is implementing an electric cooking campaign called "Pika na Power", using a television series, social media campaigns and live cooking classes to convince people to switch to electric or solar cooking (Leary *et al.*, 2021; Pika Na Power, 2022). By late 2023, the campaign had subscribed 90 000 customers, with a goal of 500 000 by 2026 (Musalia, 2023). Kenya also has innovative pilot projects to increase electric cooking access through the last-mile electrification programme, to replace biomass cooking with liquefied petroleum gas (LPG) and solar-powered electric pressure cookers (MECS, 2022), and to promote "battery-augmented" electric cooking to enable flexible cooking with solar home systems (Monk, 2021). Collaborative efforts among KPLC, government ministries, community organisations (including faith-based institutions), county governments and last-mile entrepreneurs have helped establish regional eCooking hubs in Kakamega, Kisumu, Kitui, Makueni and Nakuru (EED Advisory Limited, 2025). An eCooking tariff for households and institutions to improve the affordability of eCooking is under way.

FIGURE 11 | Examples of e-cooking initiatives and their links to clean cooking and electrification policies and programmes in Kenya



Source: (Atela *et al.*, 2021).

SUMMARY TABLE: Renewables-based electrification of heating, cooling and cooking

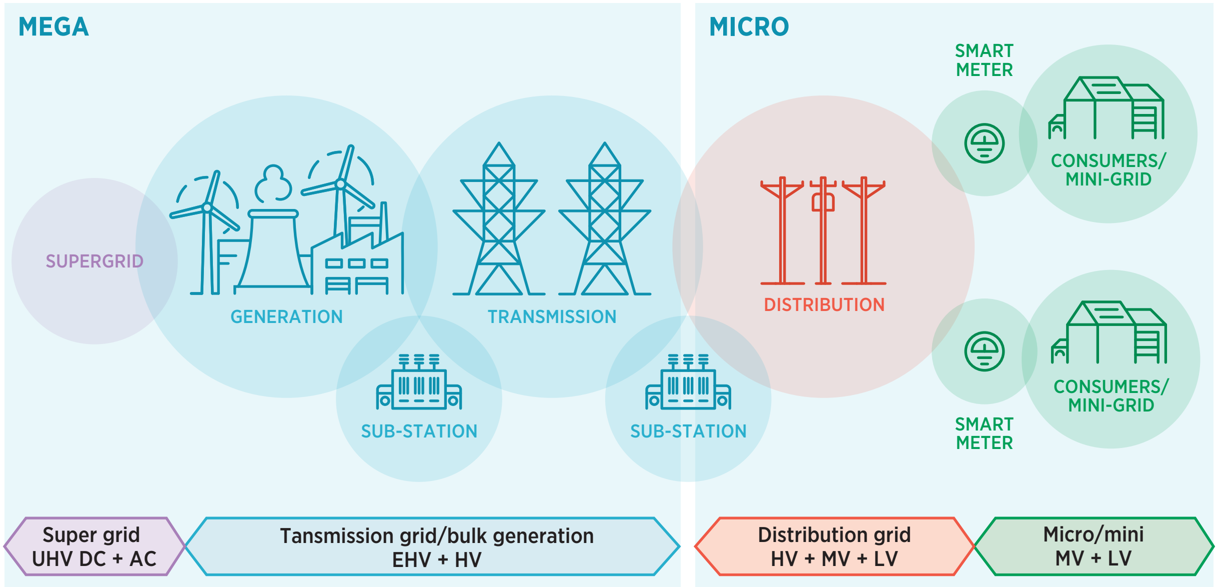
INNOVATION READINESS LEVEL		
BENEFITS	**Affordability**	
	Energy access	 Renewable electricity can power modern and clean cooking solutions in areas where the logistics of LPG distribution is not sufficiently reliable.
	Power system resilience	 Power-to-heat can contribute to a resilient power system if associated with transmission system operator control to provide balancing and ancillary services to the grid. When associated with thermal storage, seasonal optimisation can be envisaged.
	Energy security	 Reduces fossil fuels and biomass dependency.
	Sustainable development	 Enables decarbonised heating and cooking sectors. Facilitates the integration of VRE sources.
IMPLEMENTATION	**Implementation cost**	 More mature technologies with lower implementation costs than green hydrogen. The upfront cost of electric cooking solutions in a developing context can represent a barrier for households.
	Prerequisites	Awareness of power-to-heat opportunities due to the complexity and lack of standardisation of heating needs in industrial processes. Fuel stacking practices are hard to quantify and may lead to lower usage rates of electric cooking solutions. Government support is needed to overcome the awareness barrier and address subsidies to LPG as a clean cooking solution.
	Stakeholders responsible for implementation	Appliance manufacturers, governments, non-governmental organisations to contribute to awareness raising campaigns.
JURISDICTIONS WHERE IT IS IMPLEMENTED		China, India, Kenya, Rwanda, Uganda

2.4 Future grids

Grids connect generation and demand, often over long distances. Most electric appliances, except for off-grid devices such as solar lamps, must be connected to some sort of grid.

Two very different, yet complementary, grid innovations are mini-grids and supergrids (Figure 12). These grids operate at radically different scales, but both can enable wider adoption of renewable-based electricity in developing countries and can complement each other while supporting existing centralised grids.

FIGURE 12 | MEGA and micro perspectives in the setting of the entire power system



Source: (Oleinikova and Hillberg, 2020).

Notes: UHV = ultra-high voltage, DC = direct current, AC = alternating current, EHV = extra-high voltage, HV = high voltage, MV = medium voltage, LV = low voltage.

Innovation 11

RENEWABLE MINI-GRIDS

Renewable mini-grids are a form of integrated energy infrastructure with distributed energy generation resources and loads that provides autonomous capability to satisfy electricity demand through local generation, mainly from renewable energy sources (IRENA, 2019g). The term "mini-grid" typically covers everything from small grids with generation capacities of a few kilowatts (called nano or micro-grids) up to 100 MW systems that can cost-effectively power whole communities in remote areas. Mini-grids usually can be planned and built much more quickly than centralised grid expansion projects. While mini-grids date back more than a century, today's third-generation mini-grids have two big advantages over earlier versions. Thanks to advances and declining costs for batteries and smart meters, they can integrate higher shares of variable renewable generation and supply reliable electricity for a greater number of hours. In addition, they can be connected to existing grids, making them more environmentally sustainable and economically resilient to future expansions of the main grid.

Mini-grids are especially valuable in developing countries where large numbers of people currently lack access to electricity or depend on expensive and often unreliable diesel generators. Mini-grids not only can enable essential services such as lighting, refrigeration, and irrigation, they also can unleash new waves of businesses and entrepreneurial activity, from food processing and manufacturing to hotels and service like education and health care. This has the potential to spark a virtuous circle of accelerated sustainable growth, raising incomes and living standards. However, some barriers remain to their development, such as high upfront investment costs, the risk of competition from future expansions of centralised public grids, and regulatory uncertainties.

Ensuring the financial sustainability and maximising the developmental impact of mini-grid projects critically hinges on the early identification and integration of reliable anchor loads, such as local businesses, agricultural processing, or community services, and the active promotion of diverse productive uses of electricity to stimulate local economic activity and enhance revenue streams.

Renewable mini-grids provide rural electrification in Africa

Renewable mini-grids could provide electricity access to an estimated 81 million households in Sub-Saharan Africa by 2030 (SE4ALL and BNEF, 2020). Some large-scale efforts have already begun. In late 2023, the company Husk Power Systems announced an "Africa Sunshot" initiative to build 2 500 solar mini-grids in the sub-Saharan region in five years, bringing electricity to 7.7 million people and 225 000 micro, small and medium-sized enterprises (Walker, 2023).

Renewable mini-grids can transform rural economies and help create new "economic clusters". A new hybrid solar mini-grid in Bougoula, a rural commune in the Koulikoro region of southwestern Mali, now provides electricity for water pumps, agricultural processing machines and other industrial equipment. The project has improved agricultural productivity, freed women from arduous treks to fetch water and created new economic opportunities (IRENA, 2022b). In Nigeria, a solar-plus-storage mini-grid project in the Sabon Gari market is providing clean electricity to 4 000 shops previously powered by diesel generators (350 Africa, 2025; Renewable Energy Agency Nigeria, 2021), with a planned expansion to 12 000 shops.

SUMMARY TABLE: Renewable mini-grids

INNOVATION READINESS LEVEL		LOW — HIGH
BENEFITS	**Affordability**	LOW — HIGH
	Energy access	LOW — HIGH Mini-grids are a suitable alternative to costly grid extension in remote areas.
	Power system resilience	LOW — HIGH Enables the realisation of locally balanced supply and demand. Islanding or grid-connected mode can also be implemented to create a reactive grid topology.
	Energy security	LOW — HIGH Increases energy security in areas covered by the mini-grid.
	Sustainable development	LOW — HIGH Renewable-based mini-grids enable the development of local renewable resources. The local grid collectively balances decentralised renewable plants and demands and increases their economic relevance.
IMPLEMENTATION	**Implementation cost**	LOW — HIGH High investment costs linked to the need for dedicated grid infrastructure. High cost of generation/storage component.
	Prerequisites	Regulatory certainty associated with licencing and tariffs. Affordability challenges for consumers and low demand profiles. Grid codes need to be updated to clarify the specification of mini-grids and prepare the future conditions of interaction with the main grid. Standardised technical specifications and quality assurance frameworks for mini-grid components, design, and installation to ensure system reliability, safety, and longevity, particularly when projects are implemented by a diverse range of private sector developers.
	Stakeholders responsible for implementation	Community, local small and medium-sized enterprises, rural electrification agency, public utility, donors.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Democratic Republic of the Congo, Ethiopia, India, Kenya, Mali, Nepal, Nigeria, Philippines, Senegal, Sierra Leone, Tanzania, Uganda, *etc.*

Innovation 12

SUPERGRIDS – GREEN CORRIDORS

Supergrids are large grids that connect different countries or even different regions, enabling them to share their renewable resources and establish regional power markets. Using long-distance transmission lines, supergrids can connect areas rich in renewable resources to demand centres hundreds or thousands of kilometres away, helping to achieve major economies of scale, enhance cross-border integration, integrate higher shares of renewable generation and improve the overall resilience of the system (IRENA, 2019h).

Supergrids are designed to minimise losses by operating at higher voltages (at least 500 kilovolts (kV) and sometimes more than 800 kV) and, often, using direct current (DC) transmission lines instead of alternating current (AC) (IRENA, 2019h; Platzer *et al.*, 2016). For African countries with large renewable resources, supergrids could enable the export of green electricity to the European power system.

A number of supergrids already have been constructed, such as China's 3 293 kilometre-long, high-voltage (1100 kV) DC transmission line from Changji to Guquan. Many more are being planned, showing their worldwide applicability (McCalley and Zhang, 2020).

However, supergrids are still an emerging innovation. They face challenges such as long construction times and the need to interface high-voltage DC lines with existing AC grids. Widespread implementation will require strong political commitments and shared regulatory rules when the grids cross national borders. Supergrids typically can be built more quickly in countries with centralised decision making and easier regulatory processes, such as China and India. Moreover, the realisation of supergrid projects typically demands exceptionally large upfront investments and involves complex, often multi-stakeholder, financing arrangements, which can pose substantial hurdles, especially for multi-country initiatives in emerging markets and developing economies that require extensive international co-operation and risk mitigation.

Unlocking the potential of large renewable energy projects in developing countries

A study concludes that the quickest and most feasible way to bring reliable and affordable electricity to hundreds of millions of people in Africa is by building a huge central supergrid that stretches eastward from Mali and Nigeria to Ethiopia and then southward all the way to South Africa, crossing through 12 countries (Mukhtar *et al.*, 2023). In addition to solving the problem of energy poverty, the supergrid would enable the integration of huge amounts of solar and wind generation. A first concrete step to realise some of this potential is developing a vision of the future of the African power system in the Continental Master Plan (AfDB, 2021a; IRENA, 2024c; Mukhtar *et al.*, 2023).

SUMMARY TABLE: Supergrids – green corridors

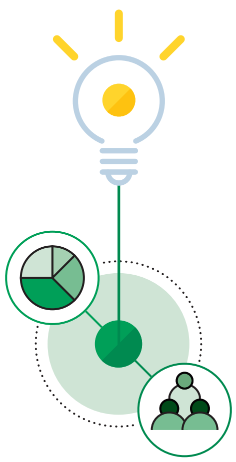
INNOVATION READINESS LEVEL		LOW HIGH
BENEFITS	**Affordability**	LOW HIGH Makes the least-cost renewable energy sources accessible, independently of the level of the local demand.
	Energy access	LOW HIGH Not primarily designed to foster energy access in remote areas.
	Power system resilience	LOW HIGH Averages the intermittency of VRE sources. Offers options for mutual support in case of critical supply shortage in a country.
	Energy security	LOW HIGH Increases energy security via the larger pool of resources that can be harnessed.
	Sustainable development	LOW HIGH Particularly suited to give access to abundant renewable electricity potentials that are distant from demand centres.
IMPLEMENTATION	**Implementation cost**	LOW HIGH High investment costs associated with the development of the supergrid infrastructure.
	Prerequisites	Strong political commitment if the anticipated supergrid involves several countries. Harmonised grid codes and shared operational procedures. Robust, independent regional regulatory bodies and transmission system operators endowed with clear mandates and sufficient authority for overseeing cross-border infrastructure planning, development, market operation, tariff setting, and effective dispute resolution mechanisms as a critical institutional prerequisite for successful long-term operation.
	Stakeholders responsible for implementation	Transmission system operator, regulators, governments existing power pools, multilateral organisations.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Brazil, Chile, China, India, African Union

03 BUSINESS MODELS AND KEY CHANGE AGENTS

A well-functioning power system, capable of integrating the innovative technologies outlined previously and delivering on the promise of sustainable and inclusive growth, fundamentally requires a corresponding evolution in business models. These models must be efficient in generating and equitably sharing value, encompassing profits, services, and broader socio-economic benefits, at all stages from producers to consumers. This is particularly the case in contexts of emerging markets and developing economies, where traditional utility models may be insufficient or ill-suited for decentralised and community-focused solutions.

This section describes key innovative business models and the role of pivotal change agents, grouped into three categories: business models that place the consumer at the centre, innovative funding models, and key change agents that harness synergies among specific sectors to support the adoption of renewables by both institutional and private agents (Figure 13).

FIGURE 13 | Innovations in business models and key change agents



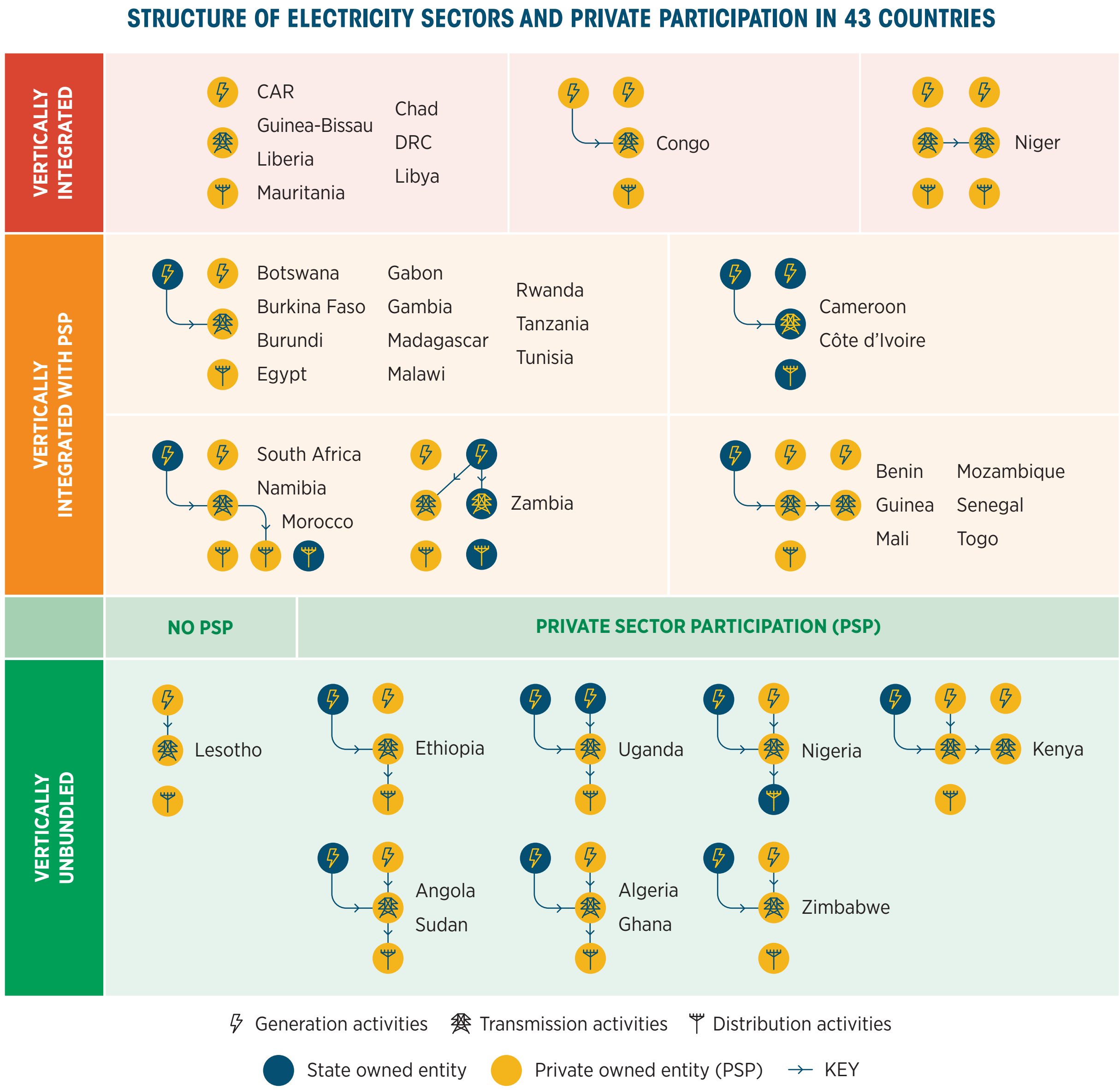
BUSINESS MODELS AND KEY CHANGE AGENTS

Consumer at the centre	**13** Energy community
	14 Decentralised productive uses
	15 Peer-to-peer trading
	16 Aggregators
	17 Storage as a service
Innovative funding models	**18** Pay as you go (PAYGO)
	19 Crowdfunding and financial bundling for electricity access
	20 Corporate renewable sourcing
Ecosystem enablers	**21** Key change agents to support renewable-based development programmes
	22 Powering a sustainable health and education ecosystem
	23 Renewable energy synergies for modernised railway infrastructures
	24 Renewable energy for resilient agriculture and farming systems

3.1 Consumer at the centre

Traditional electricity markets are centralised, dominated by vertically integrated utilities, many of which are state-owned. For example, the power sectors in Africa are mainly vertically integrated with state-run systems (as in Liberia) or private actors (as in Côte d'Ivoire), although unbundled systems exist in Lesotho and Uganda (which also has a state-owned transmission system operator) (Figure 14) (APUA and AfDB, 2019).

FIGURE 14 | Structure of the power sector in Africa



Based on: (APUA and AfDB, 2019).
Notes: CAR = Central African Republic; DRC = Democratic Republic of Congo.

A growing model for generating electricity is contracting with independent power producers (IPPs), who provide the required capital in exchange for risk mitigation measures, such as take-or-pay contracts. IPPs build power plants and collect revenues from the sale of electricity.

However, innovative bottom-up business and ownership models are also emerging, placing the consumer at the centre and providing revenue streams to consumers. These new models can bring numerous advantages besides energy access, such as better acceptance of projects and increased local jobs. This can be especially beneficial in African countries, where commercial relationships that include low-income customers can empower communities, boost efforts to increase electricity access and fuel new entrepreneurial activities.

The following sub-sections describe five innovative business models that feature the consumer at the centre. They do face barriers, such as lack of financing, the slow diffusion of technical knowledge in rural communities, and lack of supporting technologies, such as smart meters. But these models offer hope for accelerating the energy transition by providing bottom-up solutions.

Innovation 13
ENERGY COMMUNITY

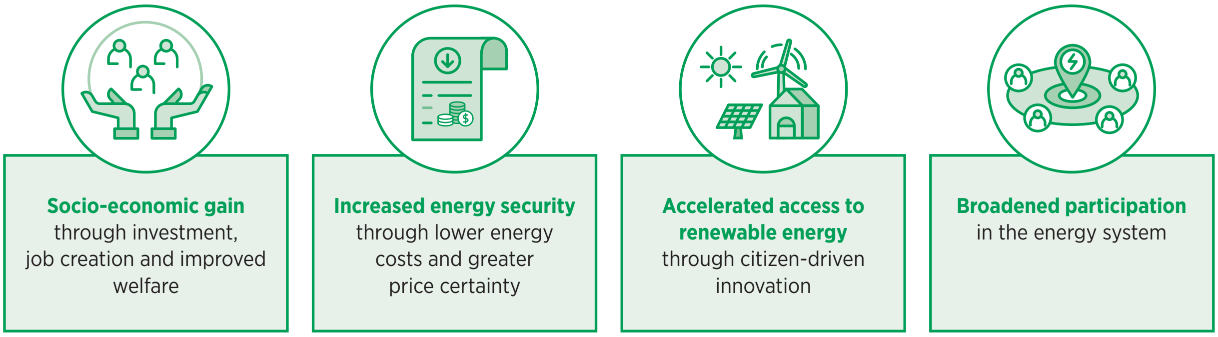
An energy community provides an alternative or a supportive model to the traditionally dominant state-owned or private energy utility. It can play a substantial role in the energy system by allowing the engagement of communities in renewable energy projects and supporting infrastructure, by sharing ownership, responsibilities, decisions and benefits. Beyond increasing renewable energy supply, the energy community can provide multiple social, economic and environmental benefits and ensure that these benefits are shared more widely (IRENA Coalition for Action, 2024).

An energy community can also serve as a crucial incubator for local innovation, developing energy solutions and service models that are specifically tailored to the unique needs and resources of the community, thereby fostering a more resilient and adaptive energy landscape. It is thus crucial to shift the narrative around renewables from solely climate change mitigation to emphasising local development benefits and productive use of energy for communities. Similarly, the energy community is not simply a means of providing energy, but also a means to reach development goals defined by the local community. In this way, energy becomes the platform though which a community can achieve its development goals. Setting the right narrative guides policy, and setting the right policy guides funding (IRENA, 2025a).

To be effective, energy community projects require community engagement, ownership, control, and the retention and sharing of benefits/profits. Innovation in engagement is critical. This involves creating structures to embed ownership and agency within communities, especially in developing world or off-grid contexts. Effective community engagement has been shown to reduce system costs up to 20% and to mitigate key socio-technical risks, including undersized systems, poor maintenance and unmet demand (IRENA, 2025a).

In the energy community model, communities own and manage the energy-related assets (usually distributed energy resources), giving them control of the project and of the distribution of economic and social benefits (IRENA, 2022b). The model offers a greater sense of ownership, higher acceptance of energy projects, and greater flexibility in mobilising local supply and demand. It also can empower local communities and ensure more inclusive development (Figure 15). However, barriers to scaling up energy communities include a lack of technical expertise and limited access to conventional financial instruments due to lower profit rates.

FIGURE 15 | Potential benefits of energy community



To make an energy community viable, there is a need for innovative financial mechanisms that are accessible and tailored to the local context. This includes exploring local bonds that a community can buy (potentially even by selling assets such as livestock), implementing outcome-based financing and designing revenue-sharing models to incentivise local operators for maintenance and healthy system operation. Enabling policies that allow for bi-directional power flow (from community to grid) and direct sales to creditworthy off-takers (such as mines or data centres) can ensure economic viability (IRENA, 2025a).

Building local capacities is crucial for communities to understand, operate and benefit from energy projects. This includes providing technical training for operation and maintenance and guiding communities on productive uses of energy for income generation. Facilitating the exchange of experiences and learnings among communities is also vital, allowing them to learn from each other's governance models, negotiate effectively with developers and incorporate diverse perspectives such as gender (IRENA, 2025a).

AM-IDE © Shutterstock.com

Energy communities in Colombia

An estimated 404 000 households in Colombia do not have electricity access, mainly in rural and remote areas that have limited access to electrical infrastructure. Meanwhile, around 29% of households report difficulties paying for public utilities, including electricity. To tackle these challenges, the country's Ministry of Mines and Energy has included energy communities in the Just Energy Transitions Roadmap as a solution to promote energy democracy, improve electricity provision in vulnerable areas and achieve universal energy access. The Colombian government included energy communities in the National Development Plan 2022-2026 to regulate them as a legal figure for distributed generation. The installed capacity of Colombia's energy communities will be limited to 5 MW or less, and the projects would first serve communities' own energy needs, with the surplus available for sale to other energy users via the national system, if interconnection is available.

Community-owned hydro and solar mini-grids in Tanzania

A review of mini-grid projects in Tanzania (Odarno *et al.*, 2017) found that the most common ownership models for solar and hydro mini-grids are community-based and faith-based.[4] For example, the 300 kilowatt (kW) Lupande, Madunda and Mawengi community hydro mini-grid is owned by the village, which sets tariffs in a collegial manner with approval by all customers; five of the seven board members are elected by the community. Solar mini-grids are a more recent development in Tanzania than hydro facilities. Most have adopted a community ownership model, although they often face governance and cost recovery challenges. In the Leganga community, the governing committee has struggled to collect revenues, and poor metering has led to wasteful use of electricity (Odarno *et al.*, 2017).

[4] *Faith-based models are a specific type of community model where religious organisations own the mini-grid and contribute to electricity access as part of their community engagement.*

SUMMARY TABLE: Energy community

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Can be beneficial to affordability through a collectively agreed tariff-setting method.
	Energy access	LOW – HIGH Collectively owned and operated asset. Empowers remote and vulnerable communities, offering a solution for electricity access.
	Power system resilience	LOW – HIGH Not the main objective, but can help if the community mini-grid becomes connected to the main grid
	Energy security	LOW – HIGH Diversifies the energy mix, and local generation reduces reliance on imported energy sources.
	Sustainable development	LOW – HIGH Contributes to wider adoption of renewable energy projects.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH Does not rely on costly infrastructure.
	Prerequisites	Updated regulations are needed to specify the rules for the participation of community as supplier. Support from national and local policy makers is important to promote community-owned projects. Local capacity building, awareness building. Digitalisation is a crucial component for successful projects, for community engagement, demand assessment, and energy planning, and as well for efficient operation and maintenance in remote locations, integrating digital technologies for remote control and monitoring is vital. Establishing digital payment systems is necessary to ensure cost-effective management, particularly for payment collection. Also requires the development of low-cost, reliable metering technology suitable for measuring small-scale energy consumption.
	Stakeholders responsible for implementation	Community members, ICT infrastructure provider, rural development agency, regulator.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Colombia, Kenya, Nepal, South Africa, Tanzania, Zimbabwe

Innovation 14

DECENTRALISED PRODUCTIVE USES OF ELECTRICITY

Productive uses of electricity refer to the ways that electricity (often renewable) is used to create economic value, enhance productivity and improve livelihoods. This goes beyond basic household needs and encompasses activities that generate income, create jobs and improve existing livelihoods. There is a growing recognition that productive uses of electricity need to be integrated within a broader ecosystem approach to be truly successful.

Implementing strategies to support productive uses of electricity and creating local value and economic development is key. Examples include refrigeration for food conservation, mills for grinding, phone chargers, dryers and many others. Such uses foster and kick-start local economic activity, stimulating economic development and creating local employment (IRENA, 2021c). They have the additional benefit of providing steady revenue streams for renewable generation projects, which lowers the financial risks of developing and investing in those projects. The combination of renewables and productive uses can create a virtuous economic cycle, in which productive uses enable more rapid development of renewables, thus stimulating greater economic activity and even more favourable conditions for renewables development.

Essentially, productive uses of electricity offers a double dividend. It increases revenues for end users and provides additional social and economic benefits. At the same time, it provides steady anchor loads for electricity suppliers, which reduces their financial risks (IRENA and SELCO Foundation, 2022).

An important enabler for productive uses of electricity is to reform financing practices and attract patient capital. A better understanding of the particularities of lending for productive uses of electricity is needed, especially in last-mile contexts where issues such as limited appetite for debt for smaller businesses, foreign exchange risks and informal activities are prevalent. Encouraging the availability of "slower, patient" capital, such as more equity rather than debt, is also beneficial, given the long-term nature of local economic development that productive uses of energy fosters.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Productive uses of electricity in Africa

In Senegal and Mauritania, the Progrès-Lait ("Progress Milk") initiative is using off-grid solar plants to provide electricity for cooling and pasteurising milk. Led by two non-governmental organisations, the programme supports artisanal livestock rearing, an important source of revenues and jobs in rural areas, while also providing power for lighting, phone charging and grinding. Successful projects include 20 kW facilities in the villages of Diambanouta (Enda Énergie, 2018) and Taki (Ndarinfo, 2021), which have created at least 25 green jobs. Similar solar-powered milk conservation initiatives have been carried out in Kenya, Tunisia (Rojas *et al.*, 2018) and Uganda (EEP Africa, n.d.). In Senegal, solar systems are used to power sewing machines and a refrigerator to preserve and cool milk and other drinks, and to produce ice water, in addition to irrigation to increase milk production beyond the rainy season (GIZ, GOPA/Arepo, 2023).

In Uganda, a hybrid solar 600 kWp mini-grid began operations on Lolwe Island in 2022. The project supplies clean, reliable electricity to more than 3 000 households and 700 businesses and enables raw materials to be transformed into value-added products. The uses include water-pumping, distribution, and purification services; modern fish-drying facilities; and ice-making devices to conserve daily fish catches. Developed by ENGIE Equatorial, the mini-grid also enables the use of electric fishing boats and motorcycles (Engie, 2022).

Renewable mini-grids empowering women in Nigeria

In 2017, two 10 kW mini-grids were installed in the Baawa and Kadabo communities in Nigeria, providing renewable energy supply to 79 households and 12 businesses. Communities buy energy from the mini-grids through a pay-as-you-go model. Mini-grids and energy bill payments are monitored by local employees. Women in the communities have benefited from the mini grids in several ways. Each community was assigned an 18-metre solar tunnel dryer and a solar kiosk. Local women manage the equipment and earn income by renting out the dryer to farmers, charging mobile phones and selling products through the kiosk. The solar dryers allow local farmers, many of whom are also women, to dry their products quickly and efficiently. As a result, women improved their financial independence and social status and can support their families (IRENA Coalition for Action, 2024).

SUMMARY TABLE: Decentralised productive uses of electricity

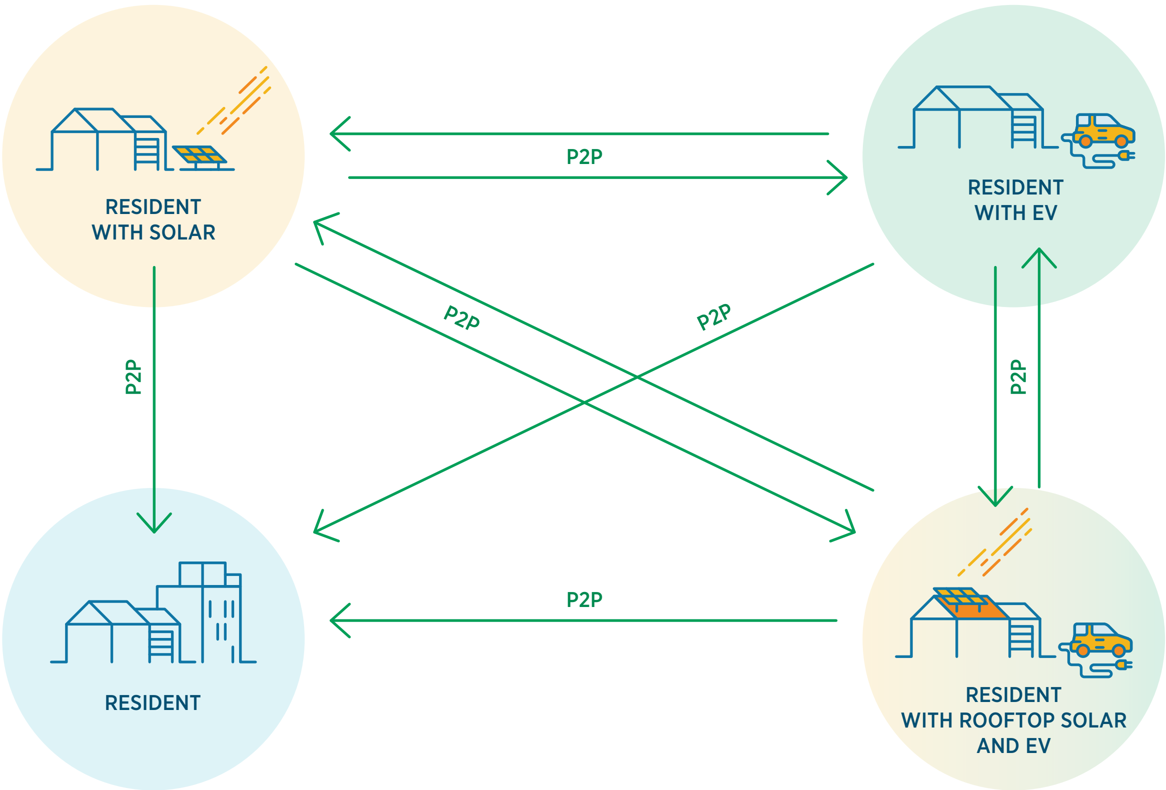
INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Targets affordability by increasing consumers' ability to pay for the provision of electricity.
	Energy access	LOW – HIGH Can serve as anchor load and help reach other customers.
	Power system resilience	LOW – HIGH The load curve can indirectly reduce the ratio between the peak and the average demand by providing a more constant daytime load.
	Energy security	LOW – HIGH Increases the security of supply for productive uses.
	Sustainable development	LOW – HIGH
IMPLEMENTATION	**Implementation cost**	LOW – HIGH Requires the capacity to invest in both the generation of electricity and the productive uses, including the wider ecosystem (*e.g.* skills development, market linkages).
	Prerequisites	Shift policy focus from minimal access to intentional planning for productive uses of energy: Policies need to intentionally plan for more productive uses. This also means that the energy ministry should broaden its perspective beyond only larger projects to consider the diverse and complex needs across different value chains and local contexts for productive uses of energy. Policies and regulations need to incentivise reliability over lower costs of equipment, and easier access to finance. The initial investment cost of the technologies that provide productive uses of electricity. Low awareness and information gaps of the owners of small businesses in the informal sector. Cross-ministerial co-operation and stable policies: Ministries of energy, agriculture and other sectors need close co-ordination to enable productive uses to gain maximum impact on livelihoods.
	Stakeholders responsible for implementation	Rural development agencies, non-governmental organisations, local community leaders.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Côte d'Ivoire, Kenya, Senegal, Tanzania, Uganda, Zimbabwe

Innovation 15

PEER-TO-PEER TRADING

Peer-to-peer (P2P) trading platforms "serve as an online marketplace where consumers and producers 'meet' to trade electricity directly, without the need for an intermediary" (IRENA, 2020b). Peer-to-peer trading allows transactions among consumers and prosumers at the retail level (Figure 16). This is facilitated by technologies such as smart metering, distributed ledger technologies (like blockchain for secure transaction recording) and robust ICT networks.

FIGURE 16 | Structure of peer-to-peer electricity trading model



Notes: EV = electric vehicle; P2P = peer to peer.

The benefits include higher profits for producers and lower costs for buyers (due to the absence of intermediaries), more resilient local grids and reduced curtailment of VRE. P2P can empower customers to adjust electricity consumption to take advantage of times of cheaper rates, while helping prosumers reduce energy wastage (Amuzu-Sefordzi, 2020). Connecting several solar home systems and enabling P2P trading, for example, allows extra generation from one solar home system to be sold to another home that needs the power. P2P trading has been demonstrated in mature power markets (Zhou *et al.*, 2020) but also offers a very efficient solution for micro- or nano-grids in developing countries.

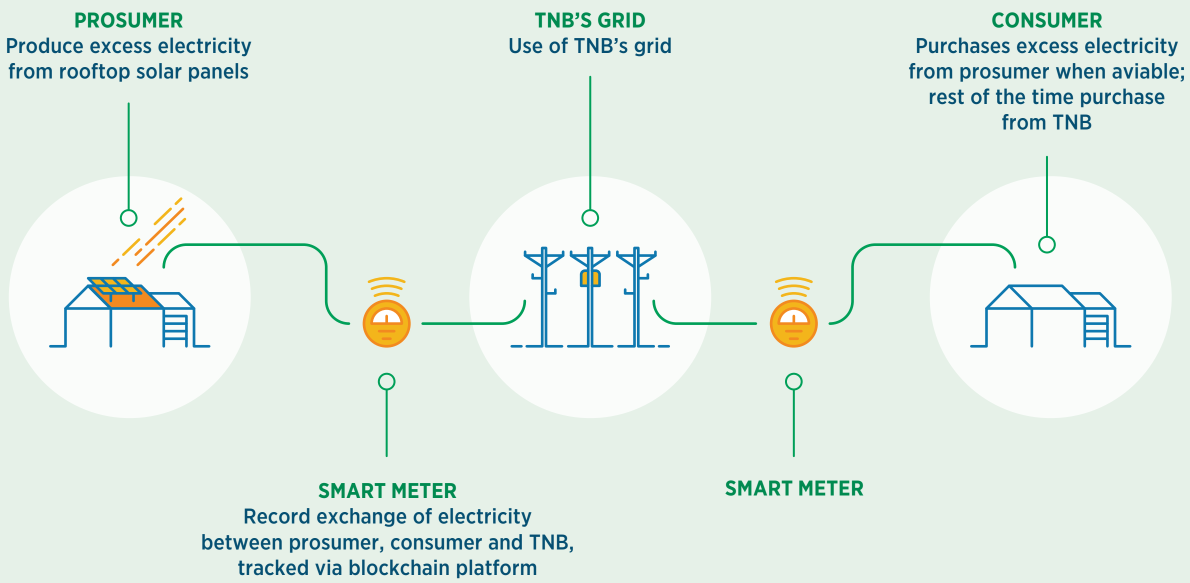
Obstacles to P2P development include the lack of a clear regulatory framework, the need for advanced metering infrastructure and a dedicated ICT network, deployment costs, network charges and the challenge of setting tariffs.

P2P trading projects in Bangladesh, Malaysia and Nigeria

In 2021, Bangladesh achieved 97% nationwide electricity access, with many rural villages adopting mini-grids. More than 100 solar P2P microgrids also have been developed, allowing consumers to power appliances, charge vehicles and trade electricity for income (WIPO Green, 2025). For example, in Shariatpur, the company SOLshare has connected rural households with and without solar home systems in a P2P electricity trading network, using metering and ICT to control electricity flows and handle payments and customer service. The network enables people to earn additional income by selling their surplus electricity, while also providing power to others for the first time (UNFCCC, 2023).

In Malaysia, the Sustainable Energy Development Authority ran the country's first P2P energy trading project, with rooftop solar systems connected not just to consumers but also to the Tenaga Nasional Berhad (TNB) grid (Figure 17), helping to balance local generation and demand (SEDA, 2020).

FIGURE 17 | Concept of peer-to-peer electricity trading project in Malaysia



Source: (SEDA, 2020).

In Bassa, Nigeria, the solar company Creeds Energy used a so-called mesh-grid developed by Okra to connect households and businesses that already had stand-alone solar systems with each other and with other potential consumers, enabling any excess power to be productively used. The system made it possible for high-consuming users, including a barber shop and a mosque, to replace diesel generation with solar electricity; it also enabled Creeds Energy to bring electricity to 46 more households than originally planned, almost double the original target (OKRA, 2024; Tim Ha, 2023).

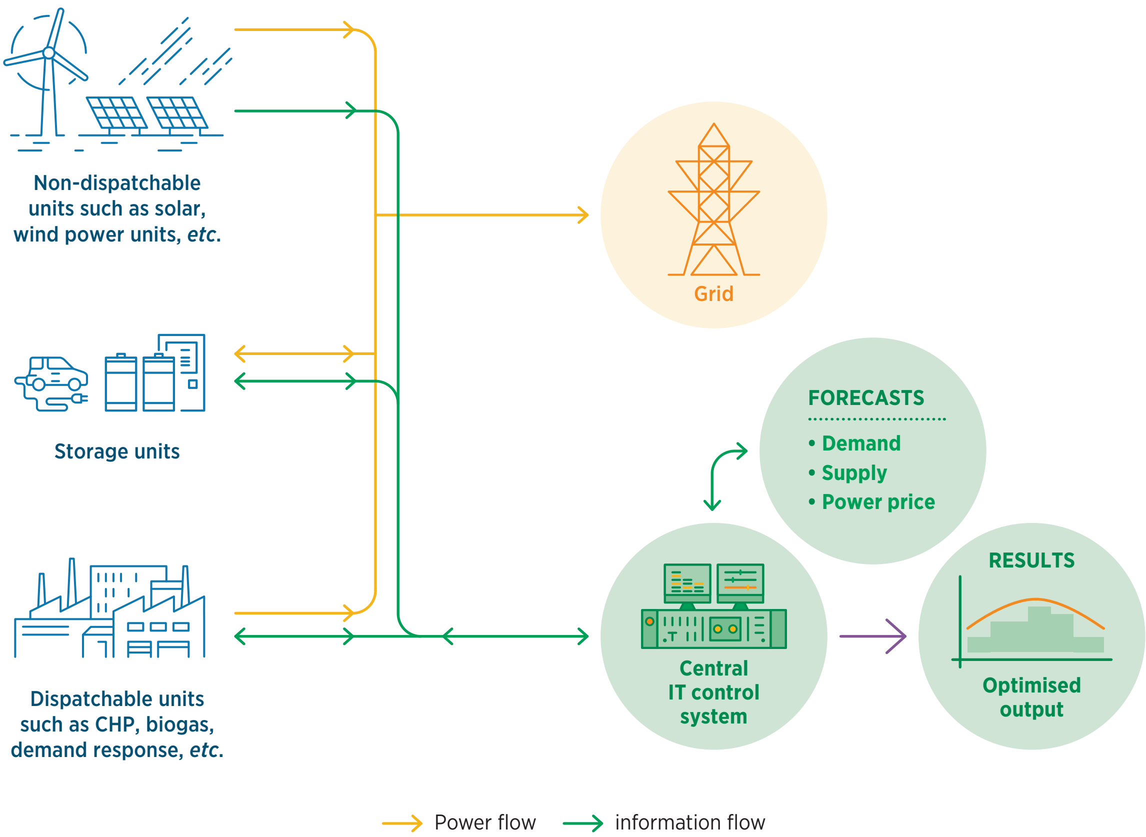
SUMMARY TABLE: Peer-to-peer trading

INNOVATION READINESS LEVEL		LOW — HIGH
BENEFITS	**Affordability**	LOW — HIGH Targets affordability by increasing consumers' ability to sell the surplus of electricity produced.
	Energy access	LOW — HIGH
	Power system resilience	LOW — HIGH P2P trading platforms enable better management of decentralised generators by matching local electricity demand and supply.
	Energy security	LOW — HIGH
	Sustainable development	LOW — HIGH
IMPLEMENTATION	**Implementation cost**	LOW — HIGH Requires the capacity to develop and invest in the ICT network to enable communication between participants, handle payments and allow monitoring.
	Prerequisites	Define clear roles of stakeholders involved in P2P, establish regulations on data collection and access, electricity prices. Technologies such as smart metering, distributed ledger technologies (like blockchain for secure transaction recording), and robust ICT networks.
	Stakeholders responsible for implementation	Rural development agencies, non-governmental organisations, local community leaders.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Côte d'Ivoire, Kenya, Nigeria, Senegal, Tanzania, Uganda, Zimbabwe

Innovation 16
AGGREGATORS

Aggregation means "operating many distributed energy resources (DERs) together to create a sizeable capacity similar to that of a conventional generator" (IRENA, 2020b). It can also mean grouping together many small sources of demand, such as heat pumps, batteries, EVs or combined heat-and-power planta in buildings and controlling them to provide balancing flexibility to the grid. Aggregator platforms require real-time data acquisition from DERs and smart meters, along with central IT control systems. The benefits include providing flexibility and ancillary services to the grid, reducing operational costs and investment needs, and enabling higher shares of VRE (Figure 18).

FIGURE 18 | Information and power flow in an aggregator business model



Source: (IRENA, 2020b).
Notes: CHP = combined heat and power; IT = information technology.

The use of aggregators is mostly hampered by the lack of clear regulatory frameworks and the need for advanced meters and ICT networks. For example, harnessing Africa's huge solar potential will require hundreds of small 20 to 50 MW projects. Aggregating those projects or the potential customers could avoid duplicating efforts and transaction costs for each project, thus reducing complexities and inefficiencies. Pilot projects and knowledge sharing can lay the groundwork for wider adoption.

Aggregation of renewable electricity services in Southern Africa

Launched in 2018, Africa GreenCo (AGC) bundles together and sells both renewable electricity and grid services such as battery storage and acts as an intermediary between renewable producers and utilities. The aggregation reduces financial risks and increases the attractiveness of renewable projects for investors. Africa GreenCo began operations in Zambia but has since expanded to Namibia and Zimbabwe. It won authorisation to be a virtual supplier of green electricity to the Southern African Power Pool (Africa GreenCo, 2021; Africa GreenCo Group, 2023).

SUMMARY TABLE: Aggregators

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Influences affordability by reducing the development cost, and pooling existing customers or storage flexibilities.
	Energy access	LOW – HIGH Can play a role in improving energy access by creating a more stable economic environment for small projects.
	Power system resilience	LOW – HIGH Mobilises more efficiently existing storage and end user flexibilities. Mutualises the risks and the variability of VRE sources.
	Energy security	LOW – HIGH Stimulates investments in new renewable capacities.
	Sustainable development	LOW – HIGH Stimulates investments in new renewable capacities.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH Requires a reliable and extended (function of the level of complexity) ICT infrastructure.
	Prerequisites	Regulatory reforms are necessary to define the set of actions that an aggregator can perform: market access conditions, possibility to provide flexibility solutions or ancillary services, the level of compensation. Needs a parallel information flow and thus requires a strong and secure ICT infrastructure.
	Stakeholders responsible for implementation	Regulators, independent power producers, system operators.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Namibia, South Africa, Zambia, Zimbabwe

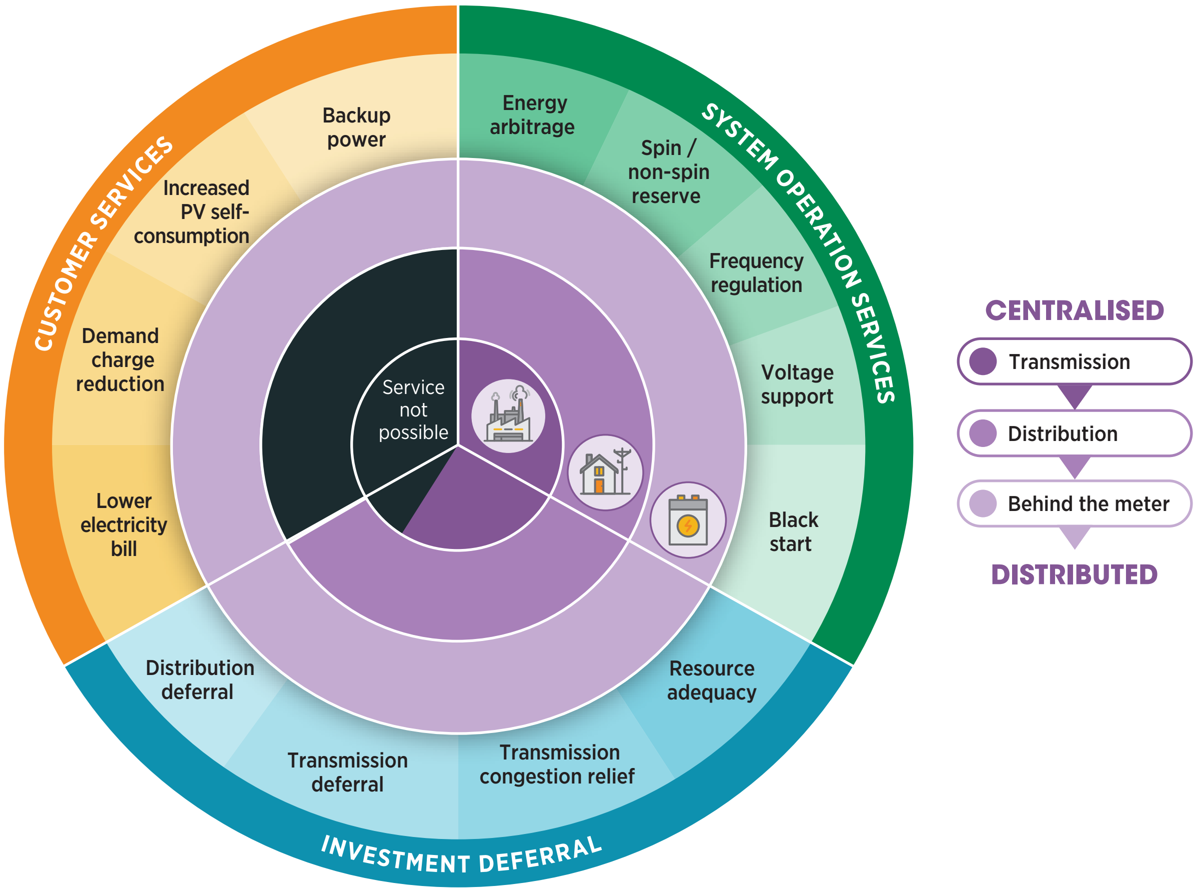
Innovation 17
STORAGE AS A SERVICE

Rather than requiring end users or utilities to bear the full upfront cost and operational risks of owning storage assets, the "storage as a service" model allows providers to offer energy storage capabilities on a contractual basis. This can take various forms, such as monthly subscription fees for dedicated battery capacity used to store surplus VRE or provide grid services, and pay-per-use models like battery swapping stations for urban electric mobility. This approach can greatly lower the entry barriers for accessing storage benefits, particularly where capital is constrained or technological obsolescence is a concern.

Rather than just supplying electricity generated from power facilities, providers can offer energy-related services (IRENA, 2020c). A particularly promising example of this innovative business model is storage. As described in Innovation 3 (Small-scale batteries), storage technologies increase system flexibility and stability, fostering greater adoption of VRE sources. They are also essential for the electrification of transport systems. However, high upfront costs can limit their use. The storage-as-a-service business model helps solve this problem by offering an alternative to owning the storage asset.

Examples include charging monthly subscription fees for the use of batteries to store surplus VRE output and provide other grid services, and setting up battery swapping stations for urban motorcycles used as taxis or delivery vehicles. Figure 19 shows 13 types of storage services, both primary and secondary (Fitzgerald *et al.*, 2015). The use of storage-as-a-service business models can be encouraged by supportive regulatory environments, such as time-of-use tariffs that provide financial incentives for storage.

FIGURE 19 | Range of estimated economic values of storage services



Source (Fitzgerald *et al.*, 2015),

Storage as a service for industrial end users in Mexico

A consortium led by a renewable electricity company plans to build a 480 MW Lithium-ion battery storage system for commercial and industrial customers in the borough of Iztapalapa in Mexico City. The project will improve power quality for industrial users, reduce high electricity costs during peak periods and lessen the strain on the grid. In the proposed service business model, users will pay for the use of the storage, sharing cost savings with the storage service provider (Pan American Finance, 2024).

Battery swapping stations for e-motorcycles in Africa

Motorcycle taxis are a dominant form of transport in Africa and are a good candidate for electrification. However, barriers to their use include high battery costs, lack of charging infrastructure, long charging times and lack of familiarity with the battery technology. These problems can be solved with a battery swapping business model, such as the one offered by Zembo (Zero Emission Motorcycle Boda) in Uganda. Since 2019, Zembo has been assembling electric motorcycles and operating solar charging and battery swapping stations in Kampala (EEP Africa and NDF, 2020). It leases and sells the motorcycles on a pay-as-you-go basis while offering battery swapping as a service, and plans to have more than 2 000 motorcycles and 60 swap stations by 2025 (Powering Rrenewbale Energy Opportunitites, 2023).

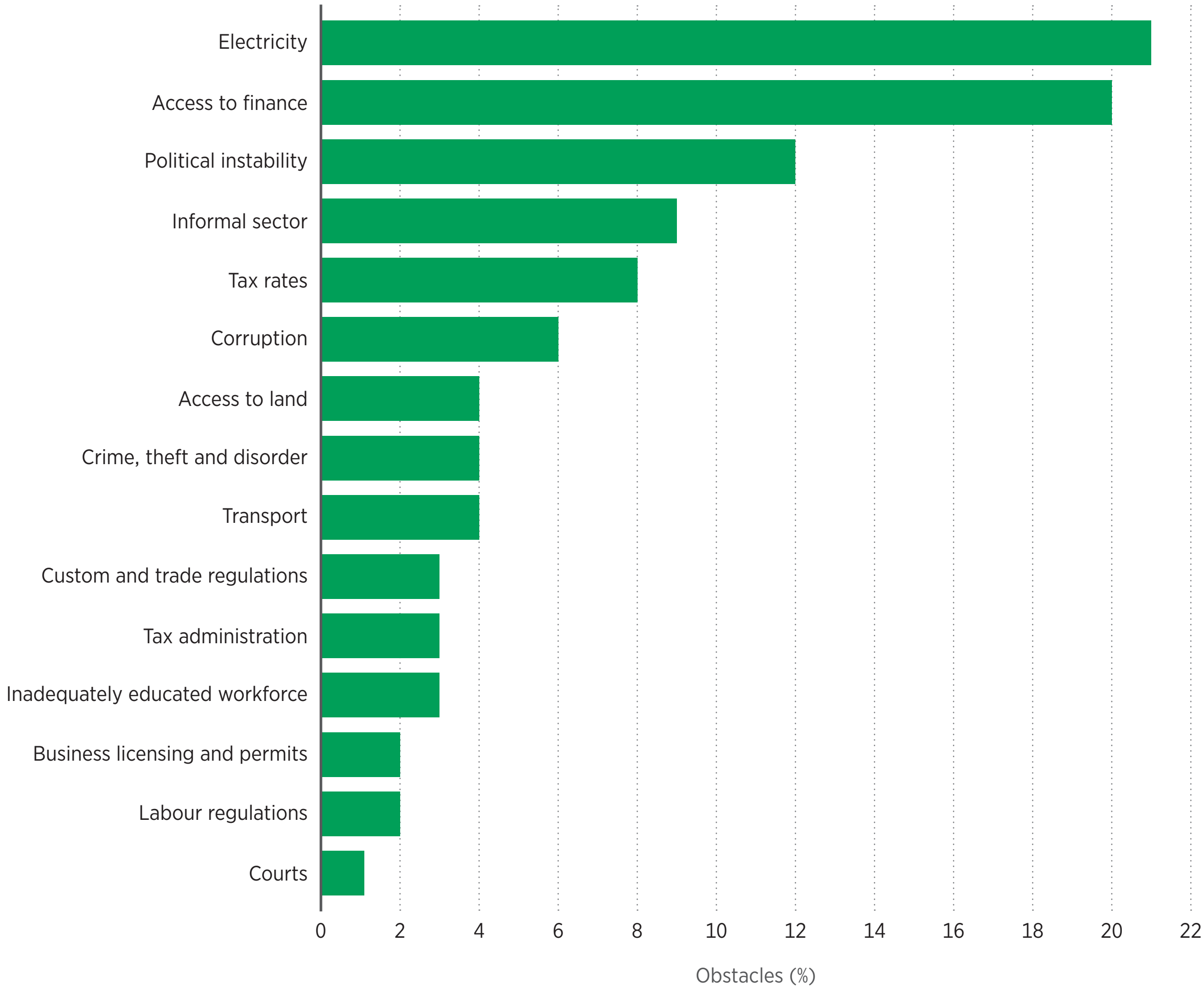
SUMMARY TABLE: Storage as a service

INNOVATION READINESS LEVEL		LOW – HIGH	
BENEFITS	**Affordability**	LOW – HIGH	Makes storage systems affordable to end users and reduces the technological risk.
	Energy access	LOW – HIGH	Can increase energy access if coupled with off-grid solutions.
	Power system resilience	LOW – HIGH	Increases resilience at the end-user level that can be improved if adequate demand response mechanisms are established.
	Energy security	LOW – HIGH	Introduces short term flexibility but does not constitute a new primary source of electricity.
	Sustainable development	LOW – HIGH	Can be coupled with renewable electricity.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH	Moderate for the end user but potentially high for the developer (in case of battery swapping), which must buy upfront a larger number of batteries and build a sufficiently dense network of stations.
	Prerequisites		Support from donors is needed at the early stage to build the initial infrastructure. The tariff structure can also impact the profitability of a battery-as-a-service business.
	Stakeholders responsible for implementation		Governments, financiers, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED			Kenya, India, Mexico, Nigeria, Uganda

3.2 Innovative funding models

Access to finance is a major obstacle for renewable project deployment in emerging markets and developing economies and is particularly acute for decentralised renewable energy solutions, such as mini-grids and stand-alone systems. Despite their critical role in energy access and local development, such systems often involve smaller individual project sizes, higher transaction costs per unit of capacity, and perceived higher risks by traditional financiers less familiar with these models (Figure 20).

FIGURE 20 | Main obstacles to business in Africa



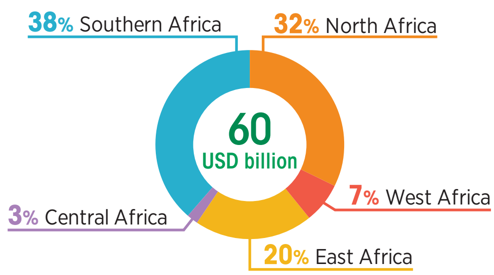
Source: (UNECA, 2020).

To effectively transition to cleaner and more resilient power systems by 2050, the annual global investment in renewables needs to more than triple, from around USD 0.5 trillion in 2022 to nearly USD 1.6 trillion by 2050 (IRENA, 2023b; IRENA and CPI, 2023).

The gap between the current investment level and the need is even greater in developing countries. From 2000 to 2020, total investments in renewables in Africa were just USD 60 billion, around 2% of the global total (Figure 21) – and the amount has actually been declining, from USD 5.3 billion in 2019 to less than USD 3.6 billion in 2022 (IRENA *et al.*, 2023).

FIGURE 21 | Cumulative renewable energy investment in Africa and globally, 2000 to 2020

USD billion, current 2020	2000-2009	2010-2020	Cumulative 2000-2020
Global	587 USD billion	2 254 USD billion	2 841 USD billion
Africa	4.8 USD billion (0.8% of global investment)	55 USD billion (2.4% of global investment)	60 USD billion (2% of global investment)
North Africa	USD 1.9 billion	USD 17.5 billion	
West Africa	USD 0.5 billion	USD 3.9 billion	
East Africa	USD 2.0 billion	USD 9.7 billion	
Central Africa	USD 0.1 billion	USD 1.3 billion	
Southern Africa	USD 0.3 billion	USD 22.4 billion	



Source: (IRENA *et al.*, 2023).

Renewable energy projects in developing countries have higher perceived risks compared to those in more developed markets (IRENA, 2025a), leading to lower levels of private investment. As a result, public direct investments were used for 44% of projects in Sub-Saharan Africa, compared to just 25% globally (IRENA *et al.*, 2023).

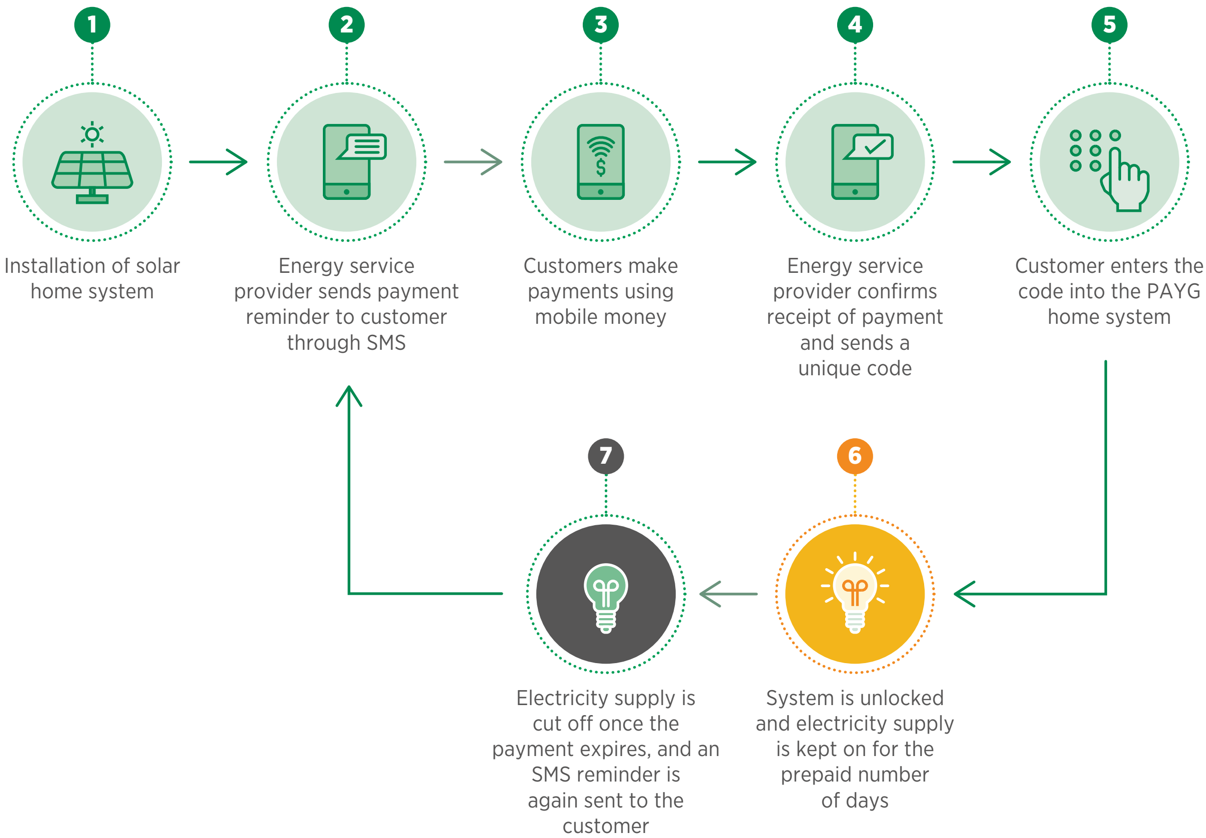
However, public finances alone are not sufficient to bridge the access gap. Moreover, the financing problem is particularly challenging for scaling up off-grid renewables generation in developing countries, a crucial piece of the access puzzle. Off-grid solutions have successfully brought power to more than 170 million people (IRENA *et al.*, 2023), but 80% of those people received only enough electricity for basic lighting. In addition, in Sub-Saharan Africa alone, 567 million people still lacked electricity access at the end of 2020 (IEA *et al.*, 2025). Scaling up off-grid generation is therefore essential. These small-scale projects, however, offer fewer economies of scale than larger projects do, and have relatively high transaction costs per installed capacity, making it harder to secure capital through conventional channels.

This section describes three innovative finance solutions: pay-as-you-go, crowdfunding and financial bundling, and corporate renewable sourcing.

Innovation 18
PAY AS YOU GO (PAYGO)

Pay-as-you-go (PAYGO) business models allow people to buy things, such as solar home systems, with a down payment followed by periodic payments over months or years. PAYGO models can also be structured so that consumers simply rent the systems. The business model can include smart meters and data analytics to facilitate operations and provide after-sales services, reducing risks such as system failure. Payments can be collected via mobile payment platforms (IRENA, 2022c; Pfeifenberger *et al.*, 2021). For companies supplying the products, PAYGO contracts generate predictable cash flows, enabling companies to service a large consumer base and attract financing (Figure 22).

FIGURE 22 | Pay-as-you-go concept



Source: (IRENA, 2020b).

PAYGO models can easily be customised to fit local needs. They have proven to be successful in providing electricity access, enabling fuel shifting from kerosene or diesel to electricity and improving living conditions.

The main challenges to using PAYGO business models for electricity access include the need for initial capital; the variable quality of available solar home systems; the lack of well-functioning remote payment systems; lack of customer knowledge; and the need for a large network of distributors to reach potential customers and to maintain the systems.

PAYGO models in Africa

Companies with PAYGO business models are growing rapidly, such as M-KOPA in East Africa (offering everything from smartphones to electric motorcycles) (KOPA, 2024), Bboxx in the Democratic Republic of the Congo and West Africa (which connects customers with clean energy, clean cooking, smartphones, financing and electric transport) (BBOXX, 2023) and SOLshare in Bangladesh (providing rooftop solar, micro-grids and electric three-wheelers) (SOLshare, 2024).

A good example is Easy Solar, a company created in 2016 to bring solar power to smaller West African countries such as Sierra Leone and Liberia, where only around 2% of rural people have access to electricity. To reach far-flung customers in small low-income countries, Easy Solar created a strong network of community-based agents and shops and offered a flexible mix of payment options, including cash payments in areas that lacked mobile money options. In 2023, Easy Solar was ranked among the top 10 fastest growing companies in Africa, reaching more than 1 million people with solar lanterns, solar home systems, clean cookstoves and other products (Easy Solar, 2023).

SUMMARY TABLE: Pay as you go (PAYGO)

INNOVATION READINESS LEVEL		LOW HIGH
BENEFITS	**Affordability**	LOW HIGH Lowers the cost of electricity services in remote areas. Offers flexible solutions to avoid high upfront costs.
	Energy access	LOW HIGH Very efficient to demonstrate viable business cases while enabling access to customers who will otherwise not be able to afford electricity.
	Power system resilience	LOW HIGH Provides alternative payment and ownership solutions.
	Energy security	LOW HIGH Provides alternative payment and ownership solutions.
	Sustainable development	LOW HIGH Increases adoption of solar systems. Triggers the replacement of kerosene lamps by energy-efficient electric lamps.
IMPLEMENTATION	**Implementation cost**	LOW HIGH High upfront costs for the company, which needs to procure the devices in advance.
	Prerequisites	To reach the poorer customers, the economic model may rely on regulated support mechanisms such as tax exemptions on imported systems. Implementation requires a dense network of selling points. Need for a well-established and secure remote payment system.
	Stakeholders responsible for implementation	Private companies, rural electrification agencies, non-governmental organisations, grant providers, mobile money operators.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Bangladesh, Ethiopia, Kenya, Senegal, Sierra Leone

Innovation 19

CROWDFUNDING AND FINANCIAL BUNDLING FOR ELECTRICITY ACCESS

Crowdfunding is the practice of financing an initiative, project or venture by raising relatively small amounts of capital from large numbers of individuals or legal entities (the "crowd"), typically with an internet-based platform (IRENA *et al.*, 2023). It can support small-scale projects through donations, debt or equity (IRENA Coalition for Action, 2020). Crowdfunding has the advantage of bypassing traditional intermediaries and funding hurdles, driving down transaction costs and enabling funding for riskier early-stage companies that may not be able to get money from commercial banks or other traditional sources. It also can raise money in local currencies, reducing currency exposure risks (IRENA and CPI, 2020).

Financial bundling involves aggregating multiple small-scale renewable projects into a larger portfolio to achieve economies of scale in financing, reduce transaction costs, diversify risk and enhance attractiveness to larger investors (Weston *et al.*, 2018).

Crowdfunding for off-grid and small-scale projects in Africa

Numerous crowdfunding platforms have sprung up to finance electricity access. For example, Trine, founded in Sweden in 2015, had raised more than EUR 93 million (USD 103 million) by mid-2024. It has invested that money in solar developers in Africa, Central and South America, and Southeast Asia, bringing electricity to more than 3 million people (Trine, 2024). Other platforms include Energise Africa, Lendahand, Kiva, and Charm Impact, which has funded solar-powered sewing machines in India, solar-powered refrigerators in Nigeria, and solar systems for hospitals in Kenya, among other projects (Charm Impact, 2024).


PradeepGaurs © Shutterstock.com

SUMMARY TABLE: Crowdfunding and financial bundling for electricity access

INNOVATION READINESS LEVEL		LOW HIGH
BENEFITS	**Affordability**	LOW HIGH Increases the affordability of renewable energy projects by improving access to financing options.
	Energy access	LOW HIGH Allows for a greater number of projects that otherwise not be implemented
	Power system resilience	LOW HIGH Does not address the power system resilience issue but a better financial viability can stimulate the installation of storage systems.
	Energy security	LOW HIGH Does not address energy security.
	Sustainable development	LOW HIGH Represents an important source of finance for renewable energy plants.
IMPLEMENTATION	**Implementation cost**	LOW HIGH Using crowdfunding platforms or bundling can reduce the transaction costs.
	Prerequisites	Regulation is needed. Support from policy makers/enabling framework is important if securitisation is provided. Essential for small-scale projects that are not the target of other financial instruments.
	Stakeholders responsible for implementation	Private companies, financial institutions.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Burkina Faso, India, Kenya, Mali, Senegal, South Africa

Innovation 20
CORPORATE RENEWABLE SOURCING

Corporate sourcing of renewables "occurs when a company actively consumes, produces or invests in renewable energy to sustain its operations – offices, factories, vehicle fleets and supply chains" (IRENA, 2018b). Companies' investments can range from purchasing green electricity certificates to developing their own generation plants.

Corporate renewable sourcing can be a valuable financing strategy for renewable electricity in developing countries. Companies are in the best position to identify the energy needs for their businesses, to assess the feasibility of renewable projects, and to make cost-effective investments in renewable electricity sources. Renewable sourcing also offers an opportunity to align the objectives of industrial development and sustainability.

Several different options are available for corporate renewable sourcing, and a number of policy measures can be used to encourage and support its use, as shown in Table 3.

TABLE 3 | Corporate renewable energy sourcing options

Corporate sourcing option	Policy measures	Examples of countries using these policies nationally or sub-nationally
Corporate PPAs	• Allow third-party sales (bilateral trade/sales) directly between corporate buyers and IPPs • Provide clear and transparent grid-access rules and "wheeling" arrangements that permit both on-site and off-site PPAs • Provide transparent and credible tracking of renewable energy attribute certificates	Argentina, Brazil, Chile, Mexico, Netherlands, Norway, Sweden, United Kingdom, United States
Utility green procurement	• Support market-based renewable energy pricing • Support tailored long-term renewable energy contracts for large-scale corporations (*e.g.* the creation of green tariff programmes) • Provide transparent and credible tracking of renewable energy attribute certificates	Netherlands, United States
Direct investment for self-consumption	• Provide clear and stable mechanism for on-site and off-site systems to feed excess electricity to the grid (*e.g.* net metering scheme) – preferably with priority dispatch for renewable energy • Provide a wheeling mechanism that allows for the transport of electricity from off-site generation to the place of consumption • Provide transparent and credible tracking of renewable energy attribute certificates	China, India, Japan, United Kingdom
Unbundled renewable electricity certificates (RECs/GOs)	• Provide transparent and credible tracking of renewable energy attribute certificates • Allow for corporations to buy electricity certificates directly	GOs in Europe; RECs in Australia, China, India, Mexico, United States

Source: (REN21, 2018).

Notes: GOs = government organisations; IPP = independent power producer; PPA = power purchase agreement; RECs = renewable electricity certificates.

Among the available options, the strongest growth has been in corporate renewable power purchase agreements (PPAs), which increased from 300 MW in 2009 to 46 GW in 2023 (BNEF, 2024). For corporations, these agreements provide a reliable source of power, which is especially valuable in countries with frequent outages. They also signal to customers and markets that companies are serious about their environmental concerns. For project developers, the agreements ensure demand from large electricity customers, which can help developers obtain easier access to funds. In 2024, Microsoft signed the largest-ever corporate power purchase agreement (PPA) for renewable energy to date, signing on for more than 10.5 GW of capacity in the United States and Europe (Kennedy, 2024).

However, countries in the Global South, and African countries in particular, are still under-represented in this emerging market. Reasons include policies that make economic growth a higher priority than emission reductions, the lack of supportive regulations and tariff policies, and power structures that make direct commercial interaction between industries and renewable project developers difficult.

Despite these difficulties, corporate sourcing has the potential to unlock significant private financial resources. In regions with unreliable grids, for example, companies can take advantage of declining costs for solar PV to ensure dependable power and to replace expensive diesel generation.

Dynamic market for corporate renewable PPAs in India

Companies in India contracted for 1.6 GW in 2018, 1.9 GW in 2019, 800 MW for the first 11 months of 2020 (WBCSD, 2018) and 922 MW in just the third quarter of 2023. Total corporate renewable capacity reached an estimated 33.2 GW (Bridge to India, 2023). The PPAs are being used in a wide range of industries. Companies with the largest renewable capacities include textile, chemicals, and cement producer Grasim Industries (Grasim, 2024), food producer Cargill, and automobile maker Tata Motors, which has committed to 100% renewable electricity by 2030, and net zero emissions by 2045, using on-site renewables, off-site renewables and renewables PPAs (TATA Motors, 2024a, 2024b).

SUMMARY TABLE: Corporate renewable sourcing

INNOVATION READINESS LEVEL		LOW HIGH
BENEFITS	Affordability	LOW HIGH
	Energy access	LOW HIGH
	Power system resilience	LOW HIGH Can better contribute to improving the resilience of power systems through innovative contracts such as those that include storage.
	Energy security	LOW HIGH
	Sustainable development	LOW HIGH
IMPLEMENTATION	Implementation cost	LOW HIGH
	Prerequisites	Renewable goals can stimulate corporate procurement. The need for technical capacity internally to implement it, ease of implementation. Support from policy makers / enabling framework. Important in India, a favourable policy has stimulated the observed dynamism.
	Stakeholders responsible for implementation	Transmission and distribution system operators, regulatory agency, private companies such as businesses and project developers, local institutions and enterprises.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Algeria, Burkina Faso, Egypt, India, Mali, Mexico, South Africa

3.3 Ecosystem enablers

Ecosystem enablers play a crucial role in advancing the energy transition and meeting sustainable development goals by fostering supportive policies, financial mechanisms, and technological innovations, and creating an environment conducive to clean energy adoption. Within this ecosystem, key change agents – such as policy makers, industry leaders, grassroots organisations and innovators – drive transformative action by championing renewable energy solutions, advocating for policy reforms and mobilising resources.

By implementing policies that promote renewable energy, offering financial incentives, and investing in infrastructure, ecosystem enablers and key change agents help overcome barriers such as high initial costs, limited grid access and technical capacity gaps. Additionally, they can support local entrepreneurs and businesses in deploying decentralised energy solutions, such as mini-grids and off-grid solar systems, which are essential for electrifying remote and under-served communities. Key change agents can also enable green development in key sectors: health and education, agriculture and farming, and infrastructure modernising, such as in railways. Through collaboration and capacity building, these stakeholders accelerate the shift towards sustainable, resilient and inclusive energy systems in developing countries.

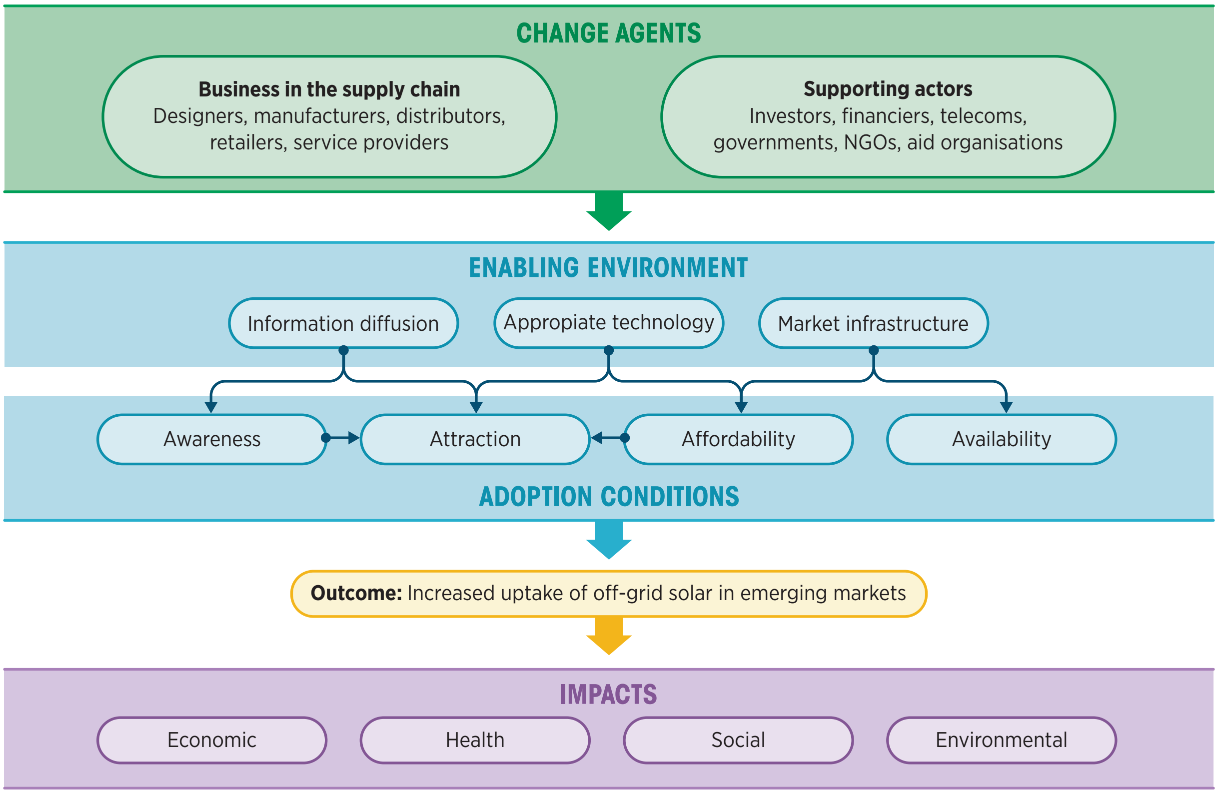
Innovation 21
KEY CHANGE AGENTS TO SUPPORT RENEWABLE-BASED DEVELOPMENT PROGRAMMES

Key change agents include businesses in the production and use of renewable energy, such as designers, manufacturers, retailers, importers and service providers, as well as supporting actors like governments, investors and international development organisations (Figure 23). Rural development agencies can be key change agents, for example, as they understand the multiple dimensions of rural development and how renewable electricity can provide irrigation or drinkable water access. Innovative local governments or municipalities can also be key change agents, as they can foster pilot projects tailored to local needs and raise awareness. These key change agents are crucial for accelerating the adoption of the technologies and business models needed to achieve the energy transition and to meet climate policy goals (Bergek, 2020; Karber, 2018; Kivimaa *et al.*, 2019).

Key change agents can help break down the silos among different ministries that can hamper progress, making it possible to take advantage of synergies across sectors (UNECE, 2017). They can set complementary goals and targets and promote collaborations and partnerships for the sharing of best practices. They are also important for the implementation of quality standards and maintenance strategies, ensuring that renewable electricity projects do not prematurely fail or under-perform from lack of maintenance.

It is important, therefore, to identify potential leaders and purposefully organise them into a network of change agents. That, in turn, will help create favourable conditions for demonstrating innovative technologies, initiating pioneering pilot projects, creating new markets, and building and diffusing knowledge.

FIGURE 23 | Roles and actions of key change agents



Source: (Karber, 2018).

Creating and strengthening networks of key change agents in emerging markets and developing economies

One simple and effective first step for strengthening the networks of change agents is creating comprehensive maps of stakeholders in the renewable ecosystem, and their concerns. Such analyses have been done for the Maldives (Ministry of Environment Maldives, 2021), Nigeria (Edomah *et al.*, 2021; SEfor ALL, 2021) and Indonesia (Yudha and Tjahjono, 2019). The Indonesian study found, for example, that only a sub-set of actors was focused on the technological and social aspects of renewables development. Broadening those concerns to other institutions could thus improve the underlying conditions for the energy transition.

Another effective step is establishing dedicated renewable energy agencies, especially in countries with less prior experience of renewable policies. For example, Togo created a dedicated rural electrification and renewable energy agency (AT2ER) in 2017 and published a directory of actors in the renewable energy sector in 2021 (Alliance for Rural Electrification and GIZ, 2021). It also helps to conduct detailed value chain analyses to better understand the market forces at play in specific countries. Examples include assessments of the off-grid solar market in Mozambique (Economic Consulting Associates and GreenLight, 2018) and Tanzania (Ipsos Tanzania, 2017). Still another approach is establishing certification schemes for sustainable energy skills. To promote high-quality projects in West Africa, the ECOWAS Centre for Renewable Energy and Energy Efficiency plans to train people to install solar systems, including creating a special programme to train women (ECREEE, 2022).

SUMMARY TABLE: Key change agents to support renewable-based development programmes

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Requires human resources and training capacities but does not involve heavy investments in the power sector. Contributes to developing a local expertise.
	Energy access	LOW – HIGH Key agents possess unique local knowledge of the energy access needs and challenges.
	Power system resilience	LOW – HIGH Does not directly contribute to power system resilience.
	Energy security	LOW – HIGH Can contribute to the definition of action that improves the energy security of planned development projects.
	Sustainable development	LOW – HIGH
IMPLEMENTATION	**Implementation cost**	LOW – HIGH Implementation costs are low for the power industry.
	Prerequisites	Support from policy makers is important to ensure that the network behaves efficiently over the long term and to give sufficient means and clear mandates to the agencies involved. Important need for capacity building activities. International donors may be needed to provide the initial funding.
	Stakeholders responsible for implementation	Rural development agencies, renewable and energy efficiency agencies, non-governmental organisations, international donors.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Indonesia, Maldives, Mozambique, South Africa, Tanzania, Togo, ECOWAS countries

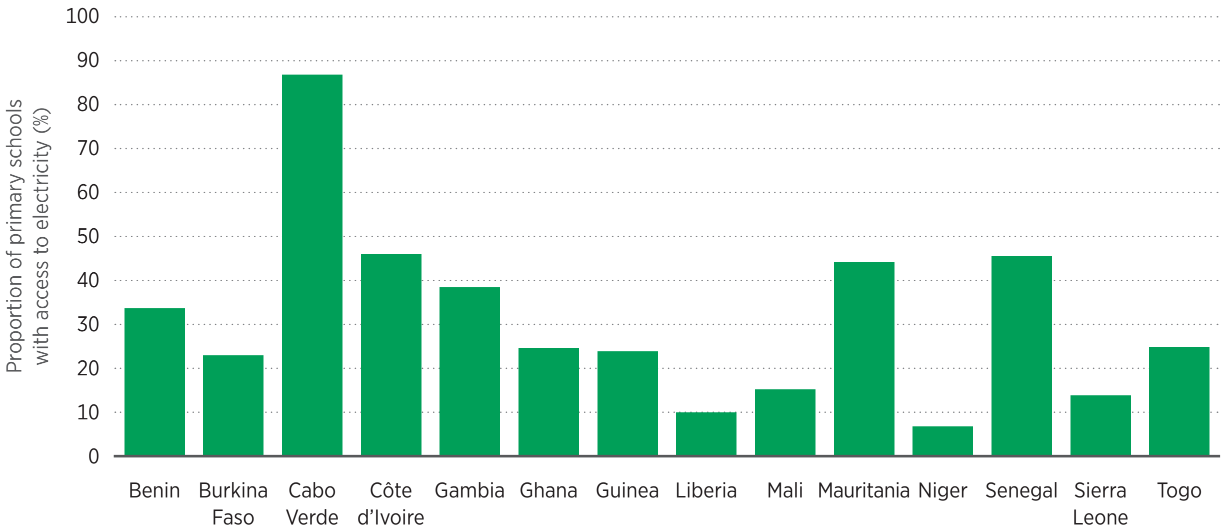
Note: ECOWAS = Economic Community of West African States.

Innovation 22

POWERING A SUSTAINABLE HEALTH AND EDUCATION ECOSYSTEM

Providing access to affordable renewable electricity not only achieves Sustainable Development Goal 7 (SDG 7),[5] it also can improve health and well-being (SDG 3) and help provide high-quality, inclusive and equitable education (SDG 4). In low- and middle-income countries, nearly three in five health facilities have unreliable electricity supplies (Cronk and Bartram, 2018), and only 12-27% of people in low-income countries have health-care system coverage (WHO, 2019). Similarly, only 72% of primary schools around the world have electricity – with the rate dropping to 31% in Sub-Saharan Africa (UNESCO, 2021). Figure 24 shows the rates for West African countries.

FIGURE 24 | Share of primary schools in West Africa with access to electricity



Source: (UN, 2020).

There is thus a huge opportunity, particularly in Sub-Saharan Africa, to improve both health and education by supplying renewable electricity to health facilities and schools, sometimes replacing expensive and polluting diesel generation in existing facilities. Off-grid renewable generation can also help solve the problems of the insufficient number of health-care facilities and schools, enabling them to be built where they are the most needed, ahead of the arrival of the main grid. In addition, reliable electricity can improve the quality of education, enabling internet access and the use of technology.

In health care, renewable electricity enables the operation of critical medical equipment and refrigeration for vaccines. Solar-powered clinics, for example, provide energy supply to rural health-care centres. When integrating back-up solutions such as batteries, renewable electricity can ensure that life-saving treatments are not disrupted due to power outages. Similarly, schools equipped with renewable power and batteries can extend study hours, provide reliable lighting, and support the use of computers and projectors, enhancing the quality of education.

[5] *To ensure access to affordable, reliable, sustainable and modern energy for all.*

Finally, the potential benefits expand well beyond health and education, since schools and health-care facilities can provide anchor loads for renewable generation systems that also can be used to power other community initiatives and economic activities (Welland, 2017).

Electrification of education facilities with renewable energy

Analyses show that providing electricity to classrooms increased the success rate in Ghana on standard mathematics and English exams by 28% (Adamba, 2018) and reduced the dropout rate in Brazil by up to 27% (Mejdalani *et al.*, 2018). Meanwhile, eight case studies demonstrated how off-grid electrification can provide power for education and health systems (United Nations Foundation and SE4ALL, 2019), such as a World Bank-funded effort to use solar PV and batteries to electrify 560 schools and 522 health centres in Uganda. In other promising examples, Nigeria plans to electrify 200 health centres and 124 schools (The Guardian Nigeria, 2021), and the US Agency for International Development, in the past, provided a USD 1 million grant for health facilities electrification in Sub-Saharan countries (SE4ALL, 2021, 2023).

Electrification of health centres with renewable energy in Mozambique

Decentralised renewable energy (DRE) solutions can play a pivotal role in democratising essential services such as health care. DRE can catalyse a transformation of health-care delivery by helping to ensure that the design of energy systems considers the needs of the populations accessing health care, especially primary health care. In particular, DRE solutions can be used to improve:

- Maternity and child care
- Immunisation rates
- Diagnostic and laboratory services
- Preventive and therapeutic care
- Health administration
- Daily working environments of healthcare providers

Mozambique faces significant health challenges, including high rates of maternal and neonatal mortality, communicable diseases and malnutrition. Frequent extreme weather events, such as cyclones, floods and droughts, compound these issues as well as the risk of diseases like cholera, malaria and diarrheal infections, putting additional strain on an already overburdened health system.

DRE solutions offer an opportunity to pragmatically and cost-effectively address these many challenges. As a reliable power supply for health-care facilities, DRE enables the continuous operation of essential medical equipment, lighting and refrigeration for vaccines. For example, solar-powered refrigeration can help ensure a stable vaccine cold chain, minimising spoilage and helping to improve immunisation rates. Solar power can support health-care workers in providing quality care even during power outages and thus enable basic diagnostics, laboratory services and maternity care. By integrating DRE solutions, Mozambique can leapfrog traditional energy sources, ensuring sustainable and resilient health-care services that serve the needs of all communities, especially in remote and vulnerable areas.

Findings from an IRENA assessment indicate a funding need of USD 16.5 million to power Mozambique's entire primary health-care infrastructure (1 649 facilities) with reliable decentralised solar energy for all regular services. Powering all critical loads of the primary health-care facilities with decentralised solar as a back-up power source would cost an estimated USD 7.7 million. The IRENA assessment concludes that integrating DRE systems into Mozambique's health-care sector is a vital move towards making health services more reliable and sustainable nationwide (IRENA and SELCO Foundation, 2025).

SUMMARY TABLE: Powering a sustainable health and education ecosystem

INNOVATION READINESS LEVEL		LOW — HIGH
BENEFITS	**Affordability**	LOW — HIGH Efficiency, reliability, reduction of non-supplied demand.
	Energy access	LOW — HIGH
	Power system resilience	LOW — HIGH
	Energy security	LOW — HIGH
	Sustainable development	LOW — HIGH
IMPLEMENTATION	**Implementation cost**	LOW — HIGH High upfront costs but lower operational costs.
	Prerequisites	Requires strong co-ordination between state institutions in charge of health planning and education, and energy stakeholders. Support from policy makers is essential to overcome differences in expertise. Facilitating institutions will need additional financial resources to assume this role.
	Stakeholders responsible for implementation	Ministries of health and education, rural electrification agency, development agencies.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Ghana, India, Indonesia, Malawi, Maldives, Mozambique, Nigeria, Philippines, South Africa, Tanzania, Togo, Uganda, ECOWAS countries, *etc.*

Innovation 23

RENEWABLE ENERGY SYNERGIES FOR MODERNISED RAILWAY INFRASTRUCTURES

The expansion or modernisation of public infrastructure projects, in particular railway networks, can be combined with the development of a renewable electricity generation, creating synergies that benefit both the transport and power sectors.

Developing an integrated railway system, for example, is a strategic component of the African Union's Program Infrastructure Development for Africa (PIDA). Such a system would connect countries and major metropolitan areas, carrying both people and freight to support Africa's economic and demographic growth (AfDB, 2021a; African Union, 2021). In addition, the rail lines could be used as renewable energy corridors, bringing electricity to remote areas alongside the tracks. However, it is crucial to match the railway development with renewable energy deployment to provide the electricity needed, thus avoiding locking in fossil fuel power. Some models for coupling railways with renewable energy already exist, such as buying green certificates in Europe, railroads owning hydropower in Switzerland, and solar power projects developed by railway operators (IEA, 2019).

Renewable energy enables railway development or modernisation in Chile and India

The metro system in Santiago, Chile is the largest in the country and the second largest in South America. It is a leader in green energy, obtaining 100% of its electricity from renewables since 2022. The electricity is procured in part through long-term PPAs and in part from direct investments in solar panels placed close to or on rail lines (Metro de Santiago, 2024).

In India, the world's fourth longest railway network moves 23 million passengers and 3.3 million tonnes of goods per day (Directorate of Statistics and Economics and Ministry of Railways, 2021). The railway system has an ambitious modernisation plan that aims to achieve net carbon neutrality by 2030 (IRCTC, 2021) and a dedicated railway energy management company (REMC Ltd) for developing renewables projects. The plan envisions developing 3 GW of solar plant capacity on vacant land parcels in the railway system and on railway station rooftops (REMC Ltd, 2021).

SUMMARY TABLE: Renewable energy synergies for modernised railway infrastructures

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Reduces development costs by Integrating renewable energy plants in wider modernisation projects.
	Energy access	LOW – HIGH Does not directly address the energy access challenge.
	Power system resilience	LOW – HIGH Will not directly improve the resilience of the power system unless storage plants are also considered.
	Energy security	LOW – HIGH Contributes to energy security by increasing the total installed capacity.
	Sustainable development	LOW – HIGH Contributes to sustainable development by facilitating the deployment of renewable energy sources.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH Does not rely on costly infrastructure.
	Prerequisites	May require updated regulations to authorise the use of previously vacant areas for electricity production. Lasting commitment and support from policy makers are important to co-ordinate the agenda of modernisation programmes with the expansion of renewable electricity.
	Stakeholders responsible for implementation	Responsible authorities for the infrastructure of concern (ministry of transport, ministry of construction, agencies in charge of civil engineering), distribution system operator, regulator.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Chile, India

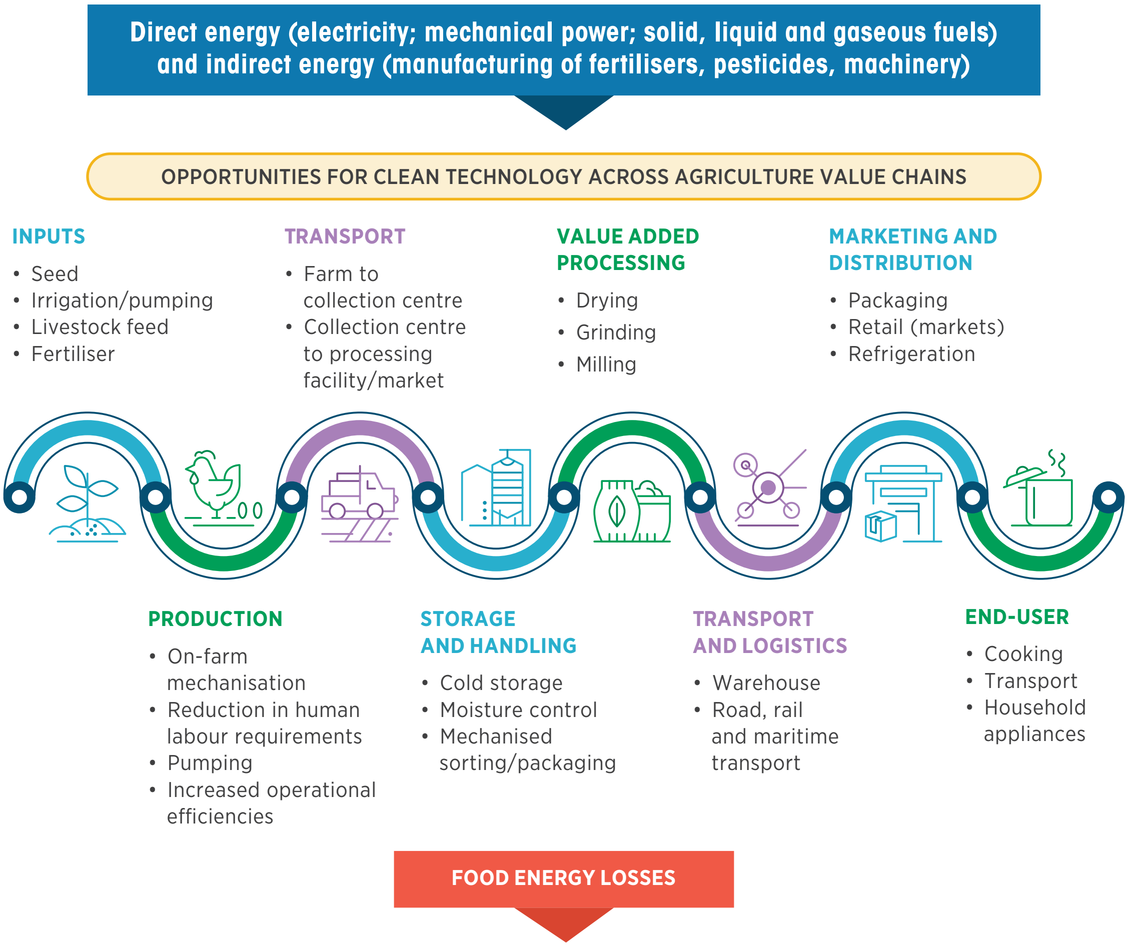
Innovation 24

RENEWABLE ENERGY FOR RESILIENT AGRICULTURE AND FARMING SYSTEMS

Modernising agriculture and the farming systems is another pressing development imperative. In Africa, increasing local production is crucial to reduce dependence on food imports and to feed a population expected to increase from 1.3 billion to 2.5 billion over the next 30 years – a challenge that will only get more difficult due to the impacts of climate change. Industrialisation of food with synthetic fertilisers and synthetic ingredients in ultra-processed food have already contributed to the climate and health crisis.

Improving productivity and reducing climate vulnerabilities, while also increasing economic growth, requires a host of technologies and changes, from better irrigation and transport systems to reducing food waste and switching to higher-yielding crop varieties, as described by the Technologies for African Agricultural Transformation (TAAT) programme. Most of these require direct or indirect energy (Figure 25).

FIGURE 25 | Energy flows in the agri-food system



Source: (IRENA and FAO, 2021).

There is thus a major opportunity to combine the development of renewable electricity with efforts to achieve strong and sustainable growth in agriculture and related activities. Renewable-powered agriculture is particularly suited in areas with no reliable electricity access, where it can provide clean and decentralised energy for irrigation, food storage, food processing and other activities that currently have low access to energy. In addition, solar PV panels can be installed on farms in an innovative concept called agrivoltaics or agrovoltaics (Trommsdorff *et al.*, 2022). On non-arable land, the ground under the solar panels can be used to graze cattle; on arable land, the panels protect crops from storms or heat stress and can allow higher-value crops to be grown (Edmond, 2022). Meanwhile, grass or crops reduce the temperature under the PV panels, increasing their efficiency and their electricity production.

Barriers to the adoption of renewable electricity in rural communities include limited access to credit, reluctance to change existing practices, lack of knowledge and local land tenure rules (Rodriguez *et al.*, 2009). Agrivoltaics solutions also require diverse stakeholders to work together, including land owners, PV business developers, farmers and communities. Overcoming these barriers will require a "cross-sector and multi-stakeholder co-ordination among government, the private sector and civil society, both nationally and sub-nationally" (IRENA and FAO, 2021).

An integrated approach in the Philippines

In the Philippines, the ministries of energy and agriculture joined together in 2021 to launch a renewable energy programme for the agri-fishery sector (IRENA and FAO, 2021). One of its flagship initiatives is the I-PURE Mindanao project (Integration of Productive Uses of Renewable Energy for Inclusive and Sustainable Energisation). By the end of 2023, I-PURE had supported two solar-powered corn processing facilities, in Arakan and Kidapawan (NEA, 2023); a solar-powered rice miller in Tulunan; a solar-powered coffee processing facility in Kalamansig; several solar-powered water systems and seaweed dryers; and enough solar generation to provide electricity to more than 6 000 homes (IRENA, 2023d).

Innovative agrivoltaics pilot projects in Africa

In two pilot projects in Kenya and Tanzania, the partial shade cast by solar panels built over farm plots doubled the yields of Swiss chard and soya beans, and brought small increases in the yields of maize, while reducing the amount of irrigation water needed. Another project, Agrivoltaics for Mali and The Gambia (APV-MaGa), aims to build one demonstrator facility in Mali and four demonstrators in The Gambia. Each will be tailored to local needs, using renewable electricity to power irrigation pumps, cereal mills, cold storage units and other services (Evans, 2024; WEF, 2022). It will also evaluate potential business models (APV-MAGA, 2023). Similar pilot projects are being launched or considered in Kenya (Edmond, 2022), Zambia (B. I. Africa, 2023) and Ghana (Kemausuor and Amponsah, 2021).

SUMMARY TABLE: **Renewable energy for resilient agriculture and farming systems**

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Increasing the revenues of rural populations improves their ability to pay for their electricity supply.
	Energy access	LOW – HIGH Improves energy access in rural areas.
	Power system resilience	LOW – HIGH Does not target a more resilient power grid.
	Energy security	LOW – HIGH Contributes to energy security in rural areas by providing a decentralised resource adjusted to the needs of the local value chain.
	Sustainable development	LOW – HIGH Facilitates the deployment of renewable energy sources and replaces fossil-based alternatives.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH Without public support, high upfront costs are an important barrier for adoption by small farmers.
	Prerequisites	Requires very good co-ordination between energy and development stakeholders who traditionally work in silos. Requires a strong awareness and knowledge sharing component to ensure that the farming communities understand and claim ownership of the energy dimension. Requires sustainable business models for farmers and the solution developers.
	Stakeholders responsible for implementation	Responsible authorities for rural electrification, agriculture, and energy, non-governmental organisations and farmer co-operatives.
JURISDICTIONS WHERE IT IS IMPLEMENTED		China, Ghana, Kenya, Mali, Philippines, Rwanda, The Gambia, Zambia

04 MARKET DESIGN AND REGULATION

The technology already exists for the transition to a renewable-based energy system. However, energy systems based on renewables are fundamentally different from traditional systems. In contrast to fossil fuel power plants, wind and solar plants have high investment costs (CAPEX) but very low, close to zero, operational costs (OPEX). As a result, the financial viability and rapid deployment of renewable energy projects depend heavily on securing predictable and stable revenue streams.

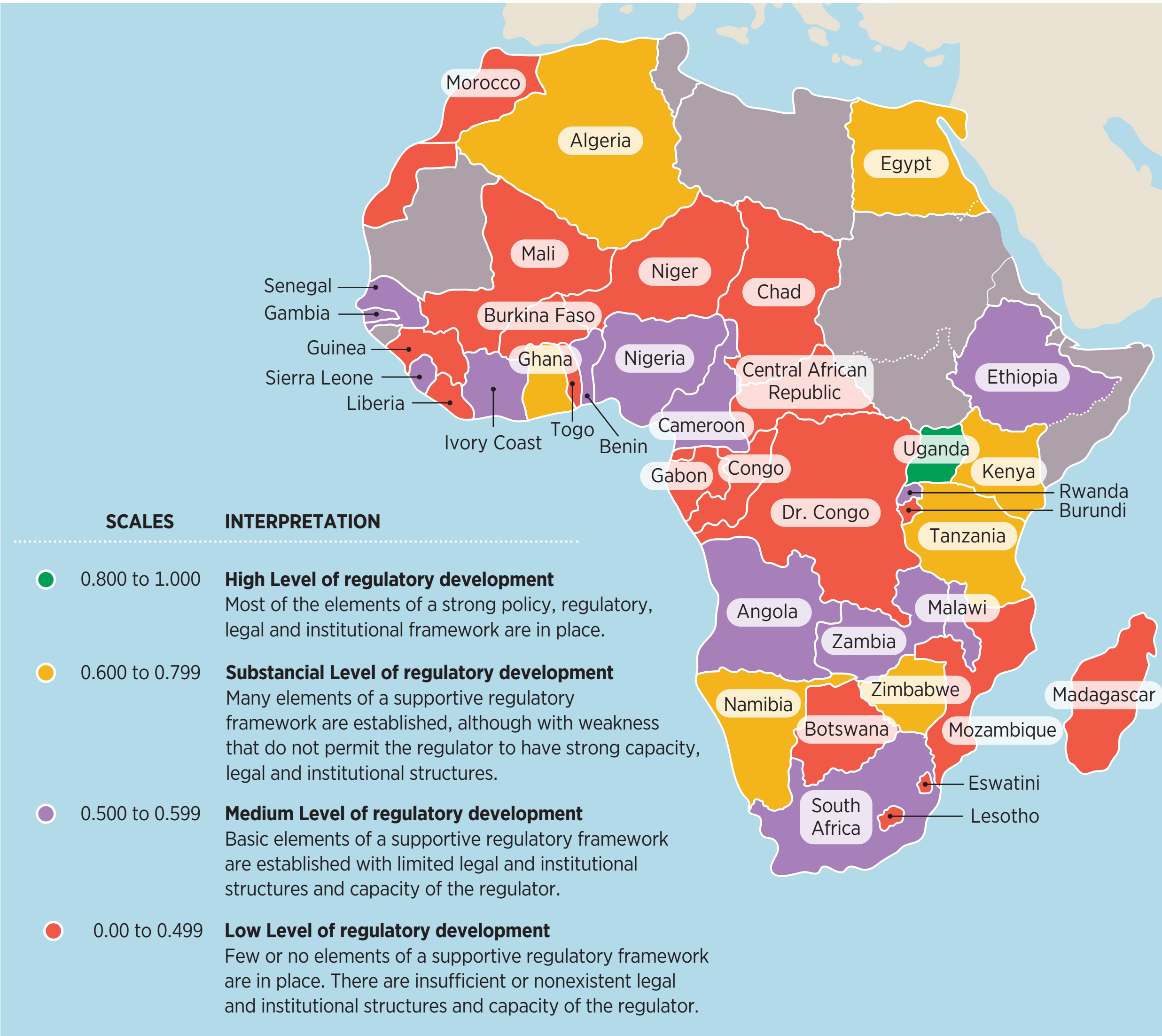
In addition, as the share of renewables in the electricity mix increases, the so-called cannibalisation effect emerges: when large amounts of wind and solar are generating simultaneously, they decrease the marginal price of the system and depress wholesale market prices, precisely at the times when these plants are producing the most. This dynamic reduces the marginal value of renewable generation and makes it more challenging for projects to ensure stable and sufficient revenues over their lifetime. Both regulated and liberalised power systems share the challenge of reformulating their procurement and allocation mechanisms to support the post-transition power system and to facilitate the transition process itself (IRENA, 2022d).

In addition, a renewable-based energy system can have many more generation sites, which typically are smaller and much more widely distributed than large centrally located power plants. This decentralises the system and can also empower consumers. Furthermore, integrating very large amounts of variable electricity generation is a challenge that asks for increased operational flexibility, and therefore new regulations to enable and remunerate this flexibility.

Innovations in regulations and market designs are key to incentivise the deployment and integration of large shares of renewables. These regulations and market designs must also provide the right incentives to invest in and operate the renewable power system, including ensuring sufficient economic returns for the investments made. This need for innovative market designs and regulations is particularly acute in developing countries, which must rapidly expand their power sectors to meet the growing electricity demand and to increase access to reliable power.

At the same time, with increased decentralisation and off-grid solutions to address the lack of energy access, countries often must manage the development of both mini-grids and main grids, while also transitioning from nationally operated power systems to regional or continental systems. Without strong and supportive institutional and regulatory frameworks, they could end up with costly stranded assets. For example, cross-border trades in West Africa could be an important strategy for integrating large amounts of VRE, but their potential has been largely untapped because the necessary regulatory framework has yet to be developed (World Bank, 2025c). Similarly, private sector investments in renewable generation have been hampered by the high cost of finance and the lack of a clear regulatory framework, despite impressive cost reductions in wind and solar technologies. Figure 26 shows that the majority of African countries are still at low or medium levels of regulatory development, according to a measure called the Electricity Regulatory Index (ERI) (AfDB, 2021c).

FIGURE 26 | Electricity Regulatory Index for African countries

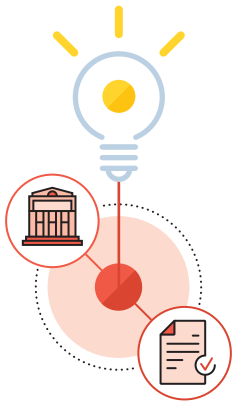


Source: (AfDB, 2021c).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

This section identifies nine regulatory and market designs innovations that can accelerate the energy transition and support sustainable development based on renewable solutions (Figure 27). The innovations are divided into three categories: regulatory and fiscal support for renewable energy deployment, empowering consumers, and regulation enhancing operational reliability.

FIGURE 27 | Innovations in market design and regulation



MARKET DESIGN AND REGULATION

Regulatory and fiscal support for renewable energy deployment	• **25** Development-linked fiscal instruments • **26** Renewable energy auctions with socio-economic requirements • **27** Renewable portfolio standards
Empowering consumers	• **28** Time-of-use tariffs • **29** Innovative pricing for prosumers • **30** Regulation for mini-grids
Regulation enhancing operational reliability	• **31** Regional integration • **32** Innovative ancillary services • **33** Grid connection codes

4.1 Regulatory and fiscal support for renewable energy deployment

There are several policy instruments that can support the deployment of renewables, targeting either specific technologies or specific actors, such as industries, households and independent producers. Their main objective is to improve the profitability of renewable energy projects. This section focuses on three types of policy tools that have proven their worth in emerging economies: fiscal instruments, auctions and renewable portfolio standards.

Innovation 25
DEVELOPMENT-LINKED FISCAL INSTRUMENTS

Fiscal instruments can improve the financial competitiveness and profitability of renewable energy investments. Such fiscal incentives include tax incentives, customs and import-duty exemptions (which lower costs for imported renewable technologies), and capital depreciation measures or capital allowances. These fiscal instruments must be carefully designed, however, to provide sufficient incentives without hampering other priorities because of forgone tax revenues. Among the fiscal policies that render renewable energy more affordable are tax incentives (such as VAT), customs and import duty exemptions, and capital depreciation / capital allowances.

To address concerns that such measures can disproportionately benefit large foreign investors or generate significant foregone revenues, governments can strengthen their design by linking incentives to clear development objectives – such as local job creation, supporting participation of small and medium enterprises, or technology transfer – and by conducting regular cost–benefit reviews from a national development perspective. In this way, fiscal instruments become not only tools to lower project costs but also levers to align renewable energy investment with national development priorities.

Another key aspect is facilitating local currency lending and denominating PPAs (at least partially). Local currency PPAs are helpful to address the risks of currency devaluations that may otherwise cripple the ability of power off-takers to make payments to power producers in hard currency (such as the USD) at times when the domestic currency plummets. The approach has significant advantages: it can mitigate impacts of foreign currency fluctuations on PPA payments, stimulate local financial markets and investors to engage in renewable energy investments, and avoid placing all the risk on consumers. Such an arrangement is more readily acceptable if project financiers are also domestic, such as the national development bank, local lenders and institutional investors (such as pension funds and insurance companies) (IRENA, 2020c). A complementary mechanism to address foreign currency risks is to facilitate local currency lending for projects with development capital channelled through intermediaries including national banks or non-banking financial institutions. Several countries, including Bangladesh, Brazil and Jordan, have piloted such approaches to catalyse investment in the renewable energy sector (IRENA *et al.*, 2023).

Fiscal incentives in Nigeria, Ethiopia and Madagascar

To encourage the use of solar home systems in Nigeria, where nearly 90 million people (55.4% of the population) lack electricity, the government reduced the VAT for solar home systems and exempted them from import duties. However, those policies have been relatively ineffective, in part because of delays in obtaining the exemptions and because of higher import duties or taxes on some components (Africa Clean Energy Technical Assistance Facility, 2021). This example illustrates the importance of the specific policy designs and suggests a pathway to improving them.

Other countries with fiscal support policies are Ethiopia and Madagascar. In 2019, Ethiopia exempted solar products under 15 watts peak (Wp) as well as certified solar home systems from the 35% duty tax and the (up to) 100% excise tax on imported products. Meanwhile, Madagascar has reduced corporate income taxes for investments in renewable energy and has exempted wind turbines, solar PV panels, hydropower generators, solar water heaters, batteries and other technologies from VAT and import duties (GET Invest, 2023).

SUMMARY TABLE: Development-linked fiscal instruments

INNOVATION READINESS LEVEL		LOW HIGH
BENEFITS	Affordability	LOW HIGH Makes renewable energy systems more affordable.
	Energy access	LOW HIGH Can increase energy access if it includes off-grid systems.
	Power system resilience	LOW HIGH Does not address power system resilience.
	Energy security	LOW HIGH Can impact energy security by ramping up the installed capacity.
	Sustainable development	LOW HIGH Promotes investments in renewable electricity.
IMPLEMENTATION	Implementation cost	LOW HIGH Creates short-term fiscal revenue losses that can be compensated by medium-term gains and socio-economic benefits.
	Prerequisites	The precise selection of technologies and components that are included in the fiscal measures can impact their effectiveness. This is, for instance, the case for batteries in solar home systems. Link the fiscal incentives to local development. Wide support from policy makers is needed to have a sufficiently ambitious measure.
	Stakeholders responsible for implementation	Governments, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Bangladesh, Ethiopia, Ghana, Kenya, Madagascar, Nigeria, Senegal

Innovation 26

RENEWABLE ENERGY AUCTIONS WITH SOCIO-ECONOMIC REQUIREMENTS

Competitive auctions can be a powerful tool for renewable energy development. For project developers, they lock in stable payments for electricity generated over the contractually agreed period, ensuring favourable returns and reducing risks. For governments, they offer control over the number of projects that are awarded contracts, and reveal the prices that will be paid for each unit of renewable electricity (IRENA, 2019i).

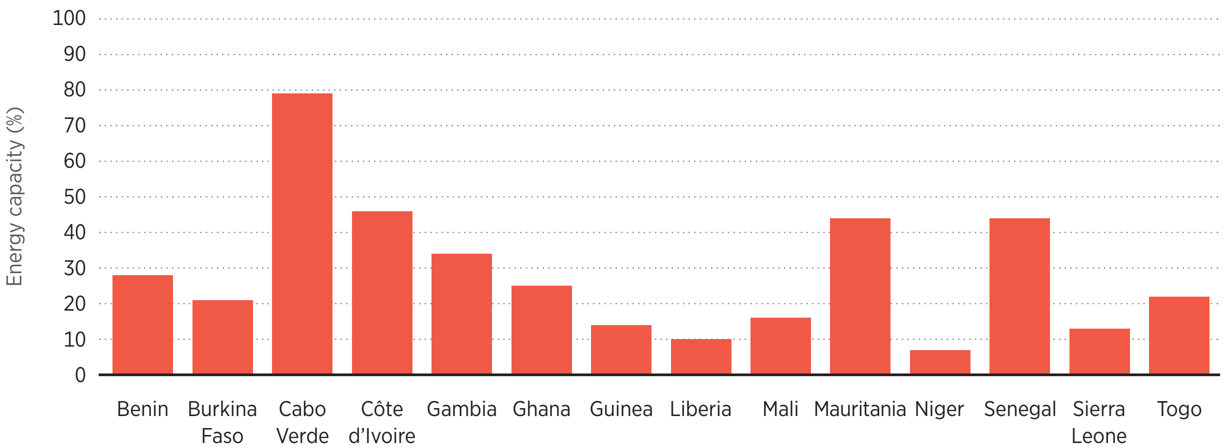
Renewable energy auctions with socio-economic requirements are particularly important in developing countries, where the dual challenges of expanding energy access and promoting inclusive economic growth are critical. By embedding criteria such as local content, job creation, skills development, community ownership, and gender inclusion into auction design, governments can ensure that renewable energy investments deliver tangible national benefits beyond simply providing electricity.

Renewable auctions can be designed to include requirements for achieving specific socio-economic benefits, such as domestic value creation (jobs, industrial development, local content), local development (skills training, community ownership) and social inclusion (gender equality). Different criterion to incentivise socio-economic development can be given substantial weight in auction evaluation, even if this leads to slightly higher tariffs, ensuring that the outcomes of renewable energy procurement contribute meaningfully to national development objectives rather than focusing solely on minimising costs.

Auctions can include penalties for delays or under-building (IRENA, 2018b). In addition, they can encourage the use of storage or hybrid systems to help enable VRE integration in power grids, such as in the Midelt project in Morocco combining concentrated solar power (CSP) and solar PV, and the Golomoti project in Malawi that links solar PV with a Li-ion battery (IRENA and AfDB, 2022).

While South Africa is far in the lead in the number of competitive auctions, these mechanisms are being used in more half of the countries in each African region (except Central Africa) (Figure 28).

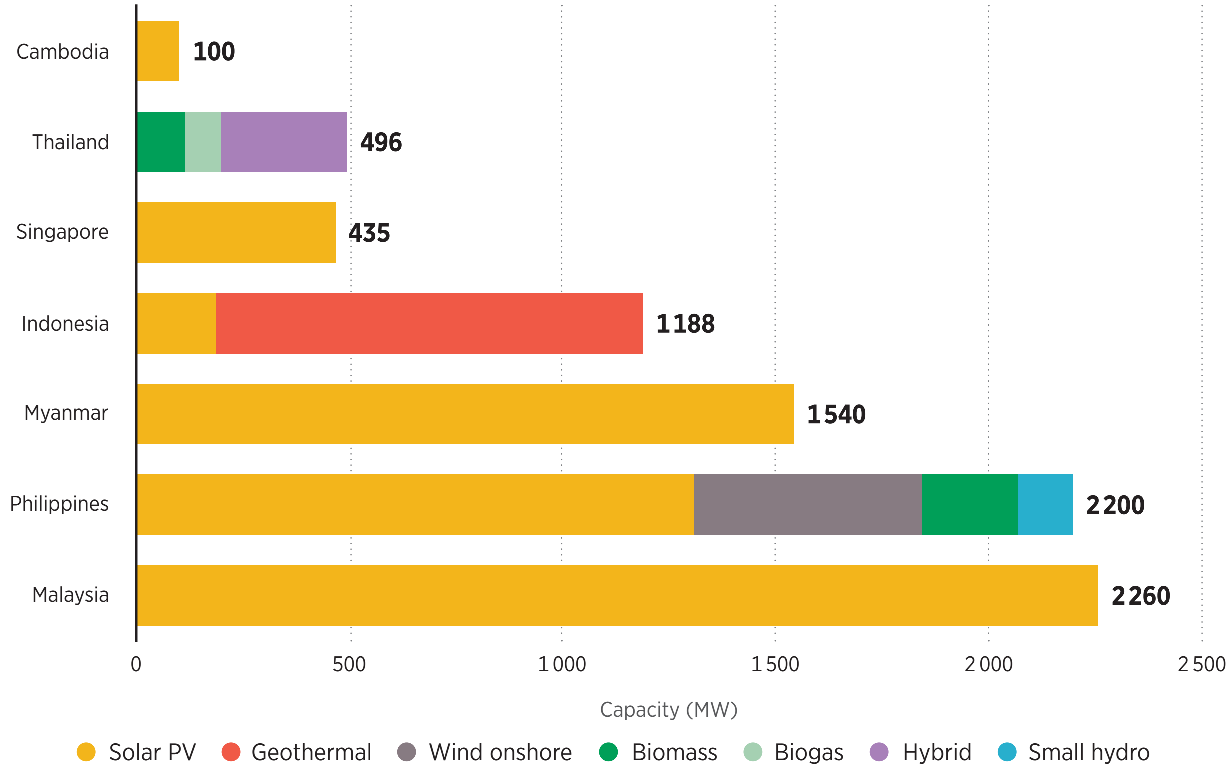
FIGURE 28 | **Renewable energy capacity awarded through auctions in Sub-Saharan Africa (MW)**



Source: (University of Cape Town, 2024).

Auctions are also an important instrument for renewables deployment in Southeast Asia (Figure 29). Technology-specific auctions are the region's preferred choice. They enable the introduction of chosen technologies to benefit from the available resources while serving the system's needs. They also ensure diversification of the energy mix and support the development of a local industry for given technologies. Solar PV auctions are the most popular and are held in Cambodia, Indonesia, Malaysia (the LSS programme), Myanmar, the Philippines (Private Solar PV Auction) and Singapore (SolarNova Programme and Floating Solar Systems) (IRENA, 2022e).

FIGURE 29 | Renewable energy volumes auctioned in Southeast Asia, by source, up to July 2022



Source: (IRENA, 2022e).

In Latin America, Brazil and Peru were both early adopters of auctions. More recently, Argentina, Chile and Mexico have joined the trend of innovating with auction designs. Driven by the success of auctions in neighbouring countries and by the conducive structure of its power market, Colombia is the latest country to adopt this instrument.

Auctions in Morocco designed for socio-economic goals and system integration

The auction for the Noor-Ouarzazate Power Station, the first complex to combine solar PV and CSP, sought to develop a domestic industry and create local economic opportunities. It included investments in amenities and social services such as drainage, irrigation channels, and community centres, and the project provided jobs to 6 430 Moroccans (70% of the total workers) (IRENA and AfDB, 2022). These initiatives underscore how auction designs can align renewable energy deployment with broader socio-economic goals, fostering inclusive development alongside clean energy expansion.

Requirements for socio-economic development in auctions in Southeast Asia

Requirements for socio-economic development have been a common design element in Southeast Asian auctions. In Indonesia, the use of local content for products and services is prioritised not only in auctions, but in the broader electricity sector and general investments. For solar PV, the level of domestic components for modules had to be at least 50% by 2018 and 60% by 2019. In Malaysia, requirements had been limited to the bidder being a local company with Malaysian equity of at least 51%, or a consortium of legal entities including a minimum of one local company, in which the Malaysian equity must also be at least 51% (SEDA, 2020). However, the country's fourth auction went further, as only companies that were 100% Malaysian-owned were allowed to take part, in addition to companies listed on the Malaysia stock exchange with at least 75% of their shares held by local people or companies.

GET FiT Uganda is an example of successful and co-ordinated support mechanisms for renewables

In 2014, Uganda became the first Sub-Saharan African country other than South Africa to embark on a renewable energy auction programme through competitive bidding: the Global Energy Transfer Feed-in Tariff (GET FiT) Solar Facility. Winning projects in the GET FiT programme are guaranteed payments of USD 0.11/kWh as a feed-in tariff but compete for the lowest premium payment on top of this tariff. By the end of 2022, the programme had resulted in a portfolio of 17 renewable energy projects – using solar PV, hydropower and bagasse technologies – with a combined installed capacity of 158 MW. The projects have lowered electricity costs by displacing expensive fossil fuel, created the equivalent of 12 900 full-time jobs, and leveraged USD 165 million in private financing and USD 290 million in public financing (KfW and Multiconsult, 2022).

SUMMARY TABLE: Renewable energy auctions with socio-economic requirements

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Contributes to stable economic perspectives for renewable energy systems.
	Energy access	LOW – HIGH Can be designed to selectively target regions with energy access issues.
	Power system resilience	LOW – HIGH Does not address power system resilience.
	Energy security	LOW – HIGH Can impact energy security by ramping up the installed capacity.
	Sustainable development	LOW – HIGH Promotes investments in renewable electricity and depending on the design can bring socio-economic benefits.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH Tenders and auction have proven their ability to promote projects with the most competitive cost.
	Prerequisites	Risk of delays or under-building by awarded project developers. Risk of discontinuous investment cycles due to the schedule of auctions. Compliance rules for participants may deter small or new players. The existence of a strong supporting legal framework and administrative complexity can be implementation challenges.
	Stakeholders responsible for implementation	Governments, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Ethiopia, Ghana, South Africa, Uganda, Zambia and more than 116 countries

Innovation 27
RENEWABLE PORTFOLIO STANDARDS

Renewable portfolio standards (RPS) require utilities or electricity providers to produce a minimum share of electricity from renewable sources. The standards can be technology neutral or technology specific. Utilities or retailers can meet the RPS requirements by developing renewable energy plants themselves or by purchasing the necessary amounts of renewable electricity from others. An effective RPS policy would specify the eligible renewable technologies, provide enough lead time for utilities to devise the most cost-effective strategies, and create a mechanism for enforcing the targets and imposing penalties if the targets are not met (Heeter *et al.*, 2019). Renewable energy certificates (RECs) are used to demonstrate compliance; a REC is issued when one MWh of renewable electricity is generated and delivered to the electricity grid.

RPS can be adapted for emerging markets and developing economies by addressing key institutional, market and infrastructure challenges. Strengthening regulatory capacity to ensure accurate monitoring and enforcement can improve compliance. Coupling RPS targets with fiscal incentives, or renewable energy auctions, can attract investments and offer extra stability for investors.

RPS policies are scalable and can be easily updated to make them more ambitious, and can include cost containment mechanisms. They also have the advantage of giving power system operators more freedom in selecting among the possible technologies or approaches for meeting the standards. In practice, updating RPS targets and rules can be politically contentious and lengthy, so the initial design must incorporate clear, pre-defined review and adjustment mechanisms based on market development and technological progress to avoid policy rigidity.

Renewable portfolio standards in the Philippines

In 2017, the Philippines introduced an RPS as one of the main vehicles to achieve the country's targets of 35% renewable energy generation by 2030 and 50% by 2040. In early 2022, the Philippines' Department of Energy listed 62 solar projects (totalling 1.3 GW), along with 36 hydropower facilities, 36 biomass plants, 7 wind farms, and 6 geothermal power plants, as being eligible for meeting the RPS (Bellini, 2022). In addition, in 2023 the country raised the minimum annual increase in the share of renewable energy under the RPS from 1% to 2.5%, reflecting both the success of the policy in driving new renewable capacity and the country's commitment to accelerating the adoption of renewables (Adonis, 2023).

Renewable portfolio standards in Nigeria

The Nigerian Electricity Regulatory Commission (NERC) announced a new regulation requiring all electricity distribution companies to procure at least 10% of their contracted energy from embedded generation sources, with half coming from renewable sources. The required capacity may be procured in bulk or distributed capacities (*i.e.* through different projects) across the respective DisCos area, and was expected to be available for dispatch by 1 April 2025 (Oladipo, 2024).

SUMMARY TABLE: Renewable portfolio standards

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	**Affordability**	LOW – HIGH Secures a market for renewable energy without a direct impact on costs.
	Energy access	LOW – HIGH Does not directly target access for previously unconnected households.
	Power system resilience	LOW – HIGH Does not address power system resilience.
	Energy security	LOW – HIGH Can impact energy security through a higher installed capacity.
	Sustainable development	LOW – HIGH Efficient to create a market share for renewable electricity.
IMPLEMENTATION	**Implementation cost**	LOW – HIGH Low implementation costs for the regulator and possibility to optimise the costs for utilities with a system of tradeable certificates.
	Prerequisites	The treatment of trades with regions outside the jurisdiction concerned by the RPS system can introduce leakage issues or increase the complexity of the accounting method. Overall emissions reduction impacts of RPS systems need to be monitored. A portfolio with steam coal and 5% renewables could, for instance, be more compliant than a 100% combined-cycle plant. The existence of an effective control and dissuasive penalty system.
	Stakeholders responsible for implementation	Governments, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		China, India, Mexico, Nigeria, Philippines, Viet Nam

4.2 Empowering consumers

Emerging innovative regulations aim at empowering consumers, involving end users that can promote faster growth of renewable energy solutions. Providing incentives for consumers to shift their energy consumption away from the typical evening peak demand period can reduce the need for back-up plants in a high renewable power system, for example. Consumers can also become energy producers (or "prosumers") themselves with systems such as rooftop solar and mini-grids. The following sub-sections describe innovative designs that can empower consumers, integrate prosumers and enable demand-side flexibility.

Innovation 28
TIME-OF-USE TARIFFS

Traditionally, power system operators responded to changes in demand by ramping the electricity supply up or down. Increased share of variable generation from renewable sources requires increased flexibility, which can be also harnessed from the demand side. Demand response programmes enable end users to reduce or shift their electricity demand in response to price signals or incentives, thus contributing to the operational reliability of the power and making it easier to integrate large amounts of VRE, in addition to lowering energy costs for consumers.

One way to harness demand flexibility is time-of-use tariffs, where electricity prices vary across the day to reflect when renewable generation is scarce and can also be designed to reflect grid congestion and encourage flattening of the demand peaks. By raising or lowering electricity prices to reflect grid conditions, time-of-use tariffs provide incentives for consumers to use less electricity during costly peak times, such as by turning down air conditioners and water heaters, and to use more when prices are lower. These tariffs can apply fixed rates for large blocks of time, such as simple peak or off-peak pricing, or they can be set to vary in real time as grid conditions change (IRENA, 2020b), such as lowering prices when large amounts of VRE are available.

Importantly, significant investment is needed in smart metering infrastructure, robust consumer education and social safety nets to protect vulnerable households that lack the capacity to shift demand. This is key to ensure that time-of-use tariffs do not disproportionately burden low-income consumers rather than effectively enabling demand flexibility.

Time-of-use tariffs may not be suitable for power systems that experience daily power outages due to insufficient supply. They could, however, work when outages are pre-planned and when consumers request price signals to shift their consumption during off peak times.

Time-of-use tariffs for e-mobility in Kenya

The electricity distributor Kenya Power is implementing the e-mobility tariff approved by the Energy and Petroleum Regulatory Authority (EPRA), offering significant cost savings to EV owners. EPRA set these tariffs at KES 16 (USD 0.12) per kWh during peak periods and KES 8 (USD 0.06) per kWh during off-peak periods, a significant reduction from the domestic tariffs charged at around KES 20 (USD 0.15) per kWh. The e-mobility tariff offers EV owners greatly reduced rates compared to standard residential, commercial and industrial tariffs (Writer, 2024).

Six countries in West Africa have introduced time-of-use tariffs

The policies are similar in each country, except that Côte d'Ivoire, Mali and Togo have three pricing levels (for peak, mid-peak and off-peak periods), whereas Burkina Faso, Niger and Senegal use peak or off-peak pricing. The cost increases from off-peak to peak periods range from 24.9% in Togo to 100% in Burkina Faso and Mali (AfDB and ERERA, 2019). The countries also subsidise rates for lower-income customers.

Krisana Antharith © Shutterstock.com

SUMMARY TABLE: Time-of-use tariffs

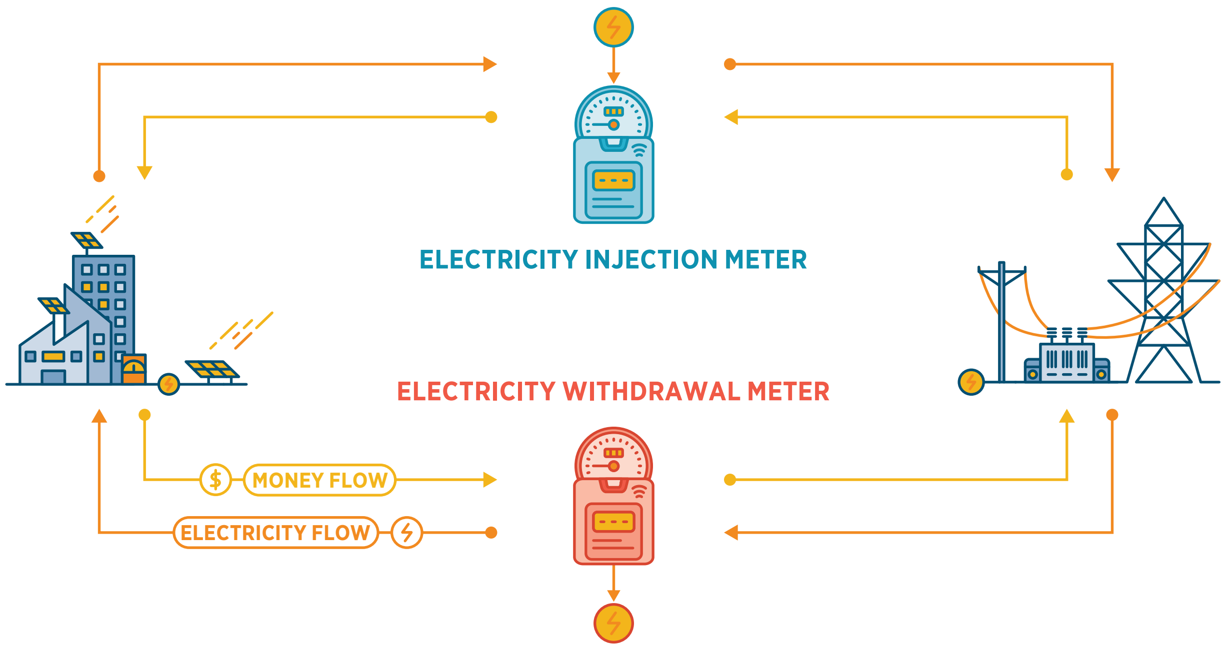
INNOVATION READINESS LEVEL		LOW — HIGH Time-of-use tariffs are largely implemented, while direct load control remains at the pilot stage.
BENEFITS	**Affordability**	LOW — HIGH Procures the option to use electricity in periods of low electricity prices, but could also lead to higher costs for inelastic and less affluent customers.
	Energy access	LOW — HIGH No direct effect on access for previously unconnected households
	Power system resilience	LOW — HIGH Influences the resilience of the system by mobilising demand-side flexibilities.
	Energy security	LOW — HIGH Can impact energy security by providing the appropriate economic incentive for investment during peak or critical periods.
	Sustainable development	LOW — HIGH Efficient to reduce the evening peak and increase consumption during periods of high renewable energy production.
IMPLEMENTATION	**Implementation cost**	LOW — HIGH Relatively low implementation costs for the regulator, but smart meters and actuators for demand response schemes will induce specific implementation costs.
	Prerequisites	Regulatory process must be supported by a roll-out of advanced smart meters. Consumer awareness and education. Transparent tariff setting method for poor customers.
	Stakeholders responsible for implementation	Governments, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		India, South Africa and several Western Africa countries for non-residential users (Burkina Faso, Côte d'Ivoire, Mali, Niger, Senegal, Togo)

Innovation 29
INNOVATIVE PRICING FOR PROSUMERS

Prosumers are electricity customers who also produce their own electricity, which they can use themselves or send to the grid. Examples include homeowners with rooftop solar systems, rural communities with mini-grids, and even plug-in EV owners. The prosumer model offers numerous benefits. It can increase access to electricity, reduce the investments needed in utility-scale power generation and grid infrastructure, increase grid flexibility, and lower electricity costs, among others. Policies or regulatory support instruments that provide incentives for prosumers can play important roles in the energy transition.

A key instrument for supporting prosumers is remunerating them for any electricity that is exported to the grid. In net metering, prosumers receive the retail price for their electricity; in net billing, the payment varies depending on time or location, but is generally at the wholesale rate (Figure 30). Net metering can be done with a single smart meter than can run forward or backward, while net billing payment can be more easily customised but requires two meters. In crafting the details of payment policies for prosumers, countries need to carefully weigh the benefits against the foregone revenues.

FIGURE 30 | Net billing scheme



Source: (IRENA, 2019j).

Net metering policy promoting small-scale solar in Namibia

As part of a series of regulatory reforms of the power sector aimed at raising the rates of electricity access (which were less than 10% in rural areas), Namibia's rules for net metering went into effect in 2017 (ITA, 2024; Von Oertzen, 2019). The policy does not pay prosumers directly; instead, it provides credits that can be used to offset monthly electricity bills (Electricity Control Board Namibia, 2016). By 2022, the policy had helped stimulate the installation of around 53 MW of privately owned and operated renewable energy, mostly small-scale solar. In addition to Namibia, at least 71 other countries had implemented net metering policies by the end of 2020 (REN21, 2021).

SUMMARY TABLE: Innovative pricing for prosumers

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	Affordability	LOW – HIGH Reduces curtailment of behind the meter generation of renewable electricity.
	Energy access	LOW – HIGH No direct effect on access for previously unconnected households.
	Power system resilience	LOW – HIGH Can improve resilience by generating electricity close to loads. Can negatively impact resilience and require grid reinforcement because of strongly modified power flows on distribution grids.
	Energy security	LOW – HIGH Can impact energy security by providing additional generation.
	Sustainable development	LOW – HIGH Efficient to promote very centralised investment in renewable energy sources.
IMPLEMENTATION	Implementation cost	LOW – HIGH The need for more advanced metering raises costs.
	Prerequisites	Regulatory process must be supported by a roll-out of advanced meters. If unplanned, large numbers of prosumers can reduce the reliability of power transfer on distribution grids. Defining the maximum size of eligible systems and the administrative burden of multiple individual contracts.
	Stakeholders responsible for implementation	Governments, energy regulatory agency, providers of smart meters, distribution system operators.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Ghana, India, Kenya, Morocco, Namibia, Philippines, Senegal, South Africa

Innovation 30

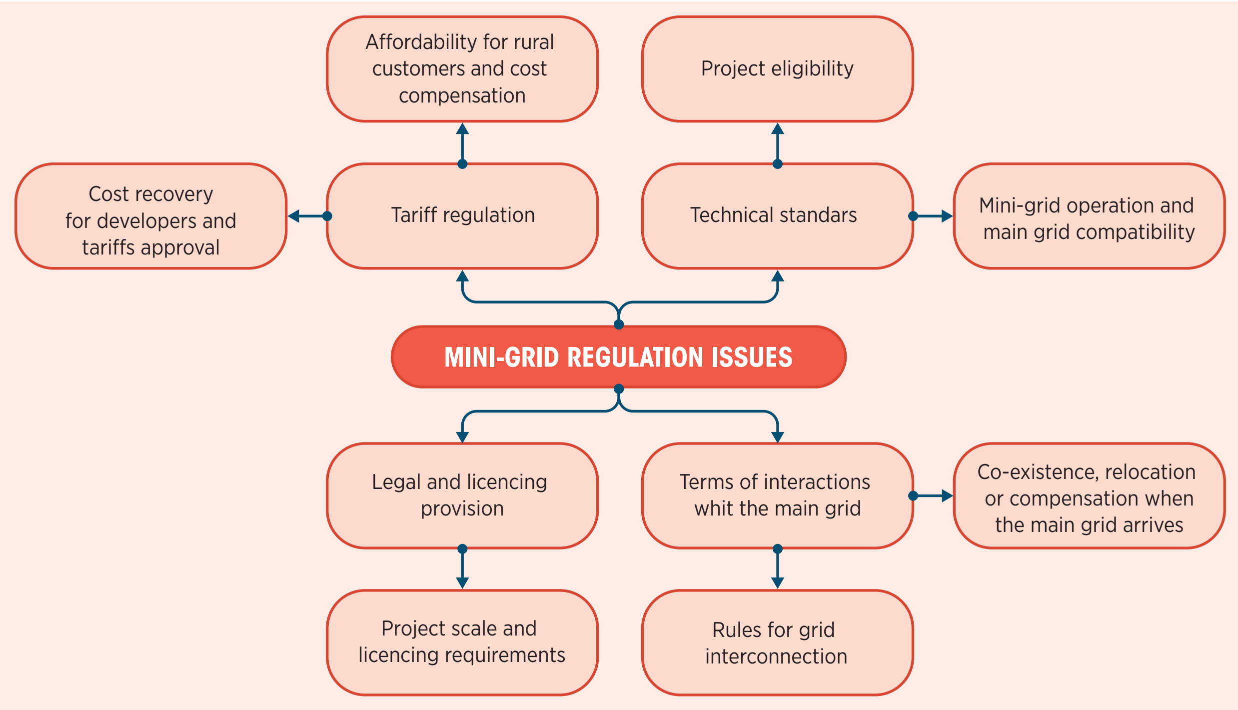
REGULATION FOR MINI-GRIDS

Mini-grids are one of the key technology innovations for the energy transition, in particular for off-grid applications and providing energy access in remote areas (see Innovation 11 on Renewable mini-grids), with the potential to provide energy access to 490 million people around the world (ESMAP, 2019).

Realising that potential, however, requires clear and comprehensive regulations to reduce the risks of investing in and operating mini-grids (IRENA, 2018c). Those regulations should include technical standards, rules for the interactions of mini-grids with the main grid, licencing and permitting frameworks, and processes for setting tariffs at levels that allow private investors to recover their costs while ensuring that electricity remains affordable for rural communities (Figure 31).

All these regulations need to be open and transparent enough to allow a comprehensive review process, in which both developers and regulators use the same methodology, assumptions and rules. It is also important to explicitly define conditions for interaction or exit options with the main grid as it expands to reduce uncertainties and the risk of stranded assets, such as providing compensation for depreciated assets.

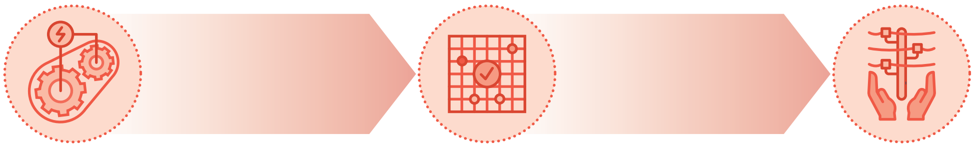
FIGURE 31 | **Synthesis of mini-grid regulatory issues**



Furthermore, mini-grids are complex systems with different suppliers. Ensuring that that they are of high quality (meeting the principles of "quality infrastructure", or QI) requires comprehensive standards, testing, certification and accreditation, inspection and monitoring, and metrology. Figure 32 shows how a strong QI increases benefits and reduces risks.

Current regulatory approaches in many emerging markets and developing economies are often too cumbersome, slow and insufficiently flexible to foster a dynamic mini-grid market. A shift towards more adaptive, light-handed and results-based regulatory frameworks that prioritise speed of deployment and service quality is important, but it is equally important to keep the balance in ensuring high quality. A balance between quality assurance and fostering local innovation is crucial.

FIGURE 32 | Goals and results of quality infrastructure for mini-grids



MINI-GRIDS CHALLENGES	QUALITY INFRASTRUCTURE ROLE	BENEFITS FOR MINI-GRIDS
• Complex systems with different suppliers • Custom designs with different solutions for various applicationsv • Regulatory/policy uncertainty • High technology costs	• Reduce project uncertainty/risk: quality assurance • Reduce downtime • Technical and regulatory clarity • Objective performance metrics for all stakeholders	• Improved financing conditions • Reduced LCOE • Enhanced trade and scalability of mini-grid markets

Source: (IRENA, 2022f).
Note: LCOE = levelised cost of electricity.

Mini-grid regulations provide clear signals to private developers in Kenya

Kenya has dramatically increased electricity access from just 25% of the population in 2010 to around 76% in 2022, with off-grid generation providing access for around 20% of the population (Cowling, 2024). One reason for this success is power sector regulatory reforms that began with the 1997 Electric Power Act and were updated in 2012. In 2021, specific mini-grid regulations were added that amended grid codes to ease interconnections with the main grid, allowed tariffs for private developers that reflected their costs, and provided financial compensation for publicly owned mini-grids, among other provisions. The regulatory tools provide a simplified and transparent regulatory framework for mini-grid tariff approval, licencing, technical guidelines, and performance and reporting. In the regulations, a participatory approach is adopted in the development and operation of the mini-grids by the local community, county governments and national government agencies. The mini-grid tariffs are determined based on prudent development and operation and maintenance costs, where engagements are held with the local community before approval (ESMAP, 2017).

In addition, the Kenya Off-grid Solar Access Project (KOSAP) provides a simplified regulatory framework for mini-grids, including licencing and tariff setting. Approved in 2017, the KOSAP aims to install mini-grids in 14 remote and under-served counties ('KOSAP Home Page', 2022; World Bank, 2024). By 2022, the project had brought access to electricity through solar home systems to around 500 000 people, and in early 2023 Kenya's energy minister announced that the country was constructing 136 solar mini-grids under the programme ('KOSAP Home Page', 2022; Miriri, 2023).

SUMMARY TABLE: Regulation for mini-grids

INNOVATION READINESS LEVEL		LOW — HIGH
BENEFITS	**Affordability**	LOW — HIGH Relevant as a cost-effective electrification strategy in remote areas.
	Energy access	LOW — HIGH Provides electricity access to previously unconnected households
	Power system resilience	LOW — HIGH Improves the reliability of supply in off-grid areas. Electricity imports or export in case of connection to the main grid can also increase the flexibility of the overall power system.
	Energy security	LOW — HIGH Contributes to energy security by fostering the use of local renewable resources.
	Sustainable development	LOW — HIGH Supports productive uses of energy business models.
IMPLEMENTATION	**Implementation cost**	LOW — HIGH Dedicated grid development costs.
	Prerequisites	Multiple authorisation requests can make the procedures for licencing lengthy and inefficient (typically 80 to over 100 weeks), slowing the ramp up of mini-grid construction. Quality assurance procedure in place.
	Stakeholders responsible for implementation	Governments, energy regulatory agency, mini-grid developers.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Ghana, Kenya, Malawi, Nigeria, Rwanda, Tanzania

4.3 Regulation enhancing operational reliability

Electricity supply and demand must be instantaneously balanced, and key physical variables such as voltage and frequency must remain within safe operational margins. Integrating large amounts of VRE increases these challenges and introduces new ones, such as the need for larger reserves and other sources of flexibility.

Strategies for enhancing the reliability of power systems are thus crucial. To be most effective, the strategies should strike the right balance between the amount of reserves and their total cost, determine what ancillary services are needed as levels of VRE increase, set compliance rules for grid connection, and take advantage of the potential contributions of regional integration.

This section focuses on three regulation or market design innovations to enhance the reliability of renewable energy-based power systems in countries: regional integration, innovative ancillary services and grid connection codes.

Innovation 31
REGIONAL INTEGRATION

Connecting electricity systems across national borders brings major benefits. Such regional integration increases flexibility, enhances security and resilience, enables greater integration of VRE, lowers overall costs and increases the customer base. In Europe, the cross-border trade of electricity brings benefits of an estimated EUR 34 billion (USD 35.7 billion) per year (ACER, 2022).

The degree of integration of regional electricity markets can be divided into three levels: bilateral trade, shallow integration and deep integration (IRENA, 2019k). Figure 33 details the amount of interconnectivity, trading arrangements and harmonisation rules that characterise each of these stages.

Establishing regional markets is not mandatory for cross-border interconnections and trade, which could work in a bilateral fashion under PPAs. The existence of a regional market may allow transparency and efficiency of cross-border energy exchange. Establishing regional markets requires adopting a shared regulatory framework and clear governance structure, with new institutions and rules. In practice, this can be challenging, given the tensions between countries' own interests and aspirations for autonomy and the need for mutual dependence in a regional market. In addition, countries that expand their power systems to boost exports could be at risk if other countries decide to reduce their imports, while importers could face uncertain supplies. These risks can be reduced by clear designs, shared governance rules and a gradual roll-out of the integration process to create trust.

FIGURE 33 | Levels of regional power market integration

Integration level	Early stage	Shallow	Deep
Interconnection infrastructure	• Bilateral power trade starts between two countries, with limited volume.	• Interconnected grids link several neighbouring countries. • Regional interconnection is fragmented and often underutilised.	• Most countries in the region are interconnected and participate in trade. • Use of regional infrastructure gradually increases.
Planning and investment co-ordination	• Planning happens at a national level, possibly with specific regional agreements to develop priority infrastructure.	• National investments are some what co-ordinated with an optimised regional investment plan.	• Planning is optimised with a regional perspective. • Harmonised methodologies may be used for national-level planning.
Technical harmonisation	• Simple rules are agreed upon for the operation of the interconnected grids.	• Some harmonisation of regulatory practices and technical & market rules exists (common data acquisition and supervision protocols are in place).	• Harmonised regulations and technical & market rules, including grid codes, exist (interoperable and similar digital technologies and platforms are in place).
Commercial trading and market design	• Long-term bilateral PPAs predominate.	• Short-term markets often supplement long-term PPAs. Transmission pricing spreads costs evenly across all users.	• Regional markets are fully competitive, cost-reflective and offer various products. • Transmission pricing evolves to be more granular.
Institutional architecture	• Bilateral agreements are popular, with no strong supranational entity involved.	• Regional regulatory bodies and/or steering committees are in place but face enforcement challenges.	• Enforceability of regional regulatory bodies and/or steering committees is at an extended level.
Examples	**Greater Mekong Subregion LTMS-PIP**	**SAPP, WAPP, EAPP, MER**	**EU Internal Market, WEIM**

Source: (IRENA, 2019k).

Notes: EAPP = Eastern Africa Power Pool; LTMS- PIP = Lao PDR-Thailand-Singapore Power Integration Project; PPA = power purchase agreement; SAPP = Southern African Power Pool; WAPP = Western African Power Pool; WEIM = Western Energy Market (USA).

It is only through the participation and co-ordination of all stakeholders, at both the national and regional levels, that the full benefits of cross-border power trading can be achieved. Several enabling factors form the pre-conditions for successful regional interconnection initiatives:

- **Strong political will to co-operate:** Inter-governmental agreements and co-ordinated political leadership are necessary to facilitate strong regional integration, for instance through regional economic communities.
- **Sound cross-border trading rules and transmission regulation:** Utilities have a crucial role in ensuring that the technical aspects of these rules do not compromise the delivery of secure, reliable and affordable electricity to consumers. Harmonising these rules can take several iterations to progressively reach higher levels of integration.
- **Regional institutions with clear and significant executive power:** Often, regional institutional design takes longer to formulate than the technical aspects of interconnection (*e.g.* hard infrastructure, grid codes), as it can be political. Designing regional institutions from the beginning of a project enables faster implementation of co-ordinated action (RETA, 2023).

Regional market integration and the future African Single Electricity Market

The power sector in Africa is structured around four regional markets: the WAPP in West Africa, the EAPP in Eastern Africa, the COMELEC in Northern Africa, and the SAPP in Southern Africa.[6] All but the SAPP are at the early stage of integration (Table 4) (IRENA, 2019k).

TABLE 4 | Comparative status of power market development in the regional power pools in Africa

Implementation progress	WAPP	CAPP	SAPP	EAPP
Recently updated regional master plan	✓		✓	✓
Completed market design	✓		✓	
Bilateral transactions already taking place		✓	✓	✓
Active day ahead market			✓	
Active long-term contracts market			✓	
Approved regional interconnection code and compliance programme	✓		✓	✓
Wheeling fee arrangement agreed upon by all member states	✓		✓	
Approved mechanism for calculating tariffs and wheeling fees	✓		✓	
Completed regional control centre			✓	
Existence of a regional database	✓	✓	✓	✓
Existence of a regional market operator				
Existence of an independent regional regulator with supranational authority	✓			
Existence of a monitoring and evaluation unit	✓			
Existence of a dispute resolution mechanism	✓			✓
Existence of a regional court for adjudication				

Source (AfDB, 2021a).

To increase energy access and unlock the renewable energy potential on the continent, the African Union has developed ambitious plans for creating an African Single Electricity Market (AfSem) by 2040, which were officially adopted in September 2023 (Delegation of the European Union to the African Union, 2023). The strategic plan calls for a harmonised regulatory framework, which would include establishing strong and financially independent regulators; harmonising tariffs; defining and applying grid codes and technical standards for renewable energy interconnections; setting models and rules for electricity contracts trades, such as PPAs; setting energy efficiency standards; and developing a sound governance structure. The plan is estimated to cost more than USD 1 trillion (Larkin, 2024).

[6] *WAPP = West African Power Pool, EAPP = Eastern Africa Power Pool, COMELEC = Maghreb Electricity Committee, SAPP = Southern African Power Pool.*

Regional electric system interconnecting Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama

The first regional effort in Latin America and the Caribbean is the interconnection of six Central American countries through the Regional Transmission Grid (Red de Transmisión Regional, RTR). Along with the physical interconnection of the individual power systems, a regional market (Mercado Eléctrico Regional, MER) was established, governed by CRIE (Comisión Regional de Interconexion Eléctrica) as the regional regulator. The operation of each electric system and the corresponding market is performed by the respective national system operator (system operator and market operator). Each of the six countries is a balancing area. However, the regional operator entity is in charge of supervising and co-ordinating all of the operators in the region and establishing minimum technical requirements to be fulfilled (Hernandez, 2021). Furthermore, the regional operator oversees any exchanges among the systems, such as those for power plants that sell to consumers in different systems, and verifies that each country has enough reserves to comply with regional performance indices.

This regional co-ordination facilitates the incorporation of large amounts of renewable energy by capitalising on different VRE resources and demand profiles in different countries. The region's dependence on hydropower has led to concerns about energy security, especially given recent extreme droughts that resulted in electricity shortages. The creation of SIEPAC (Sistema de Interconexión Eléctrica de los Países de América Central, or Central American Electrical Interconnection System), along with a higher penetration of renewable power, helped Central American countries to cope with droughts without any rationing of electricity (IRENA, 2019k).

Gianfranco Vivi © Shutterstock.com

SUMMARY TABLE: Regional integration

INNOVATION READINESS LEVEL		Initiated but remains at an earlier or intermediate (shallow stage) level of integration.
BENEFITS	**Affordability**	Provides access to the most cost-effective resource with a larger geographic scope.
	Energy access	Indirectly through the availability of more power but does not primarily target unconnected populations.
	Power system resilience	Increases power system resilience by allowing mutual support and optimised use of existing plants, reserves and storage capacities.
	Energy security	Contributes by enabling access to low-cost renewable resources.
	Sustainable development	Supports the penetration of renewables by connecting resource-rich countries to important load centres. The new institutions can promote the adoption of regional renewable energy targets.
IMPLEMENTATION	**Implementation cost**	New institution, human capital, and capacity building, harmonisation costs.
	Prerequisites	Requires strong and lasting political support for effective implementation over a long period. Requires well-functioning legal system.
	Stakeholders responsible for implementation	Governments, energy regulatory agencies, transmission and distribution system operators, regional economic communities.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Several regional power pools in Africa, African Single Electricity Market, Central America Regional Electricity Market

Innovation 32

INNOVATIVE ANCILLARY SERVICES

Power systems need to maintain stable frequency and voltage. Traditionally, centralised thermal and hydropower plants accomplish this through the inertia of their large rotating generators and their ability to accelerate or decelerate instantaneously to correct any sudden imbalance.

However, inverter-based resources (IBRs) – such as solar PV, wind and battery storage systems – connect to the grid through power electronics rather than rotating machinery. While they do not inherently provide mechanical inertia, they can be controlled to deliver new grid services with response times ranging from less than a second (for automatic primary frequency regulation) to more than 15 minutes (for activating reserves) (IRENA, 2020d). These include fast frequency response, synthetic inertia and grid-forming capabilities that can replicate or even exceed the stabilising functions of conventional generators.

As power systems evolve towards high shares of IBRs, the definition and procurement of ancillary services require a fundamental transformation. Market structures – particularly in many emerging markets and developing economies – must move beyond traditional synchronous generator paradigms to explicitly recognise and compensate these new capabilities. Without this shift, critical grid stability services will remain under-valued and under-deployed, potentially constraining the integration of renewable energy at scale.

Figure 34 shows innovative ancillary services and new participants providing these services. These services can be mandated in the grid code, or they can be bought as independent services on the market, when in place. In either case, broadening the range of actors that are allowed to provide such services is key. Tapping the high potential for solar and wind will require updated regulations and appropriate designs that reward grid stability.

FIGURE 34 | Typology of innovative ancillary services

INCREASED FLEXIBILITY THROUGH INNOVATIVE ANCILLARY SERVICE MARKETS

NEW ANCILLARY SERVICES	• Ramping products • Fast frequency response by batteries
NEW MARKET PARTICIPANTS PROVIDING ANCILLARY SERVICES	• Wind turbines providing interial response • Solar PV and utility-scale storage providing voltage support • Distributed energy resources (DERs) providing frequency and voltage control

Source: (IRENA, 2020d).

India's reform of ancillary service provision to help meet its renewable power ambitions

In the 1990s, India consolidated its multiple state grids into five regional grids, which were then integrated in one national grid. Ancillary services were provided, with primary reserves coming from centralised thermal plants and secondary and tertiary reserves coming from a smaller set of plants functioning at partial loads. However, evaluations showed that the system could not ramp up quickly in periods of high demand and did not easily allow integration of higher amounts of VRE. To address these limitations, India published a draft regulation for ancillary service provision in 2021 (CERC, 2018, 2021) . Its ideas include: a mandate to explicitly quantify the amount of services needed, and provisions for regulated procurement of secondary reserves; drawing upon a broader range of actors, including more generation plants, storage and demand side services; and setting ramping requirements.

SUMMARY TABLE: Innovative ancillary services

INNOVATION READINESS LEVEL		LOW — HIGH Stage 1 to 2 in a developing context but stage 3 to 4 in more advanced economies.
BENEFITS	**Affordability**	LOW — HIGH Reduces the high economic losses due to blackouts.
	Energy access	LOW — HIGH An unreliable power system leads to more unmet demand even in connected grid areas.
	Power system resilience	LOW — HIGH Provides more options to ensure the resilience of the power system.
	Energy security	LOW — HIGH A reliable system is also beneficial in terms of energy security.
	Sustainable development	LOW — HIGH Supports a wider adoption of VRE by ensuring a reliable and safe operation of the power system even with high shares of renewables.
IMPLEMENTATION	**Implementation cost**	LOW — HIGH Requires a strong data acquisition and communication infrastructure as well as automatic controls on several plants and grid devices.
	Prerequisites	Requires an independent regulator and clear technical guidelines. Requires clear and attractive financial compensation schemes for the providers of ancillary services.
	Stakeholders responsible for implementation	Governments, energy regulatory agencies, dispatch centres, distribution system operators.
JURISDICTIONS WHERE IT IS IMPLEMENTED		China, India, South Africa

Innovation 33
GRID CONNECTION CODES

Integrating large amounts of VRE sources into power systems requires better monitoring, controllability and technical co-ordination of the many different actors and assets. That co-ordination, in turn, requires establishing grid codes, which define the technical regulations and behaviour for all active participants in the power system (IRENA, 2022c).

The three main categories of grid codes are market codes, operation codes and connection codes. Market codes cover electricity balancing, capacity allocation and congestion management; operation codes cover system operation (including responding to emergencies); and connection codes set requirements for connecting both generators and loads. These codes should be tailored to what is both technically necessary and economically viable, and should be updated as new technologies, such as digitalisation, are adopted. Figure 35 shows how connection requirements will depend on the level of VRE integration and on the size and characteristics of the power system, which vary considerably among countries.

FIGURE 35 | Grid connection requirements depending on the level of VRE integration and the characteristics of the power system

VRE integration	SMALL SYSTEM	MEDIUM SYSTEM	LARGE SYSTEM
HIGH	• Storage facility integration • Full frequency and voltage control capabilities • Grid-forming and black-start services from storage	• Grid-forming inverters for stability issues in regions without hydropower • Frequency control and active power control performance suitable for AGC integration required	• Grid-forming services and black-start functionality to be provided by new assets connected to high-voltage levels (*e.g.* VRE power plants or large-scale storage)
STEPPING UP	• LFSM-U and active power control performance suitable for AGC integration • Requirements for enabling technologies (*e.g.* storage)	• FRT capability and active power control requirement extends to new low-voltage connections • Requirements for enabling technologies (*e.g.* storage)	• FRT capability and active power controllability required for low-voltage connections • New requirements for larger facilities • Requirements for enabling technologies (*e.g.* storage)
STARTING	• Assets must withstand wider frequency and voltage range • Need for controllability and FRT capabilities (including small DER)	• Requirements must align with the state of the art, standards and rules of the VRE industry • Power quality, protection, suitable frequency operating ranges, and LFSM-O must apply to all newly connected VRE facilities and enabling technologies • For medium-voltage connections, requirements for power remote control and FRT are needed, but are not yet crucial for low voltage connections	

Source: (IRENA Coalition for Action, 2020).

Notes: AGC: Automatic generation control; DER: Distributed energy resources; FRT: Fault ride through; LFSM-O: Limited frequency sensitive mode for overfrequency; LFSM-U: Limited frequency sensitive mode for underfrequency; VRE: Variable renewable energy.

Updated grid codes harmonise renewable energy requirements in Central America

Six countries[7] are connected in the Central American Regional Transmission Grid (RTR), which has a set of technical and market rules called the RMER (Reglamento del Mercado Eléctrico Regional). Prior to 2018, the RMER only established requirements for conventional synchronous generators, while each country maintained its own regulations for VRE. Recognising that the absence of harmonised grid codes for renewable generation was hindering development, the regional regulator, CRIE (Comisión Regional de Interconexión Eléctrica), updated the RMER in 2018 to introduce minimum requirements for VRE generators above 5 MW.

SUMMARY TABLE: Grid connection codes

INNOVATION READINESS LEVEL		LOW HIGH Less advanced countries up to 4 in countries with a well-structured power sector.
BENEFITS	Affordability	LOW HIGH Facilitates the connection of low-cost renewable electricity to the grid.
	Energy access	LOW HIGH Creates the conditions for higher power quality for consumers.
	Power system resilience	LOW HIGH Setting transparent minimum technical requirements for connected generation plants supports the safe and reliable operation of the power system.
	Energy security	LOW HIGH Contributes to a secure and uninterrupted power supply.
	Sustainable development	LOW HIGH Clear regulatory requirements will support the deployment of renewable energy sources and reduce adoption barriers associated with a fear of more frequent outages.
IMPLEMENTATION	Implementation cost	LOW HIGH Requires technical consultations, skilled personnel and capacity building.
	Prerequisites	Establishment of a grid code definition process. Explicit plans for regular updates of already defined grid codes can create adoption barriers and limit innovations.
	Stakeholders responsible for implementation	Governments, energy regulatory agency, transmission and distribution system operators, developers of generation options.
JURISDICTIONS WHERE IT IS IMPLEMENTED		India, Kenya, Nigeria, South Africa, Central American countries

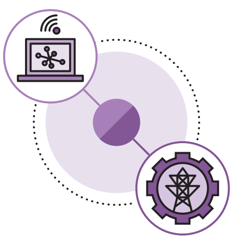
[7] *Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama.*

05 SYSTEM PLANNING AND OPERATION

While advances in renewable technologies, supportive regulations, and innovative business models are critical for accelerating the energy transition, they must be complemented by equally important innovations in power system operation and planning. In power systems with weak grids and large energy access deficits, integrating VRE requires smarter ways of managing and expanding the system.

This section proposes innovative ways to enhance the grid infrastructure with non-wire alternatives, as well as innovations for strategic planning suitable for systems with weak grids and energy access deficit (Figure 36).

FIGURE 36 | Innovations in system planning and operation



SYSTEM PLANNING AND OPERATION

Grid-enhancing innovations	**34** Storage as virtual power lines
	35 Dynamic line rating
	36 Installing innovative compensation devices on the grid
	37 Enhanced forecasting of variable renewable generation
Strategic planning	**38** Electricity losses reduction
	39 Planning for harmonised grid and off-grid developments
	40 Planning for regional interconnections

5.1 Grid-enhancing innovations

Grids are being termed as the new bottleneck in the energy transition and as one of the barriers to the integration of high shares of renewable energy. Current grids increasingly suffer from congestion, often causing curtailment of wind or solar power due to bottlenecks.

The timeline for constructing grid assets such as overhead transmission lines, in developed economies, averages around three years, with planning and permitting for the same taking up to seven years. Payback period for transmission assets vary from 20 to 40 years (IEA, 2023a; LaRiviere and Lyu, 2022). This could be exacerbated with supply chain issues delaying it further. And often, when finally constructed, the grid updates become quickly insufficient due to constantly increasing demand.

The expansion of transmission assets is impeded by lack of clarity on cost allocation, community and environmental concerns, and competitive generators. With higher shares of renewables and increasing electricity demand, there is a need reinforce existing grids, in addition to expanding and building new ones.

Transmission systems have significant untapped potential, which can be unlocked with relatively inexpensive technologies. For example, advanced power flow control technology can reroute electricity in milliseconds to bypass congested circuits, while dynamic line rating (DLR) devices monitor transmission lines to figure out when those lines can handle more current than they are normally rated to carry (Carey, 2024). These approaches can make it possible to defer costly infrastructure investments, improve system reliability, integrate more VRE, and reduce power cuts and blackouts. The following sub-sections focus on four of those innovations: storage as virtual power lines, dynamic line rating, compensation devices and enhanced forecasting of VRE.

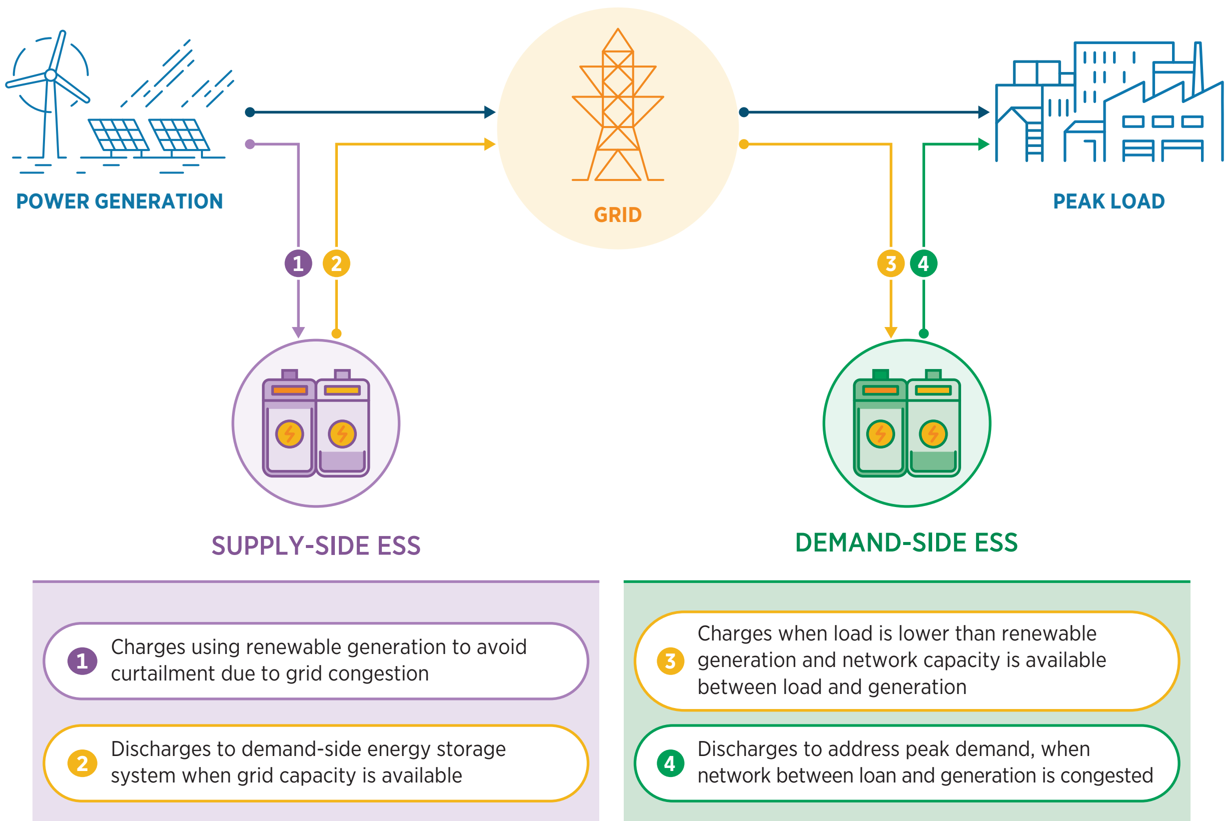
Innovation 34
STORAGE AS VIRTUAL POWER LINES

The virtual power line (VPL) concept uses two storage systems, one on each end of an existing transmission line that connects renewable generation to consumers. When the wind or solar facilities produce more electricity than the transmission line can handle, the excess power is absorbed by the upstream battery. When the renewable electricity generation drops below the line's capacity, the battery can discharge power into the line. Similarly, the demand-side battery charges up when demand is low, then supplies power when demand rises above the capacity of the transmission line (Figure 37).

Virtual power lines can be installed very quickly and are scalable. In regions with mini-grids, VPLs can even be constructed using the batteries already deployed in the mini-grids, driving down costs.

In addition to reducing congestion and curtailment, the batteries also provide additional services, such as frequency or voltage regulation, improved reliability and ability to meet higher peak loads (Kumaraswamy *et al.*, n.d.). They do, however, require higher levels of digitalisation and clear regulations on the use and ownership of the storage systems used in the VPLs.

FIGURE 37 | The virtual power line concept



Source: (IRENA, 2022a).
Note: ESS = energy storage system.

Virtual power lines proposed in Chile

Chile has ambitious plans to phase out coal plants and dramatically increase renewable generation. However, the best solar resources are located in the Chilean desert, thousands of kilometres north of the country's dense urban centres.[8] Expanding renewable generation could thus exceed the capacity of the existing grid infrastructure, which stretches around 4 300 kilometres from north to south across four interconnected power grids.[9] As a result, Chile has proposed building a virtual power line using two 200 MW utility scale storage facilities, which could allow adding 700 MW of renewable electricity (Atlas Renewable Energy, 2024; Kumaraswamy *et al.*, n.d.).

SUMMARY TABLE: Storage as virtual power lines

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	Affordability	LOW – HIGH Increases the use of low-cost renewables, is less costly than grid extension and reduces congestion costs. However, needs two storages and a more advanced data acquisition system.
	Energy access	LOW – HIGH Less congestion and better demand satisfaction on the demand side.
	Power system resilience	LOW – HIGH Allows for more flexibility.
	Energy security	LOW – HIGH The two storages increase the security of supply.
	Sustainable development	LOW – HIGH Allows more green electricity.
IMPLEMENTATION	Implementation cost	LOW – HIGH Mainly determined by cost of the storage and management system.
	Prerequisites	Regulation for an appropriate remuneration and to specify if the storages are under the control of the distribution or transmission grid operators. Grid code adaptation to specify storages as transmission assets. Support from policy makers is important to allow pilot projects.
	Stakeholders responsible for implementation	Transmission and distribution systems operators, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Chile, China, India

[8] *Sistema Interconectado Central (SIC).*

[9] *Sistema Interconectado del Norte Grande (SING).*

Innovation 35

DYNAMIC LINE RATING

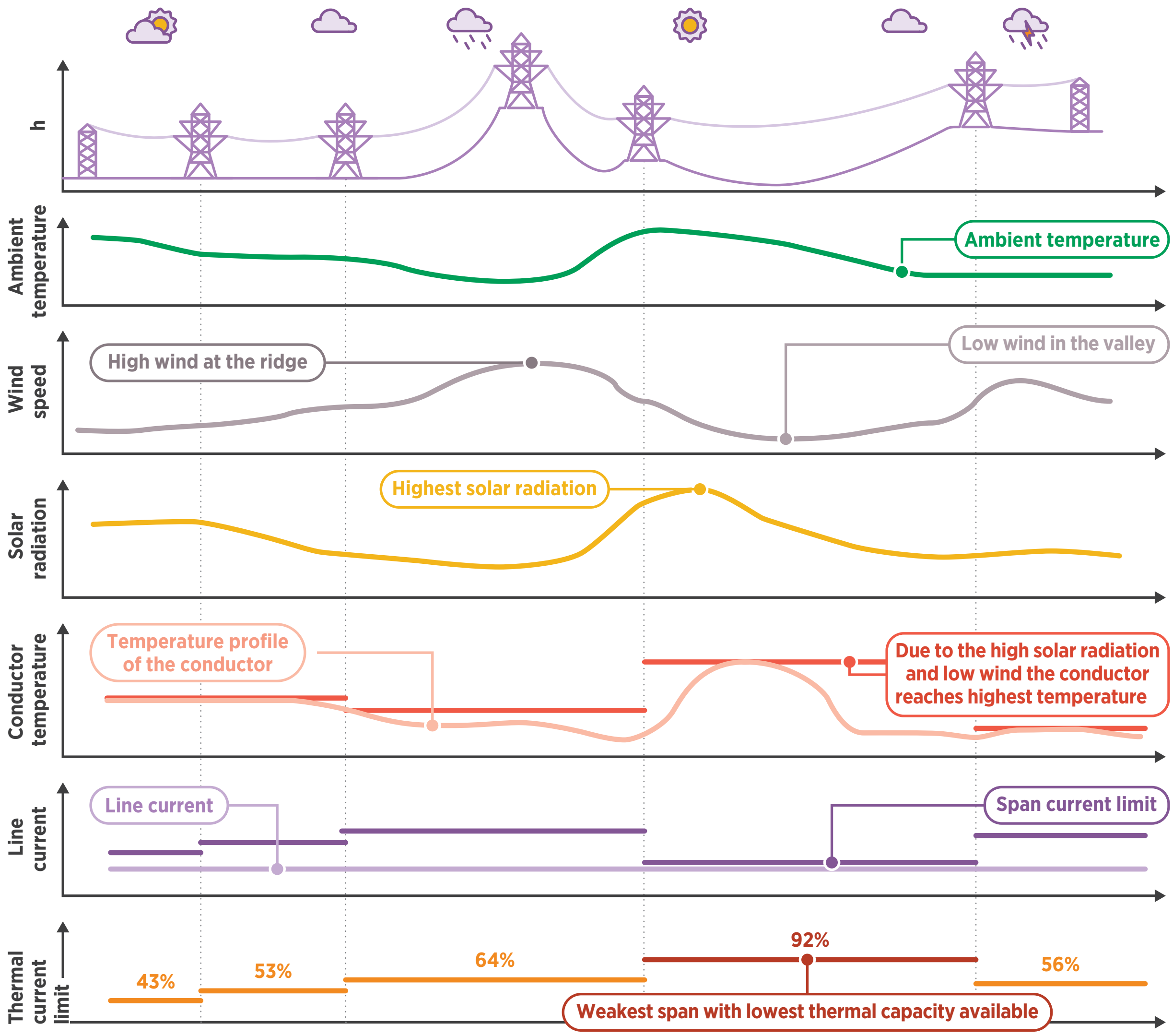
The two options to reinforce grids are to either increase the current or increase the voltage. Increasing the voltage requires additional equipment, which comes at a cost. The current-carrying capacity of a transmission line is also called ampacity, and transmission lines are rated to carry a specific amount of current. Carrying current beyond a line's design limit can cause sagging and safety issues for overhead lines and permanent damage to the insulation of underground lines. Traditionally, this rating is "static"; it does not change with weather conditions (although it could vary slightly with the season in the case of overhead lines).

However, the actual safe capacity of a transmission line can vary greatly depending on the amount of cooling or heating from wind, temperature, precipitation, solar radiation and other weather conditions. High temperatures during heat waves, for example, can reduce a line's current-carrying capacity through reduced thermal ratings. Dynamic line rating (DLR) is a system that can improve the flexibility and integration of renewables through monitoring and modifying the current-carrying capacity of transmission lines based on real-time weather conditions (Figure 38). The two types of DLR are Ambient-Adjusted (DLR-AA) and Real Time Monitoring (DLR-RTM). The difference lies in considering only or both real-time variations in ambient temperature, and effective perpendicular wind speed in the transmission line.

The DLR is installed at different parts of the system and uses sensors to measure real-time data on conductors and the weather. It uses these data to evaluate line temperatures or the amount of sagging, and calculates when the line – or even each segment of the line – can carry more power than its static rating would allow (IRENA, 2020e). DLR has been shown to increase the capacity of existing transmission lines by 30% in the line's current by transmission system operators in Europe. It is particularly beneficial for transmission lines that carry power from wind facilities because higher wind speeds provide more cooling, and thus more capacity, at the same time as they increase VRE generation (IRENA, 2020f).

With reliable hours-ahead to days-ahead forecasting, DLR can provide the emergency rating for all remaining in-service lines, thereby contributing to system planning. It can enhance grid resilience in addition to grid optimisation and therefore enhance grid capacity.

FIGURE 38 | Principle of dynamic line rating and influencing factors



Source: (IRENA, 2020f).

Implementing DLR requires a strong communication and monitoring system and supportive regulations.

Dynamic line rating in Malaysia increases capacity by 10% to 50%

Malaysia's largest power utility, Tenaga Nasional Berhad, tested DLR using sensors and a communications system on a critical 27-kilometre-long transmission line (Aziz *et al.*, 2020). The DLR was 10% to 50% higher than the conventional static rating. The pilot project aims to provide benchmarks for future implementation and offers a model for other developing countries.

SUMMARY TABLE: Dynamic line rating

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	Affordability	LOW – HIGH Avoids new investments in transmission capacity by increasing the usage rate of the existing lines.
	Energy access	LOW – HIGH Contributes to less congestion and better transmission and distribution of the amount of electricity generated.
	Power system resilience	LOW – HIGH More flexibility in the power flows through dedicated lines.
	Energy security	LOW – HIGH Reduces line tripping due to excess current.
	Sustainable development	LOW – HIGH Especially favourable to wind power integration.
IMPLEMENTATION	Implementation cost	LOW – HIGH No large infrastructure needed.
	Prerequisites	Regulation needed to authorise changes to existing transmission line rating procedures to allow DLR. Networks of reliable real-time sensors, high-resolution meteorological data and advanced analytical capabilities.
	Stakeholders responsible for implementation	Transmission system operator, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		China, India, Malaysia, Viet Nam

Innovation 36

INSTALLING INNOVATIVE COMPENSATION DEVICES ON THE GRID

Traditional thermal or hydro power plants use spinning turbines to generate AC electricity. These so-called synchronous generators have inherent real-time inertia and provide strong regulation of both voltage and frequency. In contrast, solar PV produces DC current (which must be converted to AC using devices called inverters), while individual wind turbines produce variable AC current. As a result, both need so-called compensation devices to match their output with the voltage and frequency of the grid and to provide reactive power support. Here are some of the innovative options:

- **Flexible AC transmission systems (FACTS) devices** can help achieve precise and quicker voltage support by reducing the need for reactive power. One such device is the STATic synchronous COMpensator (STATCOM). Using voltage source converters, STATCOMS are able to absorb or supply reactive current to regulate voltage (ENTSO-E, 2022). They can maintain voltage during faults and dampen power frequency oscillations.
- **Synchronous condensers** are similar to conventional generators but use electricity to create a spinning inertial reserve of few seconds in case of fault (Hong *et al.*, 2021; Igbinovia *et al.*, 2018; Jayasinghe and Bahrani, 2021). They function like a motor with no load, helping to regulate voltage and provide stability.
- **Fast-acting devices** can provide quick frequency responses (FFR) by actively injecting power and reducing load in low-inertia systems. Both battery storage and pumped hydropower can provide this fast response. Some solar and wind generators can also provide fast frequency response for short periods.
- **Advanced grid and power flow controllers** rely on fine-tuning the control of the power flows within grid lines. So-called unified power flow controllers can control the active and reactive power exchange to keep voltage within limits and also reduce transmission line congestion, for example (Gevorgian *et al.*, 2021). By injecting voltage into selected parts of the grid, they can re-route power flows over the grid to bypass congested lines, increasing overall grid capacity. Another type of device is the grid-forming inverter, which synchronises the electricity from inverter-based resources, such as wind and solar, with the grid by digitally emulating synchronous generators (Li *et al.*, 2022).

These devices are still largely in the research stage. But developing countries could play an important role by testing them in pilot projects as the countries rapidly add renewable generation capacity, potentially leapfrogging legacy power systems in developed countries.

STATCOM for renewable energy inclusion in Chinese Taipei

A ±200 Mvar STATCOM system along with associated transformer solution is being installed in Chinese Taipei, at the 161 kV transmission level, to improve the share of renewables and to enhance overall grid stability of the country's grid (Latief, 2024).

STATCOM supports wind power installation in South Africa

Synchronous compensators have been installed at several wind farms in South Africa. Results from field tests and actual fault events (Ghorai *et al.*, n.d.) show that the devices do help provide effective voltage and reactive current control. The market for these STATCOM devices in South Africa is small today, but it could be unlocked with regulatory reforms, grid modernisation programmes and grid codes to enable VRE development.

South Africa is also planning to introduce 11 synchronous condensers – four of them from re-purposed synchronous generators to support grid stability with increased shares of VRE. This will supply the required dynamic voltage support, inertia and short-circuit current identified as constraints to the inclusion of VRE. The power system operators relied on conducting planning studies with targets for renewable energy, which identified the constraints associated with inclusion of high shares of VRE. The absence of voltage regulation, inertia, and fault identification were identified as major issues from simulation studies pre-empting the installation of synchronous condensers (Creamer, 2023).

SUMMARY TABLE: Installing innovative compensation devices on the grid

INNOVATION READINESS LEVEL		LOW — HIGH
BENEFITS	Affordability	LOW — HIGH Does not directly address affordability but can reduce the cost of ancillary services.
	Energy access	LOW — HIGH Indirectly through more secured ancillary services provision.
	Power system resilience	LOW — HIGH Contribute to provision of sufficient reactive power.
	Energy security	LOW — HIGH Reduces risks of blackouts.
	Sustainable development	LOW — HIGH Enables higher integration of VRE sources.
IMPLEMENTATION	Implementation cost	LOW — HIGH No large infrastructure needed.
	Prerequisites	Implementation will be motivated by regulations, as they specify the required level of system services.
	Stakeholders responsible for implementation	Transmission system operator, energy regulatory agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Ghana, India, Kenya, Mexico, South Africa

Innovation 37

ENHANCED FORECASTING OF VARIABLE RENEWABLE GENERATION

Accurately forecasting how much electricity will be produced by renewable generation facilities hours or days ahead brings numerous benefits. In the short term, it helps enable system operators to optimally dispatch all available plants to meet expected hourly loads and to increase the stability of the grid. Over periods of days, it improves plant scheduling and helps define commitments required from thermal or storage plants. And over periods of weeks to a year, it helps network operators develop maintenance plans and anticipate possible extreme seasonal variations, in addition to making more optimal decisions about the operations of hydropower and thermal plants. For hydropower, for example, more accurate forecasting enables better basin management.

For private renewable electricity producers, more accurate forecasts enable them to maximise sales of electricity to be delivered an hour or a day ahead while minimising possible penalties for non-compliant delivery. Figure 39 shows many of these benefits.

FIGURE 39 | Benefits of weather forecasting to system operators and renewable generators

BENEFITS OF WEATHER FORECASTING	CENTRALISED FORECASTING For system operators	DECENTRALISED FORECASTING For renewable generators
SHORT-TERM FORECASTING	Improved network management and system balancing	Advantages for intraday and day-ahead electricity market trading
LONG-TERM FORECASTING	Reserve planning and operation management Planning for extreme weather events	Efficient placement of renewable plants

Source: (IRENA, 2020f).

Advanced forecasting of VRE requires a robust supporting infrastructure to provide high-resolution site-specific meteorological data in real time. It also requires Numerical Weather Prediction (NWP) models and electricity generation models to predict the power outputs from solar and wind generation units based on those data. Individual countries could work together to develop the necessary data gathering infrastructures at the regional or continental levels, and better co-ordination between utilities and meteorological departments could enable utilities to take advantage of the forecasts that those departments already provide.

Centralised forecasting of variable renewable generation in India

In 2020, India created 13 dedicated Renewable Energy Management Centres (REMCs) as part of its ambitious decarbonisation agenda (PIB Delhi, 2024). These centres are located next to local dispatch centres and use advanced scheduling and forecasting tools, along with AI, to make 15-minute, day-ahead and week-ahead forecasts (PGC India, 2022). In 2020, they covered a total installed capacity of 55 GW. In the western region of India, where VRE plants account for 24 GW of a total installed capacity of 123 GW, the forecasting system was able to accurately predict decreases in renewable generation from large-scale events, such as a solar eclipse, making it possible to increase generation from hydropower, gas and coal plants to compensate (Ahmad *et al.*, 2021).

SUMMARY TABLE: Enhanced forecasting of variable renewable generation

INNOVATION READINESS LEVEL		LOW HIGH
BENEFITS	Affordability	LOW HIGH Can reduce VRE curtailment, optimise hydropower resources and improve maintenance planning.
	Energy access	LOW HIGH Contributes to anticipating need for storage or back-up solutions.
	Power system resilience	LOW HIGH Positively affects regional access, could negatively impact stability if unchecked. Critical to anticipate and manage periods of low or very high VRE output.
	Energy security	LOW HIGH Reduces intermittency induced risks.
	Sustainable development	LOW HIGH Enables higher VRE market share.
IMPLEMENTATION	Implementation cost	LOW HIGH No large infrastructure needed.
	Prerequisites	Establishing regional meteorological offices or securing access to high-quality data. Proper market design is needed to identify the value of forecasting. Low number of weather stations in Africa.
	Stakeholders responsible for implementation	Transmission and distribution systems operators, weather forecaster, climate service developers.
JURISDICTIONS WHERE IT IS IMPLEMENTED		China, India, Morocco, South Africa

5.2 Strategic planning

The power sector includes a wide mix of technologies and very long time horizons. Many decisions made now – such as grid extensions, changes in system operations and expansions of renewable generation – will greatly affect the development of the sector, the success of countries in meeting their electricity access and decarbonisation goals, and the profitability of investments made by project developers. The major uncertainties that exist about those decisions and their effects raise substantial risks for project developers, who are seeking the most cost-effective and profitable investment options today.

These risks and uncertainties can be greatly reduced by establishing strategic long-term plans, which will help all stakeholders make better decisions. This is especially true for countries with increasing demand, as they expand their power systems and implement diverse sets of policies to support renewable energy deployment.

Developing a roadmap with long-term renewable energy targets and pathways, as well as establishing a clear regulatory framework, are key to ensure consistent policy direction, signal opportunities for local value creation, and provide predictability for investors, suppliers, developers and all other players. This roadmap should focus on strategic technologies for the country, based on a careful assessment of local natural resources, local value creation and the existing industry's capacity to adapt to evolving demand.

Another important planning element is that, instead of merely aiming for minimal electricity or energy access, roadmaps and demand projections in many countries need to be reformed to intentionally plan for more productive uses. This also means that ministries of energy should broaden their perspective beyond only larger projects to consider the diverse and complex needs across different value chains and local contexts for productive uses of energy (IRENA, 2025a).

The benefits of such strategic plans include making better use of renewable resources, attracting more investments, reducing future needs for capacity by minimising losses, and developing a common vision of the future power sector (Pfeifenberger *et al.*, 2021).

In addition, including climate resilience in power system planning becomes key. Grid modernisation efforts should go hand-in-hand with resilience building – through infrastructure upgrades, protective equipment, climate-proofing design and the integration of decentralised systems such as mini-grids for remote areas (IRENA, 2025a).

The following sub-sections describe three innovative strategic planning solutions: electricity losses reduction, planning for harmonised grid and off-grid developments, and planning for regional interconnections, whether between countries or between multiple sub-national grids.

Innovation 38

ELECTRICITY LOSSES REDUCTION

In all the energy transition pathways, electricity will be used to power increasingly more end uses, such as transport and heating. This major increase in projected electricity demand also raises serious concerns about the amount of electrical energy that could be lost in transmission and distribution systems.

The international acceptable standard for transmission and distribution losses is 10%. African countries have significant losses, with 36 countries having a reported loss range between 11% and 48% (CATF, 2025). In the developing economy of India, the recorded transmission losses varied between 3.96% and 3.30% between 2023 and 2024 (POSOCO Grid Controller of India, 2025), whereas the total transmission and distribution losses were 19% as of 2022 (Central Electricity Authority, 2025). In the developed economy of the European Union, the distribution system losses ranged from 1.95% to 22.63% in 2022, while transmission losses ranged between 0.99% and 3.96% (CEER, 2025).

Only Botswana, Lesotho and Mauritius have losses of 10% or less. In the other 36 countries, transmission and distribution losses ranged from 11% in Swaziland to around 48% in the Central African Republic. African countries' transmission and distribution systems suffer from some of the highest energy losses globally (CATF, 2025).

These losses can be of two types: technical and non-technical. Technical losses are losses in the wires and equipment used for the transmission, transformation and distribution of electricity. They include corona losses, leakage losses, dielectric losses, open circuit losses and impedance losses. Long transmission lines can result in major losses, for example. Other causes are conductors and transformers that are too small, overloading, and poor quality or ageing transformers and other devices.

Non-technical losses (or commercial losses) occur when electricity is consumed but not billed. This can be due to theft using illegal connections, faulty electricity meters or erroneous consumption estimates (Savian *et al.*, 2021). These losses are difficult to measure but are estimated at around USD 80-100 billion per year around the world (Glauner *et al.*, 2018; Hu *et al.*, 2020; Louw and Eng, 2019).

These losses constitute a substantial financial burden for numerous utilities across Africa. Non-technical losses, particularly the non-payment of utility bills by state agencies and municipalities, result in massive and unsustainable utility debts, which hinder the financial viability of energy providers and limit their capacity to invest in infrastructure upgrades or modern technologies. In South Africa, Eskom's financial struggles are attributed in part to unpaid municipal debts, which totalled around USD 4.5 billion as of 2024 (Bloomberg, 2024).

Developing countries need well-defined strategic plans for minimising these losses. To reduce technical losses, effective measures include upgrading transformers and transmission and distribution lines, implementing smart grid technologies, and adding storage in locations that maximise overall system efficiencies. For non-technical losses, plans should include provisions for spotting power theft, identifying and replacing faulty meters, conducting energy audits and creating detailed geographical information system (GIS) maps of the power systems. These steps have the added benefit of facilitating better relationships between utilities and customers, because they enable a better understanding of customer needs (USAID, 2017).

Planned programmes for loss reduction result in improved performance for network operators in Africa

In late 2016, Mozambique's national electricity company, Electricidade de Moçambique (EDM), put in place a long-term strategic plan to make the company financially viable and operationally sustainable. The plan included ten initiatives to reduce losses (estimated at up to 30%), such as creating processes and tools for calculating losses, optimising inspections by field crews, developing procedures for identifying and replacing damaged meters, and evaluating the need for new technologies, equipment and tools (AfDB, 2021b; USAID, 2017). In 2023, EDM began implementing parts of the plan through a contract with France's EDF to improve metering reliability and information about the flows on distribution networks.

In Ghana, the African Development Fund has supported loss reduction efforts by the Electricity Company of Ghana (ECG). Activities have included strengthening the distribution network in the Ashanti East and West regions and strengthening and extending the distribution system in peri-urban and rural areas. The measures have cut transmission and distribution losses from an estimated 23.4% in 2014 to 18.9% in 2018 (Antonanzas *et al.*, 2021).

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SUMMARY TABLE: Electricity losses reduction

INNOVATION READINESS LEVEL		LOW — HIGH
BENEFITS	**Affordability**	LOW — HIGH Reduces perceived levelised costs of transport and distribution.
	Energy access	LOW — HIGH Increases the amount of electricity available for end-use customers.
	Power system resilience	LOW — HIGH Indirectly through the reduction of the amount of supply needed in case of demand imbalances.
	Energy security	LOW — HIGH Improves the supply and demand balancing.
	Sustainable development	LOW — HIGH Reduces primary energy consumption, defers the need for additional capacity, improves the profitability of renewables.
IMPLEMENTATION	**Implementation cost**	LOW — HIGH Meters, communication systems and data treatment.
	Prerequisites	Support from policy makers to overcome the barriers to a transparent accounting of the type of losses. For non-technical losses, a clear legal framework is needed to define liabilities and sanctions.
	Stakeholders responsible for implementation	Transmission and distribution systems operators, energy efficiency agency.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Ghana, India, Liberia, Mozambique, Pakistan

Innovation 39

PLANNING FOR HARMONISED GRID AND OFF-GRID DEVELOPMENTS

Grid extension is achieved by building new power transmission and distribution lines, transformers and other infrastructure to connect remote and under-served users to the main grid. In densely populated urban areas, it is financially viable for utility companies to extend grid lines because the demand for electricity is high and there is varied use of electrical appliances and a large number of connections.

In remote areas and communities that have low electricity demand, on the other hand, the grid extension approach tends to be expensive and unviable. Off-grid energy systems (mini-grid or stand-alone), which operate independently of the main power grid, offer an opportunity to provide energy to remote and unserved communities. The systems typically use fossil fuels, such as in diesel generators, but they can also be powered by renewable energy technologies such as solar, wind, biomass or a hybrid.

Grid extension is the traditional approach that government programmes and funding agencies tend to use in extending electricity access to settlements. Yet grid extension requires large amounts of capital investments and time, both of which slow efforts and pace. The main grid distribution lines must be extended over long distances to reach scattered settlements and, most often, to provide for low power demands. For example, providing a rural household connection through grid expansion costs USD 1100 in Viet Nam and USD 2 300 in Tanzania. The costs are almost half this in urban areas, where it costs USD 570 and USD 600 to USD 1100, respectively, in the same countries (IRENA, 2023e).

The implication is that, often, off-grid renewable-based solutions need lower investments compared to grid-connected ones for extending full electricity access (IRENA, 2017b). Mini-grids powered by solar, hydro and biogas technologies provided electricity access to 11 million people as of 2021. Solar has proven to be the least-cost option, in addition to its ease of deployment and scalability (IEA *et al.*, 2025).

Off-grid systems are an opportunity to provide reliable and affordable electricity to all people to stimulate sustainable economic development. Achieving this sustainable and affordable power system expansion, however, is challenging, as it requires an optimal balance of grid and off-grid development and an integrated planning approach. Moreover, long lead times and long project lifetimes mean that investments made today will heavily influence the future of the power system for decades to come. This is why it is important for countries to develop detailed long-term transition plans, rather than simply reacting to immediate and visible problems (IRENA, 2017b).

Geospatial-based electrification planning tools are proving invaluable in developing these strategic plans. These tools help countries identify cost-effective pathways against which they can plan future deployments of their energy systems. For example, the Global Electrification Platform (GEP) uses the open-source ONSSET (Open Source Spatial Electrification Tool) model to analyse optimal technology solutions across 58 countries, the majority in Africa (ESMAP, 2025).

By integrating GIS, high-resolution remote sensing, and advanced analytical algorithms, these models can assess terrain, population distribution, existing infrastructure, resource availability and demand patterns to determine the least-cost electrification approach for each location. The GEP provides a valuable starting point, which can be further refined by acquiring or creating higher-quality local datasets on which these models can run, enabling increasingly precise and context-specific planning.

An effective strategic electrification plan would assess and balance the relative costs and benefits of expanding the grid versus developing off-grid and mini-grid solutions, using a least-cost approach. It would include risk mitigation mechanisms for priority projects to provide developers with protection against the early arrival of grids. It would cover institutional, regulatory, and financial needs, and could support developers by helping with land acquisitions and business models. It also would forecast supply and demand to reduce the risks of stranded investments. Tools such as IRENA's West Electrification Platform[10] (inspired by the GEP) and IRENA's Global Atlas Initiative exemplify how these geospatial approaches can be operationalised to support evidence-based decision making. Comprehensive integrated national planning would also include clean cooking.

Harmonised grid and off-grid expansion planning is effective not just for national governments, but also for regional power systems that span many countries. For instance, the Power Africa Off-Grid Project (PAOP) supports the development of solar home systems and mini-grids in nine countries: Côte d'Ivoire, Ethiopia, Ghana, Kenya, Niger, Rwanda, Senegal, Somalia and Tanzania.

The decisive role of multi-year grid /off-grid planning in improving energy access in Africa

To increase electricity access, Kenya created a National Electrification Strategy in 2018 to provide a roadmap for the necessary technical and institutional transformations (Ministry of Energy of Kenya, 2018). The plan calls for both grid expansion and off-grid solutions and specifies the investment needs for increasing the density of the grid, for grid expansion, for mini grids and for solar home systems. The results have been impressive, with electricity access rising from 44% in 2015 to nearly 78% in 2020 (Cowling, 2024; IEA, 2023b).

Another success story is Rwanda. Starting in 2008 with its Economic Development and Poverty Reduction Strategy (updated in 2013) and its Electricity Access Rollout Program, the government laid out ambitious and detailed plans to improve electricity access with both grid expansion and off-grid systems (mainly solar home systems). As part of the strategy, Rwanda's Electricity Development Corporation (EDCL) estimated the least-cost off-grid projects, considering the constraints for grid development, network components, terrain and land limitations. To select sites for the off-grid projects, the process identified communities that were too far from the grid for cost-effective connections, but that would receive substantial socio-economic benefits from electrification. The resulting progress has been rapid: households' access to electricity increased from 6% in 2009 to 75% in March 2024 (World Bank, 2024).

[10] *https://accessplanning.irena.org.*

SUMMARY TABLE: Planning for harmonised grid and off-grid developments

Kenya, Namibia, South Africa, master plans in ECOWAS countries		LOW … HIGH
BENEFITS	Affordability	LOW … HIGH
	Energy access	LOW … HIGH Supports the roll-out of the most suitable options to satisfy the demand.
	Power system resilience	LOW … HIGH Can help simulate the impact of future grid topologies on future power flows and ancillary service requirements.
	Energy security	LOW … HIGH Through the identification of potential bottlenecks or the simulation of the behaviour of the system in extreme cases. Can reduce or eliminate the need for fossil fuel imports to supply power.
	Sustainable development	LOW … HIGH Creates a vision and a long-term framework to guide investments in renewable electricity.
IMPLEMENTATION	Implementation cost	LOW … HIGH No costly generation or transmission infrastructures needed.
	Prerequisites	Regulation and grid codes must be updated to define the applicable main-grid/off-grid interaction schemes. Support from policy makers is needed to ensure that information is transparent and shared.
	Stakeholders responsible for implementation	Transmission and distribution systems operators, energy regulatory agencies.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Kenya, Namibia, South Africa, master plans in ECOWAS countries

Innovation 40

PLANNING FOR REGIONAL INTERCONNECTIONS

Interconnections between power grids, either within a single country or between countries, offer important flexibility benefits as well as grid-supporting ancillary services for systems with high shares of renewables. They allow power systems to optimise operations as weather and load varies in different parts of the interconnected region, reducing VRE curtailment and enabling higher integration of renewable generation. Interconnections between power grids can reduce the need for new generation capacity by allowing the sharing of resources and reserves, and contribute to frequency control by enabling a larger pool of rotational inertia to absorb imbalances (IRENA, 2022c; Pfeifenberger *et al.*, 2021).

Careful long-term planning is crucial, since interconnections are infrastructure projects that may take one or two decades to complete. Clear guidelines and incentives set down through environmental, trade and energy policies are crucial for cross-border electricity trading. Significant investment in transmission infrastructure is required and is subject to complex regulatory and political frameworks. In addition, the integration of diverse energy systems and regulatory regimes can present technical and operational challenges. Identifying new generation, transmission upgrades and reinforcement projects is key when planning for regional interconnections. Additionally, regulatory frameworks and market frameworks are required for an efficient and fair functioning of the regional grid. Regional grids also require an efficient regional market. Innovation 31 (Regional integration) discusses examples of successful regional grids with regional markets. Establishing a regional co-ordinating or planning entity and/or a Regional Transmission Operator,[11] is key for a successful regional grid operation.

Overall, regional interconnections and grid codes are closely intertwined, and a comprehensive understanding of both is necessary to effectively plan, design and operate interconnection projects. Careful planning and co-ordination are necessary to ensure that regional interconnections are designed and operated in a way that maximises their benefits and minimises their costs and risks. Planning for an effective framework for regional electricity trading should include regulations, transmission tariffs and grid codes, with a mechanism to enforce these rules and for dispute resolution.

Regional grid codes are clear rules to facilitate co-ordination and co-operation between regulators and system operators. They co-ordinate generating and transmission assets, factoring in the technology choices and operating procedures in each country (governing aspects, protection system settings, voltage levels, real-time monitoring and communication, frequency settings, transmission transfer capacity, voltage regulation, *etc.*). Planning for the system also needs to ensure sufficient operating reserves, covering all foreseeable operating conditions in the power system, and to include frameworks for future sharing of information, power exchange scheduling, co-ordinating maintenance, emergency operations and power system restoration.

[11] *Inspired by the US case: www.ferc.gov/power-sales-and-markets/rtos-and-isos.*

In addition to the technical aspects of planning for regional interconnections, it is paramount to overcome geopolitical complexities, deep-seated sovereignty concerns, historical mistrust and other such challenges. Establishing genuinely equitable cost-benefit sharing and robust, independent governance mechanisms is key to avoid interconnection projects being either unrealised or sub-optimally beneficial for less powerful partner states. The technical aspects of planning are often secondary to these overriding political and institutional impediments.

Interconnections in Africa

With the demand for electricity in Africa expected to triple by 2040, significant efforts are under way to form a single electricity market on the continent. This will bring together the five electricity power pools in Africa, physically interconnecting the continent's energy infrastructure. Currently the individual power pools are the Maghreb Electricity Committee (COMELEC), the Southern African Power Pool (SAPP), the Western African Power Pool (WAPP), the Central African Power Pool (CAPP) and the Eastern African Power Pool (EAPP).

The West African region has considerable energy resources, but the major sources of electricity generatio Chapter 2: Technology and infrastructure n are located far from the major consumption centres. The WAPP was created to help solve this problem, as a special institution under the Economic Community of West African States (ECOWAS). The WAPP established a regional market operator and a regional regulator and set down rules for trade between its member countries. It focuses on promoting regional co-operation among African countries to create larger markets and benefit from economies of scale, helping to boost electricity supply in 14 countries and benefiting over 244 million people via more than 4 000 kilometres of 225-330 kV transmission lines. The WAPP's approach, guided by its master plan, supports the development of more efficient and resilient regional electricity markets, which helps reduce electricity supply costs, improves security of supply through the connection of diverse generation resources, and allows for economies of scale, particularly in large-scale hydropower and solar PV development (World Bank, 2025b).

Priority projects are delivering significant impacts. The Côte d'Ivoire, Liberia, Sierra Leone, Guinea (CLSG) project has constructed 1 303 kilometres of lines and is facilitating cross-border electricity trade for around 2.8 million people. The Gambia River Development Organization (OMVG) Interconnection has improved service reliability for more than 2.5 million households and businesses and enabled Guinea-Bissau to transition entirely to hydropower imported from Guinea. The North Core Interconnection, aiming to deliver electricity to 1.2 million new rural beneficiaries, had completed 38.5% of its main transmission line as of October 2024. These efforts are enhancing electricity access, addressing energy challenges and promoting the regional electricity market in West Africa (World Bank, 2025b).

Interconnections in Central America

Another successful example of using regional interconnections to link resource-rich countries with high-demand countries is the Central American Electrical Interconnection System (SIEPAC). It connects the power grids of six Central American countries: Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama (Figure 40). The regional market started operations in 2013. Ten years later, SIEPAC has 1790 kilometres of transmission lines and has invested around USD 505 million with support from the Inter-American Development Bank. In 2018, 4.7% of the total domestic electricity supply of the six countries was traded (IRENA and KEEI, 2021). Power systems in Costa Rica, Guatemala and Panama have mostly sold electricity, while customers in El Salvador, Honduras and Nicaragua have mostly bought electricity. Analysis shows that increasing the level of interconnection from 300 MW to 2 GW could help integrate 9.6 GW of renewable generation and avoid 900 MW of gas-fired plants (IRENA, 2022f).

FIGURE 40 | Overview of the regional electrical interconnection system (SIEPAC) in Central America

Source: (IRENA, 2022f).

Notes: km = kilometre; kV = kilovolts; MW = megawatt; OPGW = Optical Ground Wire.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

SUMMARY TABLE: Planning for regional interconnections

INNOVATION READINESS LEVEL		LOW – HIGH
BENEFITS	Affordability	LOW – HIGH Optimised dispatch of available power plants located in distinct countries to access the lowest-cost resources.
	Energy access	LOW – HIGH Connects resource-rich countries to important load centres in other countries.
	Power system resilience	LOW – HIGH Enables better co-operation and mutualises flexibilities in case of incident.
	Energy security	LOW – HIGH Reduces the intermittency risk by averaging the variability of VRE over large areas.
	Sustainable development	LOW – HIGH Can reduce VRE curtailment or help mobilise large hydropower resources.
IMPLEMENTATION	Implementation cost	LOW – HIGH Interconnections require large-scale and capital-intensive infrastructure.
	Prerequisites	Regulation is needed to specify the condition of operation of the interconnections. Interconnections imply trust and higher mutual dependency. Support from policy makers is important. Upfront investment costs sharing between countries could be a challenge.
	Stakeholders responsible for implementation	Governments, transmission and distribution systems operators, regulatory agencies.
JURISDICTIONS WHERE IT IS IMPLEMENTED		Central African Power Pool (CAPP), East African Power Pool (EAPP), South African Power Pool (SAPP), West African Power Pool (WAPP), Central American SIEPAC

06 RECOMMENDATIONS: STRATEGIC PRIORITIES FOR ENABLING SUSTAINABLE DEVELOPMENT POWERED BY RENEWABLES

Innovation is the driving force of global energy transformation, and its pace is accelerating rapidly. Across countries and sectors, a wide range of innovative solutions are being tested and deployed, reshaping energy systems and expanding their applications. The power sector has led this shift, with remarkable cost reductions in solar and wind technologies and their fast-growing adoption worldwide.

This report introduces a comprehensive innovation toolbox designed to foster sustainable and socially inclusive growth powered by renewables. It highlights how renewables can strengthen resilience, expand energy access and drive local development. However, truly enabling sustainable growth calls for a holistic approach. Policy makers must balance immediate economic needs with long-term sustainability and development goals. The innovation toolbox in this report is designed to help them tailor solutions to local contexts, strengthen power system resilience and expand decentralised, productive uses of renewable energy.

For these solutions to take root and drive sustainable development, policy frameworks must extend beyond simple deployment measures. Action is needed at every level, from multilateral institutions and regional forums to national and local governments. A truly just energy transition also requires addressing equity, inclusion, and fairness, ensuring that the benefits of renewable energy reach all segments of society, especially vulnerable and marginalised groups.

IRENA identifies eight strategic priorities to create an enabling environment for renewable energy that fosters economic growth, supports energy security and drives a just energy transition. These recommended priority actions are intended to support the uptake of the innovations surveyed in this report, while also enabling policy makers to achieve multiple objectives through facilitating innovation in renewably powered energy systems.

STRATEGIC PRIORITIES FOR ENABLING SUSTAINABLE DEVELOPMENT POWERED BY RENEWABLES

1. **Foster comprehensive innovation ecosystems for self-reliance**
2. **Transform financial architecture and investment paradigms to drive sustainable socio-economic development**
3. **Prioritise local value creation and renewable technology transfer**
4. **Promote integrated planning and cross-sector co-operation for inclusive development**
5. **Enable joint strategies via South-South co-operation and regional collaboration**
6. **Reframe the energy transition through narratives that are people- and planet-centric**
7. **Strengthen and modernise electricity grids to provide equitable access to affordable clean energy**
8. **Engage and empower consumers and communities**

1. Foster comprehensive innovation ecosystems for self-reliance

Policy makers should invest in national innovation infrastructure, including skills and education. This means enhancing national innovation capabilities through continuous public investment in research institutions, technical education and local knowledge systems. This is allowing countries to absorb, adapt, and innovate beyond imported technologies, while developing a skilled workforce to lead their energy transitions. This can mean building national institutions to absorb knowledge, then adapting and innovating the technology beyond what is imported.

The limited availability of specialised labour is a significant bottleneck. To address significant skills shortages and labour market misalignments in critical sectors, policy makers should implement policies to develop the essential capabilities needed to support the energy transition and drive local economic growth. This includes addressing limited access to curricula and educational infrastructure. With Global South countries possessing the youngest labour force on the planet, there is immense potential to grow renewable energy jobs, provided there are policies to ensure decent jobs and diverse workforces.

Strengthening local innovation ecosystems reduces dependence on imported knowledge and technology, allowing solutions to be tailored to the country's unique context. Ultimately, this will enable the development of a skilled workforce capable of leading the country's energy transitions and long-term competitiveness. In this way, national institutions are able to support and develop local industries.

2. Transform financial architecture and investment paradigms to drive sustainable socio-economic development

There is a critical need to shift the investment paradigm from profit-driven to impact-driven approaches that value social and environmental outcomes alongside financial returns. Redefining risk to include the failure to achieve the Sustainable Development Goals (SDGs) is essential to ensure that no one is left behind.

In developing economies, this requires scaling up impact-driven investments, such as concessional loans and grants, to complement profit-driven investments. This innovation toolbox maps many innovations that are unable to generate profit-driven returns on investment, but that have immense impact on providing basic human rights and local development. Examples include renewable solutions to power health and education ecosystems, renewables for resilient agriculture and farming systems, *etc.*

Yet global investment flows remain starkly imbalanced. In 2024, energy transition investments reached a record USD 2.4 trillion, but half of the world's population – spread across more than 150 economies and representing a third of global GDP – received only 10% of this financing. Sub-Saharan Africa captured 2.3%, and Latin America captured 5%. Advanced economies attracted 18 times more investment per capita than developing ones (excluding China), deepening geographic disparities and dependence on imported technologies (IRENA, 2025a).

These imbalances are compounded by high capital costs and mounting debt burdens in emerging markets and developing economies, where debt service consumes a large share of government revenues. Limited fiscal space leaves countries unable to invest in domestic supply chains, innovation or renewable energy infrastructure. This creates a vicious cycle of dependence and under-development that undermines progress on energy transition and the SDGs.

Addressing these structural barriers requires rethinking the global financial architecture. Stronger international co-operation will be required to expand the availability of funds and transform aid to developing nations.

Increasing public financial flows for energy transitions in emerging markets and developing economies can be done through multiple channels, such as governments, multilateral and bilateral development financial institutions and global funds. At the same time, reforming the way multilateral development banks support developing economies must continue to emphasise the energy transition as a driver for sustainable socio-economic development.

Addressing these barriers is one of the main enablers to implement many of the innovations identified in the innovation toolbox as key for driving sustainable growth powered by renewables.

3. Prioritise local value creation and renewables technology transfer

The energy transition brings a great opportunity to create value locally and reduce import dependencies on fuels and technologies. Policies should actively support local manufacturing, skills development, job creation, and the localisation of value chains within the renewable energy sector, especially in the Global South, to build economic resilience and decrease dependencies. This demands genuine and equitable technology transfer, moving away from dynamics that reinforce historical economic imbalances.

Creating a skilled workforce to benefit and boost local value chains will also be a critical element to having a reliable and long-lasting local manufacturing capacity, nationally or regionally, and to reduce dependence on imports.

For countries endowed with the critical materials and minerals needed for the energy transition, it is essential to ensure that mining activities are subject to strong environmental and social safeguards. These safeguards must ensure that transition minerals are produced sustainably, produce benefits for local communities, and respect human rights and the environment, while also helping to generate revenues to build sustainable infrastructure and support socio-economic development locally.

In addition, developing the supply chain around domestically processing these minerals can contribute to developing high-value products to be locally used and exported. For example, policies should focus on building value chains for intermediate manufactured products, such as green steel, which provides much greater added value to the domestic economy compared to just exporting raw materials.

Moreover, having local manufacturing capacity can enable the adaptation of renewable technologies to local needs, fostering innovation that addresses region-specific challenges. This is a way to promote indigenous solutions and not rely entirely on solutions and models imported from other economies.

4. Promote integrated planning and cross-sectoral co-operation for inclusive development

To accelerate a just and resilient energy transition, it is essential to enhance cross-ministerial co-ordination and to foster collaboration among energy planners and demand-intensive sectors such as transport, agriculture, and industry, ensuring integrated and holistic planning approaches. At the same time, institutional capacity for participatory planning must be strengthened so that stakeholders can engage meaningfully from the earliest stages and throughout the process. Prioritising early stakeholder engagement, particularly with communities and end users, helps uncover real energy needs, supports co-design of systems, and ensures that diverse perspectives are reflected in policy decisions.

Finally, placing greater emphasis on demand-side planning, through measures such as identifying and addressing infrastructure gaps, can serve as a key driver of the energy transition, enabling faster market transformation and building long-term system resilience. In addition, instead of merely aiming for minimal electricity or energy access, policies in many countries need to be reformed to intentionally plan for more productive uses. This also means that ministries of energy should broaden their perspective beyond the consideration of larger projects to consider the diverse and complex needs for productive uses of energy that exist across different value chains and local contexts.

Enhancing cross-ministerial co-ordination, such as between departments of energy, agriculture, and industry, enables integrated planning approaches for electricity demand and its productive uses.

Policy makers are also responsible for establishing stable policies that build trust between ministries and the business community, which is key to supporting productive uses of energy projects. Better co-ordination among support partners, such as donors and international agencies, can also reduce overlapping efforts for ministries.

5. Enable joint strategies via South-South co-operation and regional collaboration

South-South co-operation refers to the collaboration among developing economies, mainly in the Global South, to share knowledge, skills, resources, and expertise, best practices and lessons learned. This form of co-operation relies on the fact that developing countries often face similar specific challenges and have specific needs, such as financial support or technology transfer for a just energy transition. This form of co-operation aims to foster mutual benefits and support self-reliance among these countries, reducing dependency on traditional aid models from developed nations.

Moreover, and more specifically, regional collaboration is key, harnessing the possibility of co-operation on joint generation or transmission projects and physically trading electricity, in addition to experience sharing. Regional power pool arrangements can allow countries to trade renewable electricity and take advantage of complementary resources.

Implementing regional, joint industrial policies to leverage shared resources and create economies of scale can enable building of sustainable, homegrown solutions for renewable energy sectors across the Global South.

Trade agreements at the regional level can further enhance regional development by enabling specialisation and resource optimisation – for example, one country focusing on the production of a specific energy component while others import it. Such co-ordinated industrial strategies can enable the creation of regional supply chains providing the economies of scale needed to improve cost efficiency, drive innovation and ultimately accelerate the energy transition in the region together with sustainable growth.

Harmonising technical standards and regulations within regions leads to economies of scale for manufacturers and to lower entry barriers for project developers, fostering a more integrated and efficient energy market.

6. Reframe the energy transition through narratives that are people- and planet-centric

Narrative change is crucial because it shapes public perception, policy priorities and investment flows. Powerful narratives connect the transition to what matters in people's lives: reliable and affordable energy, local jobs, healthier communities and the preservation of ecosystems that sustain all life. These narratives must honour diverse worldviews, integrating contemporary sustainability frameworks with indigenous knowledge systems that have long recognised the inter-dependence of human and ecological well-being.

For the energy transition to be successful, it also needs to be understood to contribute to countries' own priorities, visions, needs and local growth. Beyond reducing emissions, the energy transition presents an opportunity to strengthen economic resilience, improve energy security and affordability, and enhance socio-economic benefits (including public health, education, agriculture, *etc.*).

To drive action, powerful and inclusive narratives are essential. This narrative transformation requires co-creation and shared responsibility among all stakeholders – governments, private sector, communities and civil society. Through participatory and inclusive approaches, it is possible to shape narratives that inspire action and ensure that the energy transition is not only technically feasible but socially desirable and collectively owned.

The energy transition narrative should also be about:

- **Self-reliance, energy security and affordability:** Emphasising how solar and wind energy can be harnessed locally, and how domestic resources can be leveraged to develop supply chains, should be put at the centre of the narrative to untap the potential for reduced import dependency and greater control over energy resources and capture the value of the energy transition. Importantly, renewables are increasingly cheaper than fossil fuels and are not tied to volatile global markets, meaning that the energy transition can ultimately lower electricity bills and make energy more affordable for consumers.

- **Economic opportunity and value creation:** The development of renewable technologies is accompanied by the economic benefits they bring, including job creation, new business opportunities and local economic development. When the critical materials or minerals needed for building the technologies that the energy transition requires are available in a country, this holds a great opportunity for that country to build localised supply chains and to go beyond mining, but also to locally process and build a high-value product to be locally used and exported. This change emphasises that the energy transition is a strategic opportunity for economic transformation, regional competitiveness, development and innovation.
- **Community-led initiatives and approaches:** This involves empowering communities as active co-designers of the energy transition by integrating diverse local narratives into the decision making, moving beyond top-down policy prescriptions. Renewable energy projects can be tailored to local needs and managed by local stakeholders to provide direct benefits to communities. This ensures that the energy transition aligns with local priorities and delivers real social value, leveraging local and ancestral knowledge. Such a narrative is vital for building local support.
- **Sustainable holistic development:** The narrative should evolve from framing the energy transition solely as a response to climate change to positioning it as a driver of and opportunity for enabling holistic social and economic development and resilience. This, for instance, includes framing renewables as solutions that improve public health by reducing air pollution; provide reliable power for education, health care and agriculture; and empower small businesses with affordable energy access.

7. Strengthen and modernise electricity grids to provide equitable access to affordable clean energy

Grid modernisation is not solely about technology; it is fundamentally about ensuring access and that no community is left behind. Policy makers should prioritise access, affordability, and inclusion, particularly for vulnerable populations.

Also, a customer-centred approach for utilities and grid operators needs to ensure that reliability remains central to modernisation efforts. This ensures that grid improvements translate into reliable access for all populations, especially those currently lacking it.

The innovation toolbox illustrates how a variety of innovations can enhance grid resilience. These include the use of digital technologies, accurate forecasting, real-time demand response and enhanced integration of distributed energy resources. In addition, enabling the deployment of batteries can provide more reliability.

Significant investment is needed in modern, flexible and smart grids to handle high shares of variable renewables and provide reliable supply. Maximising the use of existing grid infrastructure through non-wire alternatives (NWAs) and digitalisation is key, to minimise investments needed.

A primary challenge in modernising grids in emerging markets and developing economies is the lack of investment. Policy makers need to facilitate significant investment and, critically, to ensure a socially just distribution of the costs of grid reinforcement and modernisation. This equitable distribution is essential to ensure that the investments are politically acceptable and that no one is left behind.

8. Engage and empower consumers and communities

The energy transition must be people-centric, empowering consumers and communities through technologies, digital tools, innovative business models and regulations. For a successful energy transition, innovation in how decision makers engage with consumers and communities is the true success factor – their engagement, participation and endorsement.

Creating forums of dialogue among policy makers, utilities, regulators, civil society, financiers, private sector players and local communities is key to ensure diverse perspectives to shape energy policies. Engaging local communities and civil society in planning and decision-making processes for renewable energy projects, particularly those directly affected by new developments, is key to ensure transparency and fairness, and to ensure social acceptance and address concerns related to land use and displacement.

It is important that large-scale renewable energy projects do not forget to consult or share benefits with the local communities living near the projects. Energy communities enable local stakeholders to directly benefit from energy production and gain control over energy resources. True progress requires moving beyond just installing gigawatts to invest in people, industries and policies that empower communities and countries alike.

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