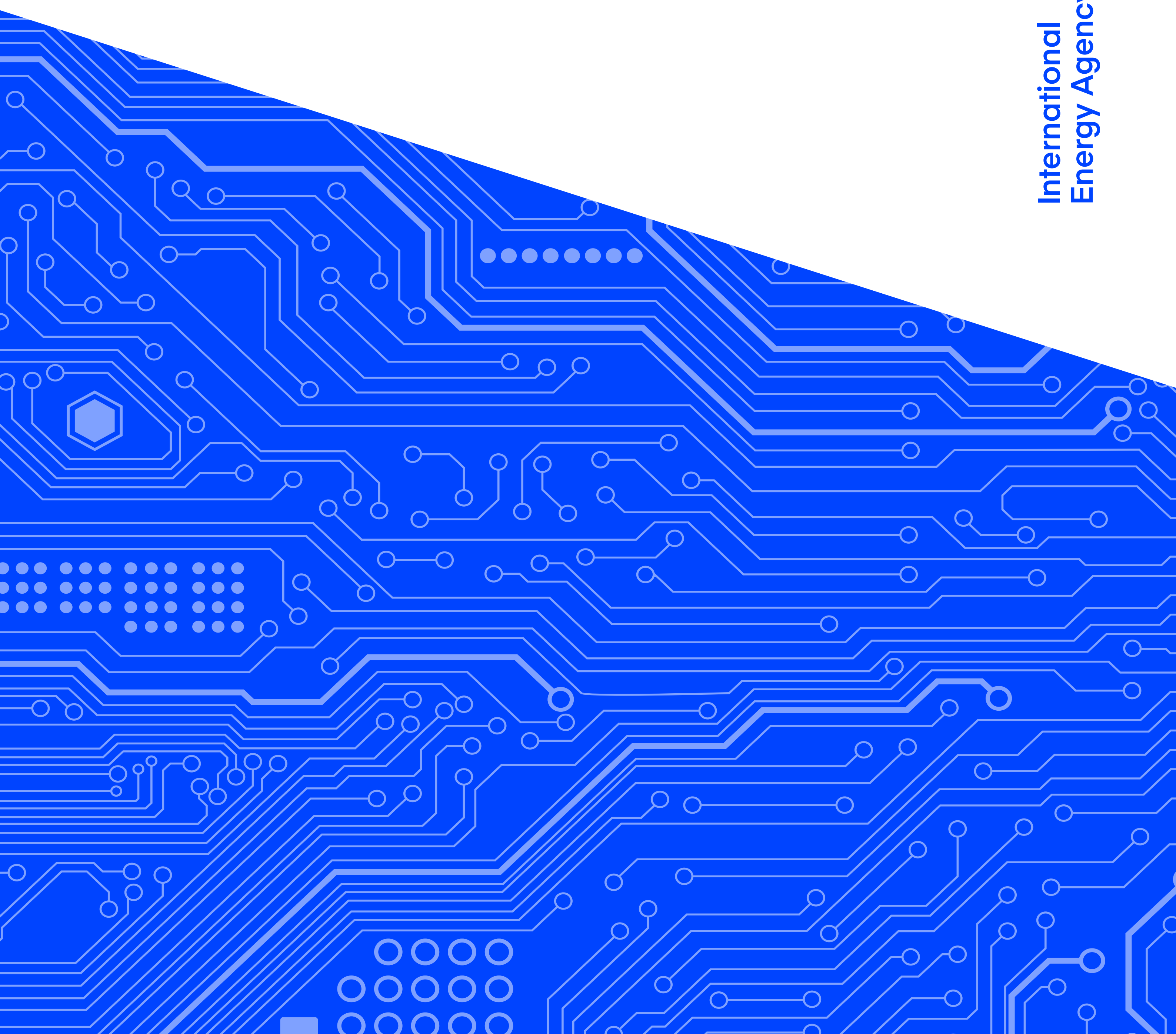
Unlocking Smart Grid Opportunities in Emerging Markets and Developing Economies

International Energy Agency



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Abstract

The clean energy transition requires a fundamental transformation of power systems, including much higher levels of digitalisation at scale across all grid domains, from generation to transmission and distribution to end-use. Strong policy attention is required to scale up investments in smarter and more resilient grids in emerging and developing economies where electricity consumption is set to grow at a rapid rate while also providing greater levels of electricity access. Investments in smarter and more resilient grids will be necessary to accommodate the greater deployment of renewable energy and enhance energy security.

Digital technologies designed for power systems are instrumental to unlock essential system services required to integrate high shares of variable renewable energy. They can also provide solutions to leverage data flows, connectivity, and management across the whole electricity system. To unlock these digital opportunities, adequate planning, investment, and policy action are needed.

As part of the Digital Demand Driven Electricity Networks (3DEN) initiative, this report provides guidance for energy policy makers on possible ways to enable and drive investments in smart and resilient electricity grids. It also gives suggestions on how to start creating an environment that supports the effective use of innovative digital technologies within the electricity sector. It draws on examples and case studies to show the wide range of digital opportunities and solutions that can help governments implement efficient and smart power systems.

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Acknowledgements, contributors, and credits

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The IEA remembers Kathleen Gaffney and her contribution to the work on energy efficiency and digitalisation. She is dearly missed.

Executive summary

Digital technologies can help resolve immediate challenges and reduce investment costs

The success of the clean energy transition requires a fundamental transformation of power systems, including much higher levels of digitalisation at scale across all grid domains, from generation to transmission and distribution to end-use. The digitalisation of grids can support utilities to address demand growth, decarbonisation challenges and improve resilience. For example, digital solutions can enable utilities to locate and fix faults more effectively and provide quicker restoration times, lowering the cost and disruption caused by outages. Digital technologies can also help improve maintenance and extend the lifetime of grid assets, which could defer an estimated USD 1.8 trillion of grid investment globally to 2050.

Globally, current investment in grids is far short of the level needed to be on track for net zero globally; annual investment in grids will need to more than double from around USD 330 billion per year to USD 750 billion by 2030, with around 75% of the investments allocated to the distribution grids to expand, strengthen, and digitalise technologies. There is great potential for raising ambitions; however, many challenges to ramp up investment remain.

This report guides energy policy makers on the functionalities digital technologies can provide for more efficient and resilient electricity grids. In addition, it outlines possible ways to enable and drive investments and create a supportive regulatory and policy environment.

Electricity is central to clean energy transitions, but numerous challenges need to be tackled

Electricity demand is set to outpace energy consumption over the next 25 years. In emerging markets and developing economies[1], demand could increase by over 2 600 TWh by as early as 2030, equivalent to five times the current electricity demand of Germany.

Due to underinvestment, electricity systems globally face myriad challenges, including inefficiencies, losses, congestion and outages. Climate change is causing further damage to assets and affecting reliability. Electrification of end-

[1] In this report, emerging markets and developing economies (EMDE) is not including the People's Republic of China.

uses, and changes in demand coupled with increasing shares of variable renewables are creating additional pressures for advanced economies, emerging markets, and developing economies.

The imperative to strengthen and modernise grids is increasingly acute in emerging markets and developing economies, where electricity consumption is set to grow at around three times the rate of advanced economies. One of the growing sources of electricity demand is cooling. Many electricity utilities were already in a difficult financial situation heading into the Covid-19 pandemic, with operational losses climbing substantially since then. Moreover, 2022 saw a reversal of recent progress in improving access to electricity, with an additional 20 million people living without access, bringing the total affected number of people to nearly 775 million.

Unreliable grids are posing severe risks to economies and people

One of the immediate benefits of power system digitalisation is improvements in reliability. The cost of unreliable grids is high. Due to electricity outages, firms in emerging markets and developing economies operate below capacity each year and must pay for backup electricity generation. IEA estimates that without an improvement in the security of electricity supply enabled by digital technologies, these losses could amount to almost USD 1.3 trillion through to 2030. This lost revenue could be vital to improving utilities' finances and boosting economic development. In Sub-Saharan Africa in 2021, the amount of electricity produced by backup generators by the end-users exceeded that of all renewable energy produced, with expenditure on backup generation exceeding the revenue of all combined national grids in the region. In some countries, unreliable grids have far-reaching effects on the economy, leading to gross domestic product (GDP) losses of up to 6%.

Beyond monetary implications, interruptions affect all critical infrastructures and can affect water and food supply, access to medical assistance, financial services, telecommunications and mobility. Thereby posing risks to health, wellbeing and safety and constraining daily activities and productivity.

In addition, globally, technical losses in grids result in around one gigaton of carbon dioxide (Gt CO_2) emissions annually, while non-technical losses are the source of lost revenue of 80-100 billion per year but also create severe safety risks for people.

Power system digitalisation is crucial for efficiency and decarbonisation

Smart grid implementation provides added value across a range of areas. The IEA estimates that digitally enabled demand response could reduce the curtailment of variable renewable energy systems by more than 25% by 2030, increasing system efficiency and reducing costs for customers. Decarbonisation can be further supported through enhanced supply and demand forecasting, enabling integrated energy planning and providing better visibility and greater electricity demand flexibility.

Many countries, including Brazil, India and South Africa, are seeing a rapid increase in the uptake of distributed solar photovoltaic (PV) systems. For example, in Brazil, distributed solar PV installed capacity rose by almost 7 GW in 2022, an increase of more than 50% in one year alone. While higher shares significantly benefit energy security and decarbonisation, managing such growth is crucial to maintain system reliability, control system costs, and ensure that utility business models keep pace with these changes.

Digitally enabled technologies are also crucial for expanding decentralised, clean energy access to communities in remote locations or low-income areas not currently serviced by electricity grids. Digital solutions can enable more efficient mini-grids and larger standalone community assets. In addition, technologies such as smart inverters can help automatically monitor and manage electricity delivery and reduce service interruptions during peak demand while increasing the productive use of electricity during lower demand.

Digital technologies can also enable better management of growing demand combined with the electrification of end-uses to help avoid unnecessary investment in grid expansion. In addition, these technologies limit infrastructure investment needs by providing real-time monitoring and control, especially in distribution systems.

For example, space cooling is one of the fastest-growing sources of electricity demand. In some countries, cooling demand in buildings already accounts for as much as 30% of peak electricity loads. Moreover, rapidly increasing ownership and use of air conditioners will likely cause it to rise even faster. From around 2 billion units today, the number of air conditioners globally could double by 2030[2], of which 590 million may be added in emerging markets and developing economies. As demand grows, the more granular locational and temporal visibility

[2] Based on the IEA Net Zero Emissions by 2050 Scenario.

of digital electricity distribution systems, combined with super-efficient appliances, can support grid stability, ensure electricity affordability and avoid localised outages.

Targeted actions can help scale up investments in smart grid implementation

To unlock these digital opportunities, adequate planning, investment and policy action are needed. For example, to bridge the investment gap and drive investments towards modernising grids, policymakers could consider actions to leverage the full range of potential investors and develop models that adequately value broader benefits.

Many potential investors exist for smart grid projects, from state-owned enterprises to private investors and multilateral organisations. Governments could support the design of projects to leverage each type of investor best, considering their preferences for the right combination of debt, equity or grant financing to mobilise capital while still ensuring appropriate risk allocation.

Policy makers could consider opportunities to aggregate small projects to increase the potential pool of investors or realise economies of scale when focusing on procurement. To attract continued inward investment and build confidence, governments can signal to the market to form a future pipeline of projects. This requires future vision, planning and implementation. Substantial potential capital is available for grid projects. Still, it is necessary to build the business case for grid reinforcement, minimise transaction costs, reduce project risk profiles, and open up new value chains. International co-operation can promote standardisation to reduce barriers and increase digital grid investments.

Beyond these points, a critical aspect is creating incentives for utilities to invest and supporting the development of plans, capacity, and tools to stimulate investments and accelerate implementation.

Five policy action areas to support smart grid implementation and continuous improvement

Beyond targeted actions to facilitate investments, this report identifies five key steps for governments to accelerate the implementation of digital technologies.

Create a coherent vision and modernise planning

A crucial first step is for governments to envision how digital grid technologies can help meet country priorities – including grid upgrades, energy access and decarbonisation. This vision can then be translated into updated policy and regulatory frameworks, which recognise the value of investments to harness digital capabilities and system efficiency. This requires engaging all stakeholders from the digital and energy spaces.

Governments can also drive investment by helping utilities adopt integrated planning. As electricity grids become increasingly complex, a whole-systems approach to planning is key to embedding digital deployment into energy and broader economic plans. Too often, planning does not include a systemic approach. It is also important to consider distributed resources and the demand side in planning and aligning investment decisions across system operators, network companies and other actors in vertically integrated and unbundled markets.

Co-ordinate implementation

Governments can help ensure coherence between energy, electricity, economy, digital and other departments, digital and energy regulators, and the digital and electricity industry. Governments can also help align national innovation systems for digital transformation with energy policy objectives. For example, large-scale demonstrations can help test digital solutions on energy infrastructure, which generally require a certain scale to validate business cases. Governments can also play an active role, including a convening one, in enhancing data access and sharing – all crucial for digital innovations to validate their business models.

Government stewardship of power system planning could also ensure that more comprehensive socio-economic benefits of digitalisation are widely and equitably shared, not least to improve access and provide the skills needed for new employment in smart grids.

Facilitate rules and regulations that adequately value digital solutions

In their regulatory capacity, governments could consider dedicated policies and regulations to incentivise and de-risk digitalisation investments. This includes considering a shift towards performance-based regulatory oversight by providing incentives and penalties to meet clean energy transition objectives and measures to support innovation.

Governments can also help incorporate the value of electricity across all policies and the importance of supply-demand balance and flexibility. Providing guidance and support for more nuanced evaluations of costs and benefits and future-proofing policies and constraints can pave the way for digitalisation to interact with electricity grids in a way that promotes systems efficiency.

Integrate resiliency and security across all electricity policy domains

In the context of mounting climate impacts, there is an opportunity to build resilience while expanding and developing power systems. Governments increasingly strive to integrate resiliency and security across all electricity policy domains, including through long-term planning and strategic frameworks such as Nationally Determined Contributions (NDCs), energy transition plans, or Low Emissions Development Strategies (LEDS) which highlight the value of physical and digital resilience. They could also ensure cyber resilience is mainstreamed across rules and regulations – which can greatly promote digitalisation investment.

Governments also have a key role in helping manage systemic risks and strengthen the ties between digital and physical infrastructure resiliency and security.

Track, evaluate and disseminate digitalisation progress

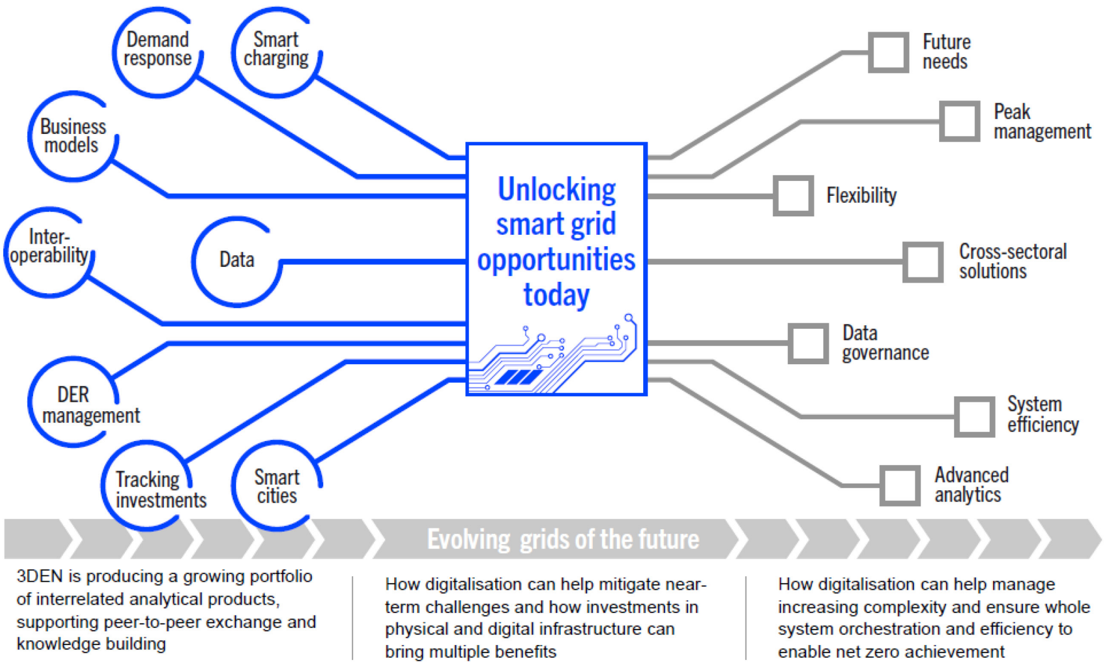
Governments can create a data-driven culture in the public sector, which includes monitoring and evaluating digitalisation progress. Targeting, implementing and enforcing government policies can all be enhanced by continuously monitoring the implementation of energy transition and digital strategies. Digital tools can play a key role in this respect, provided governments reinforce their institutional capacity to manage and monitor project implementation.

Policy makers could consider actions to promote information sharing underpinned by robust data frameworks, monitoring and evaluation. Strengthening international collaboration and knowledge sharing is vital to developing common practices and standards and identifying areas where innovation can be leveraged jointly, accelerating progress at a lower cost. Collaborative approaches are warranted for demonstration projects to provide valuable lessons on how to manage digital technologies at a larger scale and create evidence of the value created by digital solutions and technologies, which can, in turn, help de-risk future investments.

The IEA monitors electricity system digitalisation progress and provides continued guidance

Produced under the Digital Demand Driven Electricity Networks (3DEN) initiative, this publication is the first of a set of three IEA 2023 reports on grids and digitalisation as part of a growing portfolio of analysis and policy guidance.

It will be followed by an IEA Special Report on Power Grids, that will provide a global stock-take and perspectives, which in turn will be followed by a further 3DEN report “Grids of the Future” that will focus on the role of digital technologies in accelerating and integrating distributed and renewable energy technologies and the policy actions needed today. This report will look through the lens of the IEA Net Zero Emissions Scenario and examine the shifts in electricity landscapes and the functionalities needed to address these changes while maintaining security, affordability, and sustainability. This will then be used as a mirror to reflect on electricity grids today to explore what actions will be necessary to facilitate the increased demand due to cross-sectoral electrification, higher shares of variable renewable energy penetration, and how digitalisation can be leveraged as a tool to manage the intermittency of supply, provide system balancing, and ultimately increase whole system efficiency. In addition, the IEA is producing a range of knowledge products and is creating opportunities for peer-to-peer experience exchange and learning.



Introduction

Emerging markets and developing economies need reliable and efficient grids

In recent decades electricity grids in many emerging markets and developing economies have improved dramatically, with increased reliability, added capacity, and access extended to millions of people for the first time. However, these improvements have not been replicated in all regions, where some have struggled to meet growing demand with limited resources and a legacy of old, inefficient power systems. With many households still lacking access to reliable electricity, there is great potential for well-functioning, modern, digitally enabled electricity grids to drive socio-economic development.

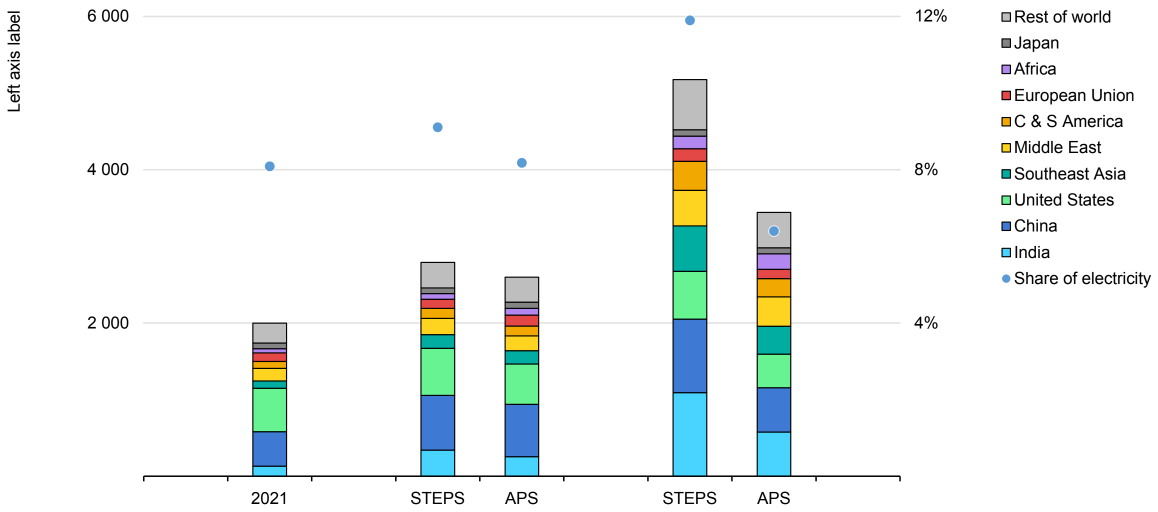
The start of the 2020s has greatly exacerbated these issues, amplifying a sense of urgency about the state of electricity infrastructure and its role in the planet's future. First, in addition to bringing the immediate burden of a major public health crisis, the Covid-19 pandemic triggered economic recessions in many emerging markets and developing economies. Second, in 2022, the Russian Federation's (hereafter, Russia) invasion of Ukraine sent shock waves through global energy markets. The spike in fuel costs in 2022-23 has created extraordinarily difficult financial circumstances for utilities around the world. Many were already under pressure to minimise price increases, as customers are particularly sensitive to price hikes and still maintain financial strength. The impact on utilities in emerging markets and developing economies is even more debilitating as it slashes funds available for investment when such financing needs to increase substantially and rapidly. For many utilities, the need to deal with a continual flow of pressing challenges makes it impossible to plan or direct limited resources towards embedding modern functionalities during routine asset replacements. Ultimately, this can lead to stranded assets or inefficient technological lock-ins. In turn, unreliable supply and associated load-shedding practices create a vicious circle that further undermines utility revenues.

These recent crises highlight the increasing urgency to transform energy systems in line with the 2015 Paris Climate Agreement. The latest (2023) assessment from the International Panel on Climate Change (IPCC) concludes that to limit global warming to 1.5°C, global CO_2 emissions must be reduced by nearly one-half by 2030 and reach net zero by around 2050. This hinges on two major transformations: bringing online vast amounts of clean electricity generation, much of it variable; electrifying large volumes of demand. To achieve a people centred and inclusive clean energy transition that enhances people's lives, an overarching challenge is to ensure access to reliable, affordable, and sustainable electricity.

With growing populations, increased urbanisation and economic development leading to an increased standard of living, electricity demand is expected to continue to increase significantly in the coming years. Electricity demand in emerging markets and developing economies could increase by over 2 600 TWh[3] by as early as 2030, equivalent to five times the current electricity demand of Germany. One of the growing sources of electricity demand is cooling.

Opportunities exists to develop and implement strategies that shift towards electrification. While still in the early stages in most emerging markets and developing economies, electrification of heating, transport and many industrial processes will also drive electricity demand and change demand patterns.

Space cooling demand by region in the Stated Policies Scenario and Announced Policies Scenario by 2030 and 2050



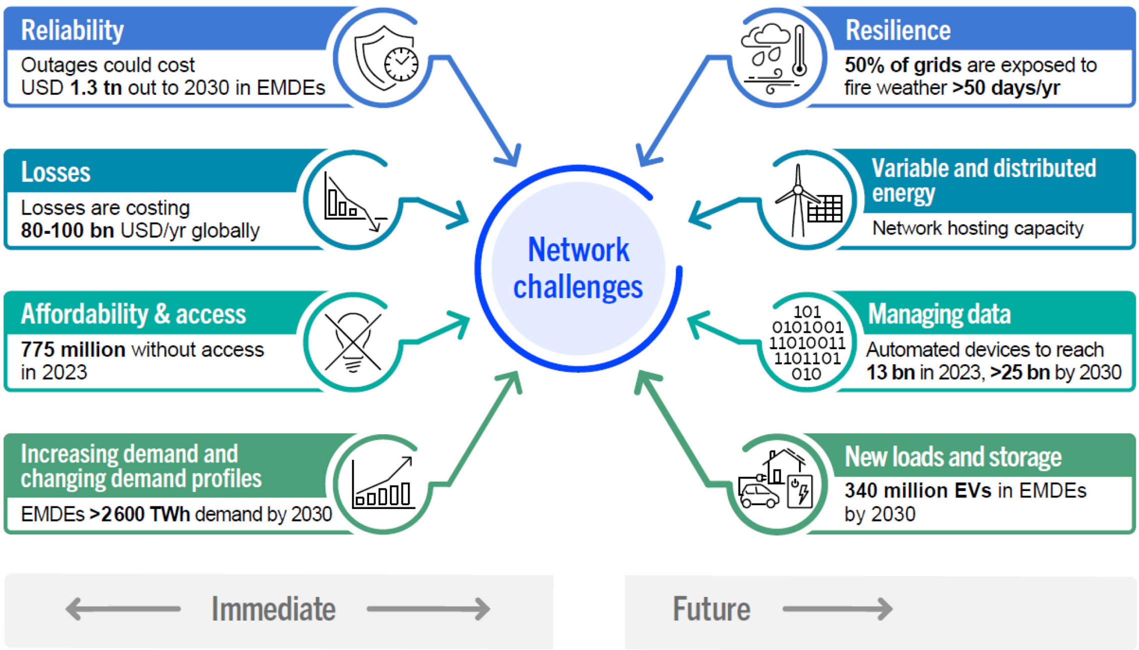
Note: Electricity demand for cooling rises by 3 200 TWh to 2050 in the Stated Policies Scenario (STEPS); growth is cut by more than 50% in the Announced Pledges Scenario (APS) thanks to air conditioner and building envelope efficiency gains.

Whether emerging markets and developing economies can leverage this opportunity depends heavily on whether electricity generated can be delivered efficiently and reliably to demand centres – which raises the core question of grid preparedness. In recent years in many emerging markets and developing economies, there has been good progress in financing and constructing additional generation capacity. However, the effectiveness of these responses, in particular the amount of new variable renewables that could be interconnected to the grids,

[3] Based on IEA Announced Pledges Scenario, electricity demand for EMDE countries excluding the People's Republic of China.

will depend on the grid infrastructure itself and operational readiness of grid operators, at distribution and transmission level. Private investment has also not helped alleviate the situation: the international focus has been kept on channelling investment flows toward generation assets.

Current and future challenges for electricity grids in emerging markets and developing economies



Underinvestment is holding back development

Today we are experiencing a global energy crisis – not just oil but also gas, coal, and electricity. The shortages of gas and coal are driving electricity prices up and making electricity unaffordable and, in some cases, unavailable. While much of the attention has been on Europe, this crisis is affecting emerging and developing countries even more including through growing inability to pay te high prices for gas and coal that we now see in world markets. This is causing electricity security concerns in some countries – such as Pakistan, Bangladesh, India, and Thailand facing difficulty to secure gas contracts with all the potential negative impacts on the health of citizens and on economic growth and development. Concerns about electricity grid reliability and the cost of grid-supplied electricity are driving more and more consumers to invest in alternatives, often fossil-fuelled generators. This places additional pressure on already weak utilities. In markets with the highest fossil fuel-based generator use, including much of Sub-Saharan Africa, spending on fuel for generators now exceeds that of the entire electricity grid.

However, these are symptoms of a broader, chronic issue: the cost of long-term underinvestment in electricity infrastructure in many parts of the world. There are cost and value implications for energy utilities, businesses, citizens, and the national economy.

Insufficient infrastructure is constraining economic growth

It is estimated that due to electricity outages, each year firms in emerging markets and developing economies experience an efficiency loss of around USD 38 billion due to operating below capacity, sales losses of USD 82 billion, fixed and variable costs for back up electricity generation of USD 65 billion, all of which could amount to almost USD 1.3 trillion through to 2030. In some emerging markets and developing economies, the loss of electricity is more frequent. On average, Nigerian firms for example, experience 25 electricity outages in a typical month, while in Bangladesh, firms reported over 100 electricity outages a month.

There are obvious impacts from electricity outages to a firm relying on electricity for productive work, shops and markets being affected, and food manufacturing being forced to stop production and creating supply chain issues. Many firms rely on electricity for card payment, for staff working from home or onsite, or for administration purposes. The global economic effects of electricity outages are not spread evenly. China, it is estimated that the interruption costs to firms for a single outage event is around USD 200 million. Firms in high-income countries experience, on average a loss in sales of as little as 0.5% annually, whereas firms in EMDEs can experience as much as 5.5% loss in sales.

Measuring the costs of insecure electricity supply

One metric used to estimate the economic effects of insecure energy is the value of lost load (VoLL), which is seen as the price society is willing to pay to avoid an electricity cut. Studies show that the VoLL in the European Union ranges up to more than USD 130.00/kWh, and in the United States and New Zealand to more than USD 250.00. In Indonesia, it is calculated to be just over USD 2.00/kWh while in Brazil, it is less than USD 1.50.

The VoLL can be used to evaluate direct costs of limited amounts of energy not supplied, dependant on several factors such as the affected stakeholders, the time of day, duration, frequency and season of the disruption. However, it does not fully reflect all the broader costs to society of interruption, especially for high-impact events or lack of access.

Losses are weakening utilities and contributing to emissions

One issue that contributes to both grid instability and poor financial standing of utilities is losses. In both electrical transmission and distribution systems, there are two categories of losses: technical losses (TL) and non-technical losses (NTL).

Some TL are a function of the size of a grid and are due to the distances electricity needs to travel along transmission and distribution systems. However, technical losses can also be attributed to aging infrastructure or faulty workmanship at weak points where cables are jointed together or terminated at transformers or switchgear. Infrastructure operating outside of its designed parameters for example, where underground cables, overhead line conductors or transformers are inadequately sized for current they are carrying – will also exacerbate efficiency losses.

In contrast, NTL are linked to other factors such as faulty meters, unregistered meters or fraudulent meter reading teams; bypassed meters; or illegal connections to the distribution system; or incorrect billing by the utility. NTL can be from both residential and large non-residential users. Indeed, when NTL are greater than 25% of supply to the system, then it is likely to be from large commercial or industrial users.

Globally, technical losses in grids result in around 1 gigaton of carbon dioxide (Gt CO_2) emissions annually. The IEA estimates that reducing worldwide losses towards efficient levels of around 5% – from as much as 18% in some regions today – could reduce these emissions by over 400 million tonnes (Mt CO_2), which is more than the total annual emissions of Mexico. Globally, it is estimated that the commercial effects of non-technical losses amount to between USD 80-100 billion each year.

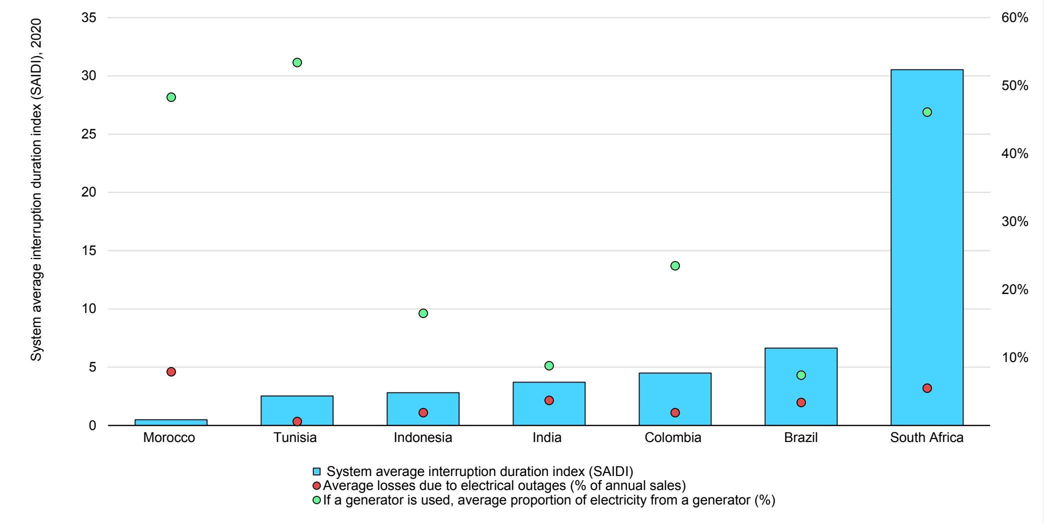
The additional burden of weak grids

To mitigate the intermittency of electricity supply, many firms faced the decision of whether to accept that there will be periods in which activities will cease because of outages or to invest in an element of self-resilience. This is usually an emergency backup generator, which most of the time relies on diesel as a source of fuel.

Firms incur additional costs to acquire and operate such systems. It is estimated that, each year, firms in emerging markets and developing economies spend USD 6 billion to procure generators and almost USD 60 billion on operating costs for fuel and maintenance. In India, for example, commercial and industrial entities consume up to 300 litres of diesel each hour during outages of up to 6 hours per day. In Sub-Saharan Africa, the collective spend on fuel for generators is more than the expenditure for operating the combined national grids. This further reinforces the trap of the vicious cycle of underinvestment in electricity infrastructure. In Sub-Saharan Africa, backup generator capacity was 45 GW in 2021, more than all the renewables-based generation capacity in the region. Nigeria alone has 13 GW, with 40% of total electricity produced from backup generation.

Worsening financial difficulties experienced by many emerging markets and developing economies utilities are hampering investment in new transmission and distribution assets, resulting in a progressively obsolescent system. For firms, the additional running costs for backup generation can be twice as expensive as grid-connected electricity. Between 2021 and 2022 in Nigeria, for consumers using a mix of grid and backup generation, electricity costs increased by 150 to 170%; those dependent on diesel generators alone have faced an increase of 220 to 260%.

Economic effect to firms due to insecure electricity supply, with average annual electricity service interruptions



Source: IEA (2023), IEA analysis based on World Bank (2023), and World Bank (2019), The Business Costs of Unreliable Infrastructure in Developing Countries (accessed 30 May 2023)

Backup generation is also linked to environmental issues in developing countries, contributing over 100 Mt CO_2 emissions annually, which is more than the total emissions of Belgium. It also creates localised ambient (outdoor) air pollution with deadly levels of particulate matter. Globally, ambient air pollution is responsible for over 4 million premature deaths annually, and disproportionately affects developing countries. People in Africa are six times more likely than those in the United States to die prematurely from air pollution.

The main factors for NTL can be unaffordability for the user, poor customer-energy utility relations where unpaid consumption is viewed as a means of protest and a culture of non-payment has been established, or faulty equipment where the customer or utility may be unaware of an issue. In Ghana, after multiple interventions, NTL is over 25% of gross electricity generated and has an estimated cost of over USD 400 million annually. In 2021, NTLs in Brazil amounted to almost 36 TWh, costing around USD 1.8 billion.

Loss of life is another challenge, particularly for those who come in to contact with live cables while actively involved in illegally obtaining electricity – or do so unwittingly. One electrical distribution utility in Ghana stated that in their operational area alone covering 30% of the country, between 2014 and 2022, over 180 people suffered electric shock, of which more than 130 were fatally injured. The true number is likely to be much higher, particularly in rural areas where incidents may go unreported. For example, in Uganda's Eastern region, there are an estimated 50 incidents of electric shock occur per week.

The Ghanaian Dumsor Crisis

Dumsor is translated from local dialects in Ghana as "quench and kindle" or "off-on" and is used colloquially to describe persistent electricity outages. *Dumsor* has provided a fascinating insight into how unreliable supply reduced the value of electricity and created a vicious cycle of reduced willingness to pay.

Initially, a capacity shortage precipitated the *Dumsor* due to reduced water levels in the Volta Hydroelectric Dam. To increase the security of supply, additional gas turbines were brought online in subsequent years, but damage to a Nigerian gas pipeline supplying Ghana led to further capacity shortages and subsequent electricity outages. The economic effects from *Dumsor* over the period 2012-16 have been estimated as a GDP loss somewhere between USD 320-920 million, amounting to between 2-6% of Ghanaian GDP. At the subnational level, the effects of outages were not evenly spread across the electricity grid, with some feeders experiencing more loss of supply incidences.

The data from a 2019 study on non-payment of electricity in Ghana demonstrated how these events contribute to a vicious circle. There is an almost 17% increase in unpaid electricity bills from customers on the most-affected sections of the grid compared to those that had uninterrupted supply, with the average debt standing at almost three times the monthly charge. This situation of poor quality of supply, high non-payment of bills and low financial performance of the utility is not the case only of Ghana. Of 76 utilities in the 45 countries of Sub-Saharan Africa, around one-in-three recover their operating and debt-service costs. Without government subsidies, this ratio falls even lower, to one-in-four.

Millions have lost access to electricity

The first priorities for electricity policy across Africa remain increasing access and improving reliability for end-users. In 2022, some 80% of firms and close to 60% of households in the region face regular unplanned and lengthy outages. Electricity access remained unavailable for almost 775 million people in 2022 – mostly in Sub-Saharan Africa. In fact, up to 30 million people across the continent who previously enjoyed access can no longer afford electricity. This number is on the increase, reversing a decade of steady improvement.

Fewer than 6 in 10 African households are connected to an electric grid. Preliminary findings from an ongoing IEA assessment indicate that around one-third of African households cannot afford to pay for 100 kWh per month, which corresponds to the electricity needed to power on a daily basis for four lightbulbs for four hours, a TV for three hours, a fan for six hours and a refrigerator running 24/7.

Unreliable electricity supply also causes strain on businesses, disrupting production and commerce by forcing the closure of shops and affecting revenues. Moreover, electricity quality is critical for businesses as electrical tools and machinery are sensitive to disturbances such as sags in voltage. These can lead to expensive downtime and production losses or could damage equipment with increased outlays for new equipment, repair or maintenance costs.

Pressure on electricity systems is increasing

In recent years, increasing demand for electricity, a lack of flexibility and increased frequency and severity of climate-related disasters including storms, floods and wildfires are increasing the risk profile for transmission and distribution (T&D) systems and assets. Individually or collectively, they can lead to high losses, large-scale outages, changes in transfer capacity, physical damage and accelerated aging – all of which can undermine energy access, availability, reliability and security.

Globally, around half of electricity networks are currently located in areas with a high fire weather index, meaning meteorological conditions are favourable for fires to start and spread. Some 18% of grids are exposed to a high risk of wildfires, experiencing more than 200 days of fire weather annually. In turn, over 10% of systems are exposed to tropical cyclones. In Indonesia, tropical cyclones damaged electricity transmission networks in 2019 and 2021. An extreme heatwave in 2019 triggered a havoc-wreaking combination of higher peak electricity demand for cooling and lower production capacity, resulting in rolling blackouts on Lombok Island over several weeks. In Beijing, 50% of all distribution network failures in recent years have been linked to meteorological disasters.

But not all climate change impacts are sudden and severe anomalies. In 2021, in Central and South America, lower than expected rainfall in the last few years – including in Argentina, Ecuador and Mexico – meant the Brazilian hydroelectricity grid which is around 60% of electricity gross supply experienced its worst natural inflow rate in almost 100 years. The need to use the full thermal backup capacity and to procure emergency assets and electricity exchange from foreign countries pushed up the generation-driven costs that get passed on to retail all consumers. For instance, during the peak of the financial crisis from September 2021 to April 2022, the retail segment approximately 60% of the power market, saw the variable part of the tariff increase by 980% against the same period average pattern of the three preceding years. Anticipated sea-level rise may force some countries or companies to relocate electricity grid assets. One study found that to avoid inundation, Bangladesh would have to relocate approximately one-third of all electricity plants by 2030. These data demonstrate the importance of investing to make grids more resilient.

Managing demand growth is becoming more challenging

In many places, continued urbanisation and economic development leading to increased living standards is driving high energy demand growth, particularly for electricity. Space cooling is already one of the fastest-growing sources of electricity demand, and rapidly increasing air conditioner (AC) ownership and use is likely to cause it to rise even faster. Heatwaves are expected to increase in frequency and intensity as average temperatures rise and populations grow and become increasingly urbanised, further pushing up cooling needs. By 2040 as identified in the IEA India Energy Outlook, increased demand for cooling could increase annual electricity demand by 10 %, with a daily difference between the lowest and highest air-conditioning load of over 200 GW[4], compared with less than 40 GW today.

Most people with space cooling needs still do not have access to adequate means to cool their homes. Only 10% of households have AC in India and Indonesia, compared to over 90% in the United States and Australia. Even so, the 2022 heatwaves in India created unprecedented spikes in demand from AC units and fans, causing electricity outages for millions and prompting plans to boost coal production by 100 Mt over the next three years (2023 to 2026) to satisfy increased fuel demand for electricity stations.

Electrification of many other end-uses is also rapidly changing the overall demand outlook. While still in the early stages in most emerging markets and developing economies due to lower ability to pay and limited availability of affordable models,

[4] Based on IEA (2021), Stated Policies Scenario, India Energy Outlook.

electrification of heating and transport is expected to further push up demand while also changing demand patterns. Around 20% of new car sales in the People's Republic of China (hereafter, "China") are now electric vehicles. In Brazil, India and Indonesia, fewer than 0.5% of new car sales are electric. However, many countries are seeing rapidly increasing electric two- and three-wheeler sales. In 2021, sales of two- and three-wheelers reached 230 000 in Viet Nam and 300 000 in India, and China registered 9.5 million new sales alone.

Decarbonisation requires digitalisation

Secure, affordable, clean energy transitions require large increases in investment in electricity grids. While solar, wind and other renewables receive a lot of attention in emerging markets and developing economies, a blind spot regarding the role of grids is increasingly evident. To make the transition to clean electricity generation more secure and affordable, more electricity will need to flow through T&D networks, coming from more sources and being delivered to more end-use points. Without adequate and timely investment in electricity T&D networks, developing and deploying new generation capacity may fail to deliver on both climate action goals and purely economic terms.

Faster deployment of variable renewable energy can help emerging markets and developing economies boost national energy independence and meet climate goals earlier. This potential, however, is being seriously constrained by shortcomings in two key areas: a) lack of investment in T&D grid infrastructure, including modern, digital solutions; and b) the need to strengthen planning and operational practices of utilities to modern standards in order to properly assess stability, reserves, generation, and adequacy.

The Brazilian example is illustrative. Over a 20-year period from 2003, Brazil has systematically pursued a strategy to more than double its transmission infrastructure, from 80 000 km to almost 190 000 km, and included large-scale deployment of both distributed and utility-scale variable renewables. This ambitious expansion however, posed certain challenges including transmission constraints. A recent study by the Brazilian regulator examined the transmission-driven costs embedded in electricity tariffs, and made recommendations based on node-level pricing. This provided better economic signals regarding localities where investments and reinforcements are most needed, the new regulation is designed such that transmission tariffs reflect more precisely the generation-siting costs.

Across emerging markets and developing economies, the next decade is essential to ensure electricity grids can reliably absorb the large volumes of renewable electricity needed for energy security and climate change mitigation. In parallel to substantially increased grid investments, this requires opening up systems in these regions to new technologies and solutions that support increased demand flexibility. The IEA Net Zero Emissions by 2050 Scenario: indicates that, by 2030, around one-quarter of global grid flexibility needs would be met by demand response and battery storage. Demand-side flexibility in particular grows ten-fold compared to 2020 levels to reach 500 GW by 2030 – a capacity equivalent to all of Europe's wind and solar plants in 2022.

Opportunity exists to draw on lessons learned

Many countries are actively promoting increased uptake of distributed solar photovoltaic (DPV) systems as well as demand-side and flexibility assets. All have decarbonisation benefits: if not managed carefully, however, they can create unintended stress for electricity grids. Rapid uptake of DPV, if unmanaged, can increase operational complexity and impact the resilience of transmission networks. Reverse flows in distribution feeders could lead to mass disconnection when the grid becomes unstable; in turn, additional, further stress on the grid could trigger a blackout. As such, large DPV deployment may make it necessary to reinforce certain parts of the grid. It may also require addressing net demand forecast uncertainty and create difficulties in planning and operation of electricity grids.

All of these changes could have the negative effect of reducing revenues for utilities – and thus challenge their viability. As noted above, while distribution companies in Brazil have made considerable investments to boost DPV connections, actual operations are affecting the affordability of electricity for consumers. In South Africa, frequent blackouts resulting from generation inadequacy prompted an increase of DPV installations, which had the effect of reducing supply bought from the grid and meant that surplus injected through older meters actually turned the meters backwards. This results, *de facto*, in a net-metering scheme for consumers and a financial strain for utilities – which is expected to accelerate with the launch of regulatory incentives designed to have DPV help plug the electricity supply gap. These examples demonstrate that, without adequate planning and deployment of tools to allow for visibility, monitoring, management and control, large-scale DPV deployment could become a grid problem.

Electric vehicles (EVs) are another important element in broader energy system decarbonisation. Globally, EV sales reached an historical high of 10 million in 2022. The share of electric cars in total car sales was 14% in 2022, more than 10 times their share in 2017. How EVs affect electricity demand and electricity grids will differ regionally. In Germany, adding an EV to a typical household of four people could increase its peak electricity demand by 70%. While the share of EVs in emerging markets and developing economies is still low, uptake is on the rise and projections suggest that by 2030 there could be over 240 million EVs[5], including two- and three-wheelers, on the road in EMDE countries, with another 100 million in China. Sales of electric cars in India, Thailand and Indonesia more than tripled in 2022 compared to 2021. Over half of India's three-wheeler registrations in 2022 were electric. In areas with robust grids, a high level of EV penetration can be achieved without any negative impacts. Where transformers are already overloaded, however, even low levels of EV uptake can cause disruptions.

To avoid such operational problems and lost revenues, system operators could adequately plan, develop processes, and deploy tools that allow for visibility, monitoring, management and control of large-scale DPV deployment. In fact, opportunity exists to integrate DPVs and EVs such that they contribute to improving overall system efficiency and electricity security. In Australia, the market operator has a digital register for all distributed energy resources (DER) installations such as DPV and behind-the-meter batteries to improve visibility and controllability. This enables the operator to know what has been installed and where, and which firm completed the installation. It also identifies the independent agent that could disconnect the device in an emergency situation to avoid a cascading blackout.

Smart grids can help resolve challenges faster and at a lower cost

Drawing on lessons learned in planning and execution from earlier adopters of digitalisation around the world, emerging markets and developing economies could significantly benefit from targeted smart grid deployments to both upgrade their electricity network infrastructure, and tackle the numerous challenges outlined. Early investment can help bring down the total cost of clean energy transitions over time. Smart grid implementation provides added value across a range of areas. The IEA estimates that realising the potential of digitalisation in grids could reduce the curtailment of variable renewable energy systems by more than 25% by 2030, increasing system efficiency and reducing costs for customers.

Digital technologies applicable to electricity grids encompass both hardware and software. In the first category, examples include smart meters, digital substations, sensors and other digital monitoring equipment, smart EV charging infrastructure, and smart inverters. Software solutions typically optimise use of such tools by adding capacities such as renewable generation and demand forecasting, geographic information systems (GIS), automated monitoring and decision support (AMDS) tools, advanced grid planning, and asset management. Most are

[5] Based on IEA (2023), Stated Policies Scenario, Global EV Outlook 2023.

supported by enabling infrastructure in the form of communication networks and platforms that collect, store and manage data.

By providing improved data and analytics for planning and decision making, as well as enhanced controls and automation, digital technologies support system-wide efficiency and resilience. AMDS tools, for example, help pre-empt problems on the grid and improve maintenance, thereby avoiding faults and extending the lifespan of assets. Enhanced monitoring and early warning systems also hold potential to respond more rapidly and effectively to unusual circumstances, such as extreme weather events. By providing quicker restoration times, they can lower the cost and disruption caused by outages.

Digital technologies can also help reduce losses, whether technical or non-technical, by reducing operational costs which translates into lower bills for most consumers. Lower losses also improve electricity quality, thereby reducing the risk of damage to consumer assets. Importantly as electricity grids become more decentralised, tools to better monitor and manage supply and demand can improve reliability, unlock new sources of flexibility, increase the hosting capacity of renewables and distributed energy resources, reduce curtailment of renewables and DERs, and improve productivity of plants.

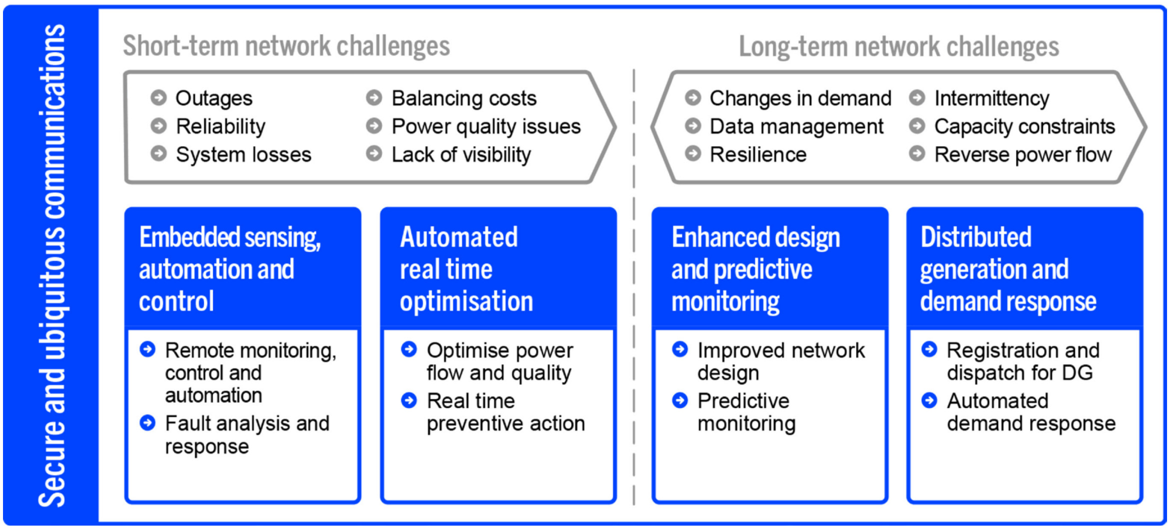
The digitalisation opportunity

Smart grid technology deployment is still low

Many countries worldwide are well underway on a journey of electricity grid modernisation, including through upgrading existing infrastructure with modern digitally enabled technologies. Others are just starting to explore what opportunities digitalisation can unlock and what challenges smart grid technologies can help resolve.

Digitalisation is a broad term that encompasses a wide range of technologies, applications and functionalities that leverage information and communications technologies (ICT). For the electricity sector, digitalisation opens new opportunities to improve the efficiency and resilience of systems by leveraging data collection and data insights to implement new levels of observability, control and automation. Digital technologies allow for increased communication among devices and facilitates both remote control and self-regulation. A smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimising costs and environmental impacts while maximising system reliability, resilience, flexibility and stability.

Digital solutions to tackle short- and long-term network challenges



Note: DG = Distributed generation.
Source: World Economic Forum, Accelerating Smart Grid Investments.

At the transmission level, advanced sensors such as phasor management units (PMUs) support faster and more flexible operation and improved control, making the grid more observable so that effects of further integration of variable renewable energy (VRE) and other technologies can be better understood and managed. At present, however, deployment is still low in some emerging markets and developing economies.

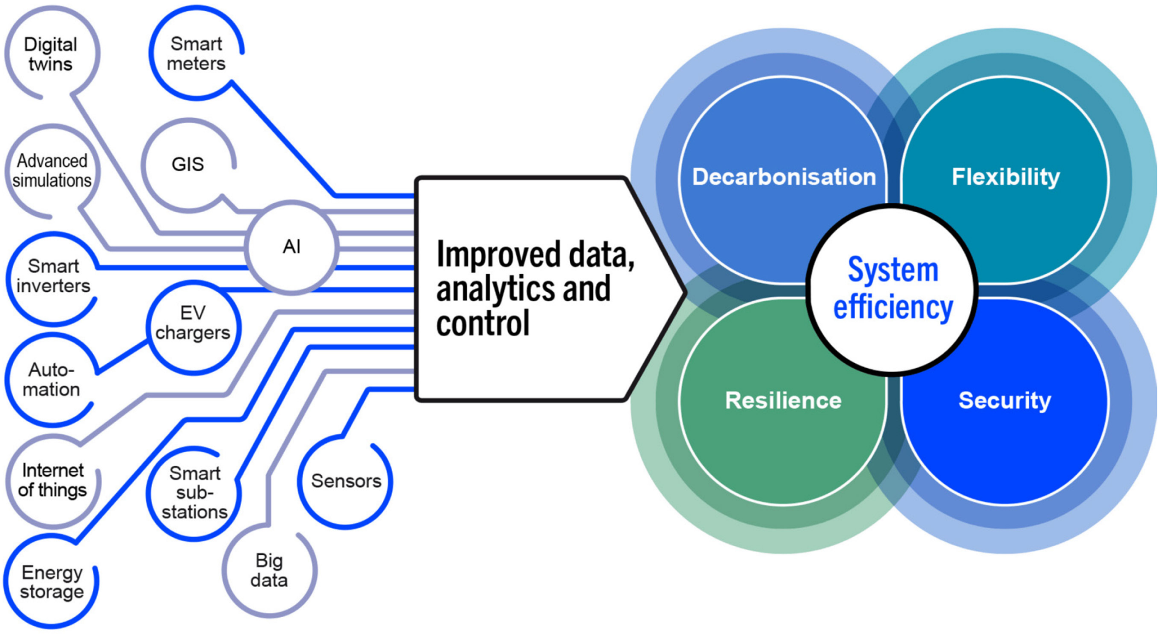
Globally, digital infrastructure investment is increasingly being directed towards distribution grid with two activities dominating. The first is the roll-out of smart meters, and secondly the automation of substations, feeders, lines, and transformers via deployment of sensors and monitoring devices. The spectrum of solutions available is becoming broader and is rapidly expanding. Examples of technologies that have potential to reduce costs and improve performance include digital twins which are digital simulations of physical infrastructure that mimic real-world conditions, and new approaches such as non-wire alternatives which use digital management to manage demand to postpone or avoid replacing sections of grid infrastructure.

The large menu of digital options is linked to an important point: there is no singular starting point or universal pathway towards establishing a smarter grid. Progress is achieved over time through systematic, incremental processes and the final state varies depending on each system. Reflecting the challenges at hand and the resources available, changes and improvements in system are usually implemented incrementally. The pathways towards smart grids will also vary across national and regional contexts; the existing state of transmission and distribution infrastructure; generation capacities and demand patterns; and priorities, needs and capabilities.

Smart grids can enable cleaner, more affordable and secure electricity

Smart grid technologies have applications across the whole electricity system, including generation, transmission, distribution and demand side. While some technologies offer functionalities for specific parts of the system, the main value of digital technologies arises from opportunities to leverage data flow, connectivity and management across systems.

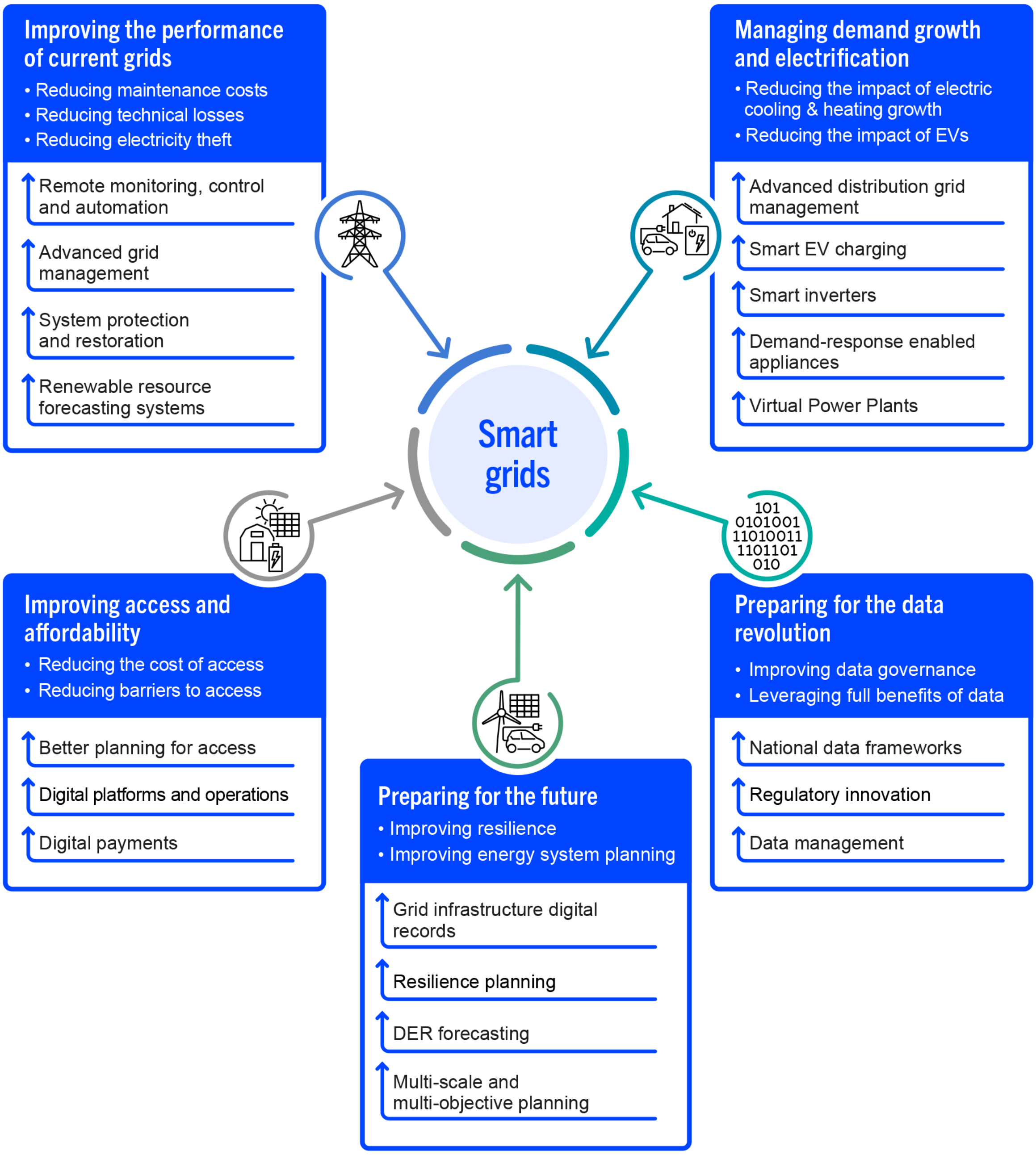
Digital solutions for clean energy and system-wide efficiency



IEA. CC BY 4.0.

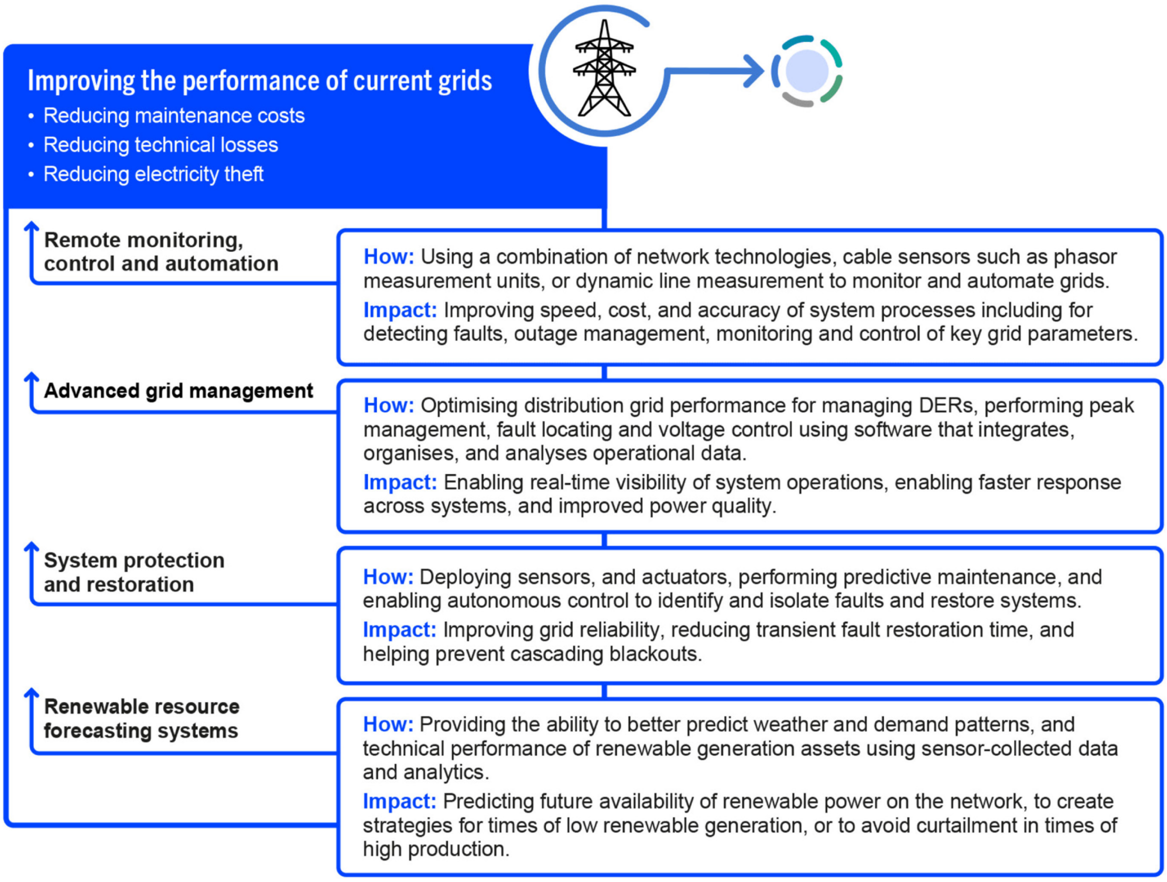
Digitalisation can provide real-time data to help improve grid operating reliability, reduce operational costs through automation while improving worker safety, and increase overall system efficiency. To capture their full benefits, technologies need to be utilised in harmony across various parts of systems. To better understand the potential of specific solutions and how they can be integrated for optimal gains, technologies and solutions can be categorised in groups based on functionalities provided.

Five main areas where digital technologies can positively impact grids today



Improving system performance reduces losses and costs

Deploying and using digital technologies creates more efficient, agile, and resilient systems in which decisions are based on robust evidence and reaction times are dramatically reduced from tens of minutes, or even hours to seconds or less. In helping to decrease losses, temper peak time strains, reduce the number and duration of electricity outages, minimise curtailment, and avoid traditional wire upgrades, digital solutions help reduce system costs. Better data and insights, coupled with enhanced system monitoring, can also help improve planning and build resilience to withstand impacts of climate change. All of these measures also provide wider public good benefits in terms of improving reliability of electricity supply, which can help create a more attractive business environment for investors and enable local businesses to develop and grow.



Reducing electricity system losses

A combination of digital technologies and approaches, including digital metering and analytics, customer-centred actions, and new payment options, can help to assess and reduce both TL and NTL. This can be done in cost-effective ways, thus ensuring available capacity is efficiently used, improving the quality of supply, boosting billing accuracy, and increasing payment collection. In turn, reducing both losses and operational and management costs for utilities can lower consumer bills.

By investing in smart meter deployment, with over 45 million units deployed globally between 2001 – 2022, network automation and digitalisation, Enel has improved the efficiency of distribution networks in many systems around the world.

There are also gains to be had in advanced economies. In Italy, this has contributed to a considerable drop in the average number of minutes of service interruption annually, corresponding to just 42 minutes in 2022, as well as loss reduction by more than 20% from 6% in 2014 to 4.7% in 2022.

When placed throughout networks, sensors provide real-time measurements and help uncover the dynamics of electricity flows. In Pakistan, the Peshawar Electric Supply Company tested a system to monitor and control distribution transformers, and achieved line loss reduction of 6.7%. Since 2005, the Ugandan utility Umeme has doubled the size of its distribution network, increased its customer base sixfold to around 1.6 million customers and reached over 99% payment recovery for electricity sold, while also more than halving losses from 38% to 17%. In Kenya, a telecom provider is planning to supply 330 000 smart meters via the build, own, operate, transfer (BOOT) model to Kenya Electricity customers. The overarching goal is to reduce both technical losses costing nearly USD 90 million annually, and non-technical losses valued at over USD 160 million each year.

Countering informal connections and reducing non-technical losses

By significantly reducing non-technical losses, digitally enabled devices are substantially improving the profitability of utilities. However, digital devices alone are insufficient to achieve such gains: in parallel, utilise typically need to implement procedures to monitor and intervene where necessary. Early trials to use digital prepaid meters to reduce non-payment of electricity by users demonstrate this point.

In Ghana, evidence shows that installing smart meters did not, by itself, reduce theft; additional intervention was needed in the form of monitoring and enforcement. A subsequent study in 2019 of a smart pre-pay meters programme reported an increase in customer bills of over 13%, demonstrating reduced NTL.

Monitoring consumption data is one means of reducing losses from meter bypassing but, similarly, it is applicable only if customers are metered in the first place. Traditional methods can also be used to further reduce NTL. Arial bundled/bunched cables (ABCs) for example, are insulated conductors can be installed on overhead distribution lines to prevent the “hooking” that leads to NTL.

Providing formal distribution systems to many locations may not be economic without heavy subsidies, as revenues from average consumption would be less than the fixed cost of the installation. There could be a case, however, for providing grants to support basic supply as a means of reducing excessive NTL and to begin formalising electricity distribution in districts with historically high losses. Such an approach would help prevent overloading electricity networks and reduce outages.

In a 2019 study of 11 smart grid pilot projects in India, all reported reduced electricity losses between 1% and 15%. In Delhi, Tata Power-DDL managed to reduce losses from 53% in 2002 to around 8% in 2020 using a combination of advanced distribution management systems, integrated GIS, smart meters, automated demand response and field force automation, in addition to network upgrades to replace old and inefficient cables, transformers and other equipment.

Decreasing outages and achieving faster restoration

By installing multiple sensors on lines and assets, utilities can rapidly locate faults. In turn, automated systems can reroute electricity to where it is needed while limiting areas affected by outages. In fact, automated systems can react more quickly than human operators, promptly isolating parts of the grid that are experiencing issues before problems spread and affect more customers. In Ghana, use of GIS, outage management systems, and automation and control on medium voltage lines resulted in a 15-fold reduction in the number of hours of average outage duration for each customer served in Accra. Colombia aims to reduce electricity outages in locations with a high proportion of overhead lines – from around 30 hours per user per year to about 5 hours by 2030 – through the use of "self-healing" auto-reclosing circuit breakers while also reducing the duration of transient faults using supervisory control and data acquisition (SCADA) and other methods of communication.

Similarly, a smart grid demonstration project in Haryana state in India sought to identify opportunities to improve the reliability of electricity supply. It showed that a combination of hardware such as circuit breakers and load break switches, and grid reconfiguration analytics in a SCADA system could significantly reduce the duration and frequency of outages – by 6.7% for SAIDI (System Average Interruption Duration Index) and 23.5% for SAIFI (System Average Interruption Frequency Index). In Florida, installation of self-healing technologies helped Duke Energy automatically restore more than 160 000 customers during a recent electrical storm, saving nearly 3.3 million hours of total lost outage time.

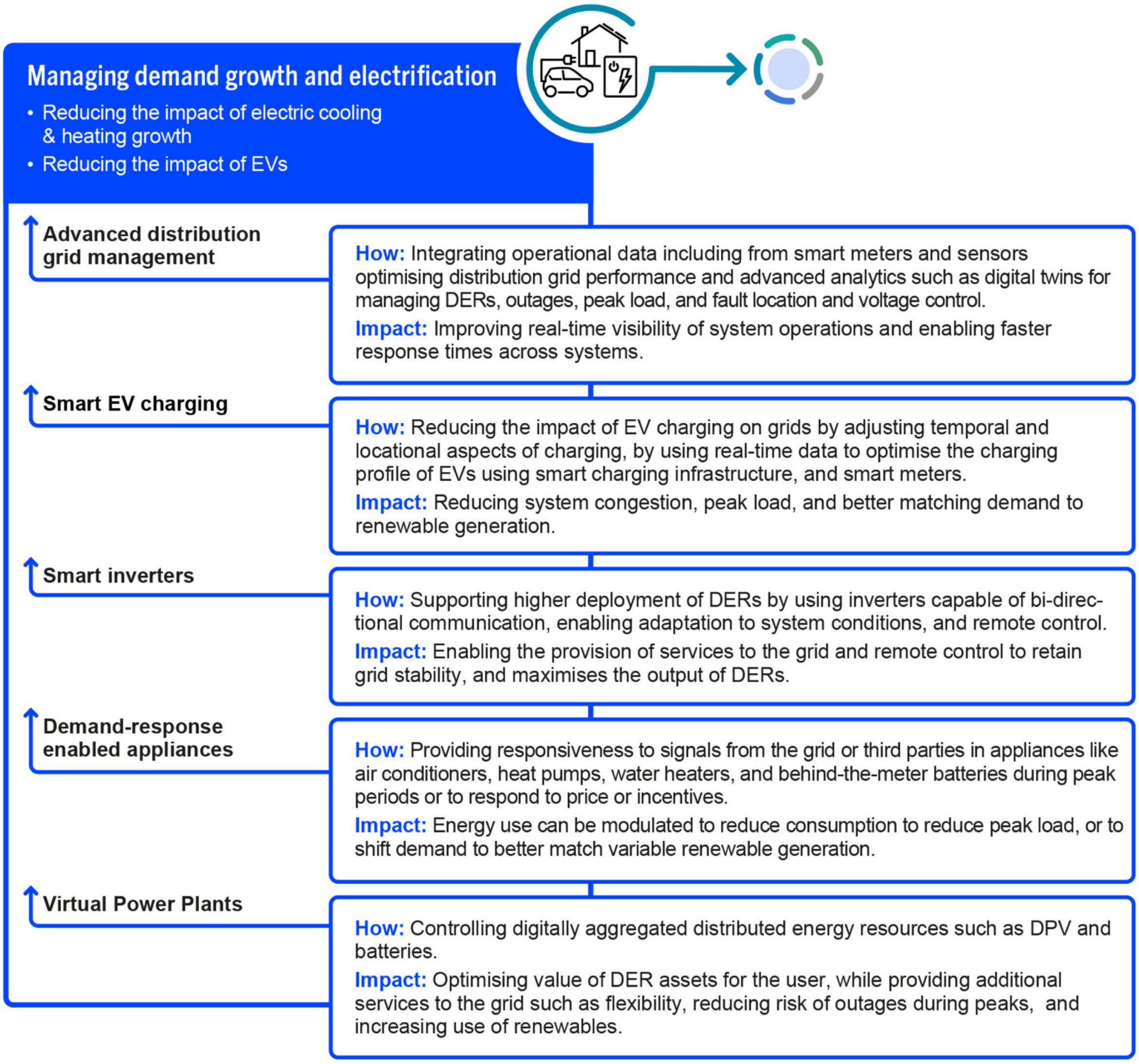
Sensors can also help detect stress on system assets, signalling the need to divert electricity or reduce consumption to avoid congestion or outages. PMUs, for example, provide synchronised, real-time measurement of multiple remote points in the grid. As PMUs have a high cost, "right-sizing" their use is critical. Analysis of the transmission infrastructure in Kenya showed that it was possible to reduce the number of PMUs needed nationwide from 31 to 26 units, thus minimising potential expenditure without lowering the quality of service. In Brazil, synchronised data from PMUs and SCADA provides real-time analysis to support decision making for enhanced monitoring of auxiliary services in the electricity market. This also improves electricity monitoring and operation, transmission capacity, and reliability of grid operation. In many situations, advanced monitoring and controls make it possible to balance electricity loads, troubleshoot and resolve issues without the need for direct interventions by technicians.

Digital technologies can also uncover vital insights that analogue approaches cannot and trigger much faster reactions, thereby lowering losses and damages. For instance, Elvira, one of Northern Europe's largest electricity companies, uses smart grid technologies to monitor unexpected changes and react before equipment fails, outages happen or fires start.

With sensors and other smart technologies, operators also have more control over electricity distribution. Energy can be monitored all the way down the line, from when it leaves the electricity plant to when it arrives at the customer.

In India, Powergrid and Adani Transmission Limited have developed integrated centralised dashboards that capture general, system-related information across a broad spectrum of parameters. Remote monitoring systems have also been installed to capture data – with a high level of granularity – on system availability, tripping and outages, which makes it possible to supervise design and respond to situations in a fraction of a second.

Advanced metering infrastructure (AMI) provides utilities with granular visibility on electricity consumption in terms of magnitude, time and place. As such, it can enable the mapping of consumption patterns and projections that can be used to develop effective demand-response programmes. In parallel, smart meters reduce costs for labour to manually record consumption while also enabling the digital environment to provide customers with choices, including a variety of tariffs and incentives to provide demand-side flexibility. Smart meters can identify events that change how owners of rooftop solar consume or store their generation. Importantly, they can also reveal opportunities to implement new business models.

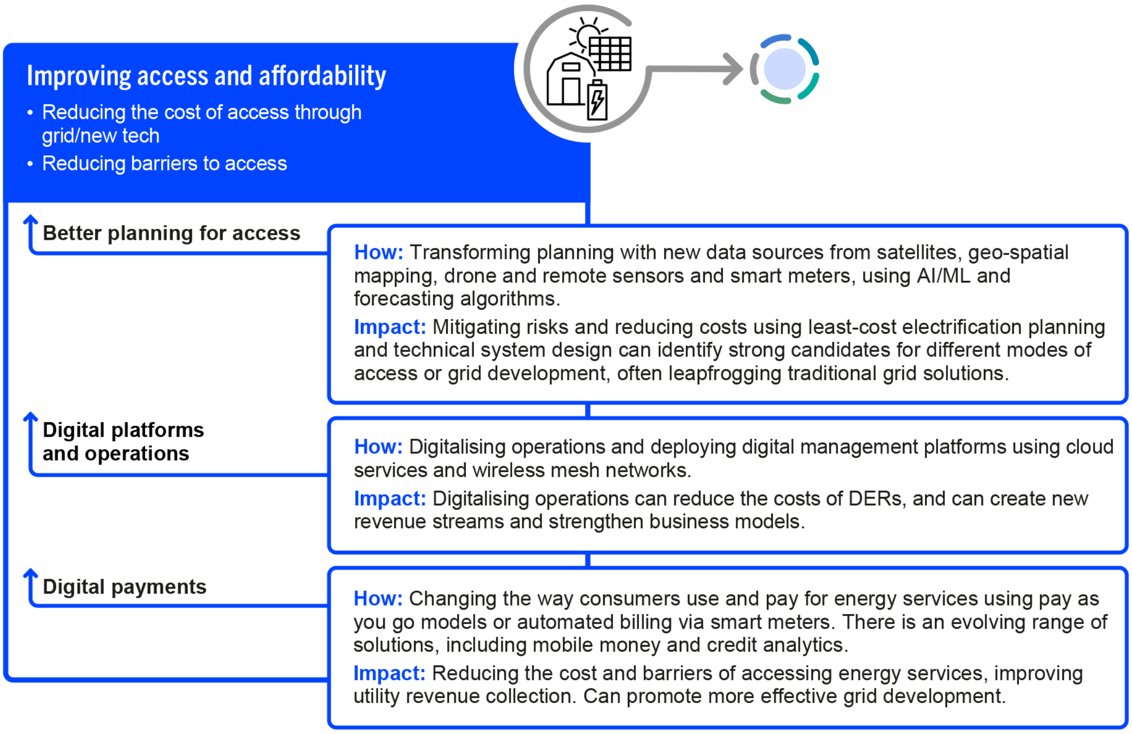


Smoothing out demand is increasingly important in systems that are growing quickly, while simultaneously aiming to decarbonise. Digital technologies can help shift, store or shape electricity demand according to the available capacity of production, transmission and distribution assets, which is increasingly important in systems that are decarbonising. They can help shift energy demand towards times of high levels of VRE production, thereby reducing curtailment.

Virtual electricity plants are networks of decentralised generation combined with flexible loads and storage systems that can remotely and automatically, manage demand as well as DERs to provide clean energy and grid services while also meeting customers' energy needs in a reliable manner. They can help reduce peak demand and related investment in additional capacity and infrastructure to serve a peak load. Such plants are increasingly being deployed across the world, with most to date in Europe, Australia and the United States. For regions and grids at earlier stages of implementing distributed generation, if the goal remains providing system-level benefits, these private aggregators can fill gaps where the rate and scale of performance of new models for consumers to use distributed generation have previously lagged.

Enabling energy access at a lower cost

Digitally enabled mobile communications technologies play a crucial role in expanding decentralised, clean energy access to communities in remote locations – particularly in challenging climates or low-income areas not currently serviced by electricity grids. Globally, at least 19 000 mini-grids are installed in 134 countries, providing electricity to about 47 million people. These small electric grid systems are usually comprised of a generation units and distribution lines that link a number of households and/or other consumers. Typically, these systems are not connected to main electricity networks. However, even on mini-grids, technologies such as smart inverters can help automatically monitor and manage electricity delivery and reduce service interruptions during peak demand while increasing productive use of electricity during lower demand.



Digitally enabled mini-grid solutions offer effective opportunities to provide energy access. Mobile off-grid solar systems with batteries, for example, can provide efficient and fast access in remote locations. In favourable geographies, standalone solar systems can provide enough electricity to cover basic needs. Potential exists for digital solutions to provide more resilient supply by further expanding and enabling more efficient mini-grids and larger, standalone community assets with islanding capabilities which enable the “islanded” section to continue operating when there are outages elsewhere in the grid. In Tanzania, mini-grids achieve 98% reliability compared with 47% for the national grid.

In Cambodia, the company Okrasolar undertook a solar peer-to-peer “mesh-grid” project to connect 140 households in 3 villages, generating enough electricity to support also providing fridges, rice cookers, kettles and food blenders. A cloud-based, mobile-enabled application connects to the system, which uses internet of things (IoT) connectivity to optimise the distribution of electricity among connected properties. The app can also be used to pay for energy or to identify issues with the system. These systems have also been deployed in Haiti, Nigeria and the Philippines. In Bangladesh, Solshare uses a similar digitally enabled, peer-to-peer platform with more than 115 mini-grids, supplying over 1 500 customers and 300 electric three-wheelers while reducing CO_2 emissions by 142 Mt annually.

In Uganda, due to good progress in recent years almost 60% of the population now has access to electricity, of which around half of those are grid-connected, and the other half are supplied by off-grid means. A new model is being trialled to accelerate the electrification of remote communities where demand is low, and costs for connection to the distribution grid would be prohibitive for prospective customers. A recent pilot project, called Utilities 2.0, has demonstrated the potential for private developers to fund remote mini-grid projects that will be operated using digital meters monitored by the national distribution system operator (DSO) Umeme. Importantly, the local network will be installed to the utility’s technical standards. This has the benefit minimising costs for customers while guaranteeing interoperability to enable easy integration to the grid-connected distribution system in the future. This could cut by half the cost of connecting the final 10 million people to the grid, currently estimated at USD 7 billion.

Remote monitoring can also facilitate management of isolated renewable electricity plants. Since 2018, the National Thermal Power Corporation (NTPC, India’s largest electricity utility) has had the capabilities to remotely operate the 800-MW Koldam hydroelectricity plant in Himachal Pradesh from its control centre in Delhi – some 300 km away.

Boosting resilience to prepare for the future

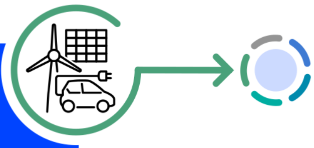
Upgrading electricity grids can be challenging in some countries, where mapping of electrical infrastructure can be incomplete or inaccurate. Without such knowledge, it becomes difficult and costly to make informed investment decisions to expand and modernise electric grid infrastructure.

Digital technologies can also provide advanced planning tools and approaches that enhance resilience for electricity grids. Key areas of current development include improving visibility and multi-scale and multi-objective modelling; integrated planning approaches across generation, transmission, distribution, and customer or third-party systems; granular, DER forecasting tools; scenario analysis tools; and inclusion of resilience as a planning objective.

Multiple entities have made progress in recent years in improving asset and system visibility through diverse platforms. The World Bank funded Africa Electricity Grids Explorer records some locations of high voltage transmission and distribution lines by leveraging OpenStreetMap, satellite imaging and GPS analysis. Much greater granularity is required for spatial analysis to identify weaknesses and improve stability. Open-source data sets and tools can support electricity access planning and help to target loss-reduction measures. In Lamwo district in Uganda, Sunbird AI is helping the Ministry of Energy to identify electrification needs and options for enabling access using Google's Open Buildings, population data and existing national data sets. Open Buildings also includes data from countries in South and Southeast Asia such as Bangladesh, Indonesia, Laos, Nepal, the Philippines, Singapore, Sri Lanka, Thailand and Viet Nam. The Clean Energy Access Tool, developed by the European Union, gathers granular geospatial data on electricity infrastructure and demographics to support electricity access decision making.

Preparing for the future

- Improving resilience
- Improving energy system planning



Grid infrastructure digital records

How: Virtual mapping (e.g. using GIS, AI/ML) of the location and technical specifications of network assets. It can be used for analysis and to simulate grid behaviour under different conditions.

Impact: Supports evidence-based decisions, including predictive maintenance and reducing the rate of failures, on planning and targeting investments.

Resilience planning

How: Mainstreaming long-term resilience as a planning objective, including other sectors and hazards outside electric utilities' usual exercises (disaster risk management, water, variable renewable resource availability)

Impact: Promotes long-term cost and risk management, shifting towards more modern regulatory models.

DER forecasting

How: Big data analytics (smart meter, weather, economic indicators, load demand, sensors) can be combined in mathematical models aided by ML and AI.

Impact: Forecasting DER growth at levels closer to the end consumer can help integrate large amounts of DERs, particularly in weaker networks; improve system management; and improve distribution network planning.

Multi-scale and multi-objective planning

How: New, multi-scale analytical tools can plan for DER growth in tandem with grid expansion, model new energy projects within digital twins and create multiple grid development pathways considering a range of policy objectives.

Impact: Grid planning efforts can be combined with renewable deployment policies, electrification and access policies, large-scale efficiency interventions, or transport planning to achieve more efficient outcomes.

Modelling and simulation tools can help grid planners analyse data and project future demand patterns. This allows them to make decisions on capacity expansions or upgrades, resulting in more efficient and cost-effective grid planning. Digital technologies, through multi-scale modelling, can also help optimise the costs associated with grid planning by identifying optimal locations for new transmission lines or substations and minimising the costs associated with construction, maintenance and operations.

These technologies can also help grid planners assess and manage the risks associated with planning exercises. Simulation tools can be used to evaluate the impact of future extreme weather events, identify potential vulnerabilities in grid systems and develop plans to mitigate those risks. Technologies can also improve communication between grid planners, operators and stakeholders. Involving market design processes in integrated planning is important to have a positive feedback loop of what is needed, who needs to deliver it and how to better incentivise behaviour to achieve those goals. Real-time data and analytics can be shared with stakeholders to help them understand grid performance and plan accordingly.

Digital technologies can help grid planners improve grid resilience. Modelling tools can simulate the impact of disruptions and identify areas or specific points at which backup electricity or other resilience measures are needed. Digital technologies can also increase resilience in more immediate ways. Early warning systems that collect and analyse multiple, real-time data sets provide utilities and other stakeholders with more time to prepare for and react to the ravages of extreme weather events. Advanced monitoring and control systems can help recovery and ensure faster reconnection of electricity for critical infrastructures or vulnerable populations, including by better scheduling restoration crews. Advanced image processing and artificial intelligence (AI) can help identify overgrown vegetation and equipment defaults from pictures collected, for example, by drones.

In India, the National Hydroelectric Power Corporation (NHPC) has launched a cloud-based software application with real-time data from the Indian Meteorological Department. By monitoring river water levels and discharges upstream and downstream of hydroelectricity plants, it serves as an early warning system that can issue warnings to allow relevant stakeholders to act. The NHPC is also planning to set up a central control room facility to monitor hydroelectric projects and plants.

Paving the way for higher shares of variable renewables

Digital technologies such as renewable energy forecasting tools and advanced distribution system management (ADMS) can reduce the cost of installing and integrating renewable electricity generation. Forecasting and ADMS help improve the productivity of renewable electricity generators. Data and analysis can also help optimise siting of renewable energy projects to improve productivity and grid integration.

Egypt, with the support of a range of international initiatives and organisations, developed a high-resolution solar atlas to help guide future investments and develop plans for efficient exploitation of solar energy. In turn, the atlas helped secure funding of USD 2.2 billion for solar projects.

Improved data and analytics can also enhance the productivity of other renewable energy assets. In India, a demonstration project using analytics of atmospheric and operational data in a wind farm boosted output by 1-3%, depending on wind speed. The additional information provides guidance for adjusting the orientation of wind turbines in a co-ordinated way to avoid the wake effect. Better data and modelling can also reduce errors associated with forecasting, as well as with product and project design. Vortex, a company specialising in wind modelling, has developed tools that enable error reduction by 3-4%.

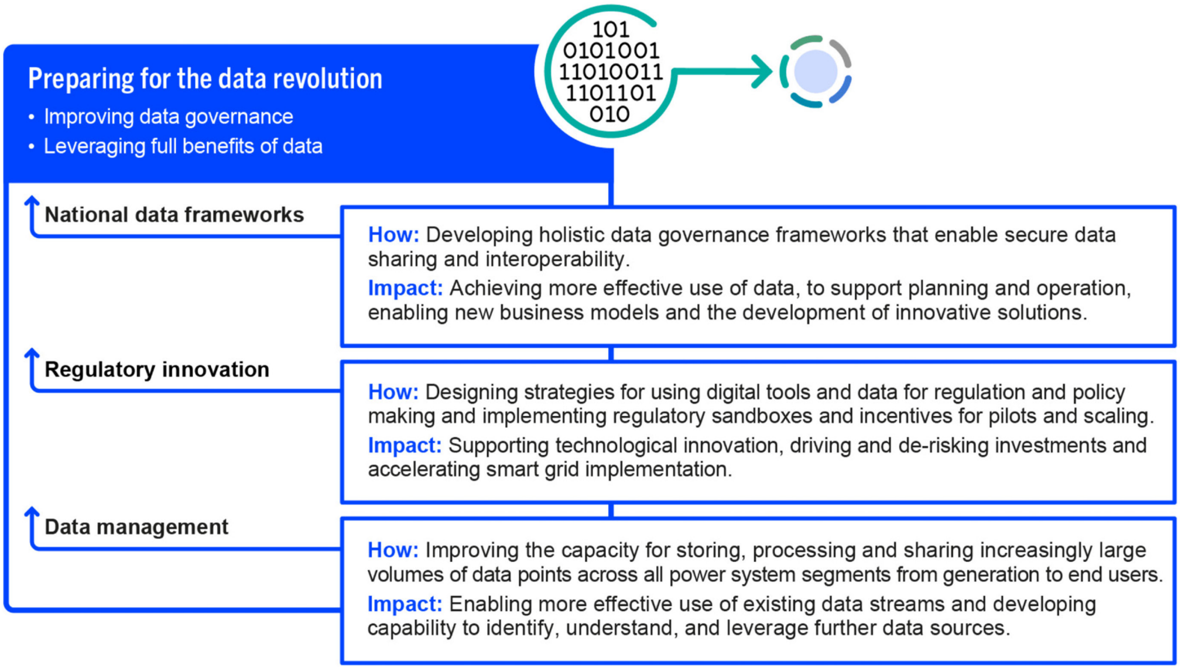
Preparing for the data revolution

The number of smart power meters worldwide exceeded 1 billion in 2022, a 10-fold increase since 2010. Meanwhile, connected devices with automated controls and sensors are expected to reach 13 billion in 2023, up from less than a billion a decade ago. This number could exceed 25 billion in 2030. In addition, there are a range of other data sources that can in combination provide insights to enable enhanced electricity system planning and operation.

Leveraging the full potential of digital solutions rests on the success of data management frameworks and strategies. Data needs to be collected, stored, analysed, and shared, while ensuring privacy and cybersecurity. Good data management can be beneficial for power systems in many ways. Granular data on consumption, combined with better demand forecasts, allows connected and automated consumer appliances (such as water heaters or electric vehicle chargers) to provide flexibility for the power system: by turning off at peak time or switching on when renewable output is high, they facilitate the integration of renewables, resolve grid congestion, and reduce peak consumption. Moreover, easily accessible high-quality data on consumption and power systems can also help commercial parties develop new services and products for power customers. It also speeds up power restoration after faults.

While large amounts of data can bring many benefits to electricity grids, current data sets are not being fully exploited and insufficient efforts are made to access and analyse new data. Globally, smart meter data utilisation is still below its potential, with only 2% to 4% of data available currently being used to enhance the efficiency of grid operations. A survey of 10 Transmission system operators (TSO) shows that most agree their control rooms do not make full use of data analytic applications, even when they have fully digitalised grids equipped with sensors and remote control. The energy system is collecting more data than ever, but too much of it remains idle, or stuck in siloed storage, with significant untapped potential. There are a range of areas that require attention to ensure more effective use of data including:

- Data security: As more data are generated and transmitted across grids, the risk of cyberattacks and data breaches increases, which could potentially compromise grid security and reliability.
- Data management: Managing and processing large amounts of data can require significant investments in data storage, processing and analysis capabilities.
- Privacy concerns: The collection and use of large amounts of data can raise questions among consumers about how their data are being used and who has access to it.
- Interoperability: With the increasing number of data sources and systems on grids, additional effort is needed to ensure interoperability among different systems and platforms.
- Human error: While digitalisation can enable greater automation of tasks on the grid, it can also change the risk of human error, as operators and technicians may be required to manage increasingly complex and sophisticated systems.



Systematic approaches and national initiatives can start to effectively address data challenges and help unlock opportunities. The UK government, the electricity regulator Ofgem and Innovate UK set up the Energy Data Task Force to develop an integrated data and digital strategy for the energy sector in 2018. The task force, in its recommendations released in 2019, highlighted that progress towards modern energy systems is hindered by poor quality, inaccurate or missing data and outlined actions needed to tackle these problems. Following these recommendations, in 2021, the Energy Digitalisation Task Force was established to continue to support progress towards effective use of data for clean and affordable energy.

Digital tools for data access and use can also be leveraged to stimulate innovation and develop low-cost solutions. The Government of Ghana and the Millennium Challenge Corporation (MCC) are investing in increasing the quality of the electric grid to reduce outages. MCC partnered with a UC Berkeley team to pilot new technologies as a way to crowdsource grid measurements using smartphones (ElectricityWatch) and low-cost, fixed-point sensors. Utilising these two sensing methodologies in conjunction with cellular networks, the team successfully piloted a uniquely scalable grid monitoring system to answer questions about when and where outages occur, how long they last and whether infrastructure improvement investments increase reliability.

Programmes and platforms can also be created to identify challenges and support innovative ideas to tackle them, such as hackathons and competitions. The data science platform Zindi works with stakeholders across Africa to develop challenges based on current issues and shared datasets, which data scientists can help to solve. The Tunisian Company of Electricity and Gas organised an AI hackathon event to help reduce the USD 60 million worth of NTL each year. By using advanced ML techniques, researchers were able to study data and ascertain that they could locate anomalies with a high level of confidence. By applying this technique to real-time, smart meter data, it is possible to alert utilities for rapid investigation. The Brazilian independent system operator has been promoting hackathon events that apply statistical and ML techniques to help foster its forecasting frameworks of hydroelectricity inflows, wind, and load. There is a range of other options in terms of crowd sourcing. Meter Hero targets schools and communities, providing both learning opportunities and data insights. In South Africa, to bridge current gaps, ESKOM is using a digital platform to crowdsource people with mechanical, nuclear, electrical, system, operations, and maintenance skills and expertise.

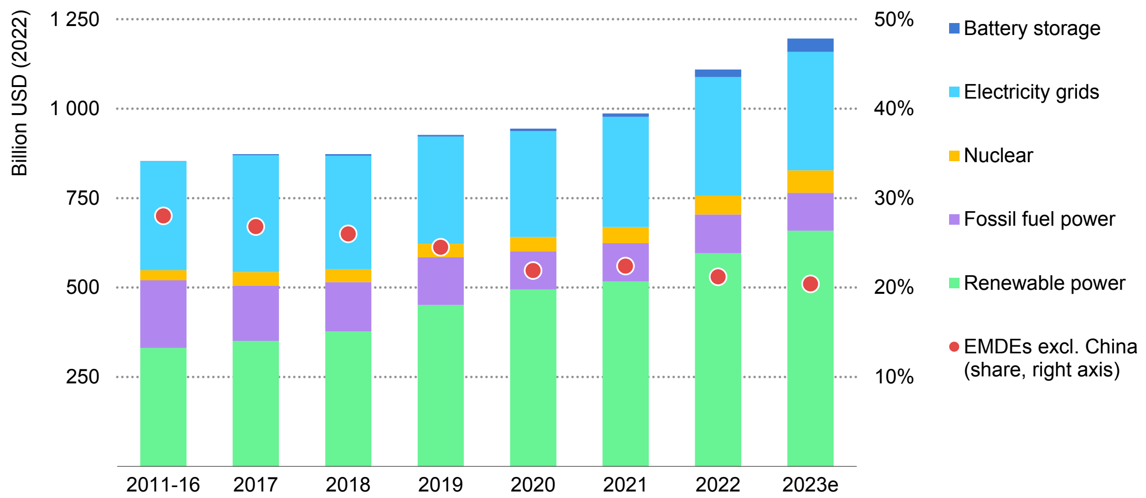
Mobile phone applications and text message notifications can help both to inform and to gather information from consumers on ongoing outages to resolve the issue. The Urja Mitra initiative in India provides a web-based and mobile outage management platform for more than 50 distribution companies. This delivers real-time outage information and is integrated with the meter data acquisition system in order to allow field staff to more effectively intervene and restore electricity.

How to get investments to flow

Grid investment is lagging

Investment in electricity network infrastructure has been lagging in recent years, which poses multiple challenges to meet current demand and prepare for the significant ramp-up required in the coming decades. The shift towards deeply decarbonised electricity systems necessitates a re-thinking of how grids operate, which could guide investment decisions. In developing economies, most investments will need to be directed towards expanding and strengthening the grid, while also shifting towards smarter and more resilient distribution grids to accommodate the increased deployment of new cooling, heating and electrified transport technologies.

Global average annual investment in the power sector by category, 2011-2023e



Note: Investment is measured as ongoing capital spending on new power capacity; all numbers throughout are in 2022 USD; Fossil fuel power includes unabated and abated power; EMDEs = emerging market and developing economies; 2023e = estimated values for 2023.

The IEA estimates that the annual average investment in grids needs to more than double from an estimated USD 330 billion in 2023 to around USD 750 billion[6] by 2030. Currently, over 75% of total global investments in grid digitalisation are directed to distribution grids with the aim to expand, strengthen, and enhance the reliability and flexibility of the grid. However, while investments in grids have increased globally, jumping 8% in 2022, the share of investments in grids in

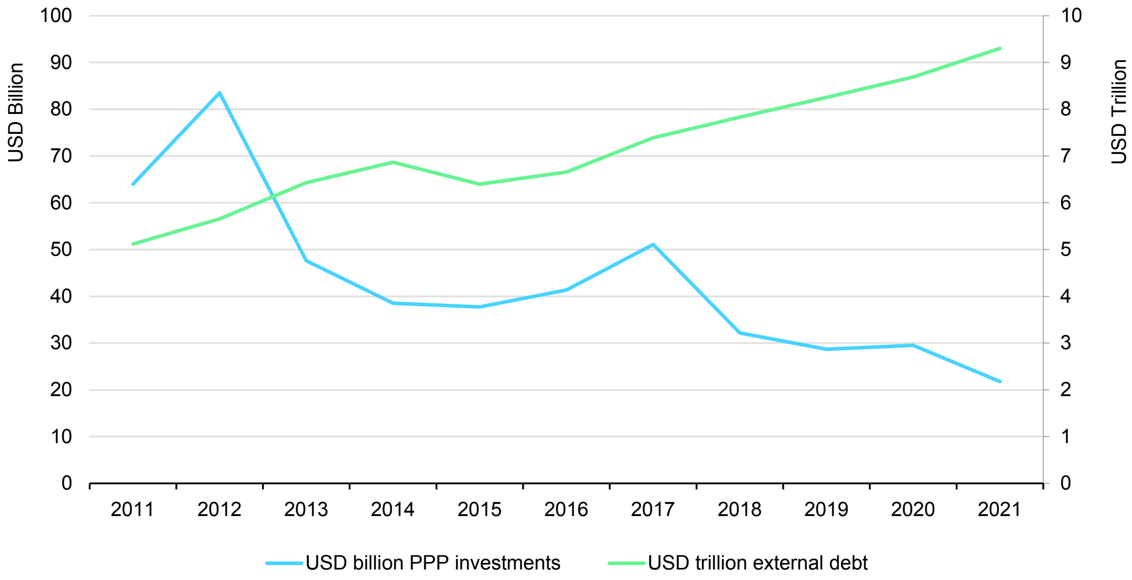
[6] Based on IEA (2022), Net Zero Emissions by 2050 Scenario, World Energy Outlook 2022.

EMDEs have fallen in the last decade. This is a worrying trend when electricity demand in EMDE is expected to grow substantially.

While each country has its own specificity, challenges related to high perceived risk and cost of capital, as well as to poor financial health of utilities, are hindering investment in grids across many countries.

After the surge in 2021 and 2022, many critical mineral prices started to moderate in 2023 but remain well above the historical averages. In 2022, copper and aluminium represented around 30% of the cost of new grid investment, 10% higher than in the investments made between 2010 and 2020. Current inflation levels are increasing the cost of clean energy technologies such as solar PV modules, batteries and inverters. The costs of solar and hybrid mini-grids are estimated to have increased by more than 20% on average in 2022; the market price of solar home systems increased by around 30% since 2020. Combined with local currency depreciation, this could discourage investment in affected countries.

Public-private partnerships investment in energy projects and external debt stocks in EMDE countries, 2011-2021



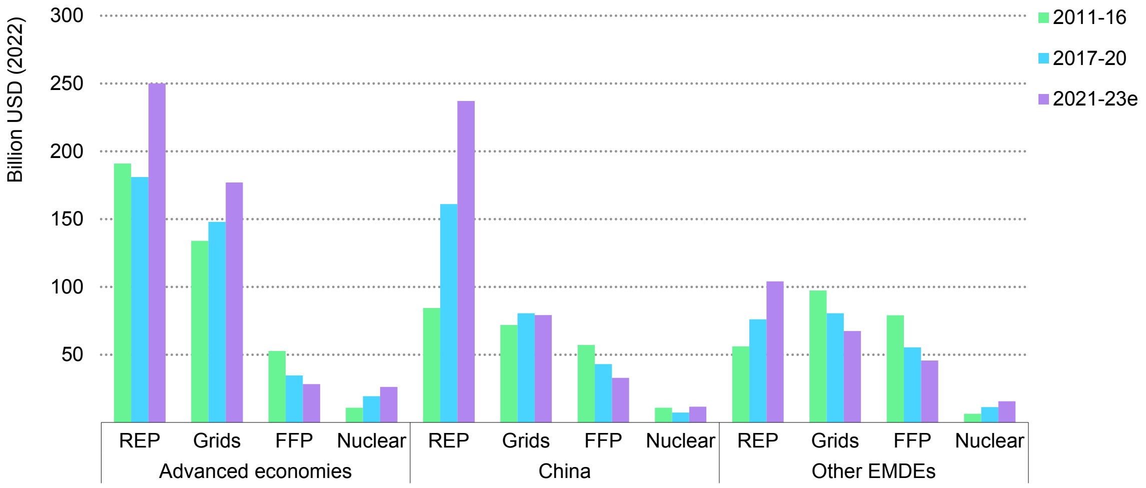
Source: IEA analysis based on World Bank (2023).

According to the Inter-American Development Bank, to ensure universal access to electricity by 2030, Latin America and the Caribbean would need to invest more than USD 25 billion in new infrastructure, mainly at distribution networks level of which 80% is in urban areas. In addition, around USD 64 billion is needed to maintain and replace distribution grid assets in the region. In India, investment in grids has trended downwards in recent years, from more than half of electricity investment in 2015 to around one-third in 2020, reflecting the challenging financial situation of distribution companies. Globally, in addition to investments in grids to maximise the potential for digitalisation, over USD 400 billion is needed for universal digital connectivity by 2030, with India alone requiring almost USD 100 billion.

The governments of many emerging markets and developing economies are under the increasing strain of debt, which has doubled in the last decade, much of it owed externally. The unprecedented challenges of the Covid-19 pandemic have added to these economic woes with a global slowdown that has pushed many countries further towards debt distress.

As national debt has risen in many emerging markets and developing economies in the last two decades, in parallel the corresponding volume of investments from public-private partnerships (PPPs) which can be used to minimise increasing national debt burdens have plummeted by around two-thirds. Additionally, many of these recent private investments have focused on the generation side rather than improving electricity grids.

Average annual investment in the power sector by geography and category, 2011-2023e



Note: REP = renewable power; FFP = fossil fuel power; batteries are excluded here; 2023e = estimated values for 2023.

The energy crisis triggered by Russia's invasion of Ukraine has created further disarray, just as many nations began to recover from the pandemic-related economic slowdown, which led to severe disruptions in financial markets, increased risk aversion among investors, and reduced economic projections. These two events also led to an increase in public debt, putting a number of countries at risk and further deteriorating investment prospects. Extreme weather events related to climate change are becoming more frequent and severe and could result in further government debt increase.

Such endogenous and exogenous pressures on national budgets further reduce the availability of public funds to invest in among others, the critical physical and digital electricity infrastructure needed to reach universal access to electricity and energy security, thus leaving a widening spending gap. This calls for identifying innovative ways to fund relevant projects to avoid saddling countries with further debt.

Investment is needed across the whole system

While there is no uniform or linear approach to updating electricity grids, some common elements underpin the overall process, namely solid infrastructure, seamless data flows and analytics, human capacity, and a comprehensive investment plan. To increase the chances of success, the latter could include not only providing capital for project implementation but also funding for operation and maintenance in the long term.

Investments will need to flow to reinforce existing grids and to improve stability with new infrastructure and modern technologies, particularly where population size and increased demand have outstripped the existing local networks.

Smart grid technology investment opportunities span the entire electricity grid, from high voltage to behind the meter of customers. They encompass hardware, software and enabling infrastructure for both communication networks and for platforms to store and manage data. Investing in decentralised solutions that are enabled by digitalisation, opens up new opportunities to fast-track affordable access to electricity through off-grid connections. In time, these can be connected to the main grid to enhance efficiency and resilience. Critically, to enable smart grid functionalities, investments in foundational technologies and infrastructures such as reliable and appropriately sized telecommunications networks are needed for a basic standard internet connection and data transfer capabilities. That involves cellular base stations, fixed line broadband for digital connectivity, data centres for data storage and processing, and the various digital devices that serve as interfaces across different devices.

In countries where the ICT infrastructure is still weak or coverage is patchy, approaches could be explored in which collaborative investment models can support build-out. Sharing networks through cross-sectoral co-operation between utilities and telecommunications, for example, creates potential to increase infrastructure utilisation and reduce unit costs. Often, fibreoptic cables installed by utilities are only partially utilised, leaving many of the glass fibres available. These unlit or “dark” fibres can be leased to third parties to use for data services, as is being done in India, Tunisia, Japan, Lesotho, and Ghana. Weak incentives or disincentives, however, are blocking investments in many countries and utilities and telecommunications companies lack knowledge of each other's operations.

Any of a myriad of digital solutions can potentially bring value and a range of benefits to the electricity system. The extent to which this value can be captured, however, will depend on skills and capacity and the degree to which data can be analysed to provide information needed to optimise the system. In turn, it also depends on the extent to which these technologies and associated data can be mainstreamed into the existing systems and operations of utilities. Which technology combinations may provide the greatest value for investment will also depend on the most pressing challenges and expected future needs in a given context.

A range of actors can play vital and complementary roles

A range of entities can directly invest or support investments in smart grid technologies, with diverse stakeholders providing expertise or know-how to achieve full implementation.

Utilities, either state-owned or private, generally expand their infrastructure with their own equity along with government funds and debt financing, often from international finance institutions (IFIs). Energy service companies (ESCOs) are increasingly taking part in PPP arrangements with utilities by providing infrastructure and equipment in exchange for service or concession contracts. Institutional investors (pension funds, hedge funds, and insurance companies) are increasingly investing in energy infrastructure. Each has its own targets in terms of transaction size, balancing their desired risk profile and overhead costs related to reaching financial close on a transaction. Some technology providers are developing models in which they finance the initial capital expenditure (CAPEX) investment of their products such as smart meters in exchange for future payments in a concession or "pay-as-you-save" service model.

The investor is not necessarily the sole financier. In nearly all cases of public investment, and even many with private investors, at least one debt financier would be involved. For public investment in emerging economies, this is generally development banks. For projects with private participation, the financing partner is generally an international or regional commercial bank, depending on the size of the investment. Even in cases of private investment, it is not uncommon for an IFI such as the World Bank or the International Finance Corporation (IFC) to provide financial de-risking products such as investment insurance for PPP arrangements.

Complex investment barriers are hindering deployment

The benefits of modern, digital electricity grids are undeniable in terms of both short-term gains and advancing towards longer-term goals for fully decarbonised and resilient electricity grids. Still, a number of hurdles and barriers are constraining investments in smart grid technology.

Often topping the list of barriers, investment in digital grid infrastructure is capital-intensive and usually involves financing smaller pieces of equipment that need to be installed in a distributed yet integrated manner. The cost of capital in some countries in emerging markets and developing economies is up to seven times higher than in the United States and Europe, even considering the higher risk levels in other riskier sectors. This creates a high bar for investments to access debt finance and to meet equity return hurdle rates.

Capital-constrained utilities have limited options to obtain low-cost debt. Raising consumer tariffs is one approach regulators use to finance investments. In EMDE regions, where household incomes are low, policy makers typically have a strong focus on electricity affordability for the majority of their population and rural electrification. Current regulatory models tend to skew investments towards physical assets rather than new technological solutions, leading to situations in which companies or utilities would rather invest in new cables than in sensors that monitor the performance of components.

Use of digital technologies also requires new knowledge, changes in workflows and different engagement among actors. According to the World Bank, utilities in developing countries often do not have the institutional knowledge or technical capacity to manage the system risks linked to smart grid services. Often, it is not only that utilities cannot implement the services, but they also lack capacity to procure such services from the private sector.

Well-planned investments in smart grid technologies can deliver significant benefits. Some benefits have public good characteristics like decarbonisation that do not fully translate into revenue for the investor. This complicates the investment decision since all benefits may need to be monetised and accounted for in order to create a positive business case. For instance, one benefit of advanced metering infrastructure is to help manage peak demand. Reducing peak demand can benefit the transmission and distribution system if, for example, it helps to defer investment in grid upgrades, avoid outages and in some cases lower the cost of generation. Investment costs are typically borne entirely by the utilities and as such, unless regulations are revised to compensate for efficiency gains, utilities would ultimately not be able to recover costs.

Different investor profiles can be leveraged to overcome barriers to investment

Public investments can help attract private capital

Public sector investments, either domestic or international, can be used to build confidence to incentivise the flow of private capital to individual projects or work programmes in emerging markets and developing economies. The Just Energy Transition Partnership with South Africa for example, is one such programme with the aim of reducing its dependence on coal, whilst also tackling the social aspects of a population reliant of the fossil fuel industry for employment. The first phase of the scheme will commit USD 8.5 billion of investments from the European Union, the US, and the UK, to South Africa through grants, concessional loans, and risk sharing instruments to de-risk projects to facilitate private sector engagement. Similarly, the Just Energy Transition Partnership with Indonesia is mobilising USD 20 billion of public and private investment, half of which from the United States, Japan, Canada, Denmark, France, Germany, Italy, Norway, and the United Kingdom, among others. Additional partnership agreements to mobilise investments could also include packages for India, Senegal, and Vietnam. Similar initiatives could be used to finance the energy and digital infrastructure investments necessary to build resilient smart grids.

Private sector participation can help fill the investment gap

At present, many utilities in emerging markets and developing economies cannot afford new infrastructure. If, however, new investment models can be implemented to cover the upfront capital costs, many smart grid investments can actually pay for themselves in a timely manner through reduced losses and operating costs, which also generate increased revenues.

To date, investment in grids in EMDEs has been undertaken mainly by state-owned enterprises (SOEs). While this share remains predominant, IEA climate-driven scenarios show that, going forward, private sector participation can help fill the investment gap and achieve universal access. In IEA climate scenarios, 70% of investment in clean energy comes from the private sector, although this share drops to around only 25% for grids. Africa, home to most of the nearly 775 million people who still lacked access to electricity in 2022, attracts less than 5% of global energy investment – of which 40% is directed to South Africa alone.

A prerequisite for private sector participation in the transmission and distribution sectors is that it is legally possible. In Brazil, for example, the current regulatory framework has enabled nearly 77% of the distribution business to be run by private utilities. Recent privatisation of Eletrobras (formerly a full SOE) may lead, in the future, to nearly 89% of private share in the transmission segment. In Brazil, Enel has already installed about 180 000 smart meters as of 2022 in the São Paulo area, within the Brazilian Electricity Regulatory Agency's (Aneel) R&D program, whose aim is to reach 300 000 installations. As a further step, Enel is planning to continue with the smart meter penetration, targeting about 1.8 million units operational by 2025. Smart meters include functionalities such as remote billing and reading, remote disconnection and reconnection. Notably, the smart meters will be produced locally, creating manufacturing and job opportunities.

To attract private investment, having stable and supportive policy and regulatory frameworks, as well as a strong governance, are essential. Other important enabling factors include a clearly defined framework under which the private sector can participate, namely what activities are allowed and related timelines, what obligations apply to the actors involved, and what remuneration mechanism might be used. In turn, visibility over the selection criteria and process is vital. The World Bank maps out preconditions necessary for optimal deployment of PPP projects in EMDEs to enable development of smart grid technologies and services. These include the stage of electricity sector reform, the operational reach of relevant utility in which smart grid technology might be deployed, and conditions under which long-term contracts with private service providers are possible.

Private sector participation models

Model	Description	Typical duration	Examples
Service contract	The awarding utility pays a periodic fee to the private operator for the supply of a specific service (e.g. meter reading and billing).	1 to 3 years	Contractor operates AMI for Finland's largest DSO for 6 years.
Management contract	The awarding utility pays a fixed fee, which might include performance improvement elements, to the private operator for the management of one or more functions (such as operations and management).	2 to 5 years	Contracts to design, build, finance, own, operate and transfer for AMI for smart prepaid metering in India. Contract to improve public utility operational and financial performance, to rebuild the electricity system and increase access in Liberia. Management contract that includes preparation of a strategic investment plan, implementation of organisational changes, the setup of a manual data and information system, and oversight of operation and management procedures in Sierra Leone.

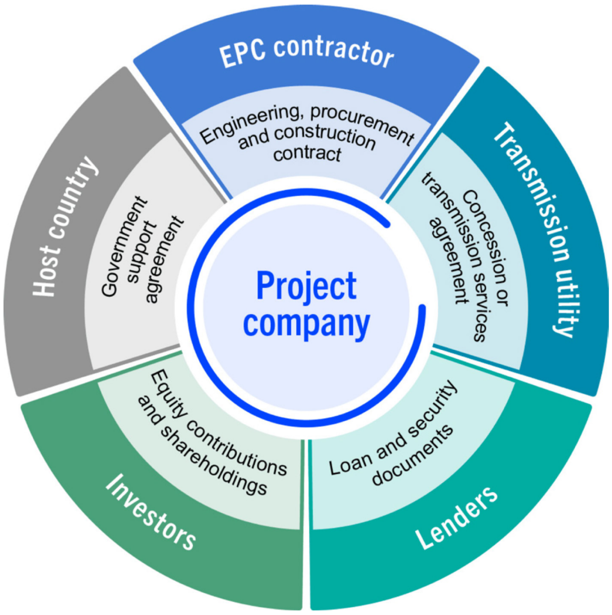
Model	Description	Typical duration	Examples
Lease agreement	The private operator manages one or more functions. It is remunerated through tariff collection and has to pay a lease fee to the awarding utility.	8 to 15 years	Contract for the generation, transmission, distribution, import and export of electricity in Côte d'Ivoire.
Concession	The private operator manages new (green field) or existing (brown field) public infrastructure, investing in grid expansion or modernisation.	20 to 30 years	Independent transmission project contracts in Brazil, Chile, India and Peru. Concession contracts for distribution utilities in Brazil. Transfer of operation rights and concession models for distribution in Türkiye. New law that allows private sector participation to build, manage, and operate electricity grids in Viet Nam.

Source: IEA (2023), RES4Africa (2021), Private Sector Participation in African Grid Development (accessed 30 May 2023).

Many private investments have focused on electricity generation projects in the form of independent power producer (IPP) contracts, which can offer a role for private capital even in regions with vertically integrated utilities. These can provide useful learning to implement similar models to support grid investment, as is the case of independent transmission project (ITP) contracts, which do not require the utilities to be unbundled. Because they enable construction of large infrastructure projects without national utilities assuming the construction risk - and are also economically efficient – ITP contracts can help reduce the financial burden to national budgets. In the United Kingdom, for example, some private constructed transmission contracts (which were competitively tendered) were estimated to generate savings of 23 to 34%. ITP contracts can be easy to finance, discrete by design and internationally tendered. In turn, they can build investor confidence. Brazil alone has over 50 000 km of transmission lines constructed via ITP contracts; other projects have been completed in Chile, India and Peru. In the case of Peru, this approach realised reduced capital costs of around 36%.

A recent and pioneering best practice example for attracting private finance in infrastructure in Africa was launched in Kenya in 2023. With funding totalling nearly USD 300 million, a pilot will proceed to build two transmission line segments and associated infrastructure, covering almost 240 km. As the first such project in Africa, it could serve as a proof of concept and build investor confidence. Such PPP vehicles could go a long way in alleviating financing pressure on the public sector. The World Bank estimates Kenya has a financing gap of 90% for new transmission projects to 2030 – a burden that the state-owned Kenya Electricity Transmission Company (KETRACO) has so far struggled to meet solely with state funding.

Independent transmission project contractual structure



Note: EPC = engineering, procurement, and construction.
Source: World Bank (2023), Linking Up: Public-Private Partnerships in Power Transmission in Africa.

On the grid edge, India has made substantial effort to support private sector participation in the considerable roll-out of smart and smart prepaid meters for public utilities.

In India, the Smart Meter National Programme (SMNP) was conceived to address the issues of high levels of aggregate technical and non-technical losses (AT&C) and piling debt of the state electricity distribution companies (DISCOMs). Both of problems have been significant barriers to investment in grid upgrades and digitalisation. The SMNP aims to replace 250 million conventional meters with smart prepaid meters by 2025 on a standardised, competitive bidding basis.

Deployment of smart meters under the SMNP has been carried out under financing models that require no upfront capital expenditure from DISCOMs or state governments. Instead, DISCOMs are required to only pay monthly lease rentals on the smart meters themselves to private operators, which they generally are able to finance through savings realised over the operation period due to reduced AT&C losses incurred.

Digital technologies can help prepare for the future

DERs, including solar PV, batteries, electric vehicles and other significant distributed loads such as air conditioners, are rapidly expanding globally. Many EMDE countries, including Brazil, India and South Africa, are showing increased uptake of rooftop solar PV systems, with South Africa adding around 500 MW in one year alone while installed capacity in Brazil rose by almost 7 GW in 2022, 51% greater compared to 2021[7]. While this provides significant benefits in energy security and decarbonisation, it is crucial to manage this growth to maintain system reliability, control system costs and ensure that utility business models keep pace with these changes.

Electricity grids in emerging markets and developing economies can capitalise on future cost reductions and the rapid deployment of mature electricity grid technologies. Better monitoring of the system from generation to end-use provides utilities with insights needed for effective planning, optimal sizing and location of assets, and information on where grid reinforcement is most urgently needed. Advanced metering increases efficiencies and reduces losses and can translate into lower customer bills.

Digital technologies are critical to balance supply and demand, ensuring the optimal use of VRE sources. This enables more targeted energy efficiency measures and implementation of demand response to lower and shift demand, thereby reducing the cost of meeting increasing peak demand. In addition, these technologies can help shift energy consumption towards times of high levels of renewable energy production, which can reduce curtailment and support electricity grid decarbonisation.

The immediate challenges experienced in EMDEs, such as high technical and non-technical losses and high energy demand growth, could significantly benefit from smart grid technology deployment. In addition, the need to deploy electricity system infrastructure reinforcement to meet increased demand could be mitigated with smart and flexible electricity systems that more effectively integrate renewable energy and lower electricity grid transition costs over time.

Targeted actions can help scale up investments that accelerate grid digitalisation

Frequent supply interruptions and chronic underinvestment in grid infrastructure are pervasive in many EMDEs. Many electricity utilities were already in a perilous financial situation heading into the Covid-19 pandemic; for many, operational losses have since climbed substantially. While decarbonisation of electricity grids will support energy security, adequate planning, strategic investments and targeted action are needed in parallel to avoid stress on the electricity grid during the transition.

To be on track globally for net zero, annual investment in grids will need to more than double in the next decade, from more than USD 330 billion per year today,

[7] Inputs provided by Brazilian Electricity Regulatory Agency (ANEEL).

to around USD 750 billion[8] in 2030. Globally investments in grids rose 8% from 2021 to 2022 but appear to flatten in 2023. However, the majority of these investments are in advanced economies and China, with EMDEs falling behind.

To fill the underinvestment gap and drive investments towards grids, policy makers could consider two overarching actions that support more specific activities. Given the wide array of potential investors for grid projects, from SOEs to private investors and multilateral organisations, governments could support the design of projects with a view to best leverage each type. This implies taking into consideration their respective preferences for the right combination of debt, equity or grant financing to mobilise capital while still ensuring appropriate risk allocation.

Policy makers could consider opportunities to aggregate small projects to increase the potential pool of investors or realise economies of scale when focusing on procurement. To attract continued inward investment and build confidence, governments can signal to the market to form a pipeline of future projects. This requires future vision, planning and implementation. While a large volume of potential capital is available for grid projects, it is necessary to identify the business case for grid reinforcement, minimise transaction costs, reduce project risk profiles, and open up new value chains. International co-operation can promote standardisation to reduce barriers and increase digital grid investments.

Beyond these points, a critical aspect is creating incentives for utilities to invest and to facilitate the development of plans, capacity and tools to support investments and implementation.

India uses innovative business models to achieve smart meter roll-out

Energy Efficiency Services Limited (EESL), a super ESCO under the Ministry of Power in India, was chosen to implement a smart metering programme at the national level. In turn, EESL entered into a joint venture with the National Investment and Infrastructure Fund (NIIF) and established IntelliSmart Infrastructure Private Limited (IntelliSmart), taking on role of demand aggregator and making the entire upfront investment for smart meters. As is often the case, bulk procurement of the smart meters through competitive bidding created economies of scale and reduced the overall costs of the smart meter roll-out. Projects are now being developed in various Indian states, amounting to 7.8 million smart meters.

The bulk-procured meters by EESL are then leased out to DISCOMs at rental rates that are equal to or lower than the calculated increase in revenue generated from

[8] Based on IEA (2022), Net Zero Emissions by 2050 Scenario, World Energy Outlook 2022.

increased billing efficiency and avoided meter reading costs. At the end of the lease period, the entire smart metering system is transferred to the DISCOM.

To date, more than 5.2 million smart meters have been installed under the programme. Between 2021-32, the programme is expected to save cumulative commercial losses of DISCOMs equivalent to USD ~115 billion – an amount almost equal to the total accumulated debt of the electricity sector. The scheme now falls under the Ministry of Power's Revamped Distribution Sector Scheme (RDSS), and is expected to be a key contributor to the scheme's stated aims of reducing AT&C losses to 12-15% and achieving cost reflectivity by 2024/25.

The targets are ambitious: India aims to implement 250 million smart meters by 2025. This implies the industry will have to increase its capability of rolling out smart meters to around 20 times its current average monthly rate.

In the future, smart meter data are expected to allow DISCOMs to analyse household energy usage patterns and benefit from demand-side management, outage prevention and distribution optimisation.

Institutional investors need to be brought on-board

In Organisation for Economic Co-operation and Development (OECD) countries alone, over USD 100 trillion has been invested each year in assets by institutional investors. However, future investment opportunities in infrastructure projects are estimated at over USD 900 billion each year in EMDE markets. However, there is additional potential in non-OECD locations as future investment opportunities in infrastructure projects are estimated at over USD 900 billion each year in EMDE markets.

Projects such as transmission networks, which have a low yield and a very long payback time, may not be suitable for some private investors. They can, however, be suitable to institutional investors that favour low-risk investments with a combination of debt and equity and a guaranteed return over a longer period of time. Recent transactions by pension funds in places such as Botswana, Chile, Nigeria, and Canada demonstrate the potential for mutual benefits for national utilities and investors. While clear demand exists for investing in grids, a major barrier to mobilising private finance is the shortage of well-structured, bankable project pipelines.

International financial institutions can assist

As smart grid investment projects can be complex and can be perceived as risky, there is a need to raise awareness of their importance within the international finance community to ensure that loans and relevant financial products are developed and accessible.

Multilateral development banks (MDBs), development agencies and other IFIs can support tailored programmes to provide access to funding and expertise. They can help to strengthen existing activities and promote more fundamental institutional and policy reforms. MDBs play a key role in helping governments create effective enabling environments for deploying digital technologies, building capacity and providing various innovative financial instruments to boost participation of the private sector.

The Global Infrastructure Facility (GIF) is a G20 initiative, providing funding and advisory support to governments, MDBs and other global partners such as the African Development Bank (AfDB), the European Bank for Reconstruction and Development (EBRD), the Inter-American Development Bank (IADB), the IFC, and the World Bank. The GIF assists in early-stage project development to act as a project preparation facility (PPF) that helps select, design, structure and prepare infrastructure projects in emerging markets and developing economies to mobilise private sector involvement. Up to Dec 2022, the GIF has assisted projects in 67 countries with an estimated total investment value of USD 87 billion, including USD 56 billion of private investment. Of the total investments, 37% has been allocated to energy projects with another 5% to ICT projects.

The Renewable Energy Integration programme, launched in 2021 by the Climate Investment Funds, offers a range of flexible cost- and risk-bearing financial instruments coupled with technical assistance to help scale up public and private investments in smart grids, energy storage and new business models. Ukraine, Fiji, Colombia, Kenya and Mali are the first countries to participate, with Brazil, Costa Rica, India, Indonesia and Türkiye being priority countries for the next phase.

The AfDB, Nordfund and other partners recently set up the Facility for Energy Inclusion (FEI) to catalyse financial support for innovative energy access solutions. It provides a range of debt products including corporate and project loans. With support from the Global Environment Facility (GEF), the FEI disburses returnable grant funding from its PPF to fund last-mile processes. This helps close transactions and fund extraordinary costs incurred in establishing innovative structures or transactions.

In Colombia, under the FENOGE Be Energy programme financed by the IADB, more than 13 000 electricity customers benefited from the replacement of light bulbs with almost 5 000 families provided with energy-efficient refrigerators and air conditioners. Additionally, solar PV solutions were installed in 18 official and social infrastructures. As part of the reconstruction process of the islands of Providencia and Santa Catalina, devastated by hurricane Iota in 2020, more than 500 solar systems with storage were installed to contribute to the sustainability and resilience of communities.

Development finance institutions (DFIs) can support specific projects to facilitate deployment of smart grids to reduce pressing issues, such as outages and low collection rates. In Brazil, the World Bank disbursed USD 272 million in the Eletrobras Distribution Rehabilitation Project which focused on six distribution companies, while Eletrobras contributed USD 148 million.

Capacity building can be supported by a range of actors to meet diverse needs. The World Bank has set up the Utility of the Future – Knowledge Exchange Platform (UKEP) to provide insights and peer-to-peer learning opportunities for utilities in EDMEs. In India, facing the need to raise awareness about and build a common understanding of smart grids, the India Smart Grid Forum, with the support of Shakti Sustainable Energy Foundation, published a smart grid handbook for regulators and policy makers.

The Puerto Rico Community Energy Resilience Initiative (CERI) is a collaboration between the Global Energy Alliance for People and Planet, Fundación Comunitaria de Puerto Rico (FCPR), and the Rocky Mountain Institute (RMI), with support from Enel North America. It fosters equitable access to affordable, resilient and clean energy in lower- and middle-income communities. Installing solar and storage microgrids, i.e. decentralised energy system that have their own sources and loads and can be islanded from the main grid, at critical facilities can improve energy resilience, enabling them to stay operational for communities during routine outages and at times of crisis. CERI blends grants and loans to create clean electricity systems tailored to each community's needs. Programme elements are designed for community involvement and ownership of the energy system, including operational training for system installation, operation and maintenance.

Grid investments can be made eligible for international climate funds

Smart grid initiatives and projects are explicitly mentioned in the NDCs of an increasing number of EMDEs, especially as they submit updated and new NDCs. Colombia assesses that, without smart grids, reaching its NDC commitment by 2030 would require an additional cost of USD 42 million per year. In 2020, Colombia included actions aimed to narrow the gap between energy use across peak and off-peak hours in its NDC. Thailand lists smart grids as a priority area under technology development transfer in its 2020 NDC. The Philippines is also exploring how smart grids can help integrate increasing shares variable renewables towards achieving its NDC commitment.

Egypt, which hosted COP27 in 2022, submitted its first updated NDC in June 2022, with smart grids identified as an important pillar of the climate strategy, notably to integrate larger shares of renewable energy generation. The revised NDC aims to significantly to improve electricity efficiency, reduce carbon emissions, and reduce the investment required for infrastructure for electrical networks through a smart grid transformation. In Indonesia, the Ministry of Energy and Mineral Resources (EMR) is planning to develop a smart grid project in 2025 aimed to address the mismatch between the locations of renewable energy sources and areas with high electricity demands. The project will promote technologies such as smart grids, smart meters and battery energy storage system (BESS). Likewise, Mauritius has embedded smart grids in its updated NDC, as a pillar of its grid modernisation strategy to integrate distributed generation. As NDCs are increasingly aligned with national energy plans and policies, smart grids targets and goals can be framed more holistically, reflecting their twin contributions to climate change mitigation and adaptation.

Enabling the use of climate funds for investments in grids in EMDEs

Given the importance of robust, reliable and flexible electricity grids to support the clean energy transition, exploring is warranted as to how climate funds could be leveraged to enable grids to support decarbonisation more effectively. Considering the scale of grid investments needed to support decarbonisation in emerging markets and developing economies, international finance is critical for mobilising the financial resources needed to help de-risk and realise the necessary investments. Recent analysis indicates that under current eligibility criteria used by financing organisations, less than 40% of the grid investment needed in these countries in 2030 would be climate finance attributable.

Important steps towards directing investments to sustainable projects and activities include both the Common Principles approach of IFIs and the EU Taxonomy developed by the European Commission. For countries in nascent stages of electricity grid decarbonisation, however, a risk exists that grid investment projects would not meet the eligibility criteria. Further clarity could enable greater access to climate finance for grid investment needs.

How to convey value and attract investors

A standalone investment opportunity in EMDEs may not be sufficiently appealing to single investors. To better position projects, it is necessary to explore valuation routes that look beyond the basic rate of return. If the benefits of a single project or an overall programme of works are explored sufficiently, it is often possible to identify greater social or environmental potential. This could introduce more sources of project financing.

Projects can be aggregated into packages to attract investment

Combining many smaller and lower cost projects, which individually may not be considered attractive, into a more significant package could create a more valuable proposition and open the work stream to a wider field of investors. The package could be either a collection of homogenous projects or a diverse offering with clearly defined outcomes and may be situated in one region or in multiple locations. It is possible to design a package that could focus on deploying individual technologies in isolation, in parallel with other work programmes where there are no operational constraints, or as part of a larger work programme.

Having clearly defined packages with identifiable deliverables improves the potential to attract investors and can also enable the participation of multiple partners in parallel to satisfy funding requirements and facilitate an accelerated programme. Aggregating multiple projects can help manage the highly fragmented investment market, reduce transaction costs, and offer economies of scale for both material procurement and labour force costs.

Funding could be provided in the form of special purpose vehicles that separate the business-specific assets from a utility or government, by joint procurement of the multiple partners seeking funding, or by collectively issuing green bonds. Cape Town in South Africa, for example, marketed green bonds to the value of almost USD 60 million in 2017 to finance the procurement of electric buses, energy efficiency improvements in buildings, water management initiatives, sewage treatment, and the rehabilitation and protection of coastal structures. The green bond market offers substantial growth potential. In 2021, the Climate Bond Initiative reported that cumulative green bond issuance stood at USD 1.1 trillion, having surpassed the USD 1 trillion milestone in December 2020. Investment in the energy sector comprises the largest share of total investment, at almost USD 355 billion, followed by low carbon buildings at more than USD 260 billion, and transport at about USD 190 billion.

Standardisation of investment criteria can help reduce transaction costs

Standards are the bridge between high-level principles and the impact measurement and management frameworks and tools that diverse organisations use for performance reporting and benchmarking. International co-operation could help to reduce transaction costs related to legal financial and technical due diligence, which can account for 1% to 10% of project of final project costs from both project design and contract design. Standardisation can reduce complexity, time involved and upfront costs while also strengthening investor rights.

The information required by investors to assess these risk structures – and the infrastructure market in general – is lacking or highly scattered, creating uncertainty. Many investors also view the lack of clear benchmarks for measuring investment performance as one of the main barriers to infrastructure investment. A lack of common definitions, low transparency and barriers imposed by confidentiality agreements, and poor collection and sharing of information on impact and outcomes also hamper progress. Greater transparency could also help credit rating agencies make more informed assessments to mobilise finance. More disaggregated data could underpin more informed private investment decisions, removing some of the uncertainty over underserved markets and their legal, regulatory and political environments.

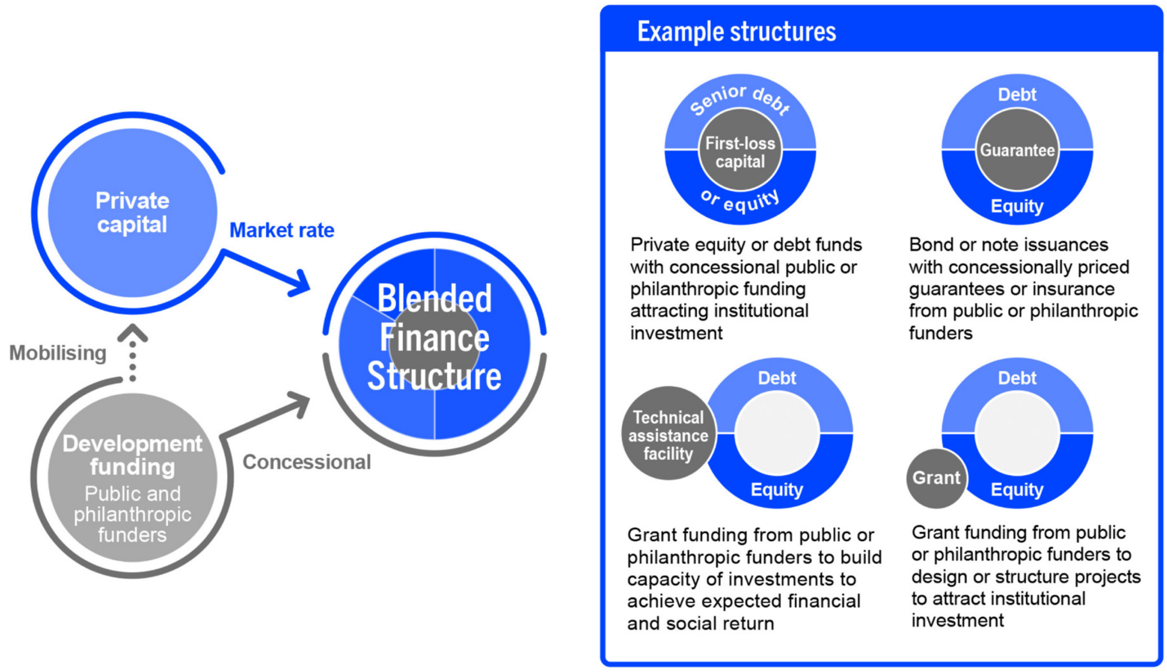
Including environmental, social and governance related value in projects could draw potential investors

Environmental, social and governance (ESG) based investments are growing from around USD 30 trillion in 2018 to USD 41 trillion in 2022, with the potential to hit USD 50 trillion by 2025. When assessing the ESG rating of a prospective infrastructure project, it is important to consider not only the risks but to also apply a scoring of potential benefits that could better position it as an investable prospect. For a utility seeking to propose ESG-compliant investments for a new section of transmission grid, for example, as the potential to reduce greenhouse gas (GHG) emissions receives a high weighting, it would obtain a better score for facilitating the connection of a utility-scale solar plant than a gas-fired electricity station. As high weightings are also applied to customer engagement and safety, a project to formalise a section of informal distribution system, for example, could be a good candidate for investment. Identifying how each project can increase energy efficiency, and thus improve the total system benefit of a digital or physical system upgrade, could improve the investment prospects. Governance of a candidate utility or host nation may also heavily influence whether an investment is deemed low or high risk. The national risk of default also features in decision making; in fact, a recent decline in ESG scores in EMDEs shows a strong correlation with worsening credit ratings.

Blended finance can help reduce investor risk

In situations of market failure, when no investor is forthcoming as a project may initially be deemed commercially unattractive because of low returns or being geographically too risky, blended finance could play a role in the first instance to create investor confidence. Similar to the potential benefits of linking multiple projects on the demand side, aggregating the supply of finance resource options can increase the potential of successfully financing projects. This approach allows heterogeneous financing organisations to invest and lend jointly, even with different objectives. This could include a combination of investors such as multilaterals, development aid, socially conscious impact investors, institutional fund managers or philanthropic organisations. Some of these entities may accept a low financial return as long as projects help them realise their developmental targets. Blended finance is designed for each project and considers country-specific risks. It can be deployed as part of a wider suite of enabling measures to scale private capital mobilisation.

Typical blended finance mechanics and structures



Source: Convergence (2022), State of blended finance.

Blended finance can be included in a proportion of project financing structures to ease investor concerns and provide a level of confidence, thereby broadening the number of prospective investors. The financing structure typically includes a combination of debt, equity or grant financing. This approach has been successful in mobilising capital to close the investment gap in EMDEs. In 2021, over USD 7 billion was mobilised through blended finance agreements, of which 29% was in the energy sector. Between 2019 and 2021, more than two-thirds of all climate-related blended financial transactions targeted Sustainable Development Goals (SDG) 7 – affordable and clean energy. Blended financing recently enabled development of a solar farm in Burkina Faso and a digitally enabled microgrid in Kenya.

Project preparation facilities can help kickstart investment

One barrier to mobilising private sector financing is that it is often difficult to identify investment opportunities. A lack of national infrastructure investment plans, energy strategies or roadmaps has the effect of obscuring where project investments are needed, when they could be built, or if they are sufficient to meet long-term objectives to reduce project risks. This is a critical challenge for attracting investments to countries and sectors in need of such infrastructure. Developing a pool of investment-ready projects requires considerable planning and capacity to address the associate financial, legal and technical challenges. International co-operation is an important means to facilitate the pooling of knowledge, support and investors. To encourage private sector investment for programmes or standalone projects, it is beneficial to create a visible pipeline of projects, which could also be enhanced through affiliation to large institution.

One example of a technical assistance scheme supported by a financial institute is the Strengthening Project Preparation Capacity in Asia and the Pacific programme, supported by the Asian Development Bank (ADB), and designed to help EMDEs prepare infrastructure projects. Various phases of the programme have focused on a cluster approach, targeting activities such as sector or policy reform, capacity building and performance monitoring, development of enabling environments of PPPs, and preparing infrastructure projects for private sector participation. The European Investment Bank (EIB) has a similar technical assistance function to enhance project success rates supporting Central Asia, Sub-Saharan Africa, and the Caribbean and the Pacific. The EIB scheme has two main funds: an EUR 80 million access to energy fund; and an EUR 75 million infrastructure fund, targeting investments including electricity and digital ICT assets. It recently provided a EUR 100 million loan for expansion and modernisation of the electricity transmission network in Argentina to support integration of renewable generation.

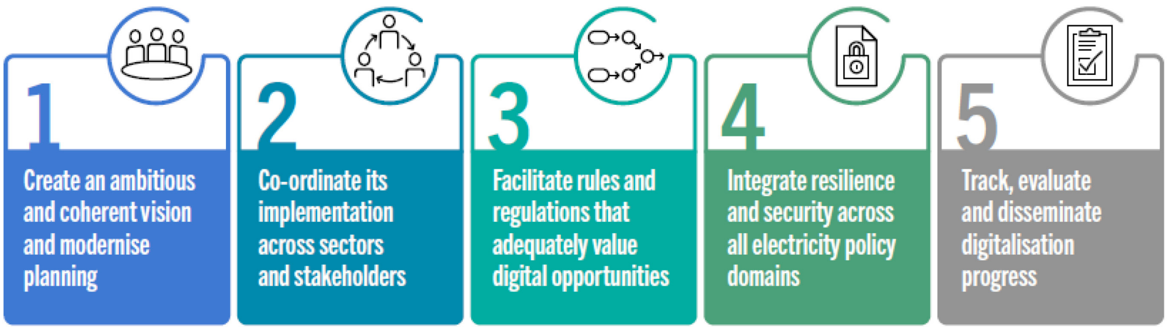
The Green Climate Fund (GCF) is a platform involving up to 194 governments, with a fund of over USD 11 billion. It aims to achieve a 50:50 balance between mitigation and adaptation in its funding. To date, it has disbursed nearly USD 3 billion. Among areas of priority such as health or forestry, it also has a focus on infrastructure and energy across three main areas; energy generation from renewable sources; transmission, distribution and storage; and promoting access to clean energy. So far, projects have been undertaken in Botswana, Central African Republic, Chile, Democratic Republic of the Congo, Haïti, India, Kenya, Mali, Namibia and Uzbekistan. The Global Investors for Sustainable Development Alliance (GISD), convened by the United Nations Secretary-General, is another example of a cross-disciplinary initiative designed to scale up private finance for sustainable projects that involves financial institutions, corporations and multilateral partners.

While governments and institutions are already taking actions to develop pipelines of projects in many regions, further strengthening is needed to achieve deployment at scale.

How to accelerate smart grid implementation

When approaching the development of a smart grid strategy, it is essential to avoid common missteps and to create new problems by not considering all of the phases required to be achieved on the digital journey. The success of smart grid deployment is highly dependent on country conditions, the specificities of local energy systems, technology choices, socio-economic goals and investment priorities. This report identifies five key areas for government action to support implementation of digital technologies and unlock the potential they hold in EMDEs.

Five key action areas to support deployment of digital technologies



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A growing body of evidence demonstrates that co-ordinated action across these five pillars can generate virtuous cycles of investment and cost recovery, and thus ensure effective and inclusive deployment of digitalised grids at scale.

Create an ambitious and coherent vision and modernise planning 1

- Engage all stakeholders in vision
- Develop roadmaps, targets and milestones to provide clarity on smart grid trajectory
- Include whole systems and DERs in integrated planning
- Leverage digital tools for long-term planning

Create a coherent vision

An important starting point to any smart grid journey is to create a unified vision of how smart grid technologies can help meet country priorities, including those related to energy access and decarbonisation. This vision can then be further articulated into strategies and roadmaps. In line with this vision, regulatory frameworks would need to be adjusted to recognise the value of investments that harness digital capabilities. This requires engaging all stakeholders from the digital and energy sectors. Governments could also clarify their own role for incorporating digitalisation in their energy transition, nationally determined contributions and low emission development strategy planning. This could include the integration of distributed energy resources, notably distributed solar PV, in ways that promote systems efficiency.

Integrated, digitally supported planning can benefit vertically integrated systems and does not require substantial restructuring. As electricity grids become increasingly complex, a whole-systems approach to planning is key to embedding digital deployment into energy and broader economic plans. This approach also considers distributed resources and the demand side in planning and in aligning investment decisions across system operators, network companies and other actors.

Develop roadmaps to provide clear direction on the expected development of digitalised grids

Investors often cite policy and regulatory uncertainty as a key risk factor for investments. This can be addressed by clear articulation of government policy, supported by legislation and regulatory changes. Vision statements, national strategies and roadmaps are key instruments to indicate medium- to long-term aims to deploy modern digital electricity grids, while well-defined short-term actions provide direction. Together, these instruments can provide a unified policy framework on which key stakeholders, including the private sector, can base their plans and actions for technology deployment, supply chain development, resource mobilisation, financing and budgeting, and capacity building, among others.

Roadmaps have emerged as a key element of grid digitalisation policy, as they provide clear direction while the process of developing roadmaps can help build consensus among key stakeholders. They are an important tool to set timeframes by outlining a temporal visualisation of the whole system, which helps show what additional investments and technologies are needed, when and where. They can also spell out the relationship of grid digitalisation with other government policies, such as energy access.

Roadmaps can also provide deeper exploration of diverse smart grid technologies and their functionalities. Without a clear vision in terms of existing and future functionality needs, the risk arises of overinvestment, investment in technologies that need to be replaced, or other suboptimal outcomes as lack of the functionalities needed can undermine optimal utilisation of assets. Early smart meter roll-out in the United Kingdom is an example of this, where some of the first meters stopped working when customers switched electricity suppliers.

An growing number of countries have recently developed roadmaps related to grid digitisation, including Chile, Colombia, Costa Rica, India and Türkiye. The Smart Grid 2023 Vision and Strategy Roadmap project, managed by Türkiye's Energy Market Regulatory Authority (EMRA) and the Association of Distribution System Operators (ELDER) includes a detailed timeline and estimated budget.

Actively engaging with relevant stakeholders throughout the process can ensure that different perspectives and concerns are addressed. This also helps to co-ordinate and align visions and strategies, including in plans elaborated by utilities. India is currently helping distribution companies assess their preparedness and elaborate roadmaps. Linking with other relevant roadmaps and plans, such as on clean energy investment and development of ICT infrastructure. China issued a national strategy in 2016 aiming to increase the proportion of renewable energy, and improve the overall efficiency of energy by leveraging IoT potential.

In addition to setting targets for deploying infrastructure and equipment, roadmaps could also establish goals for enhancing operational procedures and for expected, longer-term efficiency gains, which imply actions and linkages with other sectors.

Modernise planning towards integrated, whole system planning processes

Energy systems are in a moment of profound change, driving actors from across the sector to adapt and to anticipate needs, challenges and opportunities. Communication among actors is increasingly important, including those who may not have traditionally worked closely together. Electricity grids are increasingly complex and require integrated planning. New approaches are emerging for co-ordinated and integrated planning practices that expand the scope of traditional resource planning between the electricity sector and other sectors. Co-ordination between transmission and distribution operators, for example, is essential to maintain reliable system operation and optimise use of supply side and demand side assets.

Main characteristics of traditional and integrated and co-ordinated planning

	Traditional resource planning	Integrated and co-ordinated planning
Electricity grid context	Large, centralised conventional electricity plants, unidirectional electricity flow.	Increasing shares of variable renewables including distributed PV, demand-side resources and bidirectional electricity flow, transforming the energy landscape.
Planning process (transparency)	Top-down, transmission-distribution system planning with limited interaction; public consultation at the end of the process.	Participatory and transparent process, continuous engagement with relevant stakeholders.
Resources considered	Centralised generation, transmission and distribution.	Generation both centralised and distributed, transmission, distribution, demand-side resources and system flexibility.
Input parameters and estimation tools	Approximation, reserve margin calculations.	Multidimensional analysis, including environmental and social aspects.

Source: US Aid (n.d.), Best Practices Guide: Integrated Resource Planning for Electricity.

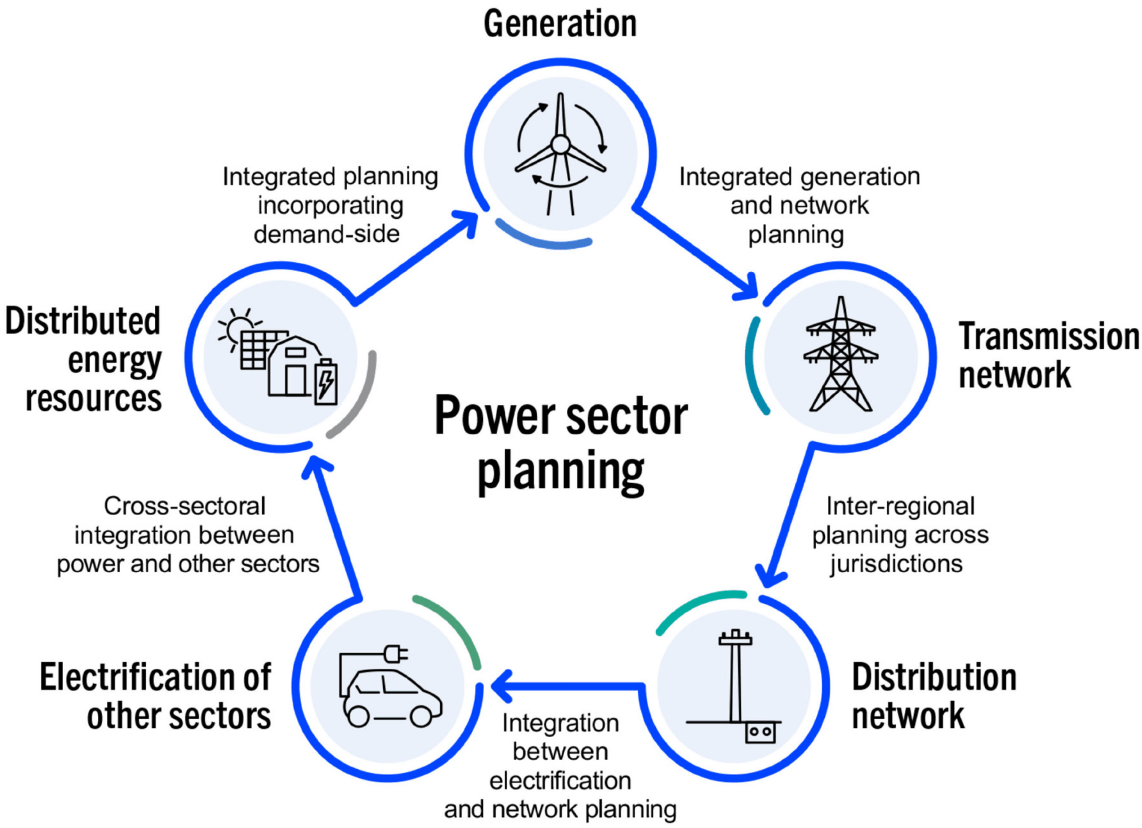
Integrated and co-ordinated planning frameworks increase transparency and provide information to market players and other stakeholders, including manufacturers, project developers, grid operators and authorities. These frameworks are crucial in co-ordinating investments in generation and grids across public and private sector actors.

Utilities around the world are evolving their approaches to grid planning. This implies deploying ICT platforms and data analytics that improve visibility of and control over a larger number of sources of generation. It also means regulators need to allow for a broader range of planning options and a re-thinking of traditional energy system planning, aiming instead to deploy nodal planning and increase the planning capacities of distribution network owners and operators.

When supported by digital solutions, integrated planning across the electricity sector enables optimal use of all assets. Conversely, investing in smart meters without associated data management strategies, frameworks and capacity to analyse, manage and utilise data and insights may fail to capture their full value, resulting in missed opportunities to optimise electricity grid planning and operation – and often a longer payback period.

New approaches to investments can help accommodate higher shares of renewable energy including from distributed sources at least cost. Traditionally, transmission or distribution network owners and operators would invest in cabling, wires and substations that can be easily accounted for and included in the regulated asset base for which they would receive a return. Smart technologies can facilitate services such as congestion management, or other ancillary services, however, markets and incentive models currently prevent participation.

Major components of electricity sector planning and co-ordinated approaches



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Frequency control is an example of a functionality that is undergoing rapid evolution. Until recently, it was mostly carried out by flexible conventional electricity plants, traditional hydroelectricity or pumped hydroelectricity storage. Today and into the future, large numbers of PV systems, coupled with storage and other dispatchable loads, could provide these types of services but may require a much finer understanding of generation and load portfolios, as well as a need to address regulatory constraints.

Innovative solutions such as co-ordinated management of distributed energy, storage or broader demand response present new challenges. To date, no standard business model or process exists for procuring non-wire alternatives. Some of these options, such as storage or distributed asset management, are modular and can be deployed where the need is greatest. Monetising these opportunities through business models that support third parties such as aggregators could be necessary. Another new challenge is that of balancing the complexity of incentives and rate structures that incentivise utilities and third parties to deploy innovative options over large numbers of consumers and equipment, and the necessity to simplify procedures.

Support utilities in developing robust plans for digital electricity grids

Once policy and regulatory frameworks are in place, the onus falls onto utilities to plan their investments in a digitalised grid. Creating robust plans is vital: if investment in digitalisation occurs in an *ad hoc* manner without integrated planning, the risk arises that solutions may not be optimally utilised and fail to deliver the value expected.

Enhanced distribution planning methodologies can ensure that utilities consistently consider non-wire alternatives. Beyond planning the distribution network and activity itself, utilities need to better integrate their planning activities with generation and transmission planning. This can be done as part of broader and improved TSO co-ordination with the distribution system operators in both planning and operation. Brazil, for example, is working on a merit order framework to reduce curtailment of renewables by the national system operator. Similarly, accelerated deployment of distributed PV will require a more digitalised distribution system, with the accompanying ICT platforms and data analytics to improve the visibility and control over a larger number of point sources of generation.

Leverage digital monitoring tools for long-term planning

Overall, grid digitalisation might lead to utilities managing higher amounts of data than experienced currently. In turn, when properly collected and analysed, such data can enable more accurate and forward-looking planning than was previously possible.

Grid operators could seek to utilise a range of digital monitoring and tracking tools, especially when facing unprecedented DPV growth. The importance of tracking where solar is being installed across a region – along with how much and what types – grows with increased deployment. Also, understanding daily patterns of intermittency will be essential for any long-term, grid-wide planning to ensure that thoughtful decisions reflect accurate information about that growth.

A lack of reliable data on DPV installations in South Africa, reflecting the tendency for DPV owners to not officially register their systems, is a great hindrance to Eskom and the government in addressing the type of grid upgrades necessary as DPV increases. While working on the regulatory and permitting side to resolve the lack of registration, thoughtful grid planning could include tracking customer consumption patterns to identify unregistered systems, installation of more smart meters, GIS mapping of known and suspected solar installations, and other digital verification tools.

Regularly tracked and analysed data could lead to better forecasting models for the grid to anticipate demand, plan around expected DPV production and other future grid trends, and create opportunities for dynamic pricing, demand-side management, and other tools.

Co-ordinate its implementation across sectors and stakeholders 2

- Ensure coherence across sectors and stakeholders
- Prioritise energy access and affordability
- Ensure benefits of digitalisation are widely and equitably shared
- Support innovation and scale up pilots
- Maximise job creation opportunities

Co-ordinate implementation

Governments could enhance co-ordination between energy, electricity, economy, digital and other departments, as well as with digital and energy regulators, and the digital and electricity industries. Taking measures towards alignment and adequate support for digital and energy research and development activities with energy policy objectives can facilitate the development of cost-effective solutions.

Governments also have a role to play in ensuring that the broader socio-economic benefits of a digital transformation are widely and equitably shared, not least to improve energy access and provide the skills needed for new employment opportunities linked to the implementation of digitally enabled, reliable grids.

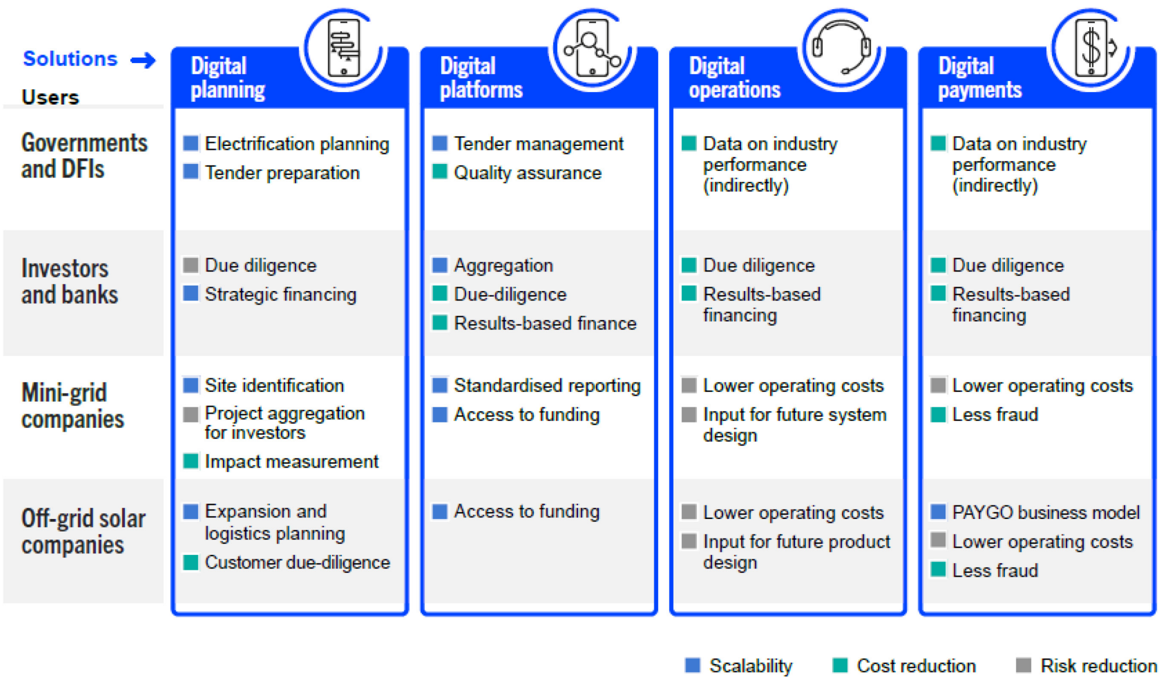
Prioritise energy access and affordability

In countries where energy access remains a challenge, access policies need to recognise the impact of the digital transformation in providing solutions for the millions of people without electricity. Governments and their rural electrification agencies are becoming increasingly experienced in leveraging digital tools to meet their socio-economic objectives. For example, increased use of geospatial analysis to estimate energy demand in rural or peri-urban areas has helped identify least-cost and most suitable electrification technologies in assessing a range of options such as grid extension, mini-grids or solar-home-systems.

Digital innovation has also resulted in a larger role for the private sector in delivering electricity services. Delivery of utility services on a pay-as-you-go (PAYGo) basis, especially when integrated with mobile payments, has helped to improve access. In Sub-Saharan Africa in 2021, almost 50% of solar home systems were based on the PAYGo model. Enabled by smart meters and two-way digital communication, these systems allow customers to spread their payments over time in small instalments, according to their consumption. This avoids a high, upfront cost. Governments could look towards policies and regulations to facilitate these opportunities.

Policy makers, donor organisations and technology developers can work together to create an enabling environment to harness digital technologies in mini-grids. Policymakers can provide long-term plans for grid extension and develop suitable regulatory frameworks so that mini-grid developers can evaluate the extent to which it makes sense to incorporate digital technologies. Policy makers can support the testing of digital solutions in pilot locations with potential for productive uses. Donor organisations could promote the use of digital technologies in mini-grids by requiring that data from mini-grids they fund is shared to inform future design. In the 2022 edition of its Digital Energy Challenge, the French Development Agency (AFD) included digital innovations in the field of mini-grids as one of three themes on which it bases selection of projects. Examples include using digital tools to facilitate interconnections with the main grid and/or other mini-grids or systems and use of geospatial data analytics for electricity demand evaluation and/or credit risk assessment.

Digitalisation across energy access value chain solutions



Note: DFI = development finance institutions. OGS = off-grid solar.
Source: TFE Energy (2020), Energy Access, Data and Digital Solutions.

Ensure benefits of digitalisation are widely and equitably shared

A range of social issues, such as skills gaps and changes in job markets, could put the digital transition at risk. The influence of energy digitalisation on creating new societal norms and behavioural patterns also needs to be considered to ensure it brings wider socio-economic benefits without exacerbating inequality and other pre-existing problems.

Digitalisation can enhance the ability of consumers to adopt technologies and solutions that enable them to manage energy consumption and costs, reduce the impact of their energy use, and reduce carbon emissions. However, facilitating access to information is a central dimension to this. All interested stakeholders could have easy access to electricity consumption information and relevant facts about electricity including time and location dimensions of electricity prices and related GHG emissions.

The shift to smarter systems has potential to create negative distributional effects in terms of system costs and benefits, and to exclude some vulnerable groups due to the complexity and costs of participating. A recent UK research programme, Smart and Fair, conducted an in-depth assessment of consumer vulnerability linked to implementation of time-of-use tariffs and a range of smart technologies and energy services. The research led to two main findings: the capabilities required for consumers to participate in and benefit from smarter systems could create uncertainty for consumers, and smart and fair outcomes may not emerge without targeted policy interventions. The research highlights key success factors to reduce the risks of consumer harm from poorly designed, smart energy offers. These include committing resources to effective market monitoring, ongoing distributional impacts analysis and re-evaluating definitions of consumer vulnerability to reflect new risks.

Measures must be taken to consider the affordability of and equitable access to digital technologies that enable consumer participation and their access to benefits such as participating in demand-response programmes. Otherwise, the risk arises of exacerbating the digital divide, leading to situations in which low-income consumers are unable to reap benefits like incentives to shift demand to off-peak, while being subjected to higher bills because of the need of utilities to recuperate costs associated with electricity grid reinforcement.

Acknowledgement of these risks is driving many government and energy actors to explicitly include principles of justice and inclusivity such as the recommendations from the IEA Global Commission on People Centred Transitions.

Maximise job creation and capacity opportunities

In parallel to or ahead of investments in digital technologies, there is a need to invest in human capacity across several related areas. These include the ability to assess which technologies to prioritise and the skills and capacity to develop smart grid investment projects, including assessing costs and benefits. In turn, investing in educational services and vocational training locally may be necessary. The education system must also provide graduates of relevant programmes with the skill sets needed to plan and operate modern digitally enabled electricity grids. These capacities are needed to derive maximum value from investments in technologies.

A growing evidence base shows that a lack of digital skills and a digital mindset are among the main barriers to the digitalisation of the energy sector. A large survey of engineers and senior executives across the energy sector, from start-ups to large corporations, revealed that 91% of energy professionals recognise a fundamental need for digital skills training. Likewise, a 2021 survey of 159 electricity and utilities executives representing a global cohort showed 89% of respondents identifying the skills gap as a main challenge to digital technology adoption – particularly related to emerging digitally enabled solutions such as vehicle-to-grid and virtual reality. The latest US Department of Energy Smart Grid System Report highlights how the application of digital technology requires more highly skilled workers and engineers, including system architects, data scientists, modelling and simulation experts, IT/OT cybersecurity specialists, and communications and digital control engineers.

Many of the policy recommendations to ensure capacity and job creation in clean energy transitions also apply to the digitalisation of electricity grids. Examples include updating academic curricula to provide the right set of skills, including technical and vocational education and training. Accounting for the time lag in building up a skilled workforce, continuing education courses and capacity-building programmes that enable active professionals to adapt to rapid industry changes are needed. Across all activities in education and training, appropriate certification, quality assurance, and monitoring and evaluation is important.

Training policies can play a critical role in encouraging current and future workers to seize the job opportunities emerging from clean energy transitions. Governments can use energy digitalisation to address employment, equity and inclusion challenges through targeted and inclusive skilling policies that prioritise vulnerable and underrepresented groups.

Digital reskilling and upskilling may be important for future clean energy jobs and several governments are deploying cross-cutting strategies. Italy recently launched a national coalition for digital skills and jobs to roll-out digital training programmes to close skills gaps. Governments are also aligning policies to promote job creation in related areas such as energy efficiency, renewables and smart technology.

Several system operators are actively training staff to equip them with new skills. In Colombia, the national interconnected system operator, is training of staff to use large, real-time data sets and develop data management systems. The National

Electric Coordinator of Chile has set up a team to analyse data being generated by multiple monitoring and information systems. In parallel, work is underway to improve data collection and management, as well as to build skills to utilise data and analysis.

In the field of energy access, several regional and international networks and organisations are launching new capacity-building efforts that focus on the nexus of energy access policies and digital tools. To develop sustainable national energy information systems and energy modelling capability in Sub-Saharan African countries, the IEA recently started a technical support and capacity reinforcement programme. The Renewable Energy Solutions for Africa (RES4Africa) Micro Grid Academy has provided vocational training on decentralised energy to 800 young people across Sub-Saharan Africa. Some countries are pioneering new access delivery models that combine clean technologies, digital solutions and large-scale training. The Togolese Agency for Rural Electrification and Renewable Energy (AT2ER) won the 2020 Ashden Award for System Innovation for Energy Access for a series of training initiatives to boost the number of solar home system installers and technicians nationally and to support the deployment of mobile money systems. As digital tools trigger new business models for energy access, they also change local job profiles. Compared to cash-based, off-grid solar models, the PAYGo model employs more people in after-sale customer relations and in technical, skilled jobs such as software design and logistics.

Facilitate demonstration and experimentation at scale

A fundamental role for governments in creating conditions for digital innovation that align with energy policy objectives is supporting large-scale demonstrations. Regulatory sandbox environments are shown to have very positive effects for digital technologies as they make it possible to test digital solutions on energy infrastructure at scale. This is needed to leverage the opportunities from data aggregation and analytics, and to validate the business cases of digital solutions. Governments can also play an active role, including a convening one, in enhancing data access and sharing – all of which are crucial for digital innovations to incentivise new business opportunities.

While many smart grid technologies are at an advanced stage of maturity, they have not been widely deployed in EMDEs. This creates the need for testing under real, local conditions and, most importantly, to test approaches and methods to build local capacity and share learnings effectively and on time. Tests can deliver invaluable lessons on managing digital technologies at a larger scale and provide evidence of the value they create.

Globally, many pilot projects have demonstrated various elements of smart grid operation; however, results and lessons learned are not always widely shared.

Increased focus on using the learnings including quantified and documented results can underpin effective replication and scaling up, ultimately encouraging more investors to support smart grid projects. In September 2021, the Italian government in collaboration with United Nations Environment Programme (UNEP) launched a call for pilot projects that provide opportunity to gain in-the-field insights, test new approaches and disseminate learnings that will feed into the IEA's Digital Demand Driven Electricity Networks (3DEN) initiative. Pilots are now being implemented in Brazil, Colombia, India and Morocco to test different approaches on how digitalisation can contribute to flexible and resilient energy systems.

Creating experimental sandboxes is another way to test digital solutions. Typically, this approach allows derogating rules or regulation for a limited period of time, usually in a well-defined geographical area. Creating sandboxes in neighbourhoods, towns or newly developed districts makes it possible to test how highly decarbonised systems function with local characteristics. This can provide valuable lessons for managing them at a larger scale and help to identify which digital solutions and technologies provide the highest value in energy security, resilience and decarbonisation. Brazil recently created a sandbox to test new tariffs for low-voltage consumers, leveraging smart meters and other technologies related to managing energy consumption.

Regardless of the modality, pilot project design should identify the problem that the pilot aims to address, while accounting for the unique geographical and socio-economic context. To maximise the value of pilots, key success factors include:

- Ensure a joint understanding of the role of the pilot in addressing context-specific opportunities and challenges so stakeholders can formulate a coherent and shared vision.
- Design the pilot according to this shared vision, prioritising activities that address the identified issues and ensuring the involvement of all relevant stakeholders.
- Since pilots are embedded in unique geographical and socio-economic contexts, they are rarely replicated exactly. Part of their value lies in leveraging the generated knowledge, established networks and strengthened legitimacy to enable further deployment.
- Develop a scaling strategy early in the design phase of the pilot. This could indicate the types of knowledge likely to be produced, the potential beneficiaries, and potential barriers to scaling and how they could be addressed.
- Engage with future users and other key stakeholders as early as possible to understand their needs and necessary preconditions for adopting the technology. To improve the scaling potential of a pilot, activities could be designed bottom-up, prioritising user needs.
- Evaluation could focus on system-level benefits and adopt a broad socio-technical perspective.

- Ensure that pilots are leveraged to build capacity for future implementation and scaling up.
- Consider how pilots can be used to de-risk investments and demonstrate a viable business case to potential investors.
- Ensure that lessons learned from pilots are leveraged to develop enabling policies and regulations.

Strengthen international collaboration and knowledge sharing

Deployment of smart grids may be pursued at different speeds in different regions, and challenges and solutions will vary. Sharing experiences, developing common practices and standards, and identifying areas in which innovation can be leveraged jointly can accelerate progress and lower costs. Given the complexity and multi-faceted nature of smart grid deployment, such efforts would benefit from both cross-cutting and deeper international collaboration.

The depth and breadth of knowledge pertaining to smart grids, as well as their rapid evolution, call for deploying a broad range of international and cross-cutting collaboration efforts, ranging from peer-to-peer exchange, and establishing communities of practice. These can help to share solutions and approaches for common challenges, build capacity and facilitate dialogue among stakeholders.

The International Smart Grid Action Network is a strategic platform to support government action for accelerated development and deployment of smarter, cleaner electricity grids around the world. The Green Powered Future Mission, a global public-private partnership, aims to demonstrate by 2030 that electricity grids in different geographies and climates can effectively integrate up to 100% variable renewable energies in their generation mix while maintaining cost-efficient, secure and resilient systems. The Regulatory Energy Transition Accelerator is a global initiative bringing together energy regulators to discuss common challenges and share best practices. The Global Power System Transformation Consortium brings together system operators to identify common, cutting-edge research questions that can inform large-scale, national research and development investments.

Facilitate dialogue among stakeholders through cross-cutting networks

Given the nascent state of deployment of some digital technologies, knowledge sharing among the expert and academic communities could facilitate drawing lessons from on-the-ground implementation, notably through relevant international agencies and multilateral and regional development banks.

International think tanks and networks also play key roles in knowledge exchange and dissemination as exemplified by Renewable Energy Solutions for Africa (Res4Africa), a foundation that supports African efforts to ensure access to affordable, reliable, sustainable and modern energy for all. Serving as a bridge between Europe and Africa, Res4Africa gathers members from across the clean energy sector to mobilise investment. Under the mandate of the African Union, the Africa Renewable Energy Initiative (AREI) is an African-led, inclusive effort to accelerate and scale up harnessing of the continent's vast renewable energy potential, including through digital technologies.

Strengthen peer-to-peer knowledge exchange to identify best practices

The World Bank's Utility Knowledge Exchange Platform is one example of an online tool to connect stakeholders in the electricity sector – including utilities, energy sector institutions, regulators, system operators and the private sector – to help utilities improve operational efficiencies. This includes finding ways to better navigate the technological change and business innovations that underpin the energy transition and are transforming the sector, notably through digital technologies.

At the national level, India Smart Grid Forum is a public-private partnership initiative established to accelerate development of smart grid technologies in the Indian electricity sector. It carries out research and analysis, and convenes experts from the public sector, industry and academia to develop enabling policies, standards and regulation. Colombia Inteligente is an initiative that engages representatives from private entities and public energy institutions to accelerate the digital transformation of electricity grid in Colombia. The network pursues knowledge exchange and promotes smart grid pilots to advance the process of regulatory change and standardisation.

Facilitate rules and regulations that adequately value digital opportunities 3

- Shift to whole-of-life total expenditures
- Support comprehensive assessments of costs and benefits of smarter grids
- Re-align incentives to drive digital and demand-side solutions
- Strengthen monitoring and better targeting of policies through digital tools

Facilitate rules and regulations that adequately value digital opportunities

Despite being regions where demand for energy is expected to grow fastest in the coming years, emerging markets and developing economies are lagging updating their electricity grids for the energy transition. Where the weak financial situation of utilities is an issue, policy makers and regulators could seek to implement adequate investment frameworks, develop least-cost system plans and correct the design of network tariffs, while also tackling high operational and commercial losses. International co-operation can provide additional financial and technical support, including concessional capital, private sector capital and inflows from international markets.

In turn, governments could consider dedicated policies and regulations to incentivise and de-risk digitalisation investments. This may include a shift towards performance-based regulatory oversight by providing incentives and penalties to meet clean energy transition objectives as well as specific measures to support innovation. Some examples include reforming planning and consenting procedures; streamlining permitting processes; increasing borrowing thresholds; issuing tax credits or grants; loan guarantees; expanding employee caps; encouraging training and skills conversion programmes; and investing in research and development.

As the digital transition will involve new products and services, and new vendors, procurement processes may also need to be restructured. Currently, utilities mainly engage with large vendors that have long track records. Going forward, utilities may need to also interact with a wider range of start-ups or smaller digital technology or service providers. As such, they may need new processes to procure and onboard resources quickly.

While a strong business case exists for investment in grid upgrades, raising the capital may be challenging and complex. Investors looking for energy transition investments tend to favour renewable projects with obvious benefits on the supply side rather than network upgrades that enable more effective transmission, distribution and use of electricity generated. It is thus important to consider current frameworks governing utility investment and to incorporate strategies that increase the return on investments in smart grid technologies.

Structure utility regulation to incentivise investments

Utility regulation is central to steering how utilities invest, including encouraging or inadvertently discouraging investment in effective digital technologies. Traditionally, regulators encouraged investment in infrastructure to generate and deliver electricity to consumers, with the regulator balancing investment needs linked to affordability and reliability of service. Going forward, regulation needs to also encourage investments in digital and demand-side infrastructure, while maintaining the balance of investment needs, consumer costs and reliable service. In this context, it is critical to consider how regulatory structures need to change to account for digital and distributed technologies. Traditional, cost-of-service regulation tends to be framed to enable utilities to recover their fixed costs with a fair rate of return on investment while passing operational costs through to consumers. Tariffs are based on a calculation of the price per kWh needed to recover these operation costs from consumers.

This framework tends to incentivise investment in infrastructure and to encourage utilities to maximise sales to consumers; it is based on the premise that once the tariff levels are set; higher sales will boost revenues and profits. The rate of return on capital expenditure encourages utilities to pursue capital-intensive projects over other digital alternatives even if, over time, the alternatives could save money for both utilities and customers, due to lack of incentive.

Overemphasis on minimising investment levels can lead to missed opportunities, such that higher levels of investment in digitalisation can actually lower consumer bills. Accelerated grid access and/or electrification may increase utility revenues more quickly. Likewise, installing AMI can significantly improve revenue collection and reduce non-technical losses, again improving bottom lines.

Key actions to consider when reviewing regulatory models to create incentives for smart grid investments include:

- Develop regulatory schemes that prompt utilities to implement the most cost-efficient solution.
- Create attractive conditions for innovation by offsetting regulatory risks and shifting away from cost-reduction only regulation.
- Enhance the remuneration toolbox by making funds available for research, development and innovation, decoupled from ordinary business-as-usual allowances.

- Set up dedicated innovation incentive schemes that can include costs for smart grid projects.
- Include incentives for operational expenses to reflect costs linked to the growing need for flexibility in distribution networks.
- Ensure stable and clear regulatory frameworks that encourage utilities to develop both short- and long-term innovations needed for system transformation.
- Explore whether a shift towards the benefits of a whole-of-life total expenditure could attract more investments.

Re-align regulatory incentives to drive digital and demand-side solutions

In most places, utilities earn a rate of return on investment on CAPEX, while they recover their costs for operational expenditures (OPEX). This usually means that much of the investment needed to integrate variable renewable energy, and increasingly complex grids to manage demand does not generate a profit. Not surprisingly, it is therefore not a main focus for utilities. Recent regulatory innovations have sought to address three key issues inherent in traditional approaches:

- The incentive to increase revenues by selling more energy.
- The incentive to increase revenues by making capital expenditures, which earn a regulated return on investment.
- The dis-incentive to invest in innovative approaches or technologies.

With these issues in mind, many regulators have shifted away from cost-of-service or rate-of-return regulation to applying a revenue or price cap, often referred to as a forms of incentive regulation. Revenue-cap regulation puts a ceiling on total revenues a utility can recover over a certain period. As the utility can retain any cost savings realised under the cap, this encourages it to improve the efficiency of operations. In turn, as the utility may not earn revenues beyond the cap – even if sales go up – it removes the incentive to maximise sales. This also means that the utility is not adversely affected if energy efficiency programmes reduce their sales.

Price caps are similar, but they put a ceiling on the prices that can be charged to customers. An important consideration is that they, therefore, do not remove the incentive to maximise sales. In both cases, the cap has some room for adjustment based on criteria set by the regulator. Most countries in Europe and many US states have introduced revenue or price cap regulation, which has helped remove the dis-incentive for energy efficiency and demand-side management programmes.

Even where a revenue cap is in place, the CAPEX bias remains. To correct the CAPEX bias, regulators are increasingly exploring the benefits of a whole-of-life total expenditure (TOTEX) approach to investment that bundles CAPEX and OPEX. A share of the investment is capitalised and earns an approved return while costs for the non-capitalised portion are passed through to consumers (as per traditional means of recovering OPEX).

By eliminating the CAPEX bias, the TOTEX approach encourages investments that would traditionally lack the lustre of an approved rate of return that matched that of infrastructure investments. The TOTEX approach may stimulate investments in smart grid technologies and demand-management strategies. Several countries have started to review regulations to facilitate investments; both the United Kingdom and Italy have introduced TOTEX.

To encourage innovation, some countries are offering an allowance for pilot projects that can be tested and scaled up. In 2010, the Italian Regulatory Authority for Energy, Networks and the Environment (ARERA) defined the criteria to select and incentivise innovative grid pilot projects with an extra remuneration for DSOs – set at 2% on the weighted average cost of capital for a duration of 12 years. Seven smart grids pilot projects were implemented and their results used to evaluate smart grids functionalities and elaborate a specific incentive regulation for DSOs.

Based on the pilot outcomes, in 2015, ARERA adopted an output-based regulation approach, meaning that incentives and premiums are based on the benefits investments bring to the system, measured by grid and system performance. As this mechanism allows DSOs to obtain derogations from ordinary regulation in critical areas for a period of four years, it encourages investments for innovative solutions for distribution network management. Through awards and penalties, it also provides incentives for quality of service.

Develop performance targets and metrics

Targeted incentives can help to ensure utility investments align with specific policy goals, from improving quality of service to reducing connection times for PV and expanding effective use of smart meters. Performance incentive mechanisms (PIMs) are a set of regulatory tools that tie a portion of utilities' earnings to desired regulatory outcomes, offering utilities opportunities to create the programmes and services needed to advance priorities. Combining PIMs with the regulatory structures discussed earlier can also help align utility incentives with policy objectives. PIMs can be layered onto traditional cost-of-service regulation, as along as regulatory oversight assures the PIMs' rewards and penalties do not over- or under-compensate utilities for the benefits they provide and/or the costs and risks they incur.

Several countries in Latin America, including Brazil, Chile, Colombia, Mexico and Peru, have included performance indicators in their regulation. When exploring regulatory reforms, learning from best and innovative practices is a useful starting point, but there is also value in learning from approaches that worked less well and subsequent adjustments or changes made. Examples of poor application are not fully understanding the business-as-usual costs before setting incentive levels, or, by basing performance on inputs rather outputs or savings achieved.

Although incentive and output-based regulatory mechanisms perform well, securing smart grid investments may require other approaches, such as innovation incentives represented as an adjustment of revenues and extra weighted average cost of capital (WACC). Several countries in Europe have adjusted their regulatory frameworks to provide incentives for R&D and pilot projects.

Consider quality standards

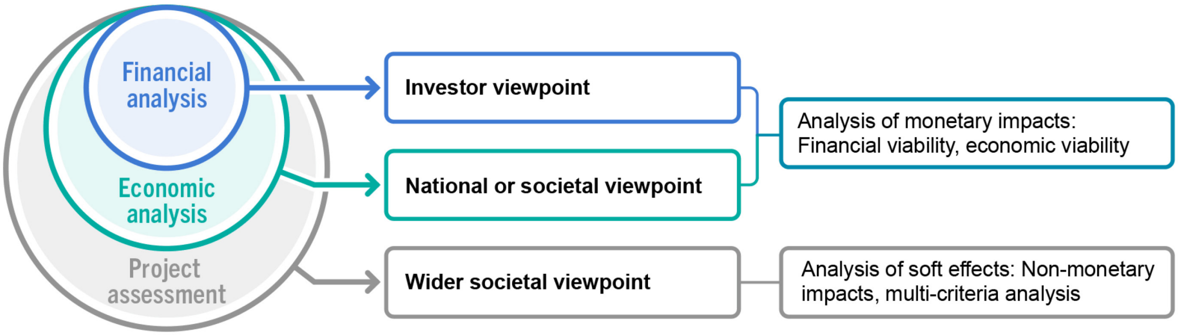
In many developing countries, consumers can be exposed to an influx of low-quality energy access products, which tends to disproportionality affect low-income populations and can erode long-term consumer confidence. This has prompted international efforts to harmonise quality assurance frameworks for off-grid solar products. Likewise, quality infrastructure for smart mini-grids includes comprehensive standards, testing, certification and accreditation. Such standards help improve project financing as well as legal, regulatory and performance certainty, thereby strengthening the market for smart mini-grids.

Support comprehensive assessment of costs and benefits of smarter grids

Appropriate methodologies to assess the economic value of smart grid projects are needed to encourage investments in them. A typical approach used is a cost-benefit analysis (CBA), which follows a systematic process to monetise benefits and relative to costs created by a smart grid initiative. Different than financial analysis, CBA covers a broader scope that includes, for example, societal impacts, irrespective of to whom the costs and benefits accrue. The outcome of such analyses may depend on the definition of the scope and methodologies used.

As smart grid projects have a range of impacts that are difficult to monetise, applying conventional approaches with a narrow scope may lead to an undervaluation of benefits. As such, more nuanced approaches are warranted that can appropriately consider multiple value elements including capacity value resulting from reduced peak demand; balancing value related to provision of balancing and shared reserves; value of production and operational cost savings by shifting electricity demand from peak to off-peak periods; value of reduced renewables curtailment; and value of higher supply reliability and security. Beyond the electricity sector itself, other smart grids can have positive impacts on environment and socio-economic development.

Multi-criteria cost and benefit analysis



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Source: Adapted from Florence School of Regulation (2022), Smart Grid Replication.

Actions that policy makers could consider include establishing guidelines and methodologies could be adapted to fit local circumstances and constraints and how existing guidance and tools could be leveraged.

When applied to smart grid evaluation, there are notable differences between a traditional CBA and a multi-criteria cost-benefit analysis (MCCBA). A CBA primarily focuses on the financial costs and benefits of smart grid investments, quantifying and monetising impacts in monetary terms. In contrast, an MCCBA takes a broader perspective by incorporating multiple criteria beyond financial considerations. It considers energy efficiency, reliability, environmental impact, cost savings, customer satisfaction, grid flexibility, and cybersecurity. While a CBA primarily relies on quantitative analysis and monetary valuation, an MCCBA involves a more complex evaluation process that combines quantitative and qualitative analysis. MCCBA explicitly assigns weights to each criterion, reflecting their relative importance based on stakeholder preferences, and allows for explicit trade-offs between different criteria, enabling decision-makers to consider a range of factors and make informed choices that align with the broader objectives of smart grid evaluation.

Integrate resilience and security across all electricity policy domains 4

- Ensure energy transition strategies value resilience
- Reward resilience in rules & regulations
- Strengthen the ties between digital and energy security
- Proactively co-ordinate data management across all stakeholders

Integrate security and resilience across all electricity policy domains

Governments can integrate security measures into both physical and digital infrastructure to promote resilience and security in their electricity policies. Strategic frameworks such as national energy transition plans, and long-term planning can incorporate resilience across regulations and rules and encourage investment in digitalisation. There is also a critical role for policy makers in managing systemic risks, including strengthening the links between digital and physical infrastructure resiliency and security.

Strengthen ties between digital and energy security

As electricity systems become more digitally interconnected, diverse, complex and automated, they also become more vulnerable to the arsenal and capabilities of cyber criminals. This increases the potential cyberattack surface and the potential scale of damage.

Electricity systems must made more cyber-resilient to withstand, adapt to and rapidly recover from incidents and attacks, while preserving the continuity of critical infrastructure operations. Policy makers, regulators, utilities and equipment providers all have key roles in ensuring the cyber resiliency of the entire electricity value chain.

The fundamental principles of cyber resiliency – i.e. embedding a culture of cyber hygiene and implementing risk management strategies – are generally applicable across all sectors and industries. Their application, however, needs to be tailored to sector-specific characteristics and needs. In the electricity sector, these include real-time requirements for and expectations of very high availability; interdependencies and cascading effects within and across systems; and a mix of new technologies and legacy assets with long lifetimes.

Enhancing the cyber resilience of electricity systems is a continuous process involving several stages: 1) identify and assess risks and preparedness; 2) implement a risk management strategy to prioritise risks and actions; 3) establish robust response and recovery procedures to follow in the event of an attack; 4) document and incorporate lessons learned from incidents; and 5) share knowledge with other stakeholders. Because cyberthreats are constantly evolving, all organisations need to continuously monitor and evaluate their vulnerabilities and risk profiles and take appropriate action.

National policy makers could consider the following actions:

- Develop national standards based on international standards and best practices. In turn, oblige stakeholders to develop guidelines and procedures. For both, require processes to update to tackle new and emerging threats and establish mechanisms to ensure compliance.
- Require that cybersecurity considerations are embedded in planning processes and in systems and operations to ensure that security is based on proactive and comprehensive approaches rather than reliant on responses that are reactive or fragmented.
- Establish frameworks for reporting on cybersecurity and to ensure information sharing among stakeholders to reduce risks and improve reaction times.
- Require that cybersecurity is embedded into procurement processes.
- Support capacity building for personnel to raise awareness about cybersecurity risks and procedures to minimise risks and react appropriately to cybersecurity breaches.

Proactively co-ordinate data management across all stakeholders

Grid digitalisation has the potential to bring significant benefits, such as better interoperability, improved visibility, and co-ordinated control. When smart grid technologies interface with users, such as smart meters and technologies for demand response, it is crucial for appropriate stakeholders to raise awareness and communicate effectively to ensure end-user acceptance and buy-in.

Deploying smart meters, sensors, remote control, automation systems, DERs and connected devices generates large amounts of new data. Sharing these data will be essential to realise greater value from these technologies. Still, policy makers and regulators may have to define the rules for who can own, access and share data. In the electricity sector, customer usage data are of interest and value to some third parties. Some regulatory areas, including California, Colorado, Illinois, and Texas, have already adopted data privacy rules that set standards for sharing data with third parties. A proposal in New York would allow utilities to sell customer data while including security provisions to keep that data safe.

Ultimately, smart grids will generate more data and create new possibilities for data analytics to provide multiple benefits. Policy makers could consider actions to promote information sharing underpinned by robust data frameworks, monitoring and evaluation, and adequate levels of security. However, risks can also arise from excessively strong data protection frameworks that prohibit or hinder data sharing that would benefit the system. These risks could also deter the development of innovative business models and new services. Therefore, a balanced approach is necessary to ensure data privacy and security while enabling the potential benefits of data sharing.

Track, evaluate and disseminate digitalisation progress

To leverage the capacities of digitalisation, governments must take steps to create a data-driven culture in the public sector. Provided governments reinforce their institutional capacity to manage and monitor project implementation, digital tools can support efficient targeting, implementation and enforcement of government policies across both energy transition and digital strategies. Digital tools can help governments evaluate progress of the implementation against goals and milestones set out in strategies and roadmaps.

As learning and exchanging knowledge and lessons from demonstration projects is also vital, governments can help strengthen international collaboration and knowledge sharing, in part to be confident that industry is adopting best practices. Collaborative approaches for demonstration projects provide valuable lessons on how to manage digital technologies at a larger scale and generate evidence of the value created by digital solutions and technologies. In turn, this can help de-risk future investments. Strengthening international collaboration and knowledge sharing are vital to developing common practices and standards, and to identifying areas where innovation can be leveraged jointly, accelerating progress at a lower cost.

Create baselines and track progress

Developing baselines and tracking progress are integral to a trajectory towards smarter grids. Frameworks to track progress should be transparent and based on indicators that help identify areas for improvement. Ultimately, showing quantitative results from implementation can help de-risk smart grid projects.

An overarching challenge in this area is that there are no universal or standardised metrics or indicators to measure how smart are grids or progress towards increasing their levels of smartness. A range of existing metrics, however, could be considered and used by countries or utilities to create a tailored set of indicators to assess the status of a given grid and track progress. Developed by Carnegie Mellon University, the Smart Grid Maturity Model has been used by utilities in diverse countries to support creation of smart grids visions and strategies. Care needs to be taken to select indicators that provide the most useful insights and to ensure the cost and effort of collecting data for each indicator are reasonable and replicable over time.

The benefits of good indicators

Several types of indicators could be considered to assess the smartness of grids. Grid quality indicators show how well a given grid is guaranteeing distribution services regardless of technologies and choice of solutions. While not specific to smart grids, such indicators are core to service delivery and, thus, crucial to monitor; specific smart grid indicators are complementary to them. Grid efficiency indicators help to evaluate if the distribution grid is cost-efficient. When selecting smart grid development indicators, it is important to aim to be technology-neutral and to prioritise the measurement of outputs such as improved grid operation efficiency, or faster restoration times, rather than financial inputs.

Examples of indicators to assess the smartness of grids

Grid quality	Grid efficiency	Grid development	Data utilisation
System Average Interruption Frequency Index (SAIFI), which measures the average number of interruptions that a customer would experience over the course of a year.	Yearly losses (by voltage level, technical and commercial).	Observability of the grid, which means the ability of assets to send data to control centres.	Data availability to utilities, consumers, third parties. Includes indicators on the quality of data and data platforms.
System Average Interruption Duration Index (SAIDI), which measures the average outage duration for each customer served in minutes or hours over a year.	Cost of grid paid for by consumer/kWh served, and per km of grid.	Controllability of the grid, which means the share of assets that can be remotely controlled, by voltage level.	Use of data when planning: availability and effective use of various set of data for grid planning.
Yearly lost load (realised and expected) and value of lost load.	Cost of grid paid for by other parties.	Availability and effectiveness of telecommunication capabilities.	Digitalisation to harness flexibility at the grid edge. Share of consumption that settled on real data vs modelled.
Yearly curtailment (realised and expected).			

Setting indicators to assess whether the electricity grid is utilising digital technologies effectively goes beyond technical requirements. Utilities in a variety of countries have used the Smart Grid Maturity Model from Carnegie Mellon University to support smart grid visions and strategies and to track deployment. It sets out several domains – such as strategy, organisation, grid operations and societal impacts – to help utilities determine where they are on their path towards developing smart grids.

Indicators on the implementation of smart grid roadmaps

Benchmarking against more specific targets, set according to the specificities of a given electricity grid, is also critical. Different countries and stakeholders may seek to realise diverse benefits in smart grid deployment. Where high technical losses make it difficult to recover costs, capturing data on loss reduction through digital technologies could be an important key performance indicator (KPI). In other systems where infrastructure is exposed to frequent intermittent tripping, faster fault restoration may be a higher priority and require different indicators for measuring progress.

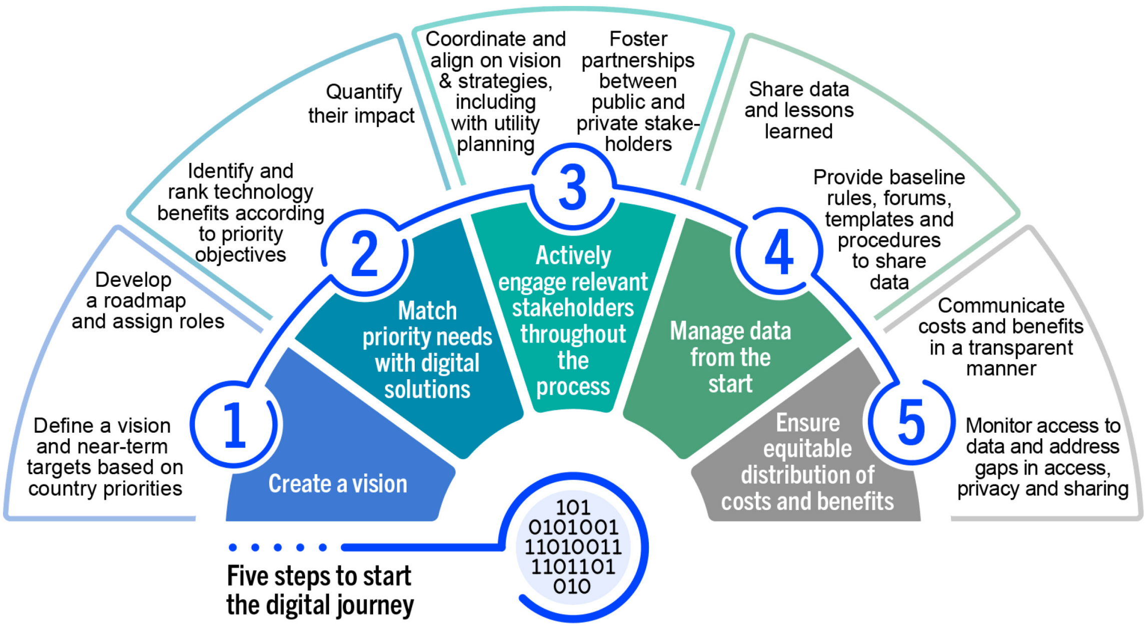
The first step to effective benchmarking is to estimate the benefits of digital technology in relation to specific aims such as avoided costs, saved energy or avoided CO_2 emissions. Cost-benefit analysis at the system scale can help to identify the most effective ways to implement smart grid technology. In Colombia, the Smart Grids Colombia Visión 2030 study identified potential benefits of smart grids, including reducing service interruption times, lower energy losses, reduced GHG emissions and increased grid investments.

Results of the cost-benefit analysis can shape the smart grid roadmap, which outline the specific steps to implement smart grid technology and achieve the desired benefits, with clearly specified KPIs. For instance, as part of the Digitisation of Energy programme, the European Union is creating a Smart Grid Indicator to define common indicators and objectives for them, so that regulators can monitor investments in digital aspects of electricity grids and measure progress.

Starting the smart grid journey today

The broad range of categories and country level examples of digital tools and technologies in this report demonstrates the many different starting points that can quickly deliver positive impacts. The previous sections in this chapter cover a wide range of areas that require attention. However, not all these actions need to or can be tackled at once. Smart grids can be created through incremental actions as well as through transformative approaches. Countries just starting their smart grid journeys could consider focusing on the following five initial steps. Above all, they start with a vision and a coalition.

The five steps to start the digital journey



Create a vision for smart grid deployment

Based on specific country needs, immediate problems (such as heavy grid losses), preparing for rapid load growth, or handling a large influx of PV on distribution systems may need to be prioritised. In relation to each aim, set out near- and long-term targets, identifying end goals and milestones that can be used to benchmark progress. Establish a roadmap to define what needs to be done, when, where and by whom. Acknowledge that not all solutions will be digital while seeking to identify where digital technologies deliver greater value, at lower cost – whether in the short or long run. Investigate transferable lessons from other large-scale deployments and ongoing demonstrations of smart grid technologies, while recognising that regional, cultural and infrastructure contexts can be vastly different. Establish a benchmark of where the grid's current status and indicators against which to measure progress towards country objectives.

Match needs with digital solutions. Identify digital technologies relevant to priority objectives and rank their costs and benefits by quantifying their potential impacts. This can help sequence priorities and keep activities focussed over time. This implies creating a culture of cost-benefit thinking across the stakeholder base and developing more formal CBA metrics and assessments.

Actively engage with stakeholders

This helps to co-ordinate and align on vision and strategies, including in plans elaborated by utilities, and to ensure that different perspectives and concerns are addressed. Collaboration and partnerships between public and private stakeholders are crucial to effectively manage risks and balance the pace of grid modernisation. It is critically important to broaden the set of stakeholders beyond traditional groups, to include digital and telecoms providers, technology manufacturers, and electricity and digital standard bodies. The growing range of smaller, third-party actors that are increasingly deploying digital grid services and solutions could also be included.

Manage data from the start

Collecting and sharing data is crucial to be able to evaluate the benefits of all smart grid projects and to capture lessons learned in the bid to achieve large-scale deployment. Willingness to learn from mistakes – and to let others do so – supports continuous improvement and scaling. Policy makers play a key role in facilitating data and knowledge exchange, including by setting baseline rules, organising forums, and providing templates and procedures for data sharing.

Ensure an equitable distribution of costs and benefits

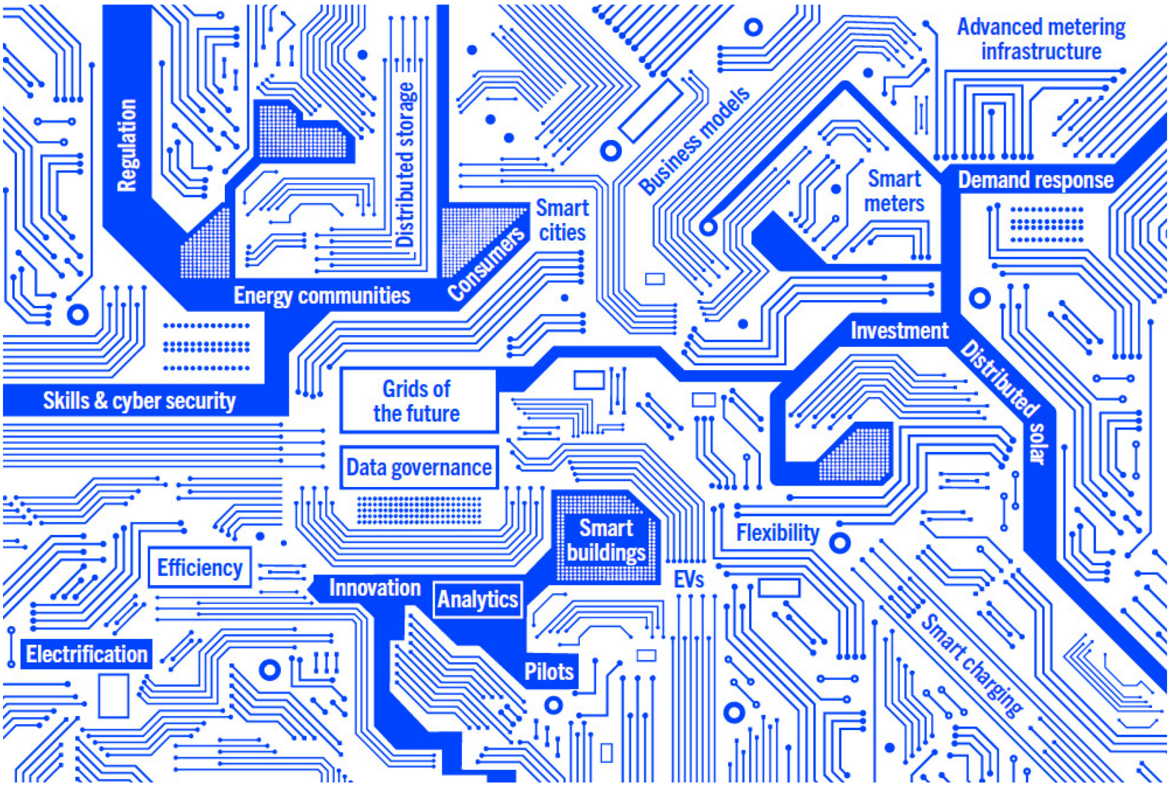
Each of the above steps helps develop a deep understanding – based on data and evidence – of costs and benefits linked to smart grid deployment. They also demonstrate the need to move beyond traditional grid metrics, towards broader societal benefits and impacts of digitalisation in areas such as air pollution, water, waste, economic impacts, or access to energy and digital services. Framing a roadmap and a policy development strategy around equity in costs and benefits is vital to stakeholder engagement, as is communicating them in a transparent manner.

The way forward

Digitalisation is reshaping the power sector, creating new opportunities across multiple applications. The rapid evolution of digital technologies is creating new functionalities and use cases. With increased data sharing across the energy value chain, and linking these data with weather models, satellite data, mobility patterns, financial services and geographic location systems, it will be possible to create innovative services with greater levels of granularity and relevance.

Across the energy sector, future challenges and opportunities are outgrowing current policy, regulatory and governance processes and structures. Proactive, data-driven and evidence-based approaches are needed to ensure that near-term decisions actively support decarbonised, affordable, inclusive and sustainable future energy systems. Digitalisation is a vital enabler; to optimise the potential of smart grids, they need to be meshed with smart policies and regulations to capture the maximum value of digital tools and the data they can deliver.

Grids of the future will be characterised by growing complexity and inter-connectedness



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Annexes

Abbreviations and acronyms

3DEN	Digital Demand Driven Electricity Networks Initiative
ABC	Arial bundled / bunched cables
AC	Air conditioner / air conditioning unit
ADB	Asian Development Bank
AFD	French Development Agency
AfDB	African Development Bank
AI	Artificial intelligence
AMDS	Automated monitoring and decision support
AMI	Advanced metering infrastructure
AREI	Africa Renewable Energy Initiative
ARERA	Regulatory Authority for Energy Networks and Environment
ASU	Air separation unit
AT2ER	Togolese Agency for Rural Electrification and Renewable Energy
AT&C	Aggregate technical and non-technical losses
BESS	Battery energy storage system
BOOT	Build, own, operate, transfer model
CAPEX	Capital expenditure
CBA	Cost-benefit analysis
CERI	Community Energy Resilience Initiative
COP	Conference of the Parties
DER	Distributed energy resources
DFI	Development finance institution
DISCOM	Distribution company
DPV	Distributed photovoltaic (solar)
DSO	Distribution system operator
EMDEs	Emerging markets and developing economies
EMR	Energy and Mineral Resources
EMRA	Energy Market Regulatory Authority
EBRD	European Bank for Reconstruction and Development
EESL	Energy Efficiency Services Limited
EIB	European Investment Bank
EMRA	Energy Market Regulatory Authority
ESCO	Energy service company
ESG	Environmental, social and governance
ESKOM	Electricity Supply Commission
ELDER	Association of Distribution System Operators
EU	European Union
EUR	Euro

EV	Electric vehicle
FCPR	Fundación Comunitaria de Puerto Rico
FEI	Fund for Energy Inclusion
FENOGE	Fondoa de Energías No Convencionales y Gestión Efficiente de la Energía
GCF	Green Climate Fund
GDP	Gross domestic product
GEF	Global Environment Facility
GHG	Greenhouse gas
GIF	Global Infrastructure Facility
GIS	Geographic information system
GISD	Global Investors for Sustainable Development Alliance
GPFM	Green Powered Future Mission
IADB	Inter-American Development Bank
ICT	Information and communication technologies
IEA	International Energy Agency
IFC	International Finance Corporation
IFI	International finance institution
IoT	Internet of things
IT/OT	Information Technology/Operational Technology
IPCC	International Panel on Climate Change (United Nations)
IPP	Independent power producer
IRENA	International Renewable Energy Agency
ISGAN	International Smart Grid Action Network
ISGF	India Smart Grid Forum
ISO	Independent system operator
ITP	Independent transmission project
KETRACO	Kenya Electricity Transmission Company
KfW	Kreditanstalt für Wiederaufbau
KPI	Key performance indicator
LAC	Latin America and the Caribbean
LEDS	Low Emissions Development Strategies
MCC	Millennium Challenge Corporation
MC-CBA	Multi-criteria cost-benefit analysis
MDB	Multilateral development bank
ML	Machine learning
NEDCo	Northern Electricity Distribution Company
NDCs	Nationally Determined Contributions
NHPC	National Hydroelectric Electricity Corporation
NIIF	National Investment and Infrastructure Fund
NSO	National system operator
NTL	Non-technical losses
NTPC	National Thermal Power Corporation
NZE	Net Zero Emissions by 2050 Scenario (IEA)
OECD	Organisation for Economic Co-operation and Development
OPEX	Operating expenditure

PAYGo	Pay-as-you-go (payment plan)
PIM	Performance incentive mechanism
PMU	Phasor management unit
PPF	Project preparation facility
PPP	Public-private partnership
PV	Photovoltaic (solar)
RDSS	Revamped Distribution Sector Scheme
Res4Africa	Renewable Energy Solutions for Africa
RETA	Regulatory Energy Transition Accelerator
RMI	Rocky Mountain Institute
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory control and data acquisition
SDG	Sustainable Development Goals
SMNP	Smart Meter National Programme
SOE	State-owned enterprise
T&D	Transmission and distribution (systems)
TL	Technical losses
TOTEX	Whole-of-life total expenditure
TSO	Transmission system operator
TVET	Technical and vocational education and training
UKEP	Utility Knowledge Exchange Platform
USD	United States dollar
VoLL	Value of lost load
VPP	Virtual power plant
VRE	Variable renewable energy
WACC	Weighted average cost of capital

Units of measure

Gt/yr	Gigatonnes per year
Gt CO_2	Gigatonne of carbon dioxide
Gt CO_2/yr	Gigatonnes of carbon dioxide per year
GW	Gigawatt
GWh	Gigawatt hour
Mt	Megatonne
MW	Megawatt
MWh	Megawatt hour
t	Tonne (metric)
Wp	Watt peak capacity

Glossary

Advanced metering infrastructure (AMI): a system that includes meters, communications, and information management networks between consumers and utilities. AMI may also provide connectivity to other types of devices such as grid sensors, switches, and DERs.

Aggregator: entity managing a portfolio of multiple distributed resources to offer services such as flexibility to power systems.

Ancillary services: services that help the electricity grid maintain balance between generation and demand.

Artificial intelligence (AI): programming models and algorithms imitating human intelligence.

Broadband line: high-speed internet access which allows for faster communication. It is largely used by utilities for substation and SCADA communications.

Cybersecurity: protection of computer systems, networks or computer programmes from offensive assault targeting devices, networks or databases.

Demand response (DR): mechanism by which electricity demand is shifted or reduced over given time periods in response to price changes or other incentives. This can be used to reduce peak demand and provide electricity system flexibility and allows utilities to cycle certain customer loads on and off in exchange for financial incentives.

Demand response management system (DRMS): software which controls and operates DR aggregations and other DR programmes.

Demand-side flexibility: capability of demand side resources to adjust load profiles across different timescales; energy flexibility and load flexibility are often used interchangeably with demand-side flexibility.

Demand-side management: the modification of energy demand by customers through strategies, including energy efficiency, demand response, distributed generation, energy storage, electric vehicles, and/or time-of-use pricing structures.

Demand-side response (DSR): actions that can influence the load profile, such as shifting the load curve in time without affecting total electricity demand, or interrupting demand for a short duration or adjusting the intensity of demand for a certain amount of time.

Digital twins: virtual replica of a physical object, building, city, or grid, used to simulate and manage operations.

Distributed energy resource (DER): a resource sited close to customers that can provide all or some of their immediate power needs and/or can be used by the utility system to either reduce demand or provide supply to satisfy the energy, capacity, or ancillary service needs of the grid. They include rooftop solar, battery storage systems, electric vehicles, among others.

Distribution system operator (DSO): organisation managing the electricity distribution grid at low-voltage level.

Dynamic line rating: automatic variation of power flows in electric cables depending on weather conditions.

Fault location, isolation, and service restoration (FLISR): a combination of hardware and software technologies that can identify the fault location automatically, isolate the faulted line section and restore service to all customers not directly connected to the faulted line section. This smart function is also referred to as a self-healing grid.

Geographic Information System (GIS): in the context of electricity systems, GIS is a software which captures, records, and displays data on grid assets and their geographic locations on a map.

Grid edge: covers all technologies that connect the energy supply side with the demand side, both hardware and software, including solar panels, EV charging infrastructure, smart appliances, and real-time grid optimisation.

Grid flexibility: ability of the power system to alleviate disruption between supply and demand.

Grid hardening: grid improvements such as rebuilding or proactively replacing assets in the electricity grid to strategically prepare to potential risks.

Grid resilience: ability of the power system to recover after disturbances such as extreme weather events or cyberattacks.

Grid services: services that support the generation, transmission, and distribution of electricity and provide value through avoided electricity system costs (generation and/or delivery costs).

Grid-interactive efficient building (GEB): an energy-efficient building that uses smart technologies and on-site DERs to provide demand flexibility while co-optimising for energy cost, grid services, and occupant needs and preferences in a continuous and integrated way.

Integrated voltage control: a process of controlling voltage to improve overall system performance, allowing a utility to reduce electrical losses, eliminate voltage profile problems and reduce electrical demand.

Internet of things (IoT): network of physical devices and sensors connected to a common network and reporting data dynamically to central receivers.

Interoperability: capability of computer systems or software to match data according to predefined standards.

Machine learning: application of computer systems that use algorithms to learn and exploit patterns from data and automatically improve themselves by reiteration.

Microgrid: a group of interconnected DERs and loads able to operate when connected to the larger distribution grid and also able to operate as an “island” when there is an outage or other grid disturbance.

Smart charging: system by which the system operator optimises the charging profile of an electric vehicle according to how much energy the vehicle needs over a specified length of time, how much energy is available, the price of wholesale electricity and grid congestion, among others. Relies on the sharing of real-time data.

Smart inverter: a power electronics device that transforms direct current to alternating current, useful for DERs integration on the grid. Its features also include voltage and frequency ride-through responses to enhance the distribution system’s stability, reliability, and efficiency.

Smart meter: a device capable of two-way communications used for measuring electricity consumption and other end-use information and transmitting this information on demand to a central location. Smart meters provide near real-time customer usage data, as well as interface with other ‘smart’ devices in the home or business.

Supervisory control and data acquisition (SCADA): a combination of hardware and software which enables the remote monitoring and control of transmission and distribution systems.

Transmission system operator (TSO): organisation managing the electricity transmission grid at high voltage level.

Variable renewable energy (VRE): clean resources which depend on variable supply, such as wind or solar energy.

Virtual power plant (VPP): a network of digitally aggregated distributed energy resources, flexibility providers and storage technologies, centrally controlled to provide efficient dispatching and integration into the power market.

Wide area network (WAN): a telecommunications network connecting distribution substations with operations and control centres and other utility facilities.

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