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THE ROLE OF SCIENCE, TECHNOLOGY AND INNOVATION IN PROMOTING RENEWABLE ENERGY BY 2030

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This series of publications seeks to contribute to exploring current issues in science, technology and innovation, with particular emphasis on their impact on developing countries.

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Reference to dollars ($) means United States of America dollars.

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1. INTRODUCTION

It is estimated that 1.1 billion people in the world today have no access to electricity. This is 14 per cent of the world's population. Some 85 per cent of those without access to electricity live in rural areas, mainly in Africa. Furthermore, 2.8 billion people do not have access to clean forms of energy for cooking (IEA, 2017a). Using traditional biomass and inefficient technologies has serious health, social and environmental consequences. Increasing access to clean forms of energy makes a critical contribution to achieving the 2030 Agenda for Sustainable Development and the Sustainable Development Goals, agreed in September 2015. Goal 7 aims primarily to ensure universal access to affordable, reliable and modern energy services by 2030. Within this, there is a target "to increase substantially the share of renewable energy in the global energy mix" by 2030.

An expansion of renewable energy could also contribute to progress towards several other Goals. A study by the International Council for Science (ICSU, 2017) showed that achieving universal energy access and increasing renewable energy is likely to have largely positive impacts on other Sustainable Development Goals.

The reduction of poverty (Goal 1) requires, among other things, the development of modern infrastructures. Renewable energy can play an important role in the development of such infrastructures. In addition, it is critical for productive capacities and income generation opportunities (UNCTAD, 2017). Renewable energy can contribute to Goal 3 by reducing the health risks associated with pollution by replacing the use of fossil fuels (Intergovernmental Panel on Climate Change, 2012). It is also relevant to gender equality (Goal 5). By replacing traditional forms of energy such as wood fuel, modern forms of renewable energy can reduce the time spent gathering wood by women and girls (Oparaocha and Dutta, 2011). Lighting through renewable energy systems can also provide greater time flexibility for domestic activities, especially for women (Millinger, 2012).

There are also clear synergies with industry, innovation and infrastructure (Goal 9) and climate action (Goal 13). Many national innovation policies and international initiatives include a focus on renewable energy technologies. Furthermore, the expansion of renewable energy is part of most national strategies to mitigate the greenhouse gases that cause climate change.

Some potentially negative interactions were also identified by the International Council for Science, which may need to be addressed. These include ensuring that any additional costs of renewable energy investments are not borne by the poor. Recent falls in renewable energy costs and the implementation of new business models have helped to mitigate this risk. Other examples include the impact of water supply infrastructure (particularly desalination) on energy demand and the impact of bioenergy on land use, especially if this leads to competition with land use for food.

This current studies paper explores the role of science, technology and innovation to achieve a substantial increase in the share of renewable energy by 2030. The paper includes six main sections that are structured as follows. Section 2 provides background on the role of renewable energy in the global energy mix. It briefly discusses recent trends and challenges for renewable energy. It also provides and overview of the status of some of the key renewable energy technologies and associated enabling technologies, and discusses some of the improvements that could occur in the future.

Sections 3 to 5 discuss innovation pathways, key issues and policies for renewable energy in more detail. These sections draw on a range of national case studies of renewable energy innovation and deployment from both developed and developing countries. Section 3 focuses on the innovation systems and the types of innovation that are relevant to renewable energy technologies. Section 4 discusses some more specific challenges for renewable energy, including technical and market challenges; mini-grid and off-grid applications; and the use of renewables in households, especially in developing countries. Section 5 explores policies for renewable energy deployment, with an emphasis on policy mixes rather than individual policies in isolation. The section also discusses the role of international cooperation.

Section 6 concludes with a set of recommendations for countries wishing to increase the role of renewable energy in their energy use. It includes a particular focus on recommendations to the Commission on Science and Technology for Development, including the role of international cooperation.

2. BACKGROUND AND CONTEXT

Renewable energy sources and technologies are diverse – and range from small-scale solar photovoltaic (PV) panels to the use of biofuels for transport. The International Energy Agency (IEA, 2016) makes four distinctions between different renewable energy technologies that illustrate this diversity:

- Variable vs dispatchable renewables. Some technologies are weather dependent (e.g. wind and solar photovoltaic), with some unpredictability in their output, while others can be dispatched when required (e.g. bioenergy).
- Centralized vs distributed renewables. Solar home systems are highly decentralized, while large-scale hydrotechnologies are used in some of the largest power plants in the world.
- Direct vs indirect renewables. For example, solar thermal technology uses the sun to heat water directly, while solar PV technology generates electricity which can then be used for a variety of energy services.
- Traditional vs modern forms of bioenergy. Traditional forms of bioenergy are still widely used in the developing world for cooking and heating using basic technologies, while more modern technologies are available (e.g. for improved cook stoves or for processing and burning biomass to generate power and heat).

Some renewable energy sources and technologies are not considered clean, such as traditional biomass that involves the direct, and often inefficient, combustion of wood and charcoal. Renewable energy can play an important role across the entire energy system. It can be used for electricity generation, transport, heating and cooling or cooking.

Renewable energy sources have been used for as long as energy systems have existed and predated the use of fossil fuels (e.g. Grubler and Nakicenovic, 1991). Modern efforts to increase the use of renewable energy sources have been driven by several interlinked motivations: to improve energy security and diversify energy sources, to encourage sustainable economic development and to protect the climate and the environment from the impacts of fossil fuel use (IEA, 2011). These motivations led to a step change in the development and deployment of a range of renewable energy technologies. Policy interventions contributed to dramatic cost reductions of some renewable electricity technologies and the rapid deployment of these technologies.

2.1 Global trends in renewable energy deployment

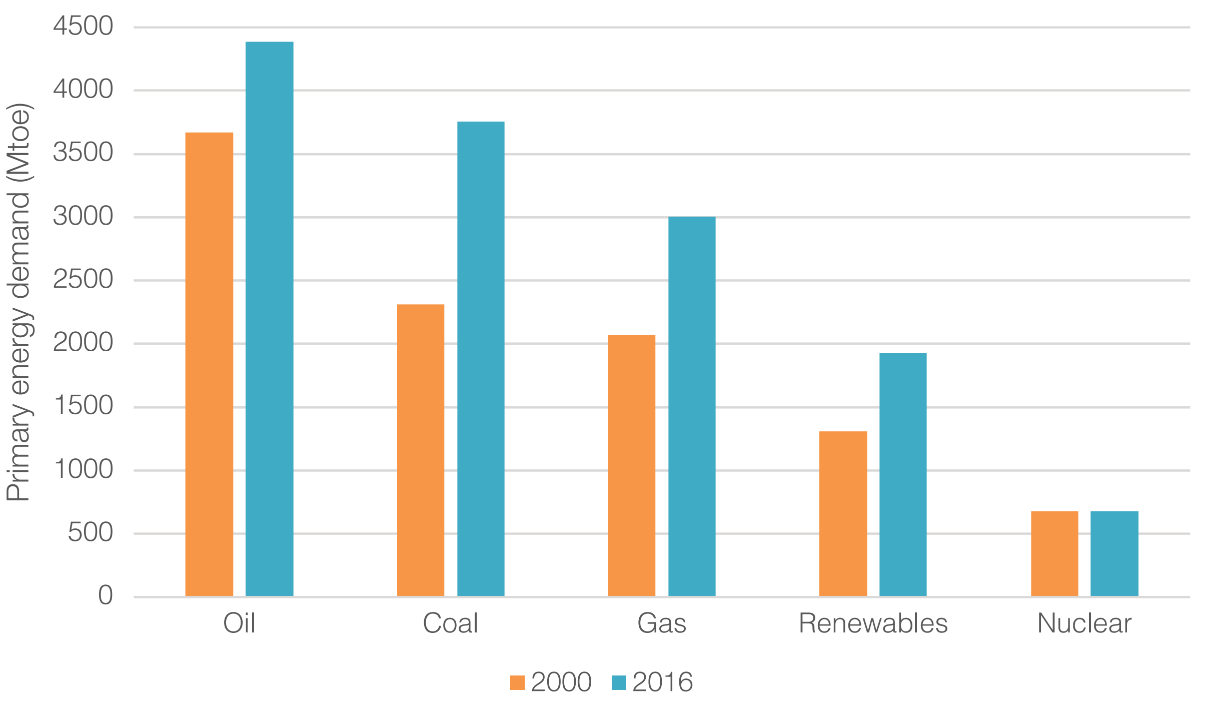
According to recent International Energy Agency (IEA) data, renewable energy accounted for 14 per cent of the global primary energy demand in 2016 (IEA, 2017a). If traditional forms of solid bioenergy are excluded, the share was 9 per cent. Figure 1 shows the contribution of renewables to global primary energy demand in comparison with those of fossil fuels and nuclear power in 2000 and 2016.

Between 1990 and 2016, the average annual growth rate of renewable energy (2 per cent) was slightly higher than the annual growth rate of primary energy (1.7 per cent) (IEA, 2018). This overall figure masks much higher growth rates for some renewable technologies. For example, solar photovoltaic energy grew by an average annual rate of 37.3 per cent; wind power, 23.6 per cent; biogas, 12.3 per cent; solar thermal energy, 11.5 per cent; and liquid biofuels, 10 per cent. By contrast, solid biofuels and charcoal – which accounted for 62.4 per cent of renewable energy in 2016 – grew at an average rate of 1.1 per cent.

The latest *BP Statistical Review of World Energy* gives more up-to-date figures, albeit on a different basis: they do not include traditional forms of bioenergy. It states that renewable energy sources, including hydroelectricity, accounted for 10 per cent of global primary energy consumption in 2016 and 10.4 per cent in 2017 (BP, 2018).

According to IEA, 23.8 per cent of electricity now comes from renewables worldwide (IEA, 2018). The majority of this (16.3 per cent) is from hydropower, with the remainder coming from bioenergy and waste (2 per cent); and wind, geothermal, solar and tidal energy (5.5 per cent combined). Over 50 per cent of new power capacity investment went into renewables in 2015, overtaking the combined annual capacity addition for fossil and nuclear plants for the first time (IEA, 2016). In 2016, renewables capacity accounted for two thirds of additions – with a record 165 GW being deployed in that year (IEA, 2017a). Wind and solar deployment has increased particularly rapidly in

Figure 1. Global primary energy demand by energy source



Source: IEA, 2017a.

the last decade, driven by market creation policies in many countries. In 2016 alone, 74 GW of solar PV capacity and 52 GW of wind capacity was installed.

Renewables supply 9 per cent of heat demand in industry and buildings, while the proportion in transport is much smaller, at 3 per cent (IEA, 2017a). Most of the latter is biofuels.

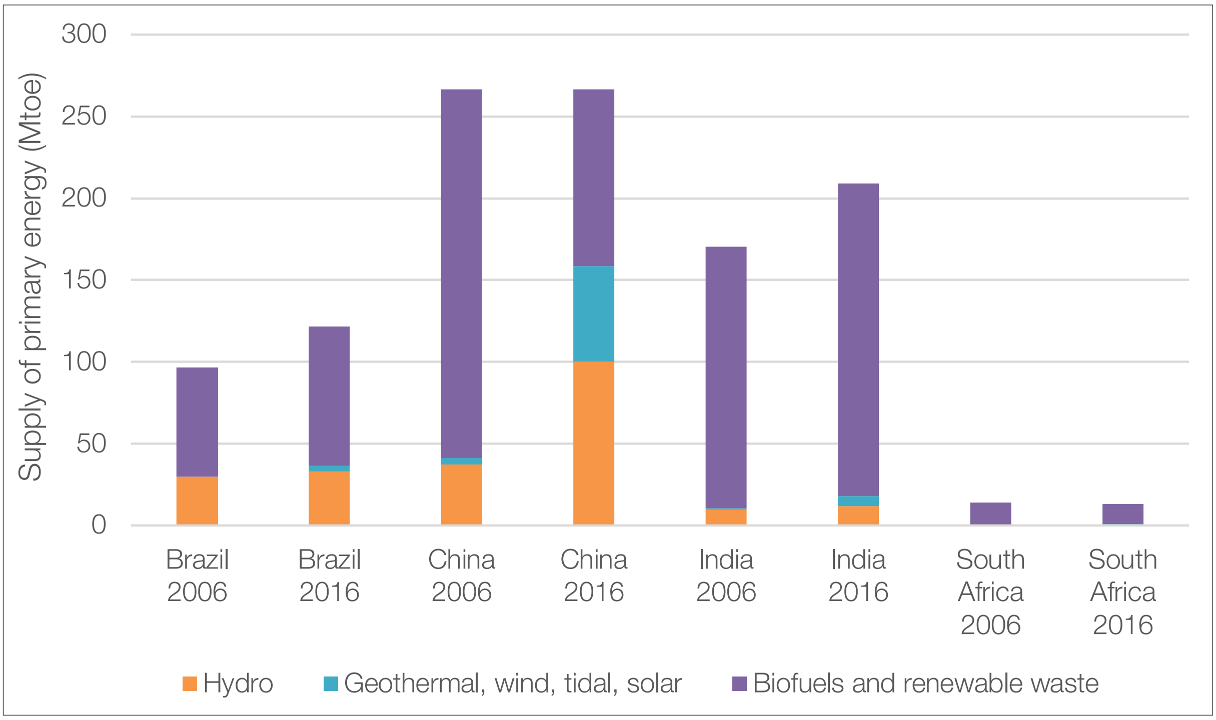
Regional figures from IEA on the use of renewable energy show significant variation between different countries. This is because the use of renewable energy largely depends on contextual factors such as geographical and environmental conditions, socioeconomic and development priorities, cultural and institutional conditions, and policy and regulatory frameworks. In OECD countries, the share of renewable energy from the total primary energy supply grew from 6 per cent in 1990 to a record 10.2 per cent in 2017. The share of renewables in electricity generation grew from 17.3 per cent to 24.9 per cent during the same period. If hydropower is excluded, the share of other renewables grew much more quickly – from 2 per cent in 1990 to 12.1 per cent in 2017 (IEA, 2018).

In non-OECD Asia – a region that includes China and India – renewable energy accounted for 14.9 per cent of primary energy in 2016. In non-OECD Americas and Africa, the share of renewable energy was much higher than in Asia – at 30.9 per cent and 49.5 per cent respectively. In each case, the use of renewable energy is dominated by bioenergy. Bioenergy alone accounted for 47.6 per cent of total primary energy demand in Africa in 2014, most of which was from traditional forms (IEA, 2018).

More detail on selected middle income and less developed countries is shown in figures 2 and 3 below. In China, for example, the contribution of renewables to total primary energy supply was almost the same in 2006 (266.8 Mtoe) and 2016 (266.6 Mtoe). But the share of total primary energy fell from 14.1 per cent to 9 per cent during this decade as investments in fossil fuel infrastructure accelerated (IEA, 2008 and IEA, 2018). However, the mix of renewable energy sources shifted markedly during that period. In 2006, 84.5 per cent of the renewable energy of China came from solid biofuels and waste, with the remainder coming from hydropower. By 2016, this share had fallen to 40.5 per cent – with hydropower accounting for 37.5 per cent and wind, solar and geothermal energy accounting for 22 per cent.

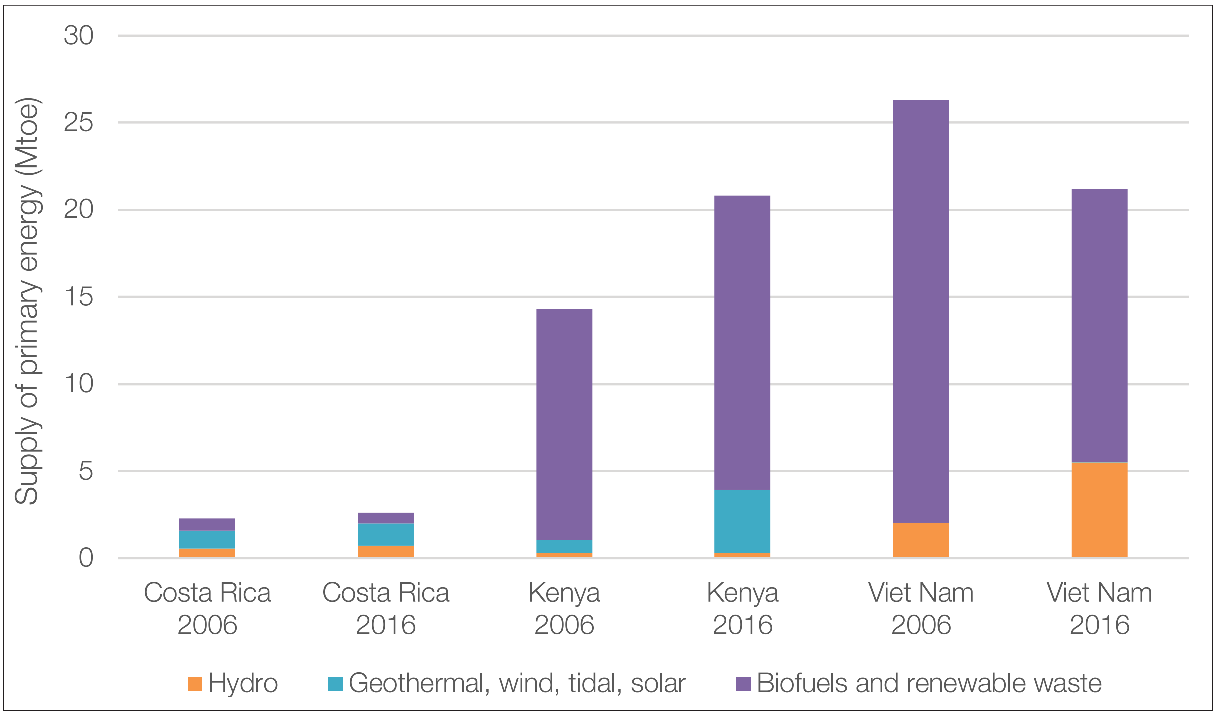
While Brazil and India use less renewable energy in absolute terms than China, the share of renewables in their energy mix is much higher – 42.8 per cent of

Figure 2. Renewable energy in Brazil, China, India and South Africa, 2006 and 2016



Source: IEA, 2008 and 2018.

Figure 3. Renewable energy in Costa Rica, Kenya and Viet Nam, 2006 and 2016



Source: IEA, 2008 and 2018.

primary energy in Brazil in 2016 and 24.2 per cent of primary energy in India in the same year (IEA, 2018). The particularly high share for Brazil is partly due to the long-standing use of ethanol in road transport, as well as significant amounts of hydropower generation.

As expected, the use of renewable energy in developing countries is often dominated by traditional forms of bioenergy. However, the share of renewables in total primary energy supply varies considerably – from 26.2 per cent in Viet Nam in 2016 to 50.5 per cent in Costa Rica and 79.9 per cent in Kenya in the same year (IEA, 2018). In all three countries shown in figure 3, this is complemented by growth in other renewables, including hydro, wind and solar.

2.2 Technological and non-technological barriers and drivers in renewable energy deployment

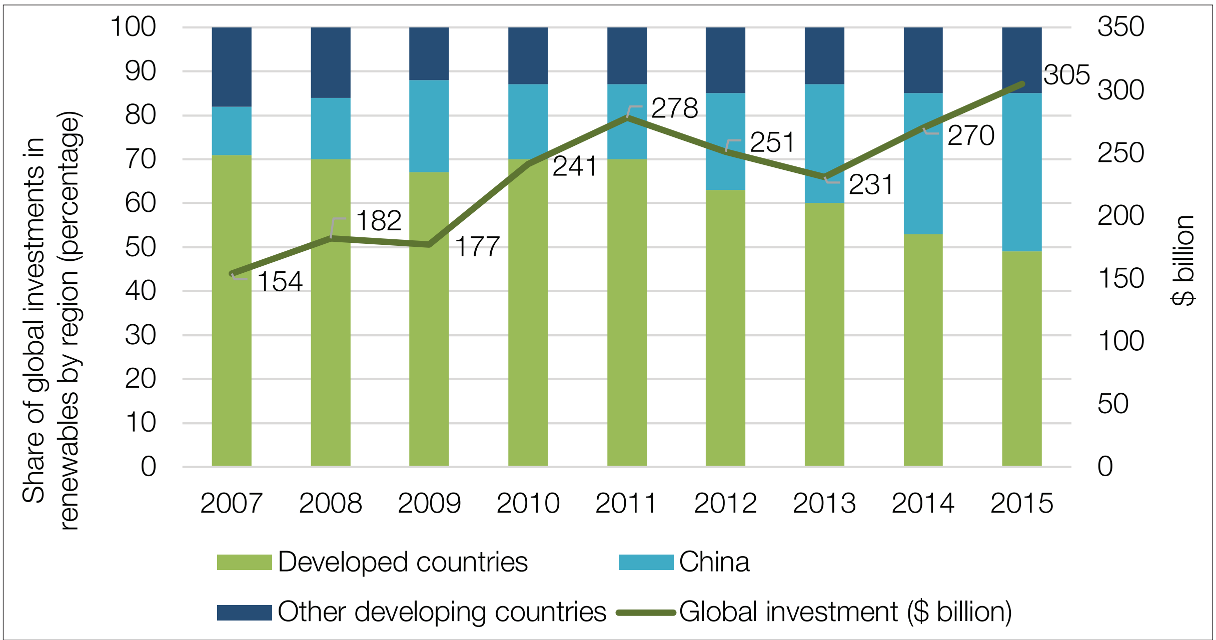
In recent years, there has been fast progress in the deployment of some renewable energy technologies. The range of factors that have promoted or inhibited renewables development and deployment are both technological and non-technological in their nature and include:

- Costs and affordability: Until recently, the costs of renewable technologies have usually been higher than those of fossil fuels. For some technologies, this gap has now started to close, especially solar photovoltaics and wind energy for electricity generation.
- Financing: This has been an important barrier to renewables deployment in many countries and has required policy intervention to provide greater certainty for investors. It remains a particularly important challenge in many developing countries.
- Technical maturity: Some renewable energy technologies are not yet ready to be widely deployed and require significant development and demonstration before reaching adequate levels of reliability and cost-effectiveness.
- Integration into electricity systems: Renewable technologies sometimes present new challenges for electricity systems and markets. This includes bottlenecks in electricity network infrastructure, limits to the ability of electricity systems to absorb variable renewables and markets that were designed for incumbent fossil fuel technologies.
- Environmental sustainability: Concerns about environmental sustainability have led to controversy about the use of some renewable energy sources. Examples include first-generation biofuels, where there are questions about life-cycle emissions and implications for land use and the impacts of large hydropower plants on regional ecosystems.
- Skills: There is a need for appropriate skills and capabilities to install, operate and maintain renewable energy technologies, as well as to design policies.

The deployment of some renewable electricity technologies has been supported by incentives implemented in an increasing number of countries. These incentives have led to rapid cost reductions which, in turn, have made these technologies more cost-effective. Auctions have been a particularly important policy for driving these cost reductions. In many countries, there has been a transition from government-administered tariffs to auction systems during the past few years (IEA, 2017b). A review by the International Renewable Energy Agency (IRENA) concluded that the average contracted price for solar photovoltaic energy fell from almost $250/MWh in 2010 to $50/MWh in 2016 (IRENA, 2017a). Average wind contract prices halved in the same period – from $80/MWh to $40/MWh. Several recent auctions in Europe have driven down the costs of offshore wind much more quickly than expected. The recent auction of the United Kingdom in September 2017 resulted in contract prices for offshore wind that are 50 per cent lower than the price of offshore wind in 2015 (Department of Business, Energy and Industrial Strategy, 2017). IEA expects almost half of all renewable electricity capacity additions to be driven by auctions in the next five years, compared with just 20 per cent in 2016 (IEA, 2017b).

Cost reductions and policy support in a number of countries have created a favourable investment climate for some renewable energy technologies. Investment in renewable energy has almost doubled, from $154 billion in 2007, to $305 billion in 2015. However, financing is still a major challenge. Estimates of the investment levels needed to reach, for example, the target of 36 per cent renewables of total final energy consumption, set by the Sustainable Energy for All (SE4A) initiative, is around $770 billion (IRENA, 2017b). According to IEA, China and developing countries are experiencing the fastest growth since 2012 (IEA, 2017b). In 2015, global investment into renewable energy was mostly due to solar photovoltaic and wind enery, which accounted for around 90 per cent (IRENA, 2017b). Figure 4 shows the recent development of global investment flows into renewable energy, as well as the regional share of these investments.

Figure 4. Global investments in renewable energy



Source: IRENA, 2017b.

Several renewable technologies are now well established including solar (thermal and PV), hydro and wind technologies. In many cases, public policy support is still required for these technologies. Although they require subsidies, bioenergy technologies for generating heat and power are also mature, as are first-generation biofuels for transport. Yet, these biofuels are controversial due to concerns about life-cycle emissions, resource sustainability and potential interactions with other uses of land (e.g. for food crops). New generations of biofuel are being developed. However, recent developments in electric vehicle technology and policy targets in many countries may mean that renewables play a more indirect role in transport. Many future scenarios foresee a rapid expansion of electric (and sometimes hydrogen) vehicles, which could increase demand for renewables to generate clean electricity or hydrogen.

There is an increasing emphasis on the technical and economic challenges of integrating larger shares of renewables into electricity grids. As the case studies in section 4 will show, some countries now have high shares of renewables, including those such as wind and solar PV that are variable or intermittent. A recent systematic review of international evidence on the costs and impacts of increasing shares of intermittent renewables on electricity systems found a wide range of estimates for these costs and impacts (Heptonstall et al., 2017). It concluded that these costs will be higher if electricity systems are not flexible. Multiple sources of flexibility are now possible, including demand-side response, interconnectors, conventional generation and storage. One implication is that further increases in renewable electricity from variable technologies will partly depend on progress with developing and deploying these forms of flexibility. This may require reforms to electricity markets so that these flexibility options can be sufficiently rewarded for the benefits they provide.

The Ernst and Young renewable energy country attractiveness index takes some of these factors into account in a regular ranking (Ernst and Young, 2018). The latest edition includes two developing countries in the top 10. China kept its first place in the most recent ranking on the basis of a continuing strong commitment to renewables deployment and the consequent postponement of coal-fired power plant plans, while India felt back to fourth place, compared with 2017, due to unfavourable policy development. The top 10 also includes the United States (second), Germany (third), Australia (fifth), France (sixth), the United Kingdom (seventh), Japan (eighth), the Netherlands (ninth) and Denmark (tenth).

2.3 New and emerging renewable energy technologies

There remains significant scope for innovation that can further improve and reduce costs of renewable energy technologies. New and emerging renewable energy technologies consist of improved or advanced forms of mainstream energy sources (i.e. solar, wind, biomass, hydro and geothermal energy), as well as completely new forms of technologies and improvements in the utilization of renewable energy sources through storage and integration.

Some advancements in mainstream energy sources, such as solar, include improvements in the material science of solar photovoltaic cells. While silicon-based solar photovoltaic energy is likely to remain dominant, a promising variety of third-generation thin film cells based on Earth-abundant materials (including copper zinc tin sulfide, perovskite solar cells, nanomaterials such as organic solar PVs, and quantum dot solar cells) is emerging in material science. Perovskite solar cells, for example, have excellent light-absorbing capacities and lower manufacturing costs. Photoelectric efficiencies improved from 10 per cent to over 20 per cent between 2012 and 2015. However, perovskites are still in the early stages of research and development, with uncertainty regarding long-term stability and feasibility for large-scale deployment (Massachusetts Institute of Technology, 2015). Third-generation solar photovoltaic cells are aiming for combinations of high-power conversion efficiency, lower cost and usage of materials, and lower manufacturing complexity and costs. Achieving all three objectives remains elusive, but with greater efforts into research and development, solar photovoltaic technology can achieve an even larger scale of deployment. Other solar energy improvements involve concentrating solar power technologies or printable organic solar cells.

Advancements in other mainstream energy sources include new wind power technologies (such as floating offshore turbines), advanced biofuels or "third generation" biofuels that use non-food crops, low-impact hydropower dams and new drilling technologies to access geothermal energy.

New sources of renewable energy are being explored, such as in marine energy, microbial fuel cells and hydrogen. Marine energy has vast potential due to the ocean's consistency, predictability and coverage of nearly three quarters of the Earth's surface. Marine energy is categorized based on different techniques of acquiring energy, such as wave energy, tidal currents, tidal power, salinity gradients and ocean thermal energy conversion. However, further developments are needed as technological challenges inhibit the potential for marine energy to capture a more significant proportion of total worldwide energy supply (Hussain et al., 2017).

Over the past 10–15 years, microbial fuel cells have emerged as a versatile renewable energy technology (Santoro et al., 2017). Microbial fuel cells have the potential to generate power from organic waste materials, while simultaneously treating wastewater. While microbial fuel cells are still a nascent technology, further research and development may validate its potential to improve sanitation in developing countries and provide energy access in more sustainable ways.

Hydrogen is attracting increased interest as a renewable energy source for heat and transport applications. Like electricity, hydrogen is an energy vector that allows for the transportation and/or storage of energy, decoupling the production of energy from its consumption in time and space. Low-carbon hydrogen can be produced by steam methane reforming (e.g. using natural gas with carbon capture and storage), gasification of coal or biomass or electrolysis of water (using renewable or other low carbon electricity technologies). Current estimates of hydrogen production costs indicate that while electrolysis is relatively expensive, compared with other production methods (e.g. biomass gasification and steam methane reforming), cost reductions are anticipated (Speirs et al., 2017).

Other emerging renewable energy technologies such as artificial photosynthesis and cellulosic ethanol energy extraction also hold promise for the transition to a sustainable and scalable energy system. Artificial photosynthesis has the capability of capturing and storing the energy from the sun, converting it into a usable fuel. Cellulosic ethanol extraction is a more recently discovered biofuel, which is derived from non-food crops or inedible waste products such as grass, paper or algae. The possible use of non-food sources for cellulosic ethanol extraction minimizes "food-for-fuel" conflicts and is less energy intensive, compared with common ethanol production sources, such as corn or sugarcane.

With the increase in innovation and deployment of different renewable energy sources, there have been improvements in the utilization of these energy sources. Some of these improvements include integration of electric vehicles into the power grid, enabling digital technologies in energy systems and developments in electricity storage technologies.

There has been minimal linkage between the transportation and electric power sectors until recently (IEA, 2017c). Integration into smart infrastructures, such as vehicle-to-grid integration, is an emerging technology with immense potential. On average, personal vehicles are on the road for about one hour a day, while the rest of the day, they are stationary – in parking lots or garages, near buildings with electrical power (Sovacool et al., 2017). There is a growing interest in developing vehicle-to-grid systems that provide a bidirectional electricity flow between a vehicle and the power grid. There is a possibility of using electric vehicles as storage devices, with the potential of selling electricity back to the grid during peak demand while the vehicles are not being used. Numerous benefits can include new business models that can incentivize owners with additional revenues, scaling application of electric vehicles beyond individual use and integration into smart infrastructure and cities. One of the motivations for using electric vehicles is the increasing trend of countries to phase out petrol and diesel vehicles. For example, India plans to do so by 2030; China, France and the United Kingdom, by 2040 (World Economic Forum, 2017). Several other countries have different target dates for the phase-out (IEA, 2017d).

As renewable energy technologies increasingly rely on digital technologies, a key future research area is in the digitalization of energy systems that become more connected, intelligent, predictable and sustainable. Transport infrastructure and electric vehicles are being increasingly used as leverage for automated, connected, electric and shared mobility. Smart power grids can match and integrate intermittent sources of electricity such as solar and wind power with transport systems on a wide scale, owing to the cross-sectoral nature of mobility. Potential benefits include greater energy efficiency and optimized energy consumption. However, automated, connected, electric and shared mobility is dependent on consumer acceptance, policy measures and technological progress (IEA, 2017e).

Digital technologies are also relevant to buildings, which account for more than 50 per cent of electricity demand. Energy in buildings is generally used for heating, cooling and lighting. Digital technologies are contributing to improved energy response through real-time data by using sensors, which can be managed and monitored through smart devices. Predictive user behaviour, which utilizes learning algorithms, is another emerging technology that can effectively balance energy loads between consumer demand and utility supply. However, the potential impact of greater connectivity of energy systems is still uncertain because of perceived consumer reservations on data privacy, cybersecurity and implications for employment due to automation.

Electricity storage technologies are undergoing rapid development and cost reductions (IEA, 2016). Storage technologies vary significantly in terms of their output, rates of charge/discharge, and the length of time they can store energy for. Storage technology development is driven in part by the growing electric vehicle market and the increasing availability of incentives offered by some countries for larger grid-scale electricity storage. In California, for example, the public utility commission has mandated that almost 2,000 MW of storage should be installed by utilities. Current battery technologies are unlikely to be sufficient to deliver large-scale seasonal storage (e.g. solar electricity stored in summer to heat buildings in winter). Therefore, there is also a need for advances in other types of heat or energy storage that can operate over longer timescales (IRENA, 2017c).

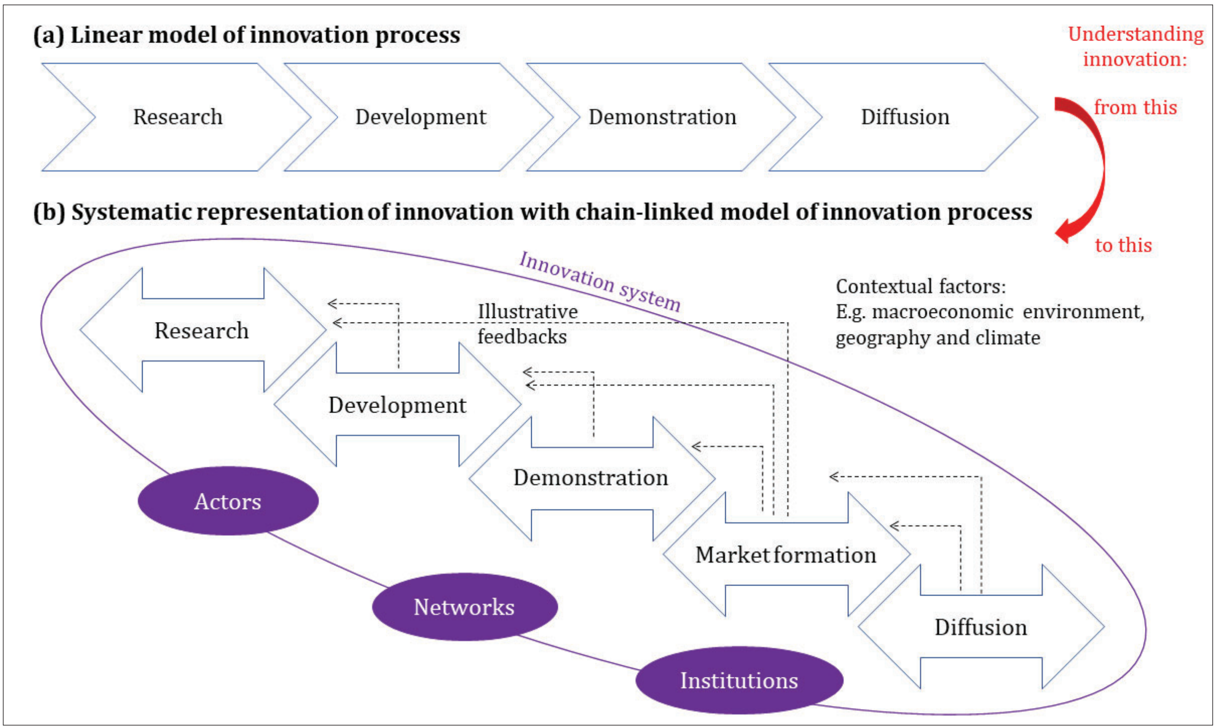
3. INNOVATION PATHWAYS TO MEET THE CHALLENGES

This section provides a general overview of the challenges of renewables innovation, and how renewables pathways may differ between different countries. First, the systemic nature of innovation processes is considered, which involves both technological and non-technological dynamics. Second, it follows from this that policy mixes are required in order to govern these processes. Third, because renewable energy systems exist within the social and technical systems and economic contexts of particular countries and regions, it follows that different countries will have different resources available to them, and different priorities, and as such may make different choices as to the pathway of renewables innovation that they pursue.

3.1 The systemic nature of renewables innovation

Early views of technological innovation presented the process as straightforwardly linear, beginning in research, moving through development and demonstration, and ultimately into diffusion, as shown in the top half of figure 5. While the essential features of this journey are still valid, accumulating evidence from studies of innovation processes reveals that the innovation process is more complex and dynamic than the linear model might suggest. In particular, as illustrated in the lower half of figure 5, there are important feedbacks between different stages, for example as increased diffusion encourages or creates cash flow for more investment in research and development. Further, the innovation chain occurs in a system context. Each stage in the innovation chain includes actors whose activities create the innovation dynamics, as well as economic activity, and who must successfully interact with each other in order for innovation to flow. There is also an institutional context, with, for example, formal institutions such as policies and market incentives, and informal institutions such as investment culture, and other practices and customs. Broader contextual factors, such as the macroeconomic environment, geography and climate, also affect the direction and success of innovation (figure 5).

Figure 5. The evolution of thinking of innovation processes: Moving from a linear model to a systematic model



Source: Gallagher et al., 2012.

The scale and scope of innovation varies widely. Chris Freeman (Freeman, 1992) drew attention to the contrast between incremental innovations that lead to improvements in existing technologies, and radical innovations that yield new inventions and/or methods of production. Both types are relevant to the case of renewable energy. While incremental innovation is important for the improvement of specific renewable energy technologies (e.g. by scaling up the size of offshore wind turbines), more radical innovations such as the development of smarter, more flexible electricity systems can help to integrate variable renewable technologies in greater proportions or at a lower cost than was previously thought possible.

However, non-technological factors, such as the institutional and regulatory environment, are also a crucial part of technological innovation (as shown in figure 5). Furthermore, non-technological innovations can also be significant to the diffusion of renewable energy. Non-technological innovations could include process and organizational innovations, social innovations, market and policy innovations, and business model innovations, such as the evolution from product-based to service-based models. This paper includes examples of several of these types of innovation.

3.2 The importance of policy mixes in governing innovation systems

There are some important implications of this model. One is that policies acting in isolation are likely to be less successful than portfolios of policies that account for each stage of the innovation chain, and for the contextual factors in which innovation systems are embedded. This includes the coordination of the actors, institutions and networks that comprise the innovation system, and the broader macroeconomic and geographical context. For example, in a review of Latin American countries, Banal-Estañol et al. argue that it is through a combination of policies that electrification has increased coverage in Latin America (Banal-Estañol et al., 2017).

Recent literature on *policy mixes* includes a specific focus on their application to sustainable innovations such as renewable energy. For example, Rogge and Reichardt (2016) contend that the general literature on such policy mixes tends to be too narrow, with a focus on three features: strategic policy goals; interactions between individual policy instruments; and the need for a dynamic perspective to account for policy change. Based on a study of the policy mix for the German energy transition, they also argue that policy mixes for innovation need to take a systems perspective and should take into account policy strategies that provide long-term direction, policy processes that influence innovation and characteristics such as policy stability.

3.3 Countries have different national renewables pathways

A country's renewable energy pathway is an important consideration, because once in place, several mechanisms, such as economies of scale, sunk investments, learning effects, user practices and lifestyles can result in so-called "lock in" for several years if not decades. This "lock-in" effect can make pathways difficult to change. Due to its strategic importance, renewable energy pathways, and related income-generation opportunities, need to have a central place in countries' national development strategies.

Innovation systems for renewable energy are embedded within country and regional contexts, and as such will be enmeshed within particular contextual factors. Some of these are largely external factors which policymakers cannot change. These conditions provide the boundaries or constraints within which innovation in renewable energy must be managed. For example, geographical or environmental conditions are critical factors in the availability of different natural resources, some of which could be used to derive renewable energy. Renewable energy policy has to take account of the natural availability of renewable resources. There may be also cultural factors within particular local contexts that must be taken into account.

Other factors are more internal and policymakers have a greater degree of control over them. For example, the policy and regulatory frameworks which apply to renewables can to large extent be managed and adjusted by policymakers and Governments. In these areas, there is significant potential to learn from the successes and challenges experienced by other countries. However, for some countries, there are clear limits to this due to constraints on the availability of finance from consumers, taxpayers or investors – and due to limits on institutional capabilities.

Other conditions have a greater bearing on the aims and priorities that policymakers have in attempting to deploy renewables. The expansion of renewable energy could have a positive impact on a number of development goals. As well as delivering the global benefit of reducing or avoiding emissions of carbon dioxide from the combustion of fossil fuels, expansion of renewables can contribute to local or national-level goals, such as lower levels of poverty, job creation, improved health and education outcomes, or gender equality.

Thus, policymakers have different resources, constraints and priorities when it comes to deployment of renewables. For example, policymakers could choose to focus on the utilization of domestic resources and of building up domestic industries and supply chains. Alternatively, they could work with neighbouring countries to pool access to natural resources, and to internationalize supply chains to allow national specialization according to comparative advantage. Policymakers may choose to focus on large-scale renewable technologies connected to demand centres through extensive transmission and distribution infrastructures. Alternatively, they could focus on decentralized small-scale energy technologies that avoid the need for transmission and distribution infrastructure – or a combination of centralized and decentralized approaches. The difference between centralized and decentralized approaches is not purely about the end-use energy service that is ultimately provided. They differ in terms of the wider socioeconomic impacts of their supply chains and in terms of the timing with which different benefits are received by different sectors of the population. As such, there is not one single optimal renewable deployment path, but rather a range of possible pathways. Choosing how to construct a renewables deployment pathway is not a one-size-fits-all exercise. It is dependent on a clear understanding of contextual factors and priorities.

4. KEY ISSUES IN THE INNOVATION AND DEPLOYMENT OF RENEWABLES

This section focuses on particular issues in the innovation and deployment of renewables. However, throughout each discussion it should be borne in mind that each of the issues is not isolated but interrelated with each of the others. As discussed in section 3, renewables deployment involves an innovation system, comprising technological, as well as non-technological contextual factors, and this requires a mix of policies as nations identify the most appropriate renewables deployment pathway to their conditions.

4.1 Technical challenges of integrating renewable energy into electricity grids

As more renewable energy is deployed, an increasing challenge is on the technical and economic aspects of integrating larger shares of renewables into electricity grids. There is now a large emphasis on infrastructure development and innovation in enabling technologies that can help to integrate variable renewables into electricity systems, including smarter electricity systems that integrate digital and so-called exponential technologies, such as artificial intelligence, and technologies to increase the flexibility of energy demand.

Energy systems are comprised not only of supply-and-demand technologies, but of infrastructures that connect them. Infrastructure is particularly significant in electricity systems, as even electricity generated close to demand requires a wire to transmit the power to the end-use device, and in cases where generators are located distantly from demand, many hundreds of kilometres of power transmission lines may be required. Such infrastructures are significant investments, and as such, once in place, have a considerable constraining and directing influence on the evolution of the supply-and-demand balance in the power system. They are thus highly relevant examples of the concept of lock-in (Arthur, 1989; Unruh, 2000 and 2002).

The future of the power grid infrastructure therefore becomes a major issue in countries that have historically invested in a power grid based around the locations of supply and demand in a largely fossil-fuel-based system, but whose plans to transition to a renewables-intensive system means that the location of power generation will substantially change (box 1).

Box 1. Adapting grid infrastructure to renewable energy deployment: Case studies

In Germany, the electricity transmission network is experiencing a challenge due to the significant wind power potential in the north of the country, but major demand centres in the south. This means that deploying wind power in the windiest northern regions will entail a huge power flow from north to south during times of high wind and high demand. As a result, the country's energy transition (*Energiewende*) also includes plans to upgrade the grid infrastructure. However, this is not without its challenges, as public acceptance is more amenable to underground cables for the electricity superhighways, resulting in increased costs.

The United Kingdom has a similar geographical challenge, as its prime renewable resources are located in more rural areas of the country that historically had lower capacity connections to the national grid, due to lower population and power demand. The challenge is to ensure that grid constraints do not hinder the deployment of renewables, while at the same time avoiding the risk of overinvesting in network capacity that is ultimately underutilized, because the generation actually built is less than predicted. The rapid growth of renewable electricity in recent years and the prospect of a rapid future adoption of electric vehicles has also led the regulator (Ofgem) and the Government to consider a range of regulatory and policy changes. These are designed to make the electricity system more flexible and to encourage system innovations such as storage, demand side response and new business models.

The United States is also making efforts to modernize its grid. The Department of Energy has developed the Grid Modernization Initiative, with activities focusing on the integration of energy efficiency, renewable power and sustainable transportation technologies into the electrical power system. The technologies and techniques required for successful grid integration include improved renewable power forecasting; energy storage technologies; advanced power electronics; grid-responsive building technologies; vehicle-to-grid technologies; and new grid sensing, control and operations approaches.

As a major component of reconstruction efforts in Fukushima, Japan is making Fukushima Prefecture a leading region for new energy future under the Fukushima Plan for a New Energy Society and the Fukushima Innovation Coast Framework. The Plan and the Framework include various efforts such as to construct large scale wind power generations in the region, to strengthen power grid for renewables and to transport, store and utilize hydrogen produced in large scale by renewables.

Sources: Agency for Natural Resources and Energy, 2017 and contribution from the Governments of Germany, Japan and the United States.

Some regions have a particularly high potential for renewables, that if harnessed, could exceed the demands of the country in which they are located. Further, offsetting diurnal and seasonal timing of renewable outputs of different regions can mean that the renewable outputs of such regions could effectively complement each other, if they were linked up into an integrated cross-national network. In Europe there is interest in a European supergrid, extending as far as North Africa, which would pool the region's renewable energy resources (European Energy Forum, 2017). The success of such projects depends upon effective regional cooperation.

In China, the wind rich areas are distant from the main coastal demand areas, which presents an interconnection challenge. China has had problems with grid connection delays and resulting curtailments to renewable produced power. Grid companies are now reluctant to purchase wind power because it is more expensive and intermittent (Gosens and Lu, 2013).

In some countries, the lack of sufficient or sufficiently reliable grid infrastructure is a major impediment to increasing electricity access. The lack of electricity infrastructure, especially outside of urban and semi-urban areas, is an issue raised in the energy policy of Uganda (MEMD, 2002).

Even if grid infrastructure is present, grid reliability and losses can be major issues. Average losses in the Southern African Development Community (SADC) for both transmission and distribution electricity networks are 19 per cent (REN21, 2015).[1] In comparison, the typical figures in the United Kingdom would be around 2 per cent for transmission and 7 per cent for distribution.

However, countries that do not currently have an extensive power grid, also have the opportunity to avoid lock-in to grids not suited to renewables, and instead to design their new grids to be consistent with the system they wish to aim for in decades from now. Achieving this successfully will require careful consideration of future demographic trends, which will dictate future energy demands, and of the location of renewable resources. Again, a regional approach to this grid planning may enable countries to pool resources in a mutually complementary way. For example, the Africa Clean Energy Corridor, launched by IRENA, is trying to look at shared cross-border resources and transmission lines (Southern African Development Community, 2016). Another important option for countries without significant power grid coverage is to consider decentralized or microgrid systems.

The temporal balancing of renewables is also a major issue as renewables achieve a greater share of electricity generation. However, this depends on whether the renewable resources are variable or dispatchable. For example, Norway has for many years operated with a share of renewables in its power mix of higher than 95 per cent. This is largely enabled by the fact that its major renewable resource is hydropower, the output of which can be effectively controlled. Denmark has relied on decentralized combined heat and power (CHP) plants and interconnections with neighbours, especially Norway, to help manage high proportions of wind power. Hydropower plays a significant role in the power mix of Portugal, along with wind. Renewables now provide on average more than 60 per cent of the country's electricity mix over a year, and there was a period in 2017 of six consecutive full days during which renewables provided 100 per cent of the country's electricity.[2]

All of these examples show that systems are already accommodating high proportions of renewables. A recent United Kingdom Energy Research Centre report into the costs and impacts of intermittency finds that the costs of accommodating high proportions of variable renewables can be manageable, especially in systems optimized with high levels of flexibility. Estimates of very high costs associated with variable renewables are typically due to assumptions of very inflexible systems (Heptonstall et al., 2017).

Increased proportions of renewables are likely to require attention to demand-side flexibility, and renewables may stimulate innovation in supporting technologies. Smart grid technologies may have a key role in managing and shifting demand loads in order to help balance the variable output of renewables.

There is an important potential convergence of electricity systems with digital and information technologies (IEA, 2017f). Such technologies may have a crucial role in enabling a system in which demands can flexibly respond to the conditions of the grid, for example responding to signals that renewable output is low by delaying flexible demands, to avoid putting

1 Contribution from the Government of Austria on the Renewable Energy and Energy Efficiency Strategy and Action Plan of the Southern African Development Community (REEESAP).

2 Contribution from the Government of Portugal.

pressure on the system, and conversely by responding to signals that renewable output is high by carrying out flexible demands at that time, to take advantage of the plentiful (and therefore cheaper) renewable electricity. Examples of demands that could be time flexible in this way could include washing machines, which could be programmed to run their cycle at the most optimal point during the day, provided the cycle is finished by a given time (say the end of the working day), or electric vehicles, which could be programmed to exert their charge during the most optimal hours, provided they have completely recharged by morning. In 2016, the approximate investment in infrastructure and software for digitalization of the electricity sector in order to enable a more flexible network operation, accurate demand response management systems and the integration of variable renewable energy resources was $47 billion (IEA, 2017f). Digital infrastructure will be a key enabler to a smarter and more responsive electricity system. However, also crucial will be policy and market incentives that create the frameworks for such technologies to operate. There is no incentive for a consumer to allow devices flexible charging patterns if they are not rewarded by the prospect of seeking out lower-cost electricity at times of oversupply. This means market structures that allow the price of electricity to vary over time (and potentially by location too).

Storage is also a key enabling technology. As discussed in section 2.3, a range of storage technologies are in development, with applications ranging from small scale to grid scale, and for rapid discharge through to interseasonal storage. In rural and off-grid contexts, a key supporting technology is battery storage, where the challenge is to reduce costs while increasing lifetime and robustness.

4.2 Renewable energy market and policy challenges

The systemic nature of renewables innovation requires the creation of a clear market demand for renewables, but also a mix of supporting policies to stimulate research and development, coordinate actors and infrastructure, align regulations and incentives, and mobilize funding.

Governments have often played significant roles in funding, organizing or driving early-stage research, testing and product development. This is because innovative products are usually unlike any that currently exist in the market, or there is no market value for them, which means that revenues from the market are unlikely to be dedicated to such kind of research by private companies. Even if private companies can see the long-term market potential of a certain piece of lab-scale technology, the experimental nature of this end of the innovation chain can make it too risky for private companies to invest in directly. Hence, government activities can be critical in either directly funding research, coordinating research activity or presenting itself as a guaranteed and large customer for an innovative technology if it is successfully developed.

One of the most well-known examples in the research-and-development end of renewable technology innovation chains is the Danish Risø National Laboratory for Sustainable Energy (box 2).

As shown in figure 5, innovation systems include a range of activities, from product research and development, as already discussed, as well as manufacturing, construction, operation and maintenance. Each of these stages is populated by actors, who through their activities add value to themselves or the economy. Although such an innovation system could be contained within one country, there is in principle nothing problematic for an innovation system to be international, within which national-level specialization occurs. However, from the national perspective, the weak points in a value chain may create vulnerabilities

Box 2. The Risø test laboratory

The Risø test laboratory was established in 1958 primarily as a nuclear power-testing centre. However, in the 1970s, it moved into wind turbine testing. The laboratory made a significant contribution to its sponsoring and acquisition of knowledge about early turbine designs, which then became a public asset. It conducted rigorous and independent tests, the results of which were made public for private actors in the Danish wind industry to benefit from. This meant that the most successful designs were proliferated much more quickly than would have been the case with individual companies working individually, meaning that the Danish industry as a whole moved quickly ahead of other national industries. Wieczorek et al. note that the Danish Riso National Laboratory for Sustainable Energy (and the Dutch Delft University of Technology) still excels in the number of journal articles per institute. The Danish turbine company Vestas is among the companies internationally submitting the highest numbers of patents (the others being General Electric (United States) and Siemens (Germany)). However, the authors note that knowledge produced by companies is often not patented or published.

Sources: Grubb et al., 2014; Maegaard et al., 2013; Wieczorek et al., 2015.

depending on social and political factors. For example, Wieczorek et al. (2013) examine the European offshore wind innovation system and observe that "the United Kingdom does not have such a strong national industry and is very dependent on foreign actors to fulfil their national ambitions". The authors continue by suggesting that "a too strong dependence on foreign actors may result in a loss of legitimacy and political support, as domestic incentives for offshore wind primarily lead to the building up of an offshore wind industry abroad". It might be added that while the manufacturers of offshore wind components are not primarily United Kingdom companies, nonetheless it is possible for them to locate manufacturing plants in the United Kingdom, thereby creating jobs in the United Kingdom, as Siemens and Dong Energy have started to do. In a later paper, it is acknowledged that "by using the domestic market and wind potential of the United Kingdom, foreign companies provide the domestic innovation system with access to foreign knowledge and skilled personnel… and contribute to national employment creation" (Wieczorek et al., 2015). However, emerging political issues could create further vulnerabilities for the United Kingdom in this regard, for example the effects on investment decisions of manufacturing companies if and when the United Kingdom leaves the European Economic Area. As such, this aspect of the innovation system of the United Kingdom may constitute a long-term vulnerability. Given that the generation of wider economic benefit can be an important part of legitimacy creation, the lack of a domestic value chain may be seen as a risk factor in the country's ambitions in deploying renewable energy.

International interactions within the innovation chain of a particular renewable energy technology can allow economic specialization, resulting in efficiency benefits for all countries involved. It might also enable countries without a fully developed innovation chain to begin activities further along the chain (i.e. manufacturing and deployment) more quickly, if they can join an international innovation chain and rely on capacities and capabilities of other countries with established activities further up the chain, such as fundamental research.

On the other hand, the internationalization of the innovation system can create tensions, given that competition is a key feature of international trade, such that the success of a sector in one country can spell demise for the same sector in another country. From the perspective of a particular country, it is worthwhile to give some consideration to the balance between domestic and international activity in the innovation chain it aspires to develop and be part of. Each section in the chain is associated with different economic activities that add value to the economy in different ways. The greater the internationalization of a country's innovation chain, the greater the potential risk of missing out on productive economic activities and resulting contributions to economic growth, from stimulating domestic activities.

For many countries, there could be trade-offs, the balance of which may vary depending on whether a long-term or short-term perspective is taken. For some countries, the near-term priorities may be to provide energy access to improve peoples' health, well-being and opportunities for income-generating employment. The benefits of providing this access as soon as possible may present very compelling reasons for accessing international innovation value chains to use technology and intellectual property already developed, so that technologies can be rolled out quickly, rather than waiting several years for the innovation chain to be built up domestically. On the other hand, a longer-term perspective might consider the economic and industrial strategy of the country over decadal time frames and might consider that building up more elements of the innovation supply chain domestically in order to provide this demand would in the longer term release greater benefits for the economy as a whole, through employment creation and associated macroeconomic stimulus.

In general, then, for countries with plans to scale up deployment of renewable energy, it is worthwhile to consider what the balance between domestic and international actors will be in its supply chain, whether such balance will enable the country to sufficiently capture economic opportunities such as job creation and industry development, and what the effect of this balance will be on the broader political legitimacy and public acceptance of the deployment policies and targets.

One example of a country that has intentionally tried to increase its domestic presence within its supply chains is China (box 3).

The Chinese wind power case study presents an interesting example of a country starting from a position behind other countries, building up a supply and innovation chain with significant involvement of foreign investment and knowledge, but then over time trying to domesticate its supply chain. This follows a pattern of industrialization that has been previously followed by other countries such as Japan and the Republic of Korea. Strategic intervention of government, with a view to building up supply chain and skills, was significant in the early stages, with the establishment of technology and knowledge transfer programmes. The case study also shows the importance of contextual factors involving actors, institutions and networks, and of feedbacks between different stages in the innovation chain. One notable feature is the role of market formation and of infrastructure in affecting the dynamics further up the innovation chain. A key policy instrument that creates domestic market demand for wind power is the renewable portfolio standard. However, because this is measured in units of installed capacity, not of energy produced, it does not provide a direct incentive to maximize the quantity of energy produced from a given installed capacity. This is compounded by the fact that grid access is lagging behind the pace of turbine construction, which means that some projects experience delays in being able to produce energy and receive payment for it. These factors reduce the incentive for companies to invest in the highest-efficiency turbines; therefore, the market is driven by a preference for low cost, even if this entails lower quality and lower efficiency. This in turn effects the ability of Chinese-manufactured turbines to compete in the international market.

Box 3. Wind power in China

Gosens et Lu (2013) identify three periods of wind power development in China (see table 3 in Gosens and Lu, 2013). The first, from 1985–2000, was dominated by government-organized transfer programmes. Manufacturing of wind turbines started using foreign technology, and national teams were set up as joint ventures for Chinese engineers to be trained by foreign engineers. From 2000 to 2007, Chinese manufacturers emerged, sourcing turbine designs in private licensing deals with foreign companies. From 2007, leading Chinese firms have begun to develop their own ownership of turbine designs. This has either occurred in collaboration with foreign firms, or through the acquisition of a foreign designing company, or designs have been developed independently.

A structure of targets and import taxes has been used to encourage domestic production and reduce imports. This has encouraged manufacturers to seek domestic suppliers. However, in some cases, foreign manufacturers have simply moved bases to China to avoid the import taxes. A small number of high-value components are still imported. For other components, Gosens et al. suggest that Chinese firms compete with lower quality but much lower cost. Strong competition has driven down prices but this has squeezed profits, which reduces R & D budgets.

There has been rapid growth in wind in China, with annual instalments doubling every year between 2003 and 2009. The Chinese domestic market has been the largest in the world since 2009. Until 2000 most turbines were foreign brands, but now 90 per cent are Chinese brands. Per kW prices in China are 35–55 per cent lower than in foreign markets, partly due to lower production costs but also because customers are more interested in quantity than quality. This is driven by the fact that the renewable portfolio standard is measured in kW of installed capacity, not kWh of energy. Long delays in grid connection have resulted in high curtailment – this also creates disincentive to pay for high efficiency turbines. Also, wind-resource-rich areas happen to be sparsely populated, making land prices low, which allows the industry to focus on larger numbers of smaller capacity turbines. The market is dominated by 1.5 MW turbines. Chinese exports are limited, partly due to this lower efficiency, which is an effect of its domestic market conditions.

China has gone to considerable efforts to re-domesticate its wind energy supply chain, having begun from a position of government organized transfer programmes. However, even now, with many foreign owned firms it is not clear how truly “domestic” the Chinese supply chain is. Policies to demand components only sourced from domestically owned companies would be against WTO rules.

Source: Gosens and Lu, 2013.

The solar PV innovation system is also highly international in nature, and the role of China is significant within it. However, in this case, Chinese-manufactured products have been highly successful in reaching international markets. Demand for solar PV was driven by market incentives provided in a number of countries, including France, Germany (box 4), Spain and the United Kingdom.

Box 4. Solar PV in Germany

In Germany, investment in the research and development of solar PV began in the 1970s, initially in the context of the oil price shocks and a resulting desire to find alternatives to fossil fuel, and subsequently in the context of major accidents at nuclear power stations, prompting an interest in alternatives to nuclear power. The R & D programme involved research institutes, universities and industry, and was supported by federal and regional funding. As well as direct grant funding, further support was provided in the form of reduced interest loans and public guarantees to secure bank loans. Production costs of solar PV in Germany decreased from $6.8/Wp in 1992 to $2.9/Wp in 2008.

From the early 1990s Germany also acted to create a market for the technology, initially through subsidy schemes and soft loans for rooftop installations, with the scheme broadened to include larger-scale installations after a slow take-up. Germany introduced feed-in tariffs in 1990, in an early example of a market creation policy for renewable energy (Jacobsson and Lauber, 2006). The policy was reformed in 2000 with the implementation of the Renewable Energy Sources Act.

Sources: Jacobsson and Lauber, 2006; Polo and Haas, 2014; Yu et al., 2016.

Box 5. Solar PV in China

When China started to develop its solar PV industry, it did not own designs. It focused on labour-intensive downstream manufacturing, rather than domestic R & D. Low labour and energy costs enabled Chinese manufacturers to keep production costs low. During the 2000s, the country's approach to PV was production based and export driven, aiming at markets which provided strong PV incentives. China exported 97.5 per cent of its modules in 2006 and 96 per cent in 2009. It supported PV manufacturing through innovation funds, regional investment support policies, loans and easy credit. More recently, China has begun to deploy solar PV at extremely large scale, as well as manufacturing.

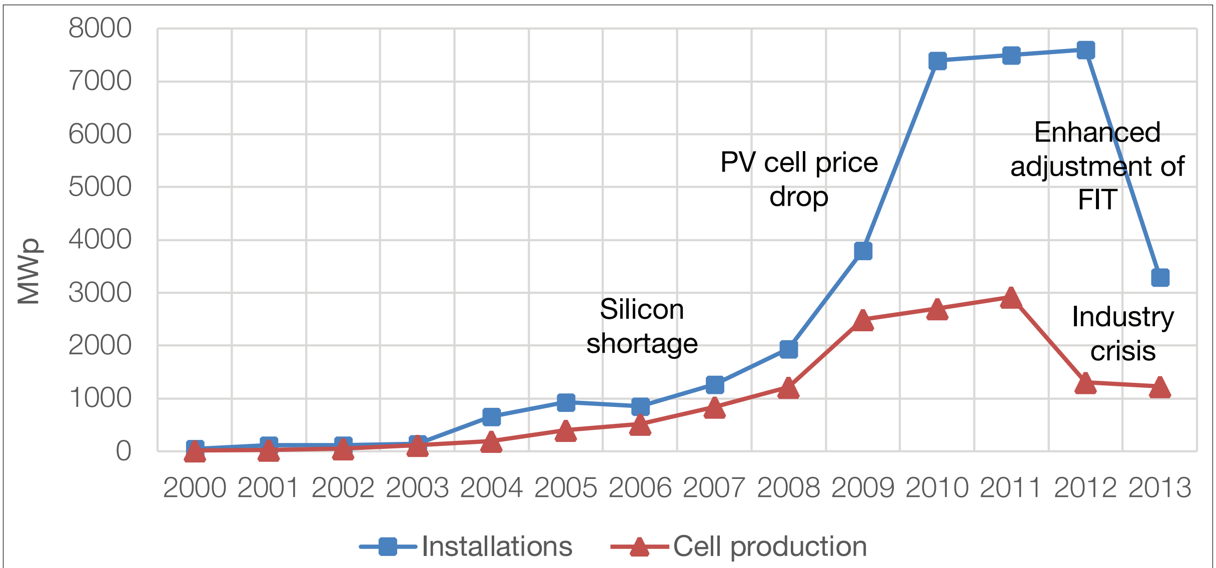
Source: Yu et al., 2016.

Meanwhile China was focusing on developing a PV manufacturing industry (box 5). In large part due to the activity of Chinese manufacturing, a rapid fall in the global cost of PV modules took place.

This resulted in a rapid uptake of installations in Germany, as shown in figure 6, as well in other European markets that had feed-in tariffs, which looked generous in relation to the much lower global market price for cells. In these countries, concerns about the spending on subsidies being much greater than expected, led policymakers to substantially and suddenly reduce feed-in-tariff rates, or in some cases to suspend them entirely. This led to a boom-and-bust dynamic, where the domestic industries of some countries were greatly reduced. Germany responded to the falling costs in 2008 by introducing a digression rate so that the 20-year fixed tariffs now decrease year on year. From 2009, the digression rate was adjusted according to the annual installed capacity (Polo and Haas, 2014). Figure 6 shows the effect of these measures on German installations, with a significant flattening out from 2010, and then a substantial fall in 2013. It also shows the effect on German domestic cell production, which dropped significantly from 2011. In Germany, the production of PV cells is now much reduced. However, the country has still maintained capacity in other areas of the PV supply chain, such as production of inverters and other components used to manufacture PV cells (Hoppmann et al., 2014).

As the case studies show, a number of internal policy drivers, as well as international factors, can contribute to the formation of supply chains related to renewable energy within a country. There are also important considerations to bear in mind in the way that renewable electricity technologies can have an impact upon the structures of the electricity market itself and the policies that govern this. The operational characteristics of renewables can require different market designs appropriate to these characteristics. Flexibility will be a characteristic of increasingly critical importance in electricity markets when the penetration of variable renewable sources becomes greater. For example, in Germany, the new Electricity Market Act included measures to "incentivize greater flexibility

Figure 6. Annual installations and PV cell production in Germany, 2000–2013



Source: Yu et al., 2016.

in the electricity system".[3] One way of using market signals to incentivize demand-side flexibility is to allow the price of electricity to vary by time and location. This would send users a clear signal as to the true cost or value to the system of using, or not using, electricity at a given time and place, taking account of the generation on the system at that moment, and of any transmission constraints that may restrict the user's access to that power. Similarly, to increase flexibility in the system through market instruments, Japan has introduced measures to build negawatt trading and virtual power plants (VPP) into the market – measures that place a value on demand response and load shifting as a means to help balance the system (Agency for Natural Resources and Energy, 2017).[4]

Such market structures are worth considering as a possible means of smoothing the transition towards high penetrations of variable renewables within electricity systems.

The Electricity Market Act also aims to "integrate the electricity market more strongly into the European internal market – cooperation with neighbouring countries to achieve energy security at a better value on a European basis".[5] Integration with neighbouring electricity system is also a useful strategy to increase overall system security, and to smooth and balance out renewable outputs in different geographical regions. The European Union as a whole is aiming towards an integrated electricity market, which could increase the potential of the region as a whole to balance a large portfolio of renewables (Wieczorek et al., 2015).

The challenges of promoting renewables have uncovered a process of policy learning in relation to the most appropriate forms of market incentives to provide for renewables. REN21 (2016) found that at the end of 2015, the policy mechanism most frequently used to promote renewable energy was the feed-in tariff, having been adopted by 110 states, provinces or countries. The feed-in tariff guarantees a fixed price per unit of electricity sold over an agreed period of time. This is an attractive form of price support for renewables which are typically dominated by high capital costs. Bulgaria, Germany, Hungary, Japan, Kenya, Portugal, Spain, Turkey and the United Kingdom are among the countries that have used feed-in-tariff-based approaches.[6]

A clear risk of the feed-in tariff however is that the Government could lock itself in to subsidizing renewables for a long term. In this context, tendering or auction-based approaches are increasingly used policy instruments to identify the price for renewable energy contracts and to deliver substantial cost reductions in renewable energy. By the end of 2015, 64 countries had held tendering rounds for renewable technologies (REN21, 2016), with noticeably low prices for solar PV being achieved in countries such as Chile and Mexico (Levey and Martin, 2016). Since then, a number of countries, including Germany, Japan, Portugal and the United Kingdom, have revised their allocation of contracts or tariffs to be delivered on an auction basis.

Other government actions can also contribute to a supportive policy environment for renewables. One important element is to create confidence in a clear, long-term direction for the industry. One example of this is the energy transition of Germany (*Energiewende*). "The *Energiewende* is our overarching goal, and our pathway into a future that is secure, environmentally friendly and economically successful." It includes the following energy-related targets for 2050: 80–95 per cent reduction in CO_2 emissions; at least 80 per cent renewables in electricity, 60 per cent renewables in energy overall; and 50 per cent reduction of primary energy consumption. These kinds of target are essential to provide "a long-term basis for planning and investment for stakeholders".[7] Another example is the overall target of the United Kingdom for reducing greenhouse gas emissions by 80 per cent from 1990 levels by 2050.

However it is important that the goals are credible. A good way of demonstrating this is to include more detailed measures, or subtargets, that can be used to demonstrate that progress is on track. For example, "to meet the challenges ahead of us, the German Government has developed a "10-point energy agenda" at the beginning of this legislative term…".[8] Equally, the 2050 carbon target of the United Kingdom is broken down into a series of five-year carbon budgets, which must not be exceeded in each five-year period, ensuring that genuine progress is being made, consistent with the long-term target.

Other kinds of legal regulatory frameworks are also a key part of the supporting architecture for encouraging and enabling investments in renewables. These are

3 Contribution from the Government of Germany.

4 Contribution from the Government of Japan.

5 Contribution from the Government of Germany.

6 Contributions from the Governments of Bulgaria, Germany, Hungary, Japan, Kenya, Portugal and Turkey.

7 Contribution from the Government of Germany.

8 Contribution from the Government of Germany.

crucial to ensure, for example, that investors have the confidence in the processes by which applications to construct power projects are considered, and how applications to connect to the grid are managed. Investors also need to have confidence in the transparency and stability of any payment support framework. In Uganda, the Scaling-Up Renewable Energy Programme Investment Plan identified barriers to deployment of renewables as inadequate regulatory, legal and institutional frameworks, including inadequate licensing for geothermal resource exploration (MEMD, 2015).[9]

The relative roles of the private sector and the State within the energy system is an issue that policymakers continue to grapple with. Latin American countries have been notable in their early activities with the privatization and liberalization of their energy systems. Macroeconomic fluctuations in the 1970s and 1980s left many Latin American countries with minimal ability to invest in public services, including the power sector. This provided an incentive to privatize and liberalize the power systems. This was further encouraged by the tendency of World Bank loans to be made conditional on privatization and liberalization. In reviewing this period, Banal-Estañol et al. (2017) suggest that the measures did improve quality of service and led to an increase in generation capacity. However, the measures did not necessarily extend coverage of the population. For private investors, there was a clear incentive to focus on urban areas where there were higher income customers and greater economies of scale. Consequently, some countries, such as the Plurinational State of Bolivia and the Bolivarian Republic of Venezuela have partially reversed these policies with renationalizations. In other countries, lack of investment in rural areas has prompted the development of specific rural electrification programmes (Banal-Estañol et al., 2017).

This experience, as well as other historical evidence, suggests that the activity of the private and the public sectors can have advantages in different ways and at different times. Private sector entrepreneurship can fuel greater creativity and innovation and can in some cases leverage greater investment resources. Box 6 provides an overview of the different roles that public, private and institutional investors can play in financing renewable energy.

9 Contribution from the Government of Uganda.

Box 6. Changing landscape in financing renewable energy

Public finance institutions. Renewable energy has often had to rely on public finance institutions, particularly in early stage project development. Public finance instruments are usually in the form of grants, subsidies and guarantees to facilitate renewable energy projects that are too risky for private sector support. For example, the Government of South Africa through the Renewable Energy Public Procurement Programme, has provided guarantees to power purchase agreements between its state-owned utility Eskom and independent power producers. More recently, public finance instruments are being used as tools to attract private capital. These include the following:

- **International financial institutions** are usually multilateral development banks that are increasingly playing a leading role in renewable energy projects. These include the World Bank Group, the Asian Development Bank, the European Investment Bank, the European Bank for Reconstruction and Development, the African Development Bank, the Inter-American Development Bank (IDB), the Asian Infrastructure Investment Bank and the New Development Bank. As an example, IDB is providing loan guarantees in the geothermal financing and risk transfer programme of Mexico.
- **Development Finance Institutions** are usually bilateral development agencies like AFD (the French Development Agency), KfW (the German Development Bank) and JICA (the Japanese International Cooperation Agency). Also, national development banks can be key actors within individual countries, like in the case of the Brazilian Development Bank (BNDES) and the South African Development Bank (DBSA).
- **Climate finance institutions** are intermediary actors that mediate the implementation of donor funds towards developing country initiatives. Examples include the Global Environment Facility (GEF), the Climate Investment Funds and the Green Climate Fund.

Private investors: new capital market instruments such as green bonds. Green bonds are gaining prominence as innovative mechanisms attracting finance for renewable energy projects in emerging economies. Green bonds are any type of bond instruments to fund projects with positive environmental and climate impact. They can be used to raise large-scale long-term financing from non-bank sources and at relatively low cost. According to IRENA (2016), nearly half of $41.8 billion green bond proceeds were invested in renewables. In 2016, more than $62 billion of green bonds were issued in the first 10 months. Despite rapid growth, green bonds accounted for merely 0.3 per cent of all bonds outstanding in 2015. Green bonds have proven to have an important role in emerging economies, notably in China and India. In India, for example, first-labelled green bonds were issued in 2015 by Yes Bank. The India rupee-linked bond had $161.5 million dedicated to financing renewable energy projects. In 2016, the Export Import Bank of India and the Industrial Development Bank of India issued a larger $500 million green bond targeting renewable energy and transport projects.

Institutional investors: pension funds. Institutional investors are a major potential source of capital for renewables. The most active institutional investment in renewable energy has taken place in Europe, reaching $7 billion in 2015. Institutional investors such as pension funds from developed economies show increasing interest in investing in developing countries. For example, three Danish pension funds (PensionDanmark, PKA and Lægernes Pension) joined forces with transport and logistics company A.P. Møller to launch a new infrastructure fund to invest in energy and transport projects in Africa. The four seed investors in Africa Infrastructure Fund I together committed $550 million.

Sources: CBI and HSBC, 2015; Bloomberg New Energy Finance, 2017; contribution from the Government of South Africa; Fixsen, 2017; IRENA, 2016 and 2017b.

On the other hand, there are areas where the private sector is less well equipped. One example is the provision of public goods (i.e. increasing energy access in rural areas) that are not immediately profitable. Situations where overall system performance would be improved through shared infrastructure can leave private sector actors struggling with inefficient solutions and require State-led coordination. Natural monopolies need careful regulation, and State involvement needs to ensure their regulation is in line with public policy priorities. There is also a significant role for the state in supporting and coordinating R & D. Mexico, for example, has created and invested in six energy innovation centres focusing on geothermal, solar and wind energy; bioenergy; ocean energy; and smart grids.[10] Furthermore, government incentive systems and procurement policies can also encourage the use of local technology and equipment, such as in the Islamic Republic of Iran and South Africa.[11]

In general, there is an important role for government to provide legal and regulatory structure, which both ensures that private sector activities are being directed in a way that is beneficial for society, and provides clarity and confidence to private sector actors themselves. Banal-Estañol et al. suggest that a significant element in the success of Latin America in increasing electrification has been the role of independent regulatory agencies providing policy stability and transparency, alongside the role of the private sector (Banal-Estañol et al., 2017). Governments can also play an important role in addressing situations where private sector investment is not occurring due to commercial risks. These and other important types of government intervention have been important lessons learned from the first rural electrification strategy and plan of Uganda (box 7).

10 Contribution from the Government of Mexico.

11 Contribution from the Governments of the Islamic Republic of Iran and South Africa.

Box 7. Lessons learned from the first rural electrification strategy and plan of Uganda

The Government of Uganda had its first rural electrification strategy and plan (RESP) for the 12-year period of 2001–2012, and its second plan for 2013–2022. During this 10-year planning period, the Government's strategy is to achieve a rural electrification access of 22 per cent by 2022 from the level of about 5 per cent in 2013. When preparing the second rural electrification strategy and plan, Uganda reached several conclusions that were derived from a systematic analysis conducted at the end of the first RESP.

First, rural electrification development needs to accelerate by adjusting the business model. The original model created a mismatch of short-term profit interest in a business that will take decades to develop. It is rather the other way around – government must lead, use patient and low-cost capital financing, build the initial organizational and infrastructure capacities for electricity services and promote electrification-related economic development and supportive measures to spur rural modernization and income growth. Thereafter it becomes feasible for private investors and commercial financing to take over.

Second, new approaches are needed for the effective marketing of consumer electricity service to aggregate and build demand; for lowering barriers to rapid accumulation of customers and to increasing energy use in productive activities; and for enforcing discipline at the renewable energy "cash register" – commercialization functions, including policing electricity and materials theft. Local models such as cooperatives, if correctly developed and supervised, give the beneficiary populations and consumers direct responsibility.

Third, it needs to be ensured that the programme scale is feasible. The previous set of rural electrification providers were struggling because they were too small. They were given the areas that are predominantly domestic and do not have the ability to balance rural household customers with more developed service areas. The rural service territories must be sufficiently large to generate revenue levels as needed to meet service providers' financial cost requirements, including cost of capital investment financing.

Fourth, planning and management for the renewable energy sector should be centralized and programme implementation simplified. The previous programme was being implemented in a disaggregated manner, with many players acting in overlapping and insufficiently coordinated roles. Rethinking the model means re-ordering the way the sector is planned and resources allocated. The best way is to centralize authority in the lead entity responsible for the renewable energy sector and ensure that electrification is carried out in harmony with the broader scope of national economic and social development planning.

Finally, there is a need to plan for long-term sustainability. The previous programme did not dispose of adequate planning and coordination of resources. It also implied an indefinite term of providing subsidy. Long-term programme sustainability means developing internal mechanisms for financing and ensuring that all other major functional requirements of rural electricity service and rural utility sustenance can, in time, be addressed independently of government support.

Source: Contribution from the Government of Uganda.

4.3 The role of renewable energy in extending access to electricity

Extensive electricity transmission and distribution networks, providing electricity access to the whole population, are common features of energy systems in developed countries. These infrastructures were developed during the last century, typically over several decades. In developing countries, electricity access often remains much less extensive. The number of people in the world without access to electricity was 1.1 billion in 2016. This is 14 per cent of the world's population, 84 per cent of which live in rural areas.

Increasing electricity access makes a critical contribution to the Sustainable Development Goals. One important contribution is by improving standards of education in schools and enabling greater study time in homes. Access to electricity can also increase gender equality (IEA, 2017f), for example by increasing the likelihood of girls finishing primary school, increasing the incomes of self-employed women and increasing employment opportunities for women by increasing the efficiency with which household tasks can be completed. IEA also notes evidence that "there are significant advantages in involving women from start to finish in the design of modern energy access technologies and programmes, and empowering women to become more involved in the provision of energy services" (IEA, 2017f).

Electricity access is also crucial to healthcare provision, for the operation of medical devices and the storage of vaccines. Almost 60 per cent of health clinics in sub-Saharan Africa have no access to electricity (IEA, 2017f). Among health clinics with electricity access, it is estimated that 60 per cent of refrigerators in health clinics in Africa are not provided with reliable electricity, causing loss of almost half of vaccines, and 70 per cent of electrical medical devices in developing countries fail, with poor power quality a significant contributing factor (IEA, 2017f).

Electricity access can create new income-generating opportunities and increase the productivity of existing activities. But energy access plans and related income-generation opportunities need to be fully integrated into a country's overall development strategies, through an energy-transformation nexus (UNCTAD, 2017). In this lens, supply and demand for energy are tackled holistically and are means for fostering economic diversification and job creation.

Sustainably managed irrigation can bring about a significant increase in agricultural yields, and electricity access is often needed to pump and move water. The use of electricity to drive mechanization helps to reduce losses in processes such as milling and can enable farmers to add greater value to their product before bringing it to market, for example by drying grain, dehusking rice or processing tea leaves (IEA, 2017f).

Electricity access also assists the productive activities of shop owners and other businesses. Industrial activities may require higher power loads, hence can be anchor loads to stimulate the extension of grid services that are not always viable for smaller demands, with domestic and small business connections following on (IEA, 2017f).

There has been progress in increasing electrification, as the number of people in the world without access to electricity has fallen from 1.7 billion in 2000 to 1.1 billion in 2016. This is mainly due to the construction of fossil-fuelled power plants and grid extension, and less so through renewable off-grid technologies. China achieved full electricity access in 2015. India has also made rapid progress in electrification in recent years, with electricity access rising from 43 per cent of the population in 2000 to 82 per cent of the population today. The Government of India has focused on grid extension, and this has been the means by which almost all those gaining access to electricity since 2000 have been connected. However the Government published a draft mini-grids policy in 2016, which could help promote decentralized renewable energy (IEA, 2017).

Globally, from 2000 to 2012, 72 per cent of the increase in electricity access came from fossil fuel generation, the remaining 28 per cent coming from renewables, mainly hydropower. Since 2012, the contribution of renewable sources to electricity access has increased to 34 per cent. The vast majority – 97 per cent – of new electricity access worldwide since 2000 has been delivered by grid extension (IEA, 2017f).

Decentralized electricity solutions can take several forms. Small off-grid systems, for example, comprised of a solar panel, battery and small appliances such as LED lamps, are relatively affordable and easy to install. Such pico systems represented 94 per cent of all off-grid solar sales in 2016. Such systems can provide valuable improvements to users' way of life, especially if the lighting provided is displacing unhealthy and dangerous lighting sources such as kerosene lamps. However they have limited potential beyond such basic applications, and the operation of loads such as refrigerators or televisions, or for the provision of loads for productive activities, would require larger arrays (IEA, 2017f).

Larger off-grid generation sources could be harnessed through arrays of PV panels, wind turbines, or small to medium-scale hydro (boxes 8 and 9). The integration of several sources within a small network of loads would constitute a mini-grid. Such a system would require a developer who would need to be able to see a clear return on investment. An enabling regulatory framework would also be required, for example, if and when the national grid arrives to the region, to establish under what terms the mini-grid would be integrated into it (IEA, 2017f).

Box 8. Harnessing the potential of microhydropower plants in the Democratic Republic of the Congo

In the Democratic Republic of the Congo, only 9 per cent of the population had access to grid electricity in May 2016. The lack of electricity in rural areas has forced people to use a variety of energy sources, including firewood, kerosene, charcoal, diesel for generators, vegetable oils and plant residues. The reliance on ligneous fuels (such as wood, charcoal and plant residues) for basic energy needs was a major driver in the destruction of forests and the rise of GHG emissions.

The exploitable hydropower potential in the country is estimated to be in the order of more than 700 TWh/year, or 66 per cent of the potential of Central Africa, 35 per cent of that of all of Africa, and 8 per cent of that of the world's. This is equivalent of 100 GW expressed as firm power capacity. There is a considerable gap, however, between the potential and the reality on the ground: less than 3 per cent (2.6 GW) is currently being exploited, mainly via large Inga Dam (2.4 GW). The plans to construct a new mega dam on the Congo River (Inga 3 project) are still at blueprint stage and have met with technical, financial and political obstacles, as well as international criticism pointing to the negative environmental and social impacts of the project.

Developing decentralized micro and microhydropower-(MHP) based mini-grid systems emerges as an economically viable, environmentally sustainable and climate-friendly power supply alternative to harness abundant hydropower resources of the country, especially in its remote and rural areas. The development and implementation of MHP is expected to benefit vulnerable groups by reducing their dependency on expensive imported and polluting fossil fuels. MHP will also reduce the demand for biomass obtained from local forests, as well as cut pollution and greenhouse gas emissions.

In its intended nationally determined contributions to UNFCCC, the Government of the Democratic Republic of the Congo made rural and urban hydro-electrification a top priority to achieve its 2030 greenhouse gas emission reduction goal. The country aims to instal 650 MW of power generation capacity through micro-, mini-, small and medium-scale hydropower plants, 8 to 10 sites with a budget of $1/W for power plants, plus $1.35/W for electricity distribution grids.

Recognizing this potential, the Government requested the Global Environment Facility (GEF) to finance a project to promote investment in MHP-based mini-grids for rural electrification in the country. The project, entitled "Promotion of mini- and microhydropower plants in the Democratic Republic of the Congo," is implemented within the framework of the Sustainable Energy for All initiative (SE4ALL) launched by the Secretary-General of the United Nations. The country joined the initiative in December 2012, bringing with it a national agenda and a strategy.

GEF contributed a grant of $3,187,669 for the project and leveraged $14,150,000 of co-financing. The project covers four areas: policies and a regulatory and institutional framework for private and community-based investments supplied by small-scale hydropower; reinforcement of the technical capacities in the technological supply chain; pilot investments in selected mini- and microhydropower stations in rural areas; and communication, management, public relations and promotion of investment.

The project is expected to lead the development and construction of 39 microgrids using hydropower technologies with a total installed capacity of 10 MW. It will provide electricity for over 200,000 homes in the poor communities of the Democratic Republic of the Congo. The project will likely avoid nearly two million tonnes of CO_2 equivalent.

Sources: Global Environment Facility, 2012 and 2018.

Box 9. Pico hydropower plant at the Rwenzori Mountaineering Services in Uganda

The Rwenzori Mountaineering Services (RMS) is a community-based non-governmental organization owned by 1,500 members of indigenous Bakonzo people.

Among its activities, RMS operates a mountain camp at the foothills of the Rwenzori Mountains in Western Uganda. Previously, the mountain camp used a diesel generator that was very expensive to operate and maintain, was noisy and provided electricity for only 3 hours per day.

The Private Sector Foundation Uganda (PSFU), in partnership with RMS, developed a pico hydropower plant of up to 5 kW. The project was implemented by the Centre for Research in Energy and Energy Conservation (CREEC). RMS contributed up to 40 per cent co-financing, so there was ownership, with additional funding from the World Bank Energy for Rural Transformation Project, which aims to improve the productivity of rural enterprises, as well as the quality of life of households in Uganda.

Implementation included civil works and installation of a cross-flow turbine and an induction motor. Two features of the pico hydropower scheme are the use of equipment sourced from within the East African region and the local capacity-building component. The turbine was manufactured at the University of Dar es Salaam (United Republic of Tanzania), and other materials were locally sourced. The plant is locally managed and operated by RMS staff trained specifically for this project. In addition, the technical skills of five university students, one graduate student and two local companies were developed.

The pico hydropower scheme commenced operations in August 2013. The project has attracted a considerable number of visitors from other communities, schools, and researchers in the Rwenzori Mountains to learn more and appreciate this decentralized electricity-generating plant. The plant put renewable energy into productive use and replaced the expensive diesel generator previously used. It increased access to electricity for tourists to power their gadgets. Savings from the replacement of diesel with a renewable energy source led to the diversification of services through charging services.

Source: Contribution from the Government of Uganda.

Whether grid-based or off-grid, affordability is a major challenge to increasing access to electricity. Even if grid access is available, high connection charges can limit the ability of poor rural communities to connect to the grid.[12] Although the development benefits are appreciable, and in some cases urgently needed, many rural communities "live below the poverty line and lack access to other basic services, such as roads, safe water and telecommunications that might act to spur their development. This means that electrification strategies there cannot rely on market solutions" (Banal-Estañol et al., 2017).

There is contrasting evidence as to whether grid or off-grid solutions are preferable. A grid-based approach would typically involve strong government involvement either through a State-owned utility, or as public–private partnership delivered in the public interest. This kind of top-down approach can take time to reach the whole of society. In such situations, it is possible that off-grid renewables may be able to provide access to electricity to communities faster than grid electrification can manage. In some cases, grid access may be available, but the power quality remains intermittent or unreliable. In such cases, off-grid options may offer an improved service.

Nonetheless, off-grid projects can suffer from negative perceptions from consumers. In many cases, off-grid electrification is seen as a temporary stage until grid electrification can be achieved. With limited capacity and hours of use, the demands met by such projects are often limited to some lighting and use for entertainment from TV and radio – productive income-generating activities are often not encouraged or achievable through such projects. Such projects can thus be perceived as inferior and temporary, creating perceptions of isolation and discrimination for users (Bhattacharyya and Palit, 2016).

There is mixed evidence as to the relative cost-effectiveness of off-grid solutions, compared with those that are grid-based. Some have argued that off-grid solutions can be a more cost-effective way of increasing energy access in remote rural areas because they would avoid the additional costs of extended electricity distribution infrastructure. However, in a review of off-grid solar PV in sub-Saharan Africa, Baurzhan and Jenkins (2016) find that the costs of PV are significantly higher in sub-Saharan Africa than the global average, due to political, financial and technological risks. Therefore, the authors suggest that grid expansion is preferable to off-grid solar in sub-Saharan Africa. In contrast, in bottom-up case studies of four communities in Togo, Practical Action (2016) finds that decentralized systems are cheaper than grid extension in all cases. Further, IEA (2017f) finds that three quarters of the additional investment required above current policies to achieve universal electrification in sub-Saharan Africa would be most cost effectively achieved by off-grid solutions. Consequently, the relative cost-effectiveness of grid, compared with off-grid solutions, can vary and must be considered in context.

Grid-based solutions typically involve upfront investments in infrastructure paid by the Government or utility and spread through customer bills. As such, the upfront cost to any individual customer willing and able to connect is relatively low – a small connection charge followed by running costs. For off-grid projects, the upfront cost may be a more significant issue, as there is no wider customer base over which to spread it. Low-income communities may be unable to pay upfront for the investments required, and investors may be equally unwilling to invest in uncertain returns due to low density

12 Contribution from the Government of Kenya.

of demand users. A range of business models may be available to try and bridge the gap between investor and customer. Banal-Estañol et al. identify three business models for attempting to increase electrification: the dealer model, concessionary model and community-led model (Banal-Estañol et al., 2017). Each requires different combinations of financing and capacity-building to be successful, and each is dependent on the energy intervention being sufficiently beneficial to the community, including in terms of income generation, to be perceived as sufficiently valuable and thus financially self-sustaining. Microfinancing and pay-as-you-go models may also enable users to spread out upfront costs. Solar Sisters, an NGO that provides support for women in establishing solar micro-business, have effectively used the pay-as-you go model. In all cases, mobilization of funds and identification of appropriate financing instruments are key (Bhattacharyya and Palit, 2016).

Private sector investors are not always interested in remote off-grid applications. One approach to address this issue could be clustering and bundling of projects which may help to achieve scale. However, this requires organizational capacity (Bhattacharyya and Palit, 2016).

A robust governance structure, clear regulatory environment and enabling policy environment are crucial. Measures to overcome barriers to private sector-led investment in small scale renewable energy projects may include standardizing the licensing procedure and providing an off-grid tariff, providing risk guarantees for commercial banks and improving technical training (Kakooza et al., 2014). The United Republic of Tanzania has been successful in promoting off-grid solutions, using innovative power purchase agreements (PPAs). Bhattacharyya and Palit emphasize the importance of a stable regulatory environment and agreeing on tariffs that are acceptable both to users and investors (Bhattacharyya and Palit, 2016). Khodayar (2017) adds that microgrids would require "a concrete business model to engage the communities, set appropriate tariffs that are comparable with utility tariffs and provide incentives and subsidies to ensure that affordable energy is supplied to customers" (Khodayar, 2017). Social tariffs are a way of increasing access to energy among the poor. Some countries achieve these through cross-subsidization, others from public funds. A challenge is that lower energy prices can disincentivize energy efficiency, and it is difficult to restrict social tariffs only to the poorest. Inefficient subsidies can also disincentivize utilities from investing in infrastructure required to improve supply (Banal-Estañol et al., 2017).

Local support, training and capacity-building are key, and a local supportive environment has to be developed for maintaining the off-grid system (Bhattacharyya and Palit, 2016). Mandelli et al. (2016) suggest that while the cost of off-grid solutions may not always be competitive with grid extension, the potential benefits to local development can be greater. One example of this is the Southern Africa Solar Thermal Training and Demonstration Initiative (SOLTRAIN), started in 2009 with funding from the Austrian Development Agency and the OPEC Fund for International Development. This initiative aims to increase the deployment of solar thermal technologies, but also to build capacity and training to support these systems. Since 2009, it has raised awareness and built competencies in Lesotho, Namibia, Mozambique, South Africa and Zimbabwe. During its first two phases (2009–2016), 187 small to large-scale solar heating systems were installed, and 2,150 people trained. In the third phase a particular emphasis will be placed on demonstration projects in organizations that support women and other marginalized groups (Southern African Development Community, 2016).[13]

In rural energy applications, the effectiveness of training and capacity-building can be enhanced by taking into account the socioeconomic context, including gender issues. One possible outcome of training engineers in rural areas in the maintenance of renewable energy systems, is that with the new skills they have acquired, they will be tempted to migrate to the cities in search of more lucrative work. This may of course constitute a success story from the perspective of the individual concerned; however, it can result in the rural renewable energy system falling into disrepair and disuse. There are also issues with maintenance in dealer and concessionary models, as the companies or dealers that install the technologies do not always provide maintenance or offer training in maintenance to communities (Banal-Estañol et al., 2017). Partly in response to this, the Barefoot College International Solar Training Programme takes an original approach to capacity-building in rural areas. Its trainees are often the grandmothers of the village, who "maintain strong roots in their rural villages and play a major role in community development". They are thus often the most effective people to train from the point of view of the sustainability of the project. The implementation of training alongside renewable energy installations requires good social and political

[13] Contribution by the Government of Austria.

understanding of how the community works (Banal-Estañol et al., 2017). In many cases, the training and involvement of the local communities, including women and the elderly who may have the strongest personal investment in their community, may be the ideal way to achieve this.

Electrification of low-income communities may not be successful if it is seen as an isolated intervention. It must be supported by a manageable business model that provides for the customer the ability to defray the upfront investment costs, at the same time as giving the investor an investment in which there is a prospect of some return. Furthermore, it should be seen as part of a strategy that is not only providing basic quality of life, but also driving broader development including income generation, and supported by other measures that support that income generation, such as infrastructure, roads and telecommunications. For off-grid systems it is particularly important to establish a supportive environment around the project. This requires both careful design of systems that are sufficiently robust for field conditions, as well as business models that include maintenance strategies.

In summary, electrification projects "need to be adapted to the socioeconomic and geographic conditions of the area. These projects also need to promote the coordination of all the institutions and local communities involved in the electrification process" (Banal-Estañol et al., 2017).

The interactions between grid, microgrid and off-grid solutions also need to be considered. Regulatory frameworks need to account for the possibility of off-grid or microgrid projects eventually joining up to an expanded grid.

4.4 Using renewable energy in the household sector for cooking

Energy use in the household sector in developing countries is a major development issue. About 2.8 billion people worldwide currently do not have access to clean forms of cooking, a number which has not changed since 2000. This has serious consequences on health, environment and gender equality. Of these, about 2.5 billion people – approximately a third of the world's population – are reliant on the traditional use of solid biomass, with 170 million cooking with kerosene and 170 million with coal. 1.9 billion of those without access to clean cooking are in developing Asia, with 850 million in sub-Saharan Africa (IEA, 2017f).

The use of such fuels for cooking presents a serious health risk. The burning of solid biomass, kerosene or coal in indoor traditional stoves creates very high levels of indoor particulate pollution, which when inhaled can cause serious respiratory problems. Kerosene is also a common source of domestic fires and of child injuries due to accidental ingestion (IEA, 2017f). At present there are an estimated 2.8 million premature deaths per year attributable to household air pollution caused by the burning of solid biomass in inefficient stoves or from the burning of coal or kerosene. Women and children are typically more exposed to these risks (IEA, 2017f).

The extensive use of collected wood fuel as a household cooking fuel has environmental impacts in areas where the rate of collection exceeds the natural renewal rate of the biomass. Wood fuel is collected for direct use in rural areas, however many countries also have significant charcoal production sectors, with charcoal being transported predominantly to urban areas. In sub-Saharan Africa, nearly 60 per cent of urban dwellers rely on charcoal for cooking (Stockholm Environment Institute, 2011). Charcoal production also exerts pressure on forest resources. Unsustainable wood fuel collection occurs throughout South America, Africa and Asia, with particular hotspots in regions of East Africa, extending from Eritrea through western Ethiopia, Kenya, Uganda, Rwanda and Burundi, and in parts of West Africa (Bailis et al., 2015). The collection of wood fuel also has socioeconomic impacts, as it is often a highly time-consuming activity. Again, women are predominantly exposed to these impacts, as cultural factors mean they are typically tasked with this activity (Practical Action, 2016). In wood fuel-using households, women spend on average 1.4 hours each day collecting fuel wood, although in some countries the average is as much as 4 or 5 hours (IEA, 2017f). Women also spend several hours each day cooking, with increased times in part due to inefficient stoves (IEA, 2017f). If this time was made available for other activities, it could contribute to women's empowerment by freeing up more time for education or income-generating activities.

Access to clean cooking is therefore an important development priority. It is also potentially one of the least expensive, as the investment that would be required to deliver clean cooking for all is one tenth of that required to deliver universal electricity access (IEA, 2017f). Goal 7 is not only about increasing the share of renewable energy from the energy mix, but also about the elimination of traditional, "dirty" biomass, and this is a pressing issue in many developing countries. Therefore, there is an urgent need to deploy alternatives to the traditional use of bioenergy for cooking and other energy services.

There are two approaches to providing access to clean cooking. One is to promote more efficient and sustainable use of biomass (for example, by producing and distributing biomethane from biodegradable waste and syngas from lignocellulosic biomass available locally)[14] or to encourage households to switch to modern cooking fuels and technologies.

Compared with a traditional three-stone stove, improved biomass cookstoves have a chimney or closed combustion chamber that reduces pollution and increases efficiency. Although these improvements do reduce health impacts, the extent to which they deliver fully clean cooking is not entirely clear, and subject to context. It has been suggested that laboratory tests tend to overestimate emissions reductions, compared with real-life performance because they rely on a fixed combination of technology, fuel, and the pot-and-burn sequence. These elements and their sequence are subject to contextual variability, and other factors such as the room size, shape and ventilation can also have a significant impact. Results from randomized control trials suggest that in practice "virtually no biomass cookstove currently on the market meets World Health Organization (WHO) standards for exposure to household air pollution" (IEA, 2017f).

Advanced biomass cookstoves, such as improved wood and charcoal stoves developed by EcoZoom (see box 10), are equipped with further technical improvements to improve the efficiency of biomass combustion, such as microgasifiers and forced draft. These designs can substantially reduce particulate pollution, compared with improved cookstove; however, even the improvements offered by forced draft microgasifiers are insufficient to meet WHO targets (IEA, 2017f). The Global Alliance for Clean Cookstoves has been working in partnership with the International Organization for Standardization (ISO) to develop international standards for cookstoves, in line with WHO guidance (Stockholm Environment Institute, 2011).

Other types of modern stoves run on LPG, ethanol, biogas, electricity or natural gas. Such stoves have much higher efficiencies and low levels of pollution (IEA, 2017f), and in general succeed in meeting WHO exposure standards (Pilishvili et al., 2016 and Quansah et al., 2017). However their use is dependent on the availability of fuel. Furthermore, some of these fuels are not renewable.

Box 10. EcoZoom wood and charcoal stoves in Kenya

EcoZoom is a company that produces and sells efficient charcoal-burning and wood-burning stoves that substantially reduce fuel costs due to their more efficient performance. It opened its office in Kenya in 2013. A key feature of EcoZoom's approach is its range of financing options. Rather than providing end-user subsidies, it provides credit terms to distributors who then pass them on to customers. The company also works with microfinance providers to provide loans attached to products. The company is piloting direct loans to customers repaid via mobile money. It also uses a human-centred design process to ensure the stoves meet the needs of customers, provides training on the use and maintenance of the product, undertakes monitoring and evaluation, provides product warranty and offers maintenance and repair, and interest free loans via Kiva microfinance. One barrier to the further dissemination of stoves is the added cost of taxes, including an import tax, on the stoves.

Source: EcoZoom, 2018.

Shifting cooking towards LPG fuel and cookstoves is an alternative pursued in a number of countries, including India. Despite significant progress in increasing electricity access, India still has significant numbers of people without access to clean cooking. Over the last 15 years the number of people without access to clean cooking has increased in India by 80 million. However, the total number has not increased since 2010, suggesting that policies have begun to take effect. The proportion of people primarily using biomass for cooking fell from 66 per cent in 2011 to 59 per cent in 2015. IEA reports that "this seems to have been driven by an increase in domestic LPG consumption, and in 2016, India became the third-largest LPG importer in the world, behind China and Japan." The Government of India aims to provide clean cooking access through LPG to 50 million households below the poverty line, by 2019 (IEA, 2017f). Several other countries are also promoting LPG. Cameroon has set a target to increase current levels of LPG use from the current 17 per cent to 58 per cent of the population. Senegal also provides incentives to encourage switching to LPG, particularly in urban areas (IEA, 2017f).

Small-scale biodigesters can be used to produce biogas from organic matter, including crop wastes, kitchen scraps, manure and sewage. In contexts where such residues would otherwise be wasted, the fuel might be considered free. The biogas produced is a methane-rich fuel that burns relatively cleanly. There are also potential for synergies with waste water

[14] Contribution from the Government of Pakistan.

treatment. A study of anaerobic digester systems installed to treat toilet wastewater in Haiti found that the system reduced coliforms and E. coli by 99.1 per cent and 98.5 per cent respectively, with chemical oxygen demand reduced by 93.6 per cent. The system produced an effective organic fertilizer, as well as biogas with an average 65 per cent methane content (Lansing et al., 2017). An anaerobic digester pilot project in the village of Dayet Ifrah in Morocco uses input material of manure and toilet wastewater, for which the system provided effective sanitation. The system also provided biogas used for heating and cooking, sufficient for a farming family of 17 people (Abarghaz et al., 2013).

However, biogas digesters require upfront investment and space for the equipment to be housed, which can be limiting factors. Their construction can create local employment but the construction requires supervision by skilled masons and plumbers. Poorly constructed structures can be leaky with poor resulting performance, and ongoing maintenance is also required (Khan and Martin, 2016). Factors that have caused biogas digesters to fail or be abandoned include structural failures or lack of maintenance leading to leakage of the gas from the system, lack of or disruption to supply of feedstock, problems caused by blockages in or flooding of the effluent storage tank or blocking of pipes and the supply of biogas found to be insufficient to meet expected needs (Ahiataku-Togobo and Owusu-Obeng, 2016; Bensah and Brew-Hammond, 2010).

There are also questions of how to store and transport the gas in order to supply users. One social enterprise operating in Africa, Asia and Latin America offers a solution in which biogas is filled directly into portable back packs that users can then carry home to connect to their appliances ((B)energy, 2017).

Biogas digesters have been rolled out extensively in several countries. In China in 2013, around 100 million people in rural areas were using biogas digesters. To date, the Indian National Project on Biogas Development has installed almost 5 million biogas plants, and in Bangladesh, the National Domestic Biogas and Manure Programme has in rural areas installed some 80,000 small-scale biogas systems using animal waste (IEA, 2017f) (box 11).

Another option available to certain kinds of agricultural systems producing starchy or sugary crops is fermentation to produce bioethanol (box 12).

Box 11. Using biogas plants for cooking in Bangladesh

To increase the access to clean cooking, Infrastructure Development Company Ltd. (IDCOL) in Bangladesh has been implementing a domestic biogas programme. IDCOL is a government-owned financial institution established to catalyse and mobilize private sector participation in the development and financing of infrastructure, renewable energy and energy-efficient projects.

IDCOL has been implementing the National Domestic Biogas and Manure Programme since 2006 with support from SNV Netherlands Development Organization and KfW. The programme has been supporting the expansion of biogas technology in rural areas, with the ultimate goal of establishing a sustainable and commercial biogas sector in Bangladesh. By June 2017, IDCOL had financed the construction of over 46,200 biogas plants throughout the country.

The programme promotes a fixed-dome-design biogas plant, with two types: a design for cattle dung and human excreta, and a design for poultry droppings. Each design has six sizes of plants of different capacities between 1.2 m^3 and 4.8 m^3 gas production capacity. The gas produced from the two largest types of plants are used for multiple houses, whereas other sizes are used for single households. The biogas produced through these plants is used for cooking and lighting of rural households, but the slurry, a by-product of biogas plants, can be also used as an organic fertilizer.

The programme is being implemented through a network of 45 partner organizations, including private companies, NGOs and microfinance institutes. According to IDCOL, the programme saves 44,300 tons of firewood every year and reduces the use of 1,400 tons of kerosene every year. IDCOL has a plan to install 60,000 biogas plants in Bangladesh by 2018.

Source: Infrastructure Development Company Ltd., 2017.

Box 12. Bioethanol in Ethiopia

The Ethiopian NGO, Gaia Association, has been developing an alternative cooking fuel by producing bioethanol from molasses, a by-product of large State-owned sugar factories. Gaia Association has also produced an ethanol stove that reduces carbon monoxide levels below the WHO threshold, and PM2.5 levels close to the WHO threshold. The NGO has commissioned a demonstration microscale ethanol plant, which will use surplus molasses from the sugar industry to produce bioethanol for households in peri-urban Addis Ababa. A significant barrier to the use of bioethanol in Ethiopia is that it cannot compete in price with kerosene, as the latter is subsidized by the Government.

Source: Stockholm Environment Institute, 2011.

Electricity and natural gas are widely used cooking fuels in developed countries, though less so in general in developing countries. South Africa is a notable case of high usage of electricity for cooking. In 2000, 50 per cent of people used electricity for cooking, and this share has now risen to more than 80 per cent, with only 8 per cent relying on wood for cooking. In China, around 12 per cent of the population, or 160 million people, use electricity for cooking, and it is reported that this share is growing rapidly (IEA, 2017f). However, electric cooking requires a relatively large electrical load, and it is relatively expensive, which makes it unlikely to be suitable as an off-grid application (IEA, 2017f). The availability of natural gas for domestic use is dependent on infrastructure, which is more likely to be cost-effective to install in areas of high population density or in the presence of industry (IEA, 2017f).

An important observation in relation to the various cookstoves and fuels described in this section is that while increasing access to clean cooking facilities has some potential overlaps with increasing the deployment of renewable energy, the two objectives are not necessarily entirely aligned. The transfer of households from traditional biomass use to LPG or natural-gas-fuelled cooking devices would have significant health benefits to households but would entail an increase in fossil fuel consumption. Similarly, to the extent that clean cooking can be provided by electricity, whether this is aligned with the increased deployment of renewables depends on whether the additional electricity generation capacity built to meet this demand is from renewable sources.

Furthermore, while the potential synergies between the Sustainable Development Goals are often emphasized, sometimes there can be tensions between them. In this case, some of the solutions nearest at hand for achieving the overall aim of Goal 7 (ensure universal access to affordable, reliable and modern energy services by 2030) may not be the same solutions that would promote one of Goal 7’s targets, to increase substantially the share of renewable energy in the global energy mix by 2030.

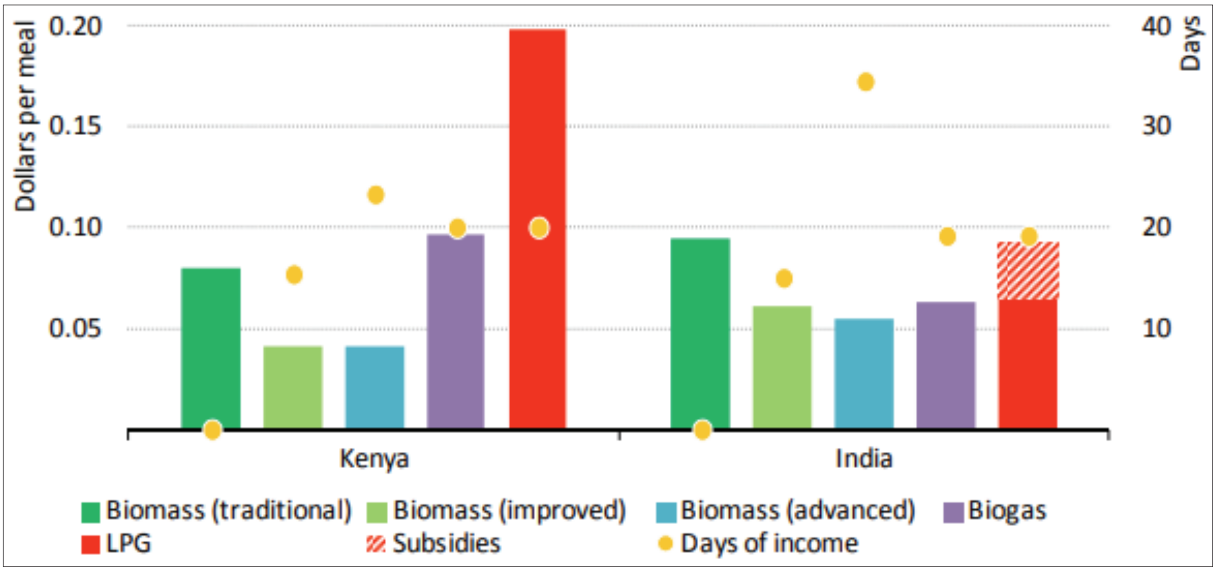
Some options would be consistent with increased deployment of renewable energy. In many regions, the rate of wood fuel collection exceeds the natural renewal rate of the biomass (Bailis et al, 2015), meaning that at this rate of usage, biomass is a non-renewable resource. If improved efficiency cookstoves were able to contribute to reducing the rate of wood fuel collection below its natural renewal rate, this would mean that the resource itself could be considered renewable. As such, an increase in use of renewable energy would have effectively occurred. The use of biological processes to produce biogas or biofuels from crops, biowastes or agricultural residues would meet ambitions to deploy renewable energy at the same time as providing a fairly clean burning cooking fuel. However, these options have other constraints, which may mean they are not the first to be chosen.

There are numerous barriers to promoting access to clean cooking. Affordability is a key constraint. Despite its drawbacks, the use of biomass in traditional stoves may appear to be a low-cost technology for households because the fuel is considered free. Households may not factor in the opportunity cost of the time spent collecting fuel wood. However, even if such opportunity costs are considered, the affordability of clean cooking may still not be clear cut. Figure 7 shows the costs per meal of certain clean cooking options in Kenya and India, in comparison with the traditional use of biomass. The costs include the investment cost of the stove, cost of the fuel and opportunity cost of collecting fuelwood, averaged out on a per-meal basis. The figure shows that even with the inclusion of opportunity costs, the cost per meal of cooking with biogas and LPG in Kenya is greater than traditional biomass use, LPG substantially so. In India, the costs of all alternatives on a per-meal basis are below the traditional use of biomass. However, the real cost of LPG is only marginally below it, with subsidies required to bring its costs down to the level of the other options.

Another important factor is the relation of upfront costs to running costs. Figure 7 also represents the upfront costs required to invest in the equipment required by the alternative cooking methods in terms of days of income needed. The typical investment costs of around 15–20 days of income are substantial and represent a significant barrier to low-income households. Advanced biomass stoves in India appear to have a particularly high investment barrier, equivalent to more than 30 days of income. Improved biomass stoves often have the lowest upfront cost and are therefore often the most accessible option.

Further economic factors that could inhibit the uptake of alternative fuels are that some households engage in wood fuel collection in order to sell it, as well as using it, hence it is a source of income generation (IEA, 2017f). Similarly, charcoal production is a significant activity in many rural economies in African countries.

Figure 7. Cost of cooking a meal in Kenya and India



Source: IEA, 2017f.

Notes: Poor in this figure is defined as a person living at the poverty line ($1.9 per day). Cost includes the stove, fuel and the opportunity cost of collecting fuelwood. Fuelwood is assumed to be collected, and the opportunity cost is calculated assuming that gathering fuelwood takes 1.1 and 1 hours per day for India and Kenya respectively, which could be redirected towards income generation, which, with the number of days' income to purchase the stove, is valued at the poverty line. A "standard" meal is defined as cooked for 45 minutes on an improved cookstove, requiring approximately 3.64 megajoules of final energy per meal. Note that the cost of attaining an LPG cylinder, typically a deposit, is not included, but can contribute to the financial barrier.

In 2007 the charcoal industry in sub-Saharan Africa was estimated to be worth more than $8 billion and to employ more than 7 million people (Stockholm Environment Institute, 2011).

LPG has to be bought in relatively large amounts, which can also be an upfront cost constraint. Pay-as-you-go business models can start to address these barriers, as can subsidies (IEA, 2017f).

Alternative cooking fuels and technologies will not be accepted in practice if they do not deliver an appropriate quality of service and performance that reflects the customs and practices of the user. Such qualities could include the speed of boiling and the physical robustness of the stove to certain preparation techniques. In some cases the smoke created by a traditional biomass stove confers a flavour upon the food that has become an essential part of it. As a result, smokeless alternative technologies may not be considered for the preparation of that particular food. These kinds of cultural factors can inhibit take-up of alternative cooking technologies, or can result in fuel stacking – the use of different stoves, including traditional and modern, for different purposes. More general awareness of the risks of smoke may be low.

According to Practical Action (2016), a case study in rural Bangladesh found that women did not perceive significant health risks associated with the smoke coming from their stoves. Indeed, both men and women valued the smoke as a means of deterring insects.

The viability of alternative cooking technologies also depends strongly on the availability of the relevant fuel and an associated distribution infrastructure. Biogas and biofuel options can be limited by environmental and geographical conditions (Practical Action, 2016). LPG requires a distribution infrastructure, including reliable roads. In some remote rural areas, the lack of availability of alternative fuels and the limited investment potential in new technologies, due to low overall demand, makes improved biomass cookstoves the only option (IEA, 2017f).

Overcoming such barriers requires a range of approaches. Access to clean cooking has tended to be less of a priority than access to electricity in terms of policy targets and actions. But there is no reason it should not be given equal priority, given the serious health impacts that can arise from traditional biomass cooking.

Household energy use is embedded in cultural practices, and it is vital that any intervention to improve access to clean cooking be firmly embedded in and informed by the social and cultural context. This must include an awareness of the full range of values attributed to traditional cooking methods, potentially including attributes which might not externally be understood as positive, such as the smoke itself. Suggested alternative solutions will only succeed if these are established collaboratively with local users, among whom it is particularly important to engage with women (IEA, 2017f). Thus, to improve chances of success, the social and cultural fabric of the particular setting must be considered. There are several initiatives trying to address the issues of energy, gender, health and climate together with women's empowerment, employment and representation in the energy sector. Notable examples include the Global Alliance for Clean Cookstoves, SEforALL, ECOWAS Energy-Gender Policy and Regulation, ENERGIA and the Clean Energy Ministerial (IEA, 2017f).

In some cases, available interventions may be limited to improved biomass cookstoves; however, evidence suggests that real-world performance of these stoves may still not meet WHO standards. Further research and innovation are needed to develop stoves which can meet WHO standards in real-world conditions, and to establish international standards for these stoves.

Research and innovation are also needed to improve small-scale renewable options for producing clean cooking fuel, including anaerobic digestion and fermentation. There is also a need for place-based research to produce appropriate workable technologies.

LPG is a near-at-hand alternative that can substantially improve health outcomes, compared with cooking with traditional biomass. However, some reflection is needed as to the potential conflict in such a strategy with ambitions to reduce the use of fossil fuels and increase the deployment of renewables. Where LPG needs to be imported and is supported by national Governments through end-use subsidies, it is worth reflecting on the sustainability of this economic strategy. Long-term outcomes are important to consider, given the power of the lock-in effect in energy systems.

Education and communication about the relative advantages and disadvantages of traditional compared with modern cooking options, must also be central. Many users may be unaware of the health impacts of smoke from stoves. There also may be distrust and unfamiliarity with alternative stoves, which would need to be demonstrated as having a comparable or better functionality, if they are to be adopted.

Paying for alternative cooking fuels and technologies is a major barrier that needs to be addressed. First of all, the upfront cost, which is an inevitable part of investing in a new stove, must be managed for users who very often will not have sufficient capital. Microfinance schemes such as those offered by (B) energy ((B)energy, 2017) and pay-as-you-go business models are useful ways of defraying upfront costs. Business models must also include a strategy for ongoing maintenance of household devices and any shared infrastructure. But this must also be seen in terms of a sustainable long-term income-generation strategy for people. Users should be able to repay such costs over time and to continue to rise out of poverty. It must be acknowledged that the health value of reduced indoor pollution is not necessarily well perceived, and that for some people, a reduction in overall consumption of wood fuel or charcoal would translate into reduced income, as they earn a living from producing or selling these products. As such, household energy interventions also need to be situated within a clear understanding of the economic development strategy for the communities concerned.

5. STRATEGIES AND POLICIES

The discussion in this section is grouped under two general themes. The first is on the importance of mixes of policies in order to increase the deployment of renewables most effectively and efficiently. The second theme concerns the potential for and importance of international and interregional collaboration.

5.1 The importance of policy mixes

Science, technology and innovation policies need to take an innovation system approach (including national, regional and sectoral innovation systems) to support renewable energy. The systemic nature of renewables innovation requires the creation of a clear market demand for renewables and a mix of supporting policies to stimulate research and development, build local skills, coordinate actors and infrastructure, align regulations and incentives and mobilize funding.

Renewable energy innovation can vary in scope and scale. There are incremental innovations that lead to improvements in existing technologies, while radical innovations yield new inventions and/or methods of production. Incremental and radical innovations are both relevant to renewable energy technologies, and policies can encourage both.

Applying policy mixes, rather than individual policies acting in isolation, requires a complex system of interventions, actors and processes co-evolving over a long period of time. Comprehensive policy mixes should comprise complementary types of instruments such as feed-in tariffs, international standards, demand-side measures such as public procurement, and incentives such as mission innovation programmes and bottom-up funding mechanisms, depending on country-specific challenges, priorities and different levels of technology maturity.

When considering the prospects for transforming well-established electricity systems into systems with a much greater contribution from renewables, policies that create strong and stable market incentives for renewables are necessary. The new systems must be supported by policies that consider the structure of power markets in relation to more variable generation sources and address issues of infrastructure and market integration with neighbouring systems.

Policy mixes are crucial for increasing energy access in developing countries and the least developed countries. The potential benefits of increasing access to electricity and to clean cooking are manifold, but the barriers to low-income communities are substantial. Affordability is a major issue for grid or off-grid approaches. This challenge needs to be met by addressing upfront costs through low-interest credit and microfinancing.

To make a project sustainable, it is necessary to establish a supportive environment. This should include attention to productive and income-generating activities that will generate the income to make the increased energy access a financially sustainable option. It should include a maintenance plan, preferably involving members of the community, and it should be responsive to the needs of the community itself.

It is also important to build capabilities to increase awareness of renewable energy technologies and to develop skills to install and maintain them. In rural energy applications, the effectiveness of training and capacity-building can be enhanced by considering socioeconomic issues, including gender. It is important to build local innovative capabilities, including the ability to develop and design technologies that are adapted to local needs (UNCTAD, 2010). Measures that can support such capabilities include supporting universities and research centres that focus on renewable energy technologies or providing incentives for firms for research, development and demonstration. Some inclusive capacity-building initiatives regarding women and youth include, for example, the Clean Energy Education and Empowerment (C3E) programme that aims to encourage women's participation in clean energy careers worldwide or Sustainable Energy and Economic Development (SEED) in the United States, which aims to create economic opportunity and energy-literate communities, including energy literacy, STEM education, and job-driven skills training.[15]

The overall balance between grid extension and off-grid solutions is another important policy question, and the issue of subsidies for fuels such as kerosene and LPG requires careful consideration. All of these issues need to be considered in an integrated way.

[15] Contribution from the Government of the United States.

There is potential for synergistic benefits from considering renewables policy within broader industrial and economic policy. The latter should be based on understanding where national comparative advantage lies and acting strategically to maximize this to generate macroeconomic benefits, while meeting renewables deployment objectives. This approach to energy and economic policy is more likely to generate legitimacy and public support for the energy transition.

5.2 The role of international and interregional collaboration

Technological innovation can be accelerated both by competition and cooperation. An important aspect of policymaking is to recognize the value of both and the benefits of encouraging them as appropriate in different circumstances. The example of solar PV shows that innovation dynamics are highly international in nature, with drivers in one country having the potential to have a significant impact on others. Within these international dynamics, competition is a significant factor and can produce the positive effect of driving down costs, which from a global perspective is beneficial. However, the industrial sectors of individual countries can lose out within these competitive dynamics. The challenge for individual countries is to identify appropriate areas of specialization due to comparative advantage, within this international dynamic. Rather than solely promoting renewables through market-based instruments, another approach would be to consider policy measures that can support supply chain related domestic industries as appropriate, according to potential areas of national comparative advantage. There is a benefit of embedding renewables policy within broader industrial policy.

On the other hand, international cooperation can play an important role in increasing the deployment of renewables. International cooperation can bring different actors together along a supply chain or help them benefit from shared natural resources and shared infrastructure. As well as forming markets to which private actors can respond in a competitive environment, Governments need to be aware of where their role as a broker can improve the functioning of supply chains or enable an efficient accessing of naturally shared assets, be they natural, infrastructure, or knowledge.

Wieczorek et al. (2015) give a number of arguments for cross-border collaboration. The geographical distribution of renewables can be better harnessed through collaboration and closer connection between energy systems. Such closer ties could allow countries to focus collectively on the regions with the best resources. The greater geographical region covered by such cooperation would also have a better chance of capturing a more complementary spread of renewables, whose outputs were uncorrelated, thereby enabling a more balanced system.

There are several initiatives and plans in this area, such as the Nordic Grid Development Plan (Stattnet et al., 2017), which is looking at potential new interregional transmission lines that could transmit energy surplus in one region to the consumption centres. Another example is the Africa Clean Energy Corridor (Southern African Development Community, 2016) initiative by IRENA that aims to accelerate the development of renewable energy including cross-border trade of renewable power within the Eastern and Southern African Power Pools.

Collaboration also entails greater potential to leverage investment in innovation and experimentation zones. A good example of this is the demonstration of floating wind turbines off the coast of Scotland, which required the collaboration of Statoil, a Norwegian energy company, and Crown Estate of the United Kingdom. Furthermore, homogenous regional markets may offer greater policy stability and greater investment economies of scale than national markets. International collaboration on cross-border grid and infrastructure projects may also be of mutual benefit.

Governments can also play important roles in coordinating and bringing together the actors that are required to work together within a supply chain, to encourage them to jointly invest in areas of shared value (box 13).

Box 13. United Kingdom: Offshore wind accelerator

In the United Kingdom, the offshore wind accelerator, organized by the Carbon Trust, brought together the major project developers with the aim of reducing the costs of offshore wind by 10 per cent. The aim was to identify components of the supply chain that all of the project developers would need to call on, including designs of foundations and site-access systems, to clarify the performance needs in each case and jointly commission these from potential providers. By pooling their interests with others, each participant leveraging their own investment by many times due to the contributions of the other participants, the group as a whole was able to establish a clear market demand for the products required, at a desired cost. Thus, there can be occasions when cooperation increases efficiency more directly than competition. There is a clear role for governments to spot these opportunities and to take coordinating measures as necessary.

Source: Grubb et al. (2014).

Collaboration may also include technology transfer (Ockwell et al., 2008). The main challenge is to design policies and cooperation mechanisms that facilitate technology transfer between firms, especially in countries with emerging renewables sectors. However, technology transfer should not replace, but rather complement domestic capacity-building efforts.

China, for example, is starting to facilitate foreign wind farm development in Argentina and Pakistan (Gosens and Lu, 2013). A solar panel factory has been set up in Mozambique with joint investment by the Governments of Mozambique and India. The factory produces four types of solar panel, with a focus on off-grid applications. Mozambican technicians are being trained also in India. The factory currently employs 33 people. Though currently small scale, this factory is an interesting example of how technology and skills transfer can benefit countries by producing and deploying renewables quickly, despite lack of research and development background in the country, as well as developing new skills and employment in the manufacturing stage of the supply chain (Southern African Development Community, 2016).

International, including North–South and South–South collaboration, can have multiple forms, such as collaboration for policy learning and capacity-building; collaboration with respect to technology development; collaboration to improve interconnection of grid infrastructures across borders; collaboration to develop manufacturing capacity; or contribution through funding. One notable example of the latter is a solar PV plant in Cobija, Plurinational State of Bolivia, that was financed almost half-half by the National Electricity Company (ENDE) and Denmark.[16] The plant generates enough solar power to cover approximately half of the energy demand of the provincial capital of Cobija during daytime hours, saves a large amount of diesel, and reduces emissions. Mission Innovation and the Global Alliance for Clean Cookstoves are two further important examples of international collaboration initiatives to promote innovation in clean and renewable energy (box 14).

Box 14. International initiatives to promote innovation in clean energy

Mission Innovation is a global initiative of 22 countries and the European Union that aims to accelerate global clean energy innovation to make clean energy widely affordable. Member countries pledged to double their public investment in energy research, development and deployment (R, D & D) between 2016 and 2021, though it remains to be seen whether their actual spending matches their pledges. They have also identified seven priority innovation challenges to focus their collaborative R, D & D. Several of these challenges focus on renewable energy or related innovations, including: smart grids, off-grid electricity access, sustainable biofuels, new technologies to convert sunlight into energy and clean energy materials.

The Global Alliance for Clean Cookstoves is a public–private partnership hosted by the United Nations Foundation. Acknowledging that the use of traditional fuels and inefficient technologies is one of the most pressing health and environmental issues in developing countries, its aim is to save lives, improve livelihoods, empower women and protect the environment by creating a thriving global market for clean and efficient household cooking solutions. The focus countries are Bangladesh, China, Ghana, Guatemala, India, Kenya, Nigeria, and Uganda. Its "100 by '20" goal calls for 100 million households to adopt clean and efficient cookstoves and fuels by 2020. The Alliance has an instrumental role in supporting the research, design and rolling out of programmes for improved cookstoves, including cookstoves using biofuel and solar energy. In particular, an emphasis is given to develop markets by raising consumer awareness and ensuring availability and affordability. The Alliance brings together more than 1,600 partners worldwide, representing the private sector, governments, NGOs, philanthropists and donors, and academia.

Sources: Contribution from the Government of Canada; Global Alliance for Clean Cookstoves, 2016.

[16] Contribution from the Government of the Plurinational State of Bolivia.

6. KEY FINDINGS AND POLICY RECOMMENDATIONS

This final section summarizes some key points from the paper and discusses implications for national government policies and for the Commission on Science and Technology for Development.

6.1 Renewable energy and the Sustainable Development Goals

The achievement of the Sustainable Development Goals is highly dependent on increasing access to clean energy services. Increasing renewable energy deployment can have a substantial implication on income generation, and other development outcomes such as gender equality, health and efforts to combat climate change. Strategies to expand the use of renewable energy are therefore not only a matter of energy policy. They are also linked to wider economic, industrial and development policies.

The current share of global energy from renewables is 9 per cent, excluding traditional sources of bioenergy. But that is starting to change quickly, particularly due to the rapid expansion of renewables for electricity generation. If hydropower is excluded, the share of renewables in the global electricity mix grew from 1.4 per cent in 1990 to 7.5 per cent in 2016 (IEA, 2018).

Renewable energy sources can also play a role in other parts of the energy system beyond electricity, either directly or indirectly: in transport, heating and industry. The share of renewables in these other parts of the system tends to be smaller, especially in transport. The use of biofuels for transport has been limited in most countries due to concerns about environmental sustainability, particularly life-cycle emissions and land use implications of first-generation biofuels.

National pathways for renewable energy development and deployment vary markedly, depending on local contexts, including geographical patterns, cultural and institutional conditions, and policy and regulatory frameworks. While renewable electricity technologies have expanded rapidly in some OECD countries and emerging countries, traditional biomass comprises a large share of overall primary energy in many less developed countries. However, some developing countries such as Kenya have seen significant increases in the use of modern renewable energy technologies during the past decade.

There is significant potential for renewable energy to play a much larger role in the future. Scenarios that are designed to be compatible with the Paris Agreement under the United Nations Framework Convention on Climate Change include a significant expansion of renewable energy by 2050. Some of the most ambitious scenarios foresee renewables supplying the majority of the world's energy by this date.

6.2 Policies and strategies to support renewable energy

An innovation systems approach is a useful way to understand renewable energy strategies in different countries and contexts, and to help explain their relative success or failure. While single policies or interventions (such as supporting research and development or a feed-in tariff) are important, successful strategies are often broader. They use policy mixes to create the conditions for successful renewable energy innovation and deployment.

This highlights the important role of Governments in supporting innovation in renewable energy technologies. While much renewable energy innovation is carried out by the private sector, this does not happen in a vacuum. Governments play a crucial role in the innovation and deployment process, for example, by funding research and development, creating demand through deployment incentives, reforming energy markets and by taking other steps to strengthen investor confidence.

Important factors that explain differences between national approaches include different resource endowments and differences in technological and industrial capabilities. In relation to this, there are important questions about the extent to which individual countries will wish to couple renewable energy deployment with the location of manufacturing and supply chains within their country. Such choices need to consider the international nature of supply chains and innovation systems for renewable energy and their existing areas of scientific or industrial strength.

Renewable energy strategies are usually tailored to national circumstances, even if they include similar policies such as feed-in tariffs or auctions to drive renewables deployment. Such policies are often adapted so they are compatible with existing policy frameworks and institutional arrangements. However, there have been some important general trends in renewables policy, including, for example, the trend towards using auctions rather than administered tariffs to drive down the costs of deployment.

6.3 Challenges and opportunities for developing countries

Developing countries have particular challenges and opportunities with respect to renewable energy. For example, while some developing countries lack reliable electricity infrastructures, there is a potential opportunity to develop these infrastructures in a more sustainable way than other countries have done in the past.

Some of the most rapid progress in renewable energy deployment has occurred in middle income countries, particularly China. This has also been a major contributor to the cost reductions that have been seen in recent years. While there are some positive examples of renewable energy deployment in developing countries, these examples are often on a much smaller scale.

Renewable energy sources can play an important role at a range of scales – from bottom-up off-grid applications (e.g. solar home systems) to larger grid-scale power plants (e.g. hydropower, concentrated solar or geothermal plants). There are strongly held views and mixed evidence about the relative merits and costs of these different approaches. The most appropriate balance of the two is highly context specific. Therefore, policies for renewable energy should enable the contribution of all approaches, by creating a supporting regulatory environment and tariff structure. In addition to connecting population centres with large-scale sources of generation (including centralized renewables), plans for the development of grid infrastructure should also include strategies for how microgrids might eventually be integrated in main national networks.

Given that almost 2.8 billion people do not have access to clean cooking facilities, there is an urgent need to deploy alternatives to the traditional use of bioenergy for cooking and other energy services. This is required to tackle the negative impacts of the use of these energy sources, for example on health, gender equality and poverty. The evidence shows that policies and programmes to address this challenge must be embedded in the social and cultural contexts of the communities they involve and take account of their current energy practices, needs and expectations, and potential for productive uses. The engagement of women in this process is particularly crucial, as they frequently have predominant responsibility for household energy-related practices, including fuel gathering and cooking. Women can also be effective trainers and communicators in the managing and maintaining of new local energy systems.

Affordability is a key issue in increasing energy access through the use of renewable energy. A particular obstacle may be the upfront costs of purchasing equipment and devices. New business models can make this viable and conducive to development, for example, by using microfinance or pay-as-you-go arrangements to spread these costs. In some cases, payments for new renewable energy technologies can be structured so they are similar to the costs of the energy sources they are replacing (e.g. kerosene). However, new technologies will not be affordable if there is no increase in income generation activities. Income-generation opportunities that can arise from increased energy access must also be central to national and international strategies. Attention must be given not only to household uses but to other productive uses in the industrial, commercial and agricultural sectors.

Another barrier to affordability is subsidies for fossil fuels such as kerosene and LPG. While many of these are intended to support the poor, they can create lock-in to these fuels, prolonging the exposure to fossil fuel price risks. Subsidies also risk crowding out renewable energy technologies that could be more sustainable in the medium and long-term. Subsidized electricity tariffs may also have the unwanted effect of discouraging energy efficiency.

To avoid situations where technologies break, business models must also consider a maintenance strategy for the technologies that cannot be fixed and are subsequently abandoned. The engagement of the local communities, including women, in training for the maintenance of these systems, is an effective strategy.

6.4 International collaboration

International cooperation, including North–South and South–South cooperation, has a major role to play in increasing substantially the share of renewable energy by 2030. These include knowledge sharing, collaboration for policy learning and capacity-building, collaboration with respect to technology development, collaboration to improve the interconnection of grid infrastructures across borders and collaboration to develop manufacturing capacity.

International organizations and bodies such as the Commission on Science and Technology for Development can play an important role in supporting these forms of collaboration. With respect to policies to support renewable energy development and deployment, they can help to share lessons between countries and regions. In doing so, it will be important to recognize that policies and policy mixes cannot be simply transplanted from one context to another. This is particularly true for less developed countries when learning lessons from OECD countries or middle-income countries.

Policies can also help to identify mechanisms for improving capabilities in developing countries for renewable energy. These include capabilities to develop and implement supportive policy mixes; the development of flexible plans and regulations for the energy sector that embed incentives for renewable energy; and measures to improve capabilities to absorb, maintain and adapt renewable energy technologies to the local context.

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