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THE LEAST DEVELOPED COUNTRIES REPORT 2017

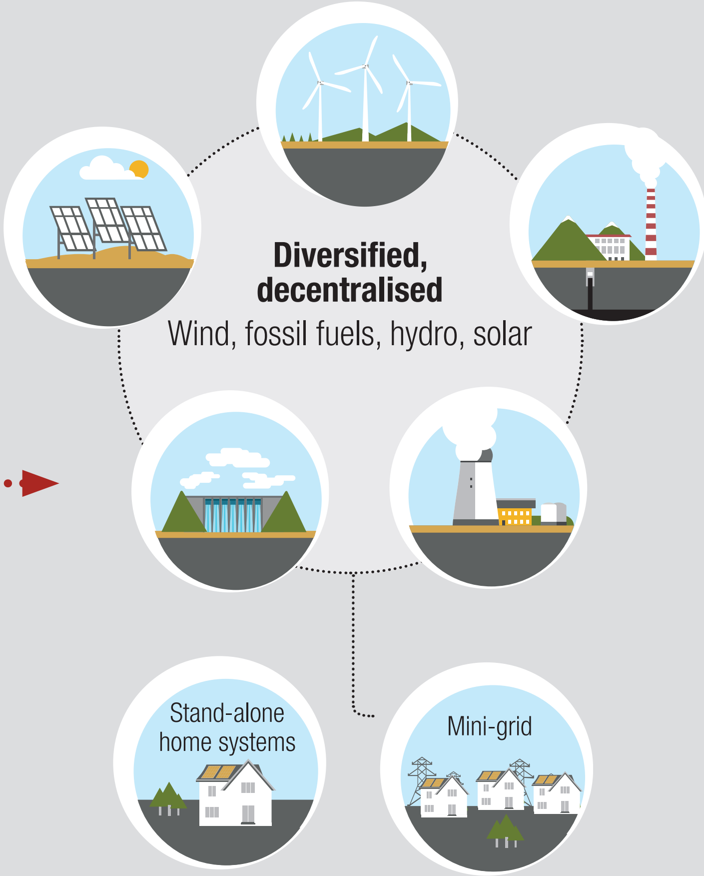
Transformational energy access

CHAPTER 3

Harnessing technologies for transformational electricity access in LDCs

ELECTRICITY SYSTEM TRANSITION

Traditional, centralized



5.5 billion

LDC imports of power-generating machinery and equipment in 2016

of which 47% is South–South trade

and they grew 18% annually between 2000–2016

52%

of LDC electricity generation is **based on renewables**

of which 51% is hydro

1% is solar and wind

CHAPTER 3
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A. Introduction

The previous chapters have highlighted the critical role of the energy sector in realizing the ambitions of the 2030 Agenda, and particularly in structural transformation. Many energy sources can be applied to productive uses, from animal traction to electricity and from conventional fuels to renewable energy; but electricity is uniquely versatile, powering all types of productive applications – lighting, information and communication technology (ICT), motive power, and space or product cooling/heating (Bhatia and Angelou, 2015). Hence, this chapter focuses on the links between the technological challenges and opportunities in electricity supply and the transformation of the economies of least developed countries (LDCs).

The chapter has four sections. Section B takes stock of recent trends in LDCs' electricity generation, assessing the role of renewables in the context of recent technological advances. Section C considers challenges in electricity distribution, particularly in rural areas, and the potential for leapfrogging to off-grid technologies to foster synergies between low-carbon energy systems and rural development. Section D looks at alternative technological choices from the perspective of electricity costs and systemic synergies and complementarities. It highlights the need for a systemic long-term approach to the electricity sector, progressively diversifying the national system by integrating a diversified portfolio of technologies, to enhance the provision of adequate, reliable and affordable electricity, in line with the needs of structural transformation. Section E discusses the scope and challenges for energy-related technology transfer; and section F concludes.

Structural transformation in LDCs will require increased use of modern energy in productive sectors

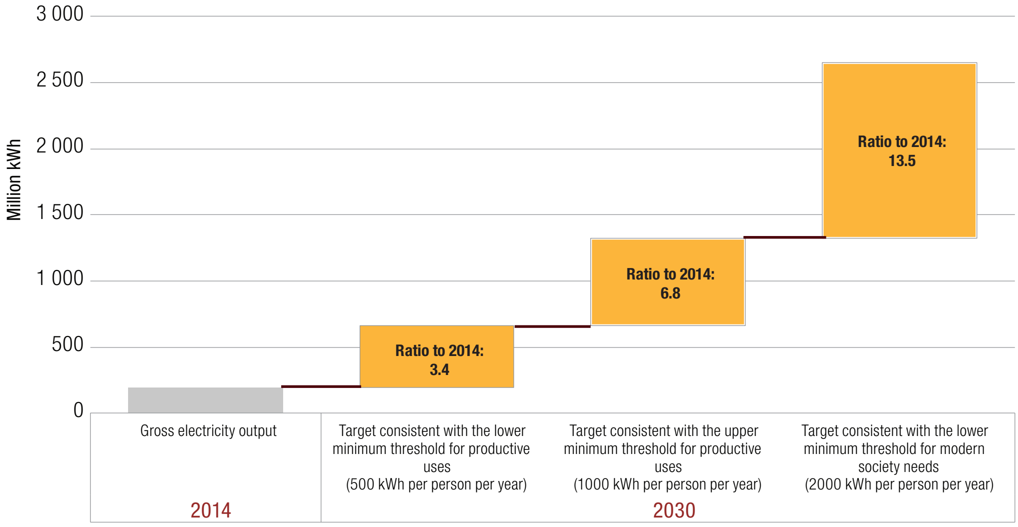
B. Taking stock of the electricity sector in LDCs

As noted in chapter 1, energy consumption in LDCs is strongly skewed towards the residential sector, with a heavy reliance on traditional biomass in total primary energy supply. Structural transformation will require a radical change in this pattern of energy consumption, with a major expansion of demand for productive purposes, and a parallel shift towards modern energy (as defined in chapter 1) — particularly as improvements in energy efficiency are unlikely to lead to less energy-intensive development paths in LDCs than in other developing countries (ODCs) or developed countries in the past (van Benthem, 2015).

Achieving universal access to modern energy by 2030, closing the long-standing "electricity divide" between LDCs and ODCs (chapter 1), and harnessing electricity technologies to stimulate sustainable structural transformation will require an enormous increase in LDCs' power generation. Combining estimates of per capita electricity supply requirements from Sovacool et al. (2012) with United Nations population projections to 2030, LDCs' combined electricity generation would need to increase to 3.4 times its 2014 level to reach the lower minimum threshold, and 6.8 times this level

Figure 3.1

LDC combined electricity output: 2014 value and various notional targets for 2030



Source: UNCTAD secretariat estimates,based on data from UN DESA, Energy Statistics Database (accessed February 2017) and Sovacool et al. (2012).

to reach the upper minimum threshold for productive uses. Reaching the minimum threshold for "modern society needs" would require an increase by a factor of 13.5 (figure 3.1).

This requires a greater expansion in electricity generation than in the period 1990–2014, and in less time. The scale of this challenge will demand enormous financial investments, considerable political will and consideration of all the available technological options.

1. LDCs' power generation mix

Different generation technologies have different characteristics (box 3.1); and the combination of energy sources used to produce electricity (the power generation mix) differs markedly between LDCs and ODCs.

Unlike other country groups, LDCs have traditionally displayed a dualistic power generation mix, relying on combustible fuel generation (overwhelmingly from fossil fuels) and hydroelectric power generation (henceforth "hydro") for nearly all their electricity needs (figure 3.2).[1] Hydro has long played a disproportionate role in these countries, accounting for more than half their combined power generation in 2014, reflecting the enormous potential of some countries in the group (notably Democratic Republic of the Congo, Ethiopia, Myanmar, Mozambique and Zambia). This further underlines the minimal role of LDC electricity generation in global greenhouse gas (GHG) emissions (chapter 1). The share of combustible fuel-based generation has increased steadily, but remains below that of ODCs and developed countries alike. Despite recent deployment of bioenergy, solar and wind technologies (section B2), the role of non-hydro renewables in grid-connected generation remains marginal, at less than 1 per cent.[2] More complex and/or less mature technologies, such as nuclear, tidal, wave and ocean power, are virtually absent from the LDC generation mix, even though several LDCs are considering the development of nuclear capacity, or exploring its feasibility (typically with the assistance of the International Atomic Energy Agency).[3]

Box 3.1 Major power-generation technologies: an overview

Several technologies are available to produce electric power from primary energy sources. This box outlines the main technologies, some of which may also be combined in hybrid systems.

Among the most widely used technologies is **combustible fuel-based generation**. This relies on a turbine driven by high-pressure steam or exhaust gas produced by the burning of *fossil fuels* (mainly coal, natural gas, and fuel oil, or diesel for small-scale generators) or *bioenergy* (solid biomass, such as agricultural waste, fuelwood, and municipal waste, or alternatively liquid biofuels or biogas). Since production is dispatchable — i.e. it can be increased or reduced to match demand with limited additional costs (except where coal is used) — oil- and gas-based generation are well suited to peak generation, back-up and system balancing. However, fuel-based generation has negative environmental effects in terms of GHG emissions and ambient air pollution.

The technologies below are generally deemed to be low-carbon in that they produce limited GHG emissions during operation. (Bioenergy is also considered as low-carbon, as it reduces the emissions associated with fossil-fuel generation).

Hydroelectric power uses the energy of flowing water to spin turbine blades, which drive a generator to produce electricity. While this most commonly uses a dam on a river to store water in a reservoir, it may also use a small canal to channel river water through a turbine.

Solar power takes two forms. *Solar photovoltaic* (PV) uses photovoltaic cells (specialized semiconductor devices with adjacent layers of different materials) to convert sunlight directly into electricity. These cells are interconnected, mounted, sealed and covered with a protective glazing to form modules or panels, which are combined into an array producing a single electrical output. *Solar thermal* energy uses concentrated solar power (focused using mirrors) to heat a fluid, powering a turbine that drives a generator.

Wind power uses the wind to drive turbines, which are generally interconnected through a system of transformers and distribution lines to form a wind power plant or wind farm. Electricity output varies with (the cube of) wind speed, so that doubling the wind speed increases power by a factor of eight. A distinction is often made between *offshore wind* and *onshore wind*.

Geothermal power generally generates electricity using turbines driven by steam extracted from geothermal reservoirs in the Earth's crust by drilling and/or pumping (or produced from hot water generated by such reservoirs) .

Marine power encompasses several distinct technologies. *Tidal power* harnesses the power of ocean tides, capturing water behind a dam or barrage at high tide, and channelling it through turbine as the tide ebbs. *Ocean thermal energy conversion* (OTEC) exploits the temperature difference between cooler deep and warmer shallow or surface seawaters to run a heat engine. *Wave power* uses a variety of methods to convert the motion of ocean waves into electricity.

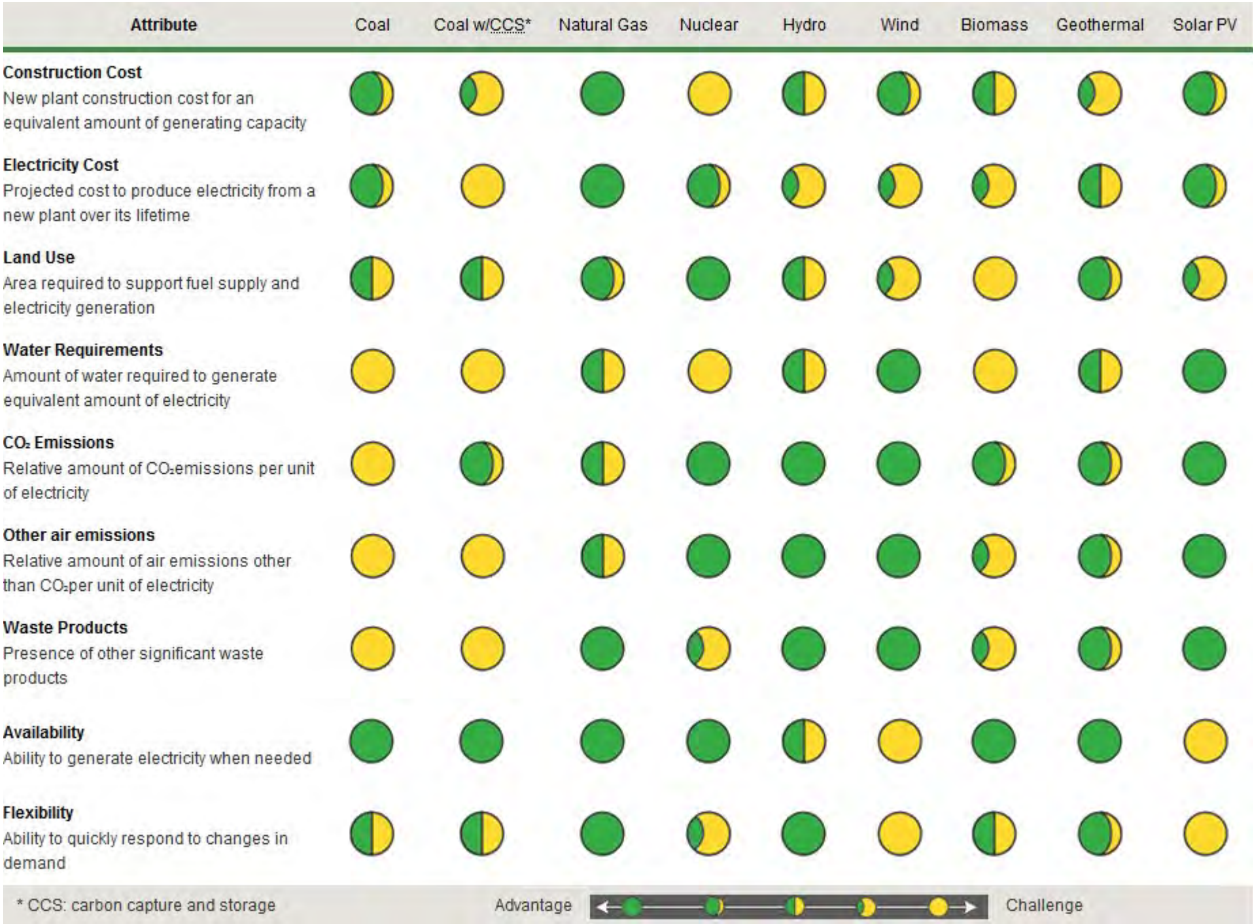
Nuclear generation generally uses the heat generated by splitting atoms of radioactive materials, such as uranium, to drive steam turbines, producing radioactive waste as a by-product. While life-cycle GHG emissions are low, nuclear power poses serious challenges in terms of radioactive waste management, risks of nuclear contamination and security-related concerns.

Box figure 3.1 presents a schematic assessment of the main technologies for utility-scale electricity generation.

Box 3.1 (contd.)

Box figure 3.1

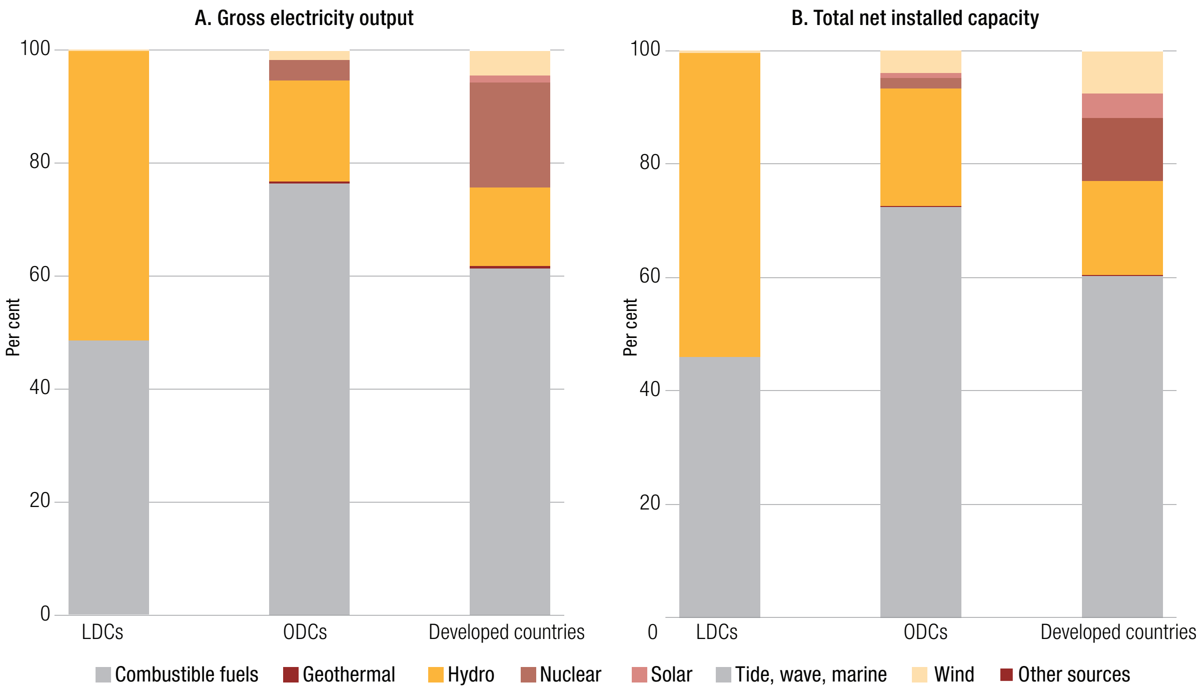
Schematic assessment of main electricity generating technologies



Source: Adapted from http://sites.epri.com/refcard/comparison.html

Figure 3.2

Power generation mix in different country groups, 2012–2014



Source: UNCTAD secretariat estimates, based on data from UN DESA, Energy Statistics Database (accessed February 2017).

LDCs have a dualistic power generation mix, based on fossil fuels and hydroelectric power

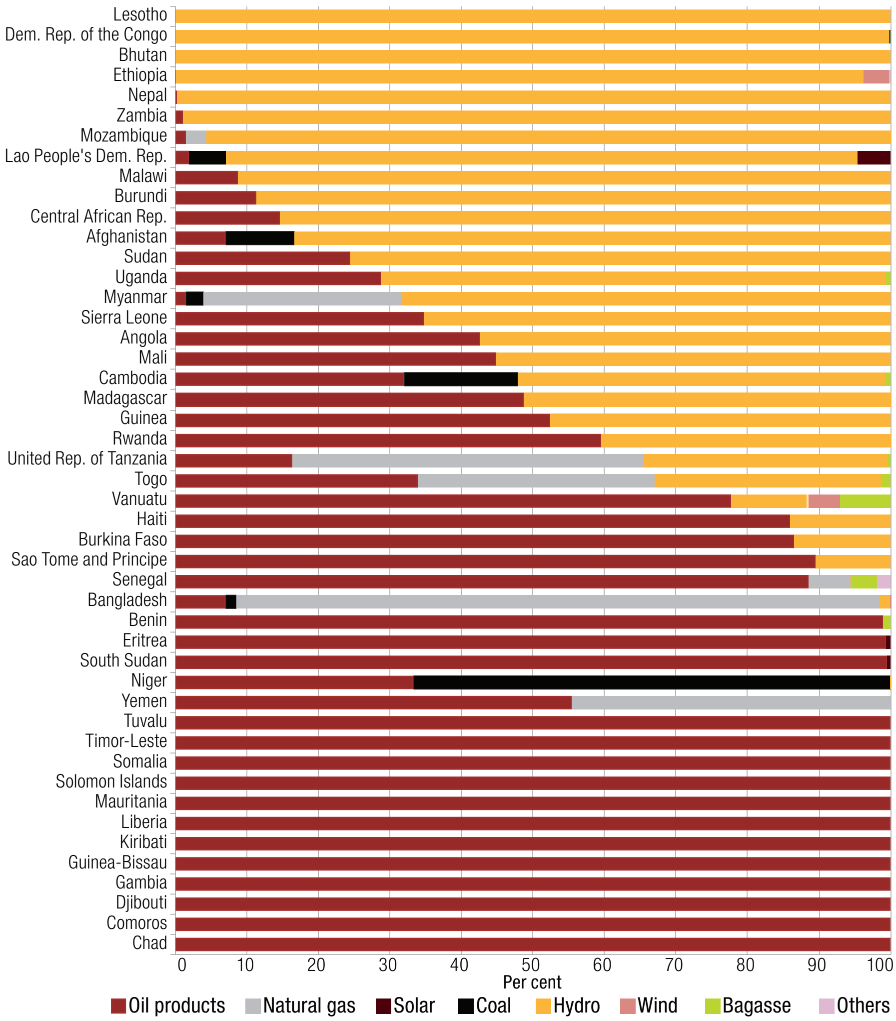
In ODCs, by contrast, combustible fuel-based generation accounts for nearly 75 per cent of electricity production and 70 per cent of capacity, while non-hydro renewables, and to a lesser extent nuclear power, play a greater and rapidly expanding role. The contrast with developed countries is still sharper. There, only 60 per cent of generation and capacity are combustible fuel-based, as much faster deployment of nuclear and non-hydro renewables has led to a more diversified generation mix.

As shown in figure 3.3, the relative importance of hydro and fossil fuel-based generation varies widely among LDCs, which can be divided into three broad groups. In the first (which comprises 12 countries, including large electricity producers such as Democratic Republic of the Congo, Ethiopia, Mozambique and Zambia), hydro accounts for more than 75 per cent of gross electricity production, the remainder being fossil-fuel and, to a lesser extent, solar or wind generation. The second group, in which hydro and fossil fuels each comprise 25–75 per cent of the generation mix, includes 13 LDCs encompassing both larger economies, such as Angola, Cambodia and the Sudan, and smaller ones, such as Malawi and Togo. The remaining 23 LDCs rely almost entirely on conventional fossil fuel-based generation, with minor contributions from hydro, solar and/or bioenergy.

Fossil-fuel-based generation is dominated by natural gas, reflecting a progressive shift towards gas-based technologies among major electricity producers. However, while oil-based generation has waned globally, it is widely used in LDCs and is the only fuel used in generation in many of the smallest LDCs. Most of the island LDCs, in particular, are heavily dependent on conventional thermal generation using

Figure 3.3

Power generation mix in LDCs: Composition of gross electricity production by energy source, 2012–2014



Source: UNCTAD secretariat estimates, based on data from UN DESA, Energy Statistics Database (accessed February 2017).
Notes: LDCs are ranked in increasing order of relevance of combustible fuel generation. The decomposition of the latter across different fuels has been computed as a weighted average of each country's fuels inputs, with weights being given by the mean efficiency rates of electricity plants, as reported in UN DESA source above.

imported fossil fuels (Dornan, 2014; Kempener et al., 2015). Conversely, coal has played a relatively limited role in LDCs' electricity generation mix, although its weight may expand somewhat as recently planned investments in new coal-based plants come online.

As of 2012–2014, aside from hydro projects, the contribution of renewable technologies to generation in LDCs remained very limited (figure 3.3): bioenergy exceeded 3 per cent of generation only in Senegal (5 per cent) and Vanuatu (10 per cent), solar only in Lao People's Democratic Republic (4.6 per cent), and wind only in Ethiopia and Vanuatu (in each case 3.6 per cent). As discussed in the next subsection, however, there is evidence of an acceleration of non-hydro renewable energy deployment in LDCs since 2014, and utility-scale plants currently under construction will increase their weight in the near future.

2. The broadening array of renewable technologies[4]

Recent technological advances, together with mounting concern about climate change, have stimulated growing interest in the opportunities offered by (non-hydro) renewable-energy technologies in LDCs and ODCs alike. At the 22nd Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) (COP22), the Climate Vulnerable Forum (including 24 LDCs[5]) pledged to achieve 100 per cent renewable energy by 2050. Thus, half of the 47 LDCs — including island LDCs dependent on fossil-fuel generation as well as others with a larger share of renewable energy — consider a transition to a low-carbon power sector a strategic long-term objective. Other LDCs, such as Lao People's Democratic Republic, Mozambique and Uganda, are also experimenting with the deployment of various renewable-based generation technologies.

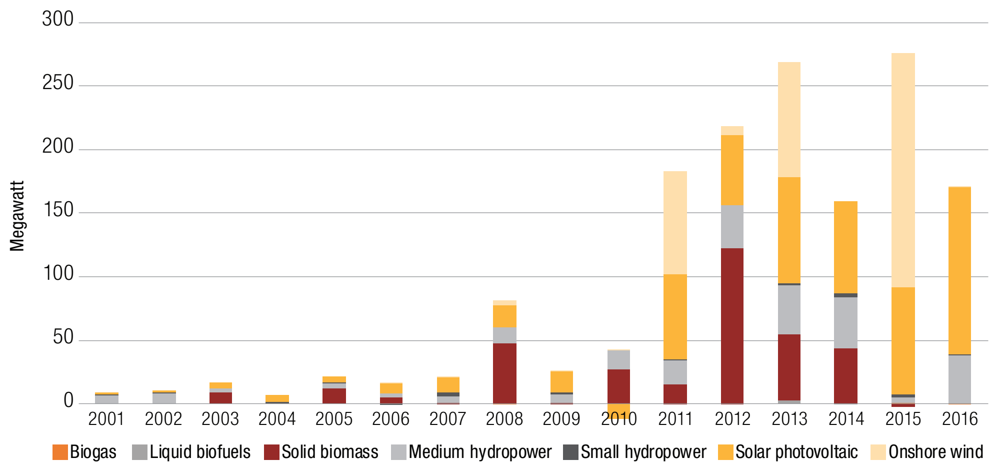
While their relative importance has contracted slightly as other renewable technologies are deployed, **large hydro plants** (defined by the International Renewable Energy Agency (IRENA) as those with capacity greater than 10 Megawatts (MW) continue to account for more than 90 per cent of LDCs' renewable-based capacity and some 80 per cent of their renewable-based generation. Since large hydro also comprises the overwhelming majority of prospective net capacity additions, this predominance is set to continue over the medium term. Moreover, large hydro is the backbone of the generation mix not only in major hydro producers, but also in several smaller LDCs, such as Burundi, Cambodia and Rwanda.

Despite the continued prevalence of large hydro, there is an incipient but accelerating uptake of other renewable technologies in LDCs, including smaller-scale hydro, bioenergy, wind and solar (figure 3.4). Net capacity additions using these technologies have increased strongly since 2010, by more than 200 MW annually, exploiting a broad range of energy sources.

Medium and small-scale hydro (with capacity of 1-10 MW and below 1 MW respectively) have long been present in LDCs, though on a limited scale. However, LDCs' combined installed capacity for medium hydro nearly doubled between 2000 and 2016, from 257 MW to 495 MW, while small hydro also increased from 45 MW to 63 MW. Electricity output from medium hydro rose by more than 80 per cent from 9,723 GWh in 2000 to 17,887 GWh in 2014, while small hydro output increased from 159 GWh to 203 GWh. At the forefront of this increase have been Democratic Republic of the Congo, Lao People's Democratic Republic, Madagascar, Mozambique, Nepal, Rwanda, Uganda and Zambia. While these technologies generally still account for a relatively minor proportion of total generation, there is growing evidence of their effectiveness in serving rural

Figure 3.4

Net capacity additions for renewable-based generation in LDCs, 2001–2016 (excluding large hydro)



Source: UNCTAD secretariat estimates, based on data from IRENA database (accessed March 2017).

Meeting LDC energy needs will require more hydro and fossil-fuel generation as well as faster deployment of other renewables

communities, especially where population is sparse and electricity demand weak (Murray et al., 2010; Sovacool et al., 2011; Gurung et al., 2012).

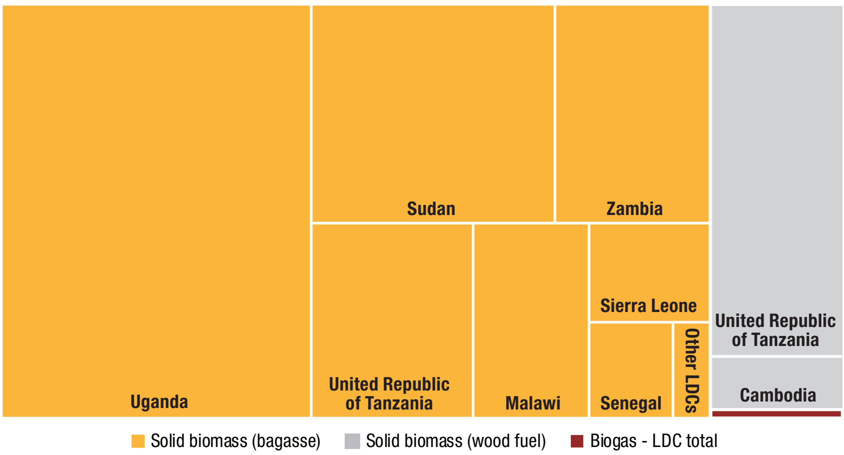
Though dwarfed by large and even medium-sized hydro, **bioenergy** generation has been scaled up significantly in a number of LDCs, notably in East Africa. Net installed capacity in LDCs as a whole more than doubled between 2009 and 2016, to 500 MW, while generation surpassed 750 GWh in 2014 (the latest available year), with Uganda leading the way (figure 3.5). Solid biomass (bagasse and to a lesser extent fuelwood) accounted for most of this output, while other technologies (including agricultural or urban waste, biogas, liquid biofuels, etc.) have been introduced too recently to make a significant contribution.[6]

The diffusion of solar and wind in LDCs is also increasing rapidly, but again from a very low base and so far only based on solar PV and onshore wind technologies (box 3.1).[7] The number of LDCs reporting **solar** capacity rose from 10 in 2000 to 40 in 2016, while their total solar generation increased from just 6 GWh to 446 GWh in 2014. Bangladesh leads the group in PV generation (figure 3.6), accounting for nearly half of their total output, largely due to widespread use of solar home systems (section C).

Despite a later start (in 2006, according to IRENA data) and as yet less widespread application (in 11 countries), **wind** technologies in LDCs have witnessed even stronger growth, surpassing 500 GWh in 2014. As shown in figure 3.7, this mainly reflects investments in utility-scale wind farms in Ethiopia, where three plants are already operating and five more are under construction (Monks, 2017), with more limited use in Bangladesh, Cambodia, Eritrea, Madagascar, Mauritania, Somalia and Vanuatu (although only in Vanuatu is the contribution to the energy mix significant).

Figure 3.5

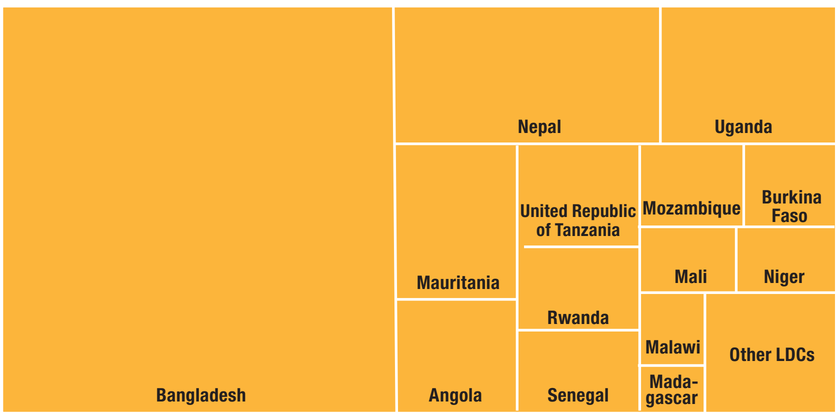
Distribution of bioenergy electricity generation across LDCs, by main technology, 2014



Source: UNCTAD secretariat estimates, based on data from IRENA database (accessed March 2017).

Figure 3.6

Distribution of solar PV electricity generation across LDCs, 2014



Source: UNCTAD secretariat estimates, based on data from IRENA database (accessed March 2017).

Figure 3.7

Distribution of onshore wind electricity generation across LDCs, 2014

Source: UNCTAD secretariat estimates, based on data from IRENA database (accessed March 2017).

Thus, while a growing number of LDCs have started to exploit non-hydro renewable generation technologies, their penetration remains very limited, and only a handful have yet moved beyond small-scale demonstration projects or off-grid energy systems into utility-scale renewable generation. Similarly, despite their proven technical potential, no LDC has yet experimented with concentrated solar power or offshore wind. While new technologies for bioenergy, solar-based generation and storage systems could change this picture, this limited progress highlights the important barriers to technology adoption. Such constraints include the limits to scale economies arising from limited demand, tight financing conditions and institutional weaknesses, especially for technologies that entail relatively high capital expenditures (Labordena et al., 2017).[8]

This situation is consistent with an S-shaped pattern of penetration of new energy technologies, with a relatively long initial period of cost discovery through small-scale demonstration projects before larger-scale deployment of the most appropriate technologies (Lund, 2010). In-depth understanding of the technical and economic dimensions of the new technological options needs to become entrenched, through imitation, network effects and/or conscious policy measures, before industry-level economies of scale can be harnessed to create a critical mass that spurs energy transition further (Grubler, 2012; UNCTAD, 2014b).

Overall, meeting LDCs' growing energy needs will likely require both an expansion of hydro and fossil-fuel-based generation — traditionally the backbone of LDCs' power generation mix — and an accelerated deployment of other (non-hydro) renewables at utility scale.[9] Continued policy commitment is hence critical to accelerate the penetration of renewable-based generation, as LDC players identify and adapt the technologies that best suit the local context. However, as discussed later in the chapter, challenges and trade-offs remain, technically, economically, socially and environmentally.

Distribution systems need to be upgraded as electricity production is increased

3. The conundrum of electricity distribution in LDCs

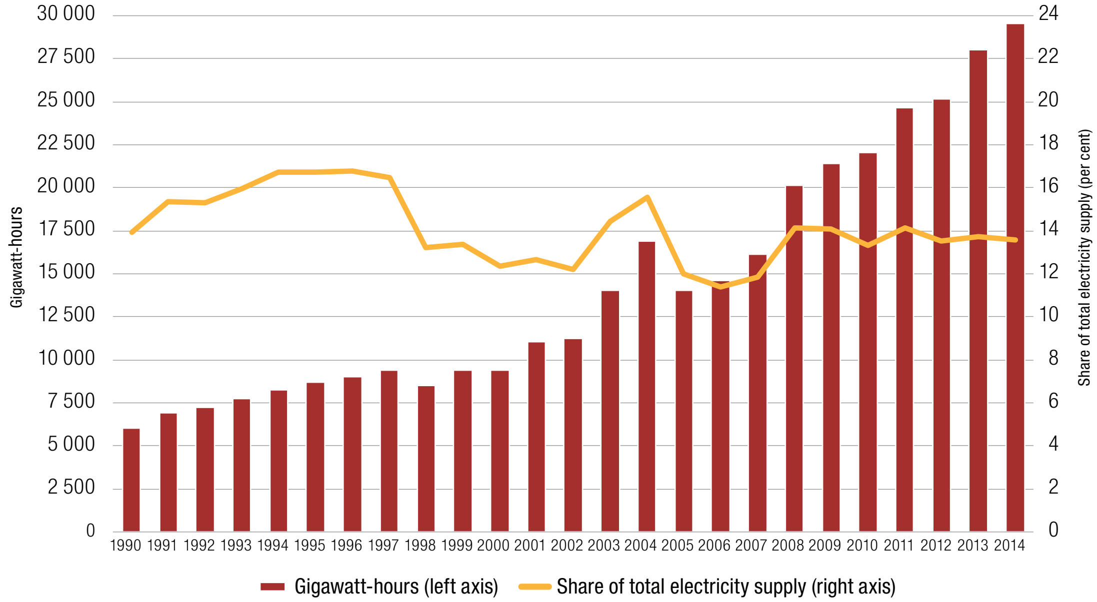
While universal access and powering structural transformation in LDCs will require a colossal scaling-up of electricity production, distribution systems are at least as important, both for outreach and for efficiency (Eberhard et al., 2011). The ability of LDCs to reap the benefits of technological progress depends critically on the grid's quality in terms of voltage levels and reliability as well as its extension. Equally, the appropriate portfolio of energy technologies depends on each country's own initial conditions, including the technical and economic potential for electricity generation and its location relative to consumers, as well as the existing distribution system. However, transmission and distribution (T&D) has often been neglected both in the policy discourse and financially (Hogarth and Granoff, 2015).

Power grids in LDCs typically reflect the legacy of traditional structures oriented towards large centralized electricity generators serving urban customers and large industrial clients (particularly exporters) (IEA, 2014a; Africa Progress Panel, 2017). Despite recent progress, the density of transmission lines remains extremely low by international standards, and local grids remain poorly interconnected internationally (and sometimes even nationally). While Africa provides the classic example of fragmented electricity markets, with low density of transmission lines and a plethora of different specifications (UNEP, 2017), LDCs in other regions face similar challenges. In Afghanistan, for instance, the interconnection of regional grids has been envisaged only since 2013 (ADB, 2013).

As discussed in chapter 1, distribution networks in most LDCs are also dilapidated, resulting in high T&D losses, which undermine the reliability of electricity supply and reduce energy efficiency. On average, T&D losses have hovered at around 14 per cent of LDCs' combined electricity supply since 1990 (figure 3.8), compared with a world average of 7–8 per cent. Moreover, the lack of progress in reducing loss rates implied, in light of the growth in electricity generation, that losses have actually skyrocketed in absolute terms, reaching in

Figure 3.8

Transmission and distribution losses in LDCs, 1990–2014



Source: UNCTAD secretariat estimates, based on data from UN DESA, Energy Statistics Database (accessed February 2017).

2014 the order of 30,000 GWh (roughly the combined electricity output of Mozambique and the Sudan). These inefficiencies, coupled with the additional costs faced by producers owing to outages and unreliable electricity supply, give rise to substantial impacts at the macroeconomic level, estimated at between 0.5 and 6 per cent of gross domestic product (GDP) in 12 African countries, including 8 LDCs (Eberhard et al., 2011: 10).[10]

Without a decisive improvement in energy efficiency, the magnitude of T&D losses (compounded by non-technical losses and demand-side inefficiencies, such as low-quality components and inefficient appliances) could push the ambitious Sustainable Development Goal (SDG) targets out of reach, especially in the context of climate-change mitigation and adaptation (IPCC, 2014; Ouedraogo, 2017).[11] Efforts to boost electricity generation in LDCs thus need to be complemented with upgrading of the T&D network. Moreover, the importance of the latter will be further amplified by progress towards universal access and structural transformation, and as increasing penetration of variable renewables increases the need for system balancing and flexibility of the supporting transmission infrastructure. This gives rise to a risk that the poor quality of existing grids might constrain the viability of some technologies, interfering with the choice of the most appropriate power generation mix.

C. Distributed generation: On the verge of leapfrogging?

1. The challenges of grid extension

Efforts to address energy poverty are inevitably shaped by the spatial dimension of the existing grid network. As discussed in chapter 1, 82 per cent of people without access to electricity in LDCs live in rural areas, where electrification rates are particularly low; and this rural predominance is likely to persist (figure 3.9). However, urbanization represents an additional challenge. Rapid increases in urban electrification rates in recent years have not matched the absolute increase in urban population, so that the number of urban dwellers without access to electricity has continued to rise. The continuation of such rapid urbanization, together with progress towards universal access, is likely to result in still greater pressure on the (already poor) T&D infrastructure, reinforcing the need for upgrading.

This twofold challenge requires a pragmatic and flexible approach integrating the deployment of electricity generation technologies with improvements to the distribution network. Given the current technological landscape, grid extension remains the primary means of satisfying LDCs' energy needs for domestic use and structural transformation. T&D networks also need to be upgraded to harness the potential benefits of utility-scale renewable technologies (IEA, 2016b).

However, the costs of grid extension increase with distance from the existing grid and sparsity of population, making extension to rural areas particularly expensive. Moreover, simultaneously increasing centralized electricity generation, and extending and upgrading grids entails considerable upfront costs, which need to be matched by demand if investments are to be viable, while demand is constrained by limited purchasing power. This represents a serious obstacle to grid extension in rural areas, especially at a scale and pace consistent with the attainment of SDG 7 and the needs of structural transformation.

2. The promises of off-grid energy systems in LDCs

Off-grid technologies are increasingly regarded as offering a cost-effective solution to the challenge of rural electrification, conducive to faster deployment than grid extension and giving rise to a leaner distributed generation model, as opposed to a centralized one (Murray et al., 2010; Szabó et al., 2011; Deshmukh et al., 2013; Harrison et al., 2016; Onyeji-Nwogu et al., 2017).[12] They also have the potential to promote greater equity and inclusiveness in electrification and ease the push factors underlying unsustainable urbanization, by allowing earlier access to electricity for rural communities and supporting the development of non-farm activities.

Off-grid energy systems, in themselves, are nothing new: diesel and gasoline generators are widely used worldwide, with an estimated installed capacity of 22.5 GW globally, two thirds of which is in developing countries (Kempener et al., 2015). However, technological advances in renewable-energy and storage technologies have stimulated renewed interest in off-grid systems, bolstered by their potential contribution to decarbonization of the power sector, including through the hybridization of diesel-based generators and the islanding of local grids (Kempener et al., 2015).[13]

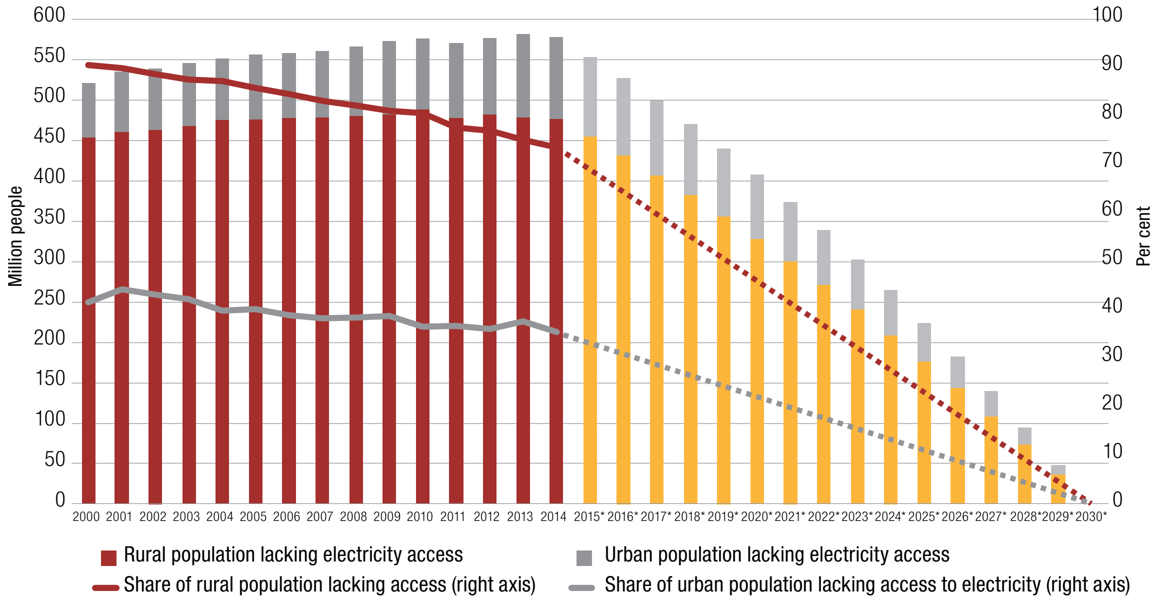
Off-grid technologies may be particularly relevant for rural electrification in LDCs

LDCs' limited urbanization and (in general) sparse rural population makes off-grid energy systems particularly relevant (figure 3.10). Beyond a certain break-even distance from the existing grid, capital costs may be lower for off-grid solutions than grid extension and conventional generators, as may operating costs, due to reduced transmission losses and potential fuel savings (Murray et al., 2010; Deshmukh et al., 2013). However, their cost-effectiveness also depends on demand, the type of load, available energy sources and technical specifications.[14] Identifying the optimal technology thus requires an in-depth analysis of the specific context, and is sensitive to assumptions on the future costs of alternative fuels, demand, load type, etc.

Despite the lack of a commonly agreed definition of off-grid technologies, they generally encompass three broad groups of technologies:

Figure 3.9

Population lacking access to electricity in LDCs by rural/urban status (2000–2014 plus forecast based on SDG 7)

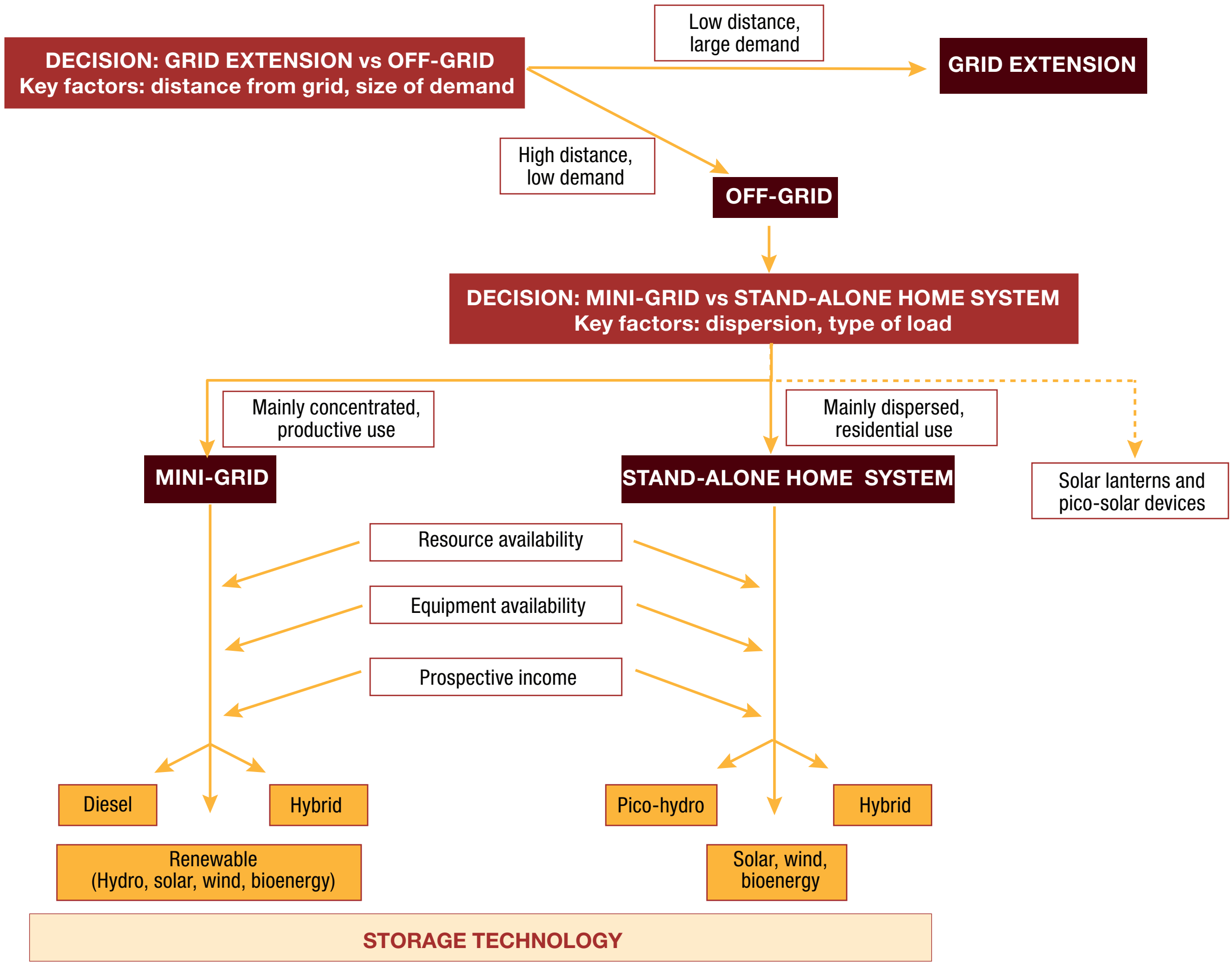


Source: UNCTAD secretariat estimates, based on data from UN DESA, Energy Statistics Database and World Population Prospects: The 2015 Revision database, and World Bank, World Development Indicators database (all accessed February 2017).

Note: * Figures after 2014 are forecasted utilizing UN DESA population projections, and assuming a linear decline in the share of rural (urban) population lacking access to electricity, consistent with the achievement of universal access by 2030. They hence take into account differential trends of demographic growth in rural and urban areas, as well as urbanization treds, as incorporated in the UN DESA population projections.

Figure 3.10

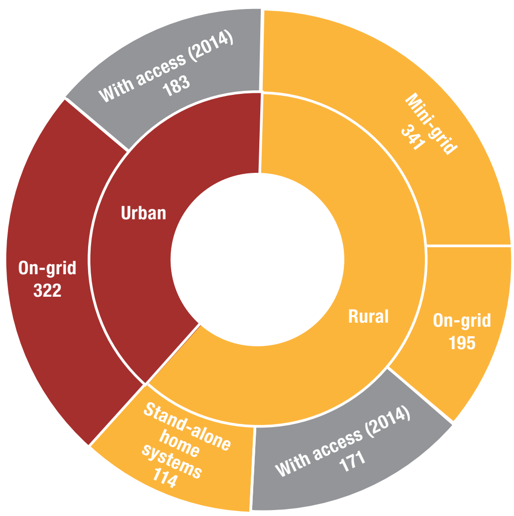
Stylized decision tree for rural electrification: On-grid vs. off-grid solutions



Source: Adapted from NORAD (2009: 3-3).

Figure 3.11

Indicative targets for LDC population gaining electricity access by 2030 (million people)



Source: UNCTAD secretariat estimates, based on data from UN DESA, Energy Statistics Database, and World Bank, World Development Indicators database (both accessed February 2017).

- *Solar lanterns and pico-solar devices*, which typically provide limited energy services (task lighting and phone charging) and often fail to meet the criteria identified by the Sustainable Energy for All (SE4All) initiative for Tier 1 energy access, but are regarded as “an important first step toward household access to electricity” (Bhatia and Angelou, 2015: 59);
- *Stand-alone systems,* consisting of a generation subsystem of small-to-medium capacity and a user’s electrical installation (e.g. solar home systems);
- *Mini-grids*, with a larger capacity (from 1 kW to 10 MW), provide centralized electricity generation and a distribution subsystem at a local level, and are capable either of operating in isolation or of being interconnected with a wider grid.

In its “Energy for All” scenario, based on universal access by 2030, the International Energy Agency (IEA) envisages that all urban populations and 30 per cent of rural populations worldwide could be connected to grids, while three quarters of the remaining rural dwellers would need to be supplied through mini-grids, and the rest through stand-alone systems (IEA, 2010). Applying these estimates to United Nations

Table 3.1

Off-grid energy systems and Sustainable Energy for All tiers for energy access

		Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Peak power capacity	Watt	-	Min. 3 W	Min. 50 W	Min. 200 W	Min. 800 W	Min. 2,000 W
	Daily supply capacity	-	Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
Availability	Hours per day	-	Min 4 hours	Min 4 hours	Min 8 hours	Min 16 hours	Min 23 hours
	Hours per evening	-	Min 1 hour	Min 2 hours	Min 3 hours	Min 4 hours	Min 4 hours
Energy services		Task light only	Task light AND phone charger	General lighting AND television AND fan	Tier 2 AND any other low-power appliances	Tier 3 AND any medium-power appliances	Tier 4 AND any high-power appliances
Typical technology			**Solar lantern**				
				Solar home system			
					Mini-grid		
					Fossil-fuel based generator		

Source: UNCTAD secretariat compilation, based on EUEI PDF (2014); Bhatia and Angelou (2015).

Statistics Division (UNSD) population forecasts for LDCs suggests that universal access by 2030 would require 571 million more people to be connected to grids and 341 million people to mini-grids, while 114 million would require stand-alone systems (figure 3.11). While these projections are only indicative, it is clear that achieving universal electricity access in LDCs by 2030 will depend heavily on both distributed generation and grid extension. As well as for countries with limited urbanization and sparsely populated rural areas, distributed generation is particularly important for small island developing States (SIDS), where off-grid systems may offer cheaper and cleaner solutions than the prevailing diesel-based generators (Dornan, 2014; Kempener et al., 2015).

While vibrant and multifaceted markets for renewable-based off-grid energy systems in LDCs have emerged only recently — apart from mini-hydro technologies, which have a more established tradition — they might have wide-ranging implications for rural electrification. The scope for off-grid technologies — notably solar ones — has been greatly increased by process and product innovations, which have driven down their costs, reduced their minimum efficient scale and are increasingly enhancing their potential for combination with appropriate storage or hybrid technologies. This has both increased the cost-competitiveness of off-grid technologies and broadened the range of technologies available to satisfy different energy needs (table 3.1).

At the low end of the spectrum, increasing penetration of solar lanterns and pico-solar devices (notably in East Africa) is allowing more people at the "bottom of the pyramid" to reach the first rung of the energy ladder (Bhatia and Angelou, 2015; Scott and Miller, 2016), while stand-alone home systems (SHSs) are emerging as a means of meeting slightly larger and more varied energy requirements, for example for low- to medium-power appliances. Increasingly, larger SHSs are also being used by community facilities, such as schools and rural health centres in unelectrified rural areas (Bhatia and Angelou, 2015).

The diffusion of these solar technologies has occurred mainly through markets, driven primarily by a sharp fall in the costs of PV modules (by 85 per cent in the last decade) and batteries, as well as a shift towards light-emitting diodes (LEDs) (Kempener et al., 2015; Orlandi et al., 2016; Scott and Miller, 2016). However, policies have also played a critical role, particularly through awareness-raising, quality-assurance programmes, grants and soft loans, and tariffs and tax reductions (Scott and Miller, 2016; Africa Progress Panel, 2017).[15]

While by no means transformational, household ownership of basic energy systems can provide meaningful savings and welfare improvements. Surveys in several LDCs suggest that solar lighting leads to significant reductions in lighting spending, lower CO_2 emissions, health benefits (especially for women and children, who typically spend more time indoors) and educational improvements (by allowing longer or more flexible study time)[16] (Grimm et al., 2014; Harrison et al., 2016; Hassan and Lucchino, 2016). They can also make some contribution to productive use, for example by allowing smallholder farmers to use ICTs, thereby improving access to market information, agricultural extension and basic financial services (UNCTAD, 2015b; Bhatia and Angelou, 2015). SHSs also play an important role for micro and small enterprises, notably in the services sector — shops, bars or hair salons — where energy requirements and needs for complementing end-use investments are typically lower than in manufacturing (Harsdorff and Bamanyaki, 2009; GIZ, 2013).[17] Larger SHSs can also be used for productive appliances, such as egg incubators, milking or sewing machines, huskers and polishers, as well as for renewable-based water pumps and irrigation systems (GIZ, 2016; Africa Progress Panel, 2017). Prior to electrification, renewable energy can be harnessed directly to diversify income sources and enhance labour productivity in non-farming activities and food processing through non-electrical technologies, such as solar tunnels for drying and evaporative refrigerators. (UNCTAD, 2015a). While the take-up of similar devices would likely be constrained by the availability of funds for end-use investments, LDCs' producers, including small and medium-sized enterprises (SMEs), might benefit significantly from harnessing the scope for technological adaptation and "frugal innovations" in the field of end-use productive technologies, including those compatible with off-grid systems (Prahalad, 2006).

A growing number of LDCs are pursuing the deployment of SHSs under rural electrification programmes, often supported by development partners, notably Bangladesh (which supports deployment with installation subsidies and credit), Rwanda (which has adopted a "rent-to-own" model) and the United Republic of Tanzania (Kumar and Sadeque, 2012; Deshmukh et al., 2013; Kempener et al., 2015). However, sustained penetration will depend on continued technological advances aimed at reducing high capital costs, space requirements and maintenance needs (IRENA, 2015; Kempener et al., 2015; Harrison et al., 2016). The availability of appropriate storage technologies and energy-efficient appliances will also be important to support SHSs for productive uses and rural non-farming activities.

Despite their undoubted welfare benefits, however, SHSs have limited effects in terms of transformational energy access, as they reach only the lowest rungs of the energy ladder. While different off-grid devices provide different levels of energy access (table 3.1), many appliances for productive use, particularly in higher value added stages of production, require medium or high power, and thus upper-tier access. Other productive uses (notably in food processing) call for a viable "cold chain", and thus reliability of electricity supply, highlighting the importance of combining variable renewables with appropriate storage and/or hybrid technologies. These considerations are in line with recent simulations on electrification options for Africa, suggesting that greater levels of energy demand — consistent with the prospects for structural transformation — move the optimal electrification option from stand-alone systems to mini-grid and to grid extensions (Mentis et al., 2017).

SHSs are also primarily suited to the energy needs of dispersed rural communities — some 11 per cent of LDCs' population in 2030, based on the IEA estimates referred to above. Survey evidence reinforces this view, suggesting that a substantial proportion of SHS owners ultimately aspire to higher tiers of electricity access (Harsdorff and Bamanyaki, 2009; Lee et al., 2016). Moreover, the development impact and sustainability of underlying business models, including energy-related microfinance and pay-as-you-go systems, deserve careful consideration (chapter 5).

Mini-grids can provide a cost-effective means of transformational energy access in remote rural areas

This highlights the importance of mini-grids, which, if appropriately designed and operated, can in principle afford a cost-effective means of transformational energy access in remote rural areas, while also enhancing system reliability, incentivizing demand-side management and generating local employment (Deshmukh et al., 2013; EUEI PDF, 2014; Kempener et al., 2015). This can promote rural development, by addressing a key constraint to the development of non-farming activities (UNCTAD, 2015a) and stimulating investment in rural electricity provision, as well as supporting a transition towards a low-carbon growth path.[18]

Looking ahead to 2030, mini-grids are therefore likely to play a more prominent role in LDCs' rural electrification, echoing the historical experience of developing countries such as China and India, where diesel- and hydro-based mini-grids have long been deployed in rural areas. These experiences also highlight the potential of mini-grids to pave the way towards grid extension, through interconnection and progressive integration into the national system (Deshmukh et al., 2013; Kempener et al., 2015). Mini-grids may be particularly important in mountainous countries and archipelagos (Sovacool et al., 2011; Dornan, 2014).

However, the smooth deployment of mini-grids on the scale required for universal access in LDCs is hindered by financial, technical, economic and institutional obstacles. First, as discussed in chapter 5, their large upfront costs make the availability of financing critical, particularly in the early phases of their roll-out, often making deployment dependent on grants or soft loans from national or international sources (EUEI PDF, 2014; Deshmukh et al., 2013). Second, the design of mini-grids needs to be tailored to site-specific

Box 3.2 **Lessons from Micro-Hydro Village Electrification in Nepal**

Started in the early 2000s, with the long-term financial support of large institutional donors, Nepal's Micro-Hydro Village Electrification (MHVE) programme has emerged as a successful scheme for scaling up the deployment of mini-hydro systems. Building on the earlier Rural Energy Development Programme of the United Nations Development Programme (UNDP), the MHVE aimed at deploying community-based micro-hydro systems ranging from 10 kW to 100 kW. Project implementation was decentralized to local governments, District Development Committees and Village Development Committees setting up Micro-hydro Functional Groups in each targeted community. By 2014, more than 1,000 micro-hydro systems had been installed, with total generating capacity of 22 MW, providing off-grid electricity access to 20 per cent of the population.

Researchers and practitioners have proposed drawing the following lessons from this experience:

Sound design of mini-grid specifications and technical standards play a key role in fostering the adoption of locally appropriate technologies matching the scale of local demand.

Robust monitoring frameworks are needed to ensure that appropriate technical standards are met and maintenance and aftersales services regularly provided.

Strong emphasis is warranted on capacity development, including activities to improve the local provision of maintenance and aftersales services (backward linkages), and to stimulate demand for energy services through productive end-uses (forward linkages), so as to embed energy projects in the local economic fabric.

Commitment to long-term cost-recovery is important for sustainability, including effective revenue collection and promotion of efficiency-enhancing technologies (hybridization, smart load limiters, energy-efficient appliances, etc.).

Clear determination of the roles of different stakeholders, and focus on institution-building components, is fundamental, to deal promptly with unforeseen circumstances, ensure social acceptance of the business model and foster a strong involvement of targeted communities. Credible long-term policy commitment, with flexible approach to implementation and reduced administrative burdens, is essential to sustaining mini-grid deployment.

Source: Sovacool et al. (2011); Gurung et al. (2012); EUEI PDF (2014); http://www.worldbank.org/en/news/feature/2015/09/26/ensuring-sustainable-rural-electrification-in-nepal.

conditions, notably resource potential (for hydro and variable renewables) or fuel-supply conditions[19] and the dynamics of demand and load profiles, so as to optimize generation and storage capacities and ensure high-quality electricity provision. In this respect, the availability of a potential anchor load — i.e., a consumer of a large and possibly stable proportion of the power generated (for instance a small factory, hospital or farmer cooperative) — supplementing households' electricity demand is usually critical to support mini-grid profitability and increase capacity utilization. Third, higher tariffs than what corresponding on-grid consumers pay have often resulted from the pressure to cope with relatively low capacity factors, substantial sunk costs, costly maintenance and revenue collection. In addition to generating grievances and pressure to be connected with the central grid, this has typically raised equity concerns and issues of cross-subsidization.[20] Fourth, given the long-term nature of mini-grid investments, regulatory uncertainty and lack of transparent planning for grid extension tend to deter mini-grid developers. This aspect, coupled with the need for community involvement and mobilization, has often generated complex institutional challenges, resulting in the lack of a proven and easily replicable business model for mini-grid installation and operation (Deshmukh et al., 2013; Africa Progress Panel, 2017).

Notwithstanding the above challenges, country experiences in mini-grid deployment, including in LDCs, offer ample scope for mutual learning and experience-sharing (box 3.2). They also point to a huge scope for South-South cooperation in stimulating technology transfer and adaptation to context-specific realities.

3. Key considerations in a changing technological landscape

The previous two sections have highlighted two mutually supportive trends with the potential to shape rural electrification in LDCs: the surge in distributed generation, and technological advances in renewable-based generation. These trends can be expected to continue, as innovations and learning effects continue to push down the cost of renewable electricity technologies and facilitate their deployment. Moreover, the modularity of renewable off-grid technologies suggests that an incremental approach to their deployment is at least feasible, and arguably desirable.

However, the parallels sometimes drawn between distributed generation and the "ICT revolution" that allowed the rapid penetration of mobile telephony in the developing world appear premature. While it has expanded significantly, the market for larger off-grid energy systems in LDCs remains limited, and is largely dependent on external support from development partners, philanthropic organizations and public utilities. Equally, while the penetration of smaller-scale off-grid systems appears to have occurred relatively smoothly in some LDCs, the diffusion of more transformational higher-power technologies such as mini-grids still faces a number of important challenges.

There is also some ambiguity as to whether off-grid solutions are an *alternative* to the main transmission grid, indicating a complete leapfrogging akin to that witnessed in the ICT sector, or a *stepping stone* towards grid extension. This is a critical issue, as it gives rise to potential tensions and time inconsistencies between support for off-grid solutions and grid extension. For potential mini-grid operators, the prospect of future competition with on-grid electricity providers with different cost structures might be a significant deterrent to investments that entail substantial sunk costs. This highlights the importance of transparency and integrated planning of grid extension and mini-grid deployment, and of appropriate regulatory frameworks, so as to avoid discouraging private investors and ensure the viability of an incremental approach.

With appropriate planning, mini-grids can be integrated into larger networks rather than being supplanted by them, on the one hand supplying electricity to the larger national grid, and on the other enhancing system reliability by preserving the capacity to operate in isolation during central grid failures. While the experiences of China, India and Nepal suggest that this option is technically viable (Deshmukh et al., 2013), it requires appropriate guidelines, including consistent technical standards and protocols for grid interconnection. Another modality is that adopted in Cambodia, where a consolidated licence provided by the national regulator allows mini-grid operators to play a small distribution role in the event of central grid extension by the public utility.

Although it has as yet received less attention, an analogous tension would appear possible between the widespread use of SHSs and the development of mini-grids (or potentially grid extension). Households with SHSs may have little incentive to purchase electricity from a mini-grid, particularly where this also entails a connection charge; and this could potentially reduce prospective demand below the minimum efficient scale for investment to be viable. While SHSs may be necessary in the context of dispersed settlement patterns, their widespread adoption in villages might thus prove an impediment to the subsequent development of mini-grids, which are likely to provide a more sustainable and lower-cost means of ensuring transformational energy access and satisfying growing electricity demand.

This highlights the importance of a carefully planned and forward-looking approach to increasing electricity access. Planning and coordination are needed between mini-grid development and grid extension, to ensure appropriate prioritization of investments, to avoid deterring potential investors, and to allow mini-grids to be interconnected and/or integrated into an overall grid as appropriate at a later stage.

While the whole array of off-grid technologies offers considerable potential for LDCs, harnessing the opportunities they provide will thus require a stepped-up policy effort and long-term policy commitment, including transparent and forward-looking plans for grid extension, and clear strategic guidelines to ensure the adoption of compatible technology standards. In light of the pace of innovation in the energy market, this calls for a flexible approach that avoids locking in particular technological solutions that may be inappropriate to the country's needs in later years. It will also require a proactive policy framework that supports and facilitates a gradual technological upgrading process, by:

- Leveraging the regulatory framework to promote the adoption of appropriate technological standards;
- Emphasizing capacity development, both for grid developers and operators and for end-users, whose behaviour can strengthen the energy system value;
- Harnessing the scope for both North-South and South-South cooperation and technology transfer, and favouring experimentation and diversification across energy sources;
- Preserving an integrated approach to energy policies.

Regardless of how rural electrification is achieved, however, experience warns against naïve presumptions about its impact on productive activities. By shaking up traditional business practices, rural electrification can provide significant new opportunities for economic diversification into non-farming activities, with knock-on effects on employment, productivity and value addition. In the short run, however, it is likely to give rise to a process of "creative destruction", with winners and losers, according to the energy requirements and intensity of each business, the availability of alternative energy sources and the need for complementary investment in end-use devices (GIZ, 2013). Moreover, the impact of electricity on enterprise profitability is subject to other bottlenecks, for example in transport infrastructure, market access and formalization, as well as depending on the adequacy of local demand (GIZ, 2013; UNCTAD, 2015a). This highlights the need for complementary policies and integration of electrification strategies into wider development strategies (chapter 6).

D. Towards a systemic approach to the electricity sector

The portfolio of technologies deployed for electricity generation, distribution and even end-use devices have wide-ranging implications for a country's power generation mix, electricity costs and power-sector performance. Appropriate technology choices therefore play a critical role in structural transformation, by allowing transformational energy access and providing suitable, reliable and affordable energy services to enhance labour productivity and foster the emergence of higher-value added activities and the diffusion of ICT. This further underlines the importance of mutually supportive development and energy policy frameworks, as the path dependence resulting from investments in energy-related infrastructure gives rise to a risk of technological lock-in, unless the dynamics of structural transformation and future energy needs are duly accounted for. In this context, while some elements of irreversibility are inevitable — since the life cycle of generating technologies spans between 20 and 60 years — risks of technological lock-in can be minimized, inter alia, by adopting a forward-looking approach to future needs against which to assess the appropriateness of the technology, leveraging modularity/scalability, allowing for easy retrofit options and ensuring interoperability. Equally, the systemic interdependence of different energy systems underscores the need for a systemic approach to the electricity sector, and related planning.

Harnessing the potential of off-grid technologies requires long-term policy commitment and integrated approach

1. Resource potential and cost-effectiveness of energy technologies

The choice among alternative energy systems is determined primarily by their relative cost-competitiveness, which depends on the interaction between energy resource potential and the technical performance of each technology. Quantifying resource

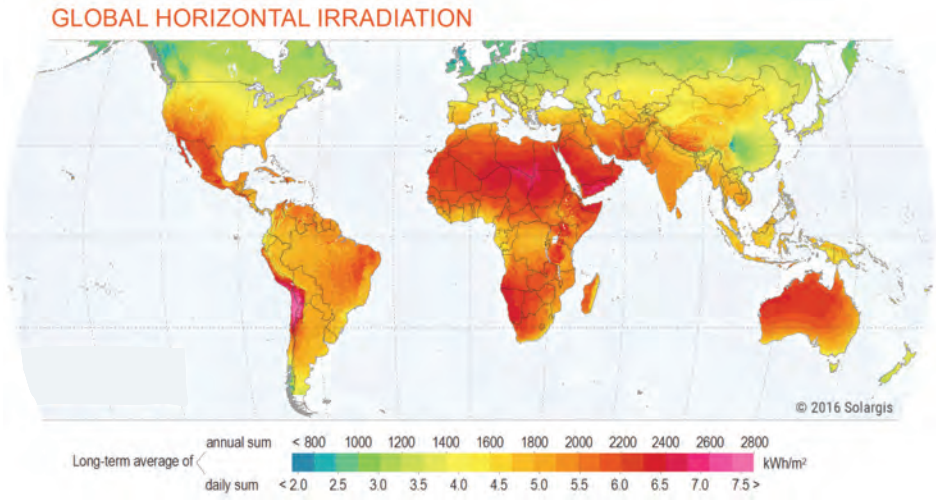
Tabe 3.2

Proven reserves of selected fossil fuels in LDCs, 2016 (estimates unless otherwise stated)

	Natural gas		Crude oil		Coal*			
					Hard Coal		Lignite	
	Million cubic meters	Share of world total (per cent)	Million barrels	Share of world total (per cent)	Million tonnes	Share of world total (per cent)	Million tonnes	Share of world total (per cent)
Mozambique	2 832 000	1 44	-	-	1.79	0.26	-	-
Yemen	478 500	0 24	3 000	0.18	-	-	-	-
Angola	308 000	0 16	8 400	0.50	-	-	-	-
Myanmar	283 200	0 14	50	0.00	3	0.00	3	0.00
Bangladesh	233 000	0 12	28	0.00	293	0.04	-	-
Timor-Leste	200 000	0 10	-	-	-	-	-	-
South Sudan	63 710	0 03	3 750	0.22	-	-	-	-
Rwanda	56 630	0 03	-	-	-	-	-	-
Afghanistan	49 550	0 03	-	-	66	0.01	-	-
Mauritania	28 320	0 01	20	0.00	-	-	-	-
Ethiopia	24 920	0 01	0	0.00	-	-	-	-
Sudan	21 240	0 01	5 000	0.30	-	-	-	-
Uganda	14 160	0 01	2 500	0.15	-	-	-	-
Senegal **	9 911	0 01	-	-	-	-	-	-
United Rep. of Tanzania	6 513	0 00	-	-	269	0.04	-	-
Somalia	5 663	0 00	-	-	-	-	-	-
Madagascar **	2 010	0 00	-	-	-	-	-	-
Benin	1 133	0 00	8	0.00	-	-	-	-
Dem. Rep. of the Congo	991	0 00	180	0.01	88	0.01	-	-
Chad ***	-	-	1 500	0.09	-	-	-	-
Niger ***	-	-	150	0.01	-	-	6	0.00
Nepal	-	-	-	-	1	0.00	-	-
Malawi	-	-	-	-	2	0.00	-	-
Lao People's Dem. Rep.	-	-	-	-	4	0.00	499	0.17
Central African Rep.	-	-	-	-	-	-	3	0.00

Source: UNCTAD secretariat calculations, based on World Energy Council (2016); CIA (2016).
Notes: * All data for coal reserves are based on 2014 estimates. ** Data for natural gas proven reserves are based on January 2012 estimates.
*** Data for natural gas proven reserves are based on January 2014 estimates.

Figure 3.12
Solar irradiation map



Source: http://solargis.com/assets/graphic/free-map/GHI/Solargis-World-GHI-solar-resource-map-en.png

potential is inherently complex, and the existing mapping of the various energy resources is far from exhaustive or accurate. Nonetheless, an increasing body of research highlights LDCs' abundant and largely untapped potential, spanning a wide spectrum of energy sources (Gies, 2016; UNEP, 2017).

With respect to fossil fuels, LDCs account for approximately 2.3 per cent of worldwide proven reserves of natural gas, 1.5 per cent of oil reserves, and 0.3 per cent of coal reserves (table 3.2).[21] However, these endowments are unevenly distributed, only about half of LDCs having any proven fossil-fuel reserves, while many others (notably most island LDCs) depend on imports. Import dependence for electricity generation is not only rooted, however, in natural resource endowments, but often also in the weakness of the refining and transformation sector further down the energy value chain (chapter 2). Besides, there appears to be significant scope to shift from emission-intensive fuels, such as coal and oil, towards natural gas for generation in a number of LDCs.

Evidence on renewable-energy potential should be treated with caution, as its quantification is complicated by spatial and technical-performance considerations. However, the available evidence suggests that LDCs could in principle harvest enormous amounts of power from renewable sources, potentially relaxing the energy constraints imposed by fossil fuel scarcity (Africa Progress Panel, 2015; Gies, 2016; UNEP, 2017). Africa, for example, has enormous renewable-energy potential, only a fraction of which is currently utilized (UNEP, 2017). Solar — the most abundant energy source in most LDCs — epitomizes this paradox. The shift towards solar electricity in LDCs is barely incipient despite much greater horizontal irradiation in most LDCs than in countries such as China or the United States with much stronger solar sectors (figure 3.12).

Several programmes, such as the Renewable Energy Resource Mapping Initiative of the Energy Sector Management Assistance Program (ESMAP) and IRENA's Global Atlas for Renewable Energy, have recently been established to assist countries in accurately mapping their resource potential as a basis for future investments. Resource potential, however, is only one side of the coin; technological advances are equally important to technology choices, not only by changing the relative efficiency of alternative energy systems, but also by potentially allowing the exploitation of previously unviable resources.

One of the most widely used metrics for cost comparison across different power-generating technologies is the levelized cost of electricity (LCOE), which represents the minimum price of electricity consistent with a given project breaking even financially over its expected lifetime.[22] However, it requires detailed knowledge of the energy sector and context, is sensitive to a set of underlying assumptions, and is generally limited to private costs (investment expenditures, operations and maintenance, fuel and decommissioning if applicable) (IRENA, 2016a). The limitation to private costs has the advantage of being very transparent in terms of the underlying assumptions, and relatively easy to understand and apply to a wide array of technologies in different contexts. However, it might be inadequate to capture all relevant dimensions, from a societal point of view.

Global LCOE trends indicate a marked improvement in the cost-competitiveness of renewable-based generation technologies since 2010, converging with conventional fossil-fuel generation (figure 3.13). This reflects technological advances in solar (and to a lesser extent onshore wind), improving technical efficiency, coupled with increasing scale economies in upstream activities. Further economies of scale and learning effects are expected to reduce costs further, according to one estimate by 59 per cent for solar PV and 26 per cent for onshore wind by 2025 (IEA, 2016b; IRENA, 2016a).[23] Other technologies, such as solar thermal and offshore wind, also have significant potential for learning effects, although this depends on their wider deployment.

Despite the increasing competitiveness of renewables globally, it is important to note the very wide variation in LCOE estimates across contexts. This implies that competitiveness advances at the global level do not automatically translate into improved competitiveness in a particular location. It should also be noted that LDCs often face particular challenges in adopting the most efficient technologies, especially where these require complex and information technology (IT)-intensive support infrastructures.

Moreover, LCOE computation is inevitably sensitive to key assumptions related to:

- Technological performance;
- Expected prices for fuels and other costs;
- Weighted average cost of capital;
- Pricing mechanisms for environmental externalities (when applicable).

While the soundness of technical assumptions can be validated only on a case-by-case basis, the sensitivity of the LCOE to the three other sets of assumptions requires greater consideration by policymakers. First, since many LDCs depend on fossil-fuel imports for their power generation, uncertainties related to future

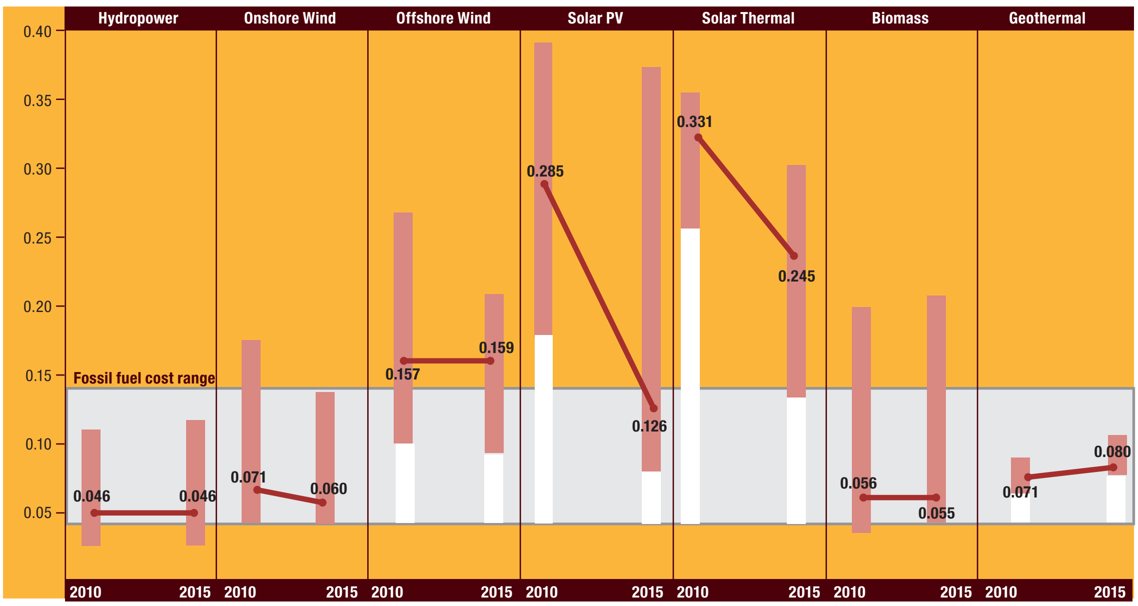
Generation mixes should reflect sustainability, inclusivity and structural transformation concerns as well as cost effectiveness

fuel prices are compounded by those concerning exchange-rate fluctuations. Consequently, technology choices may also have broader macroeconomic implications, which are not reflected in the LCOE calculation. Second, the choice of interest rate – which is typically assumed to be higher in LDCs, to account for tighter financing conditions and greater risks – has profound implications for the LCOE of capital-intensive technologies, notably renewables. With a higher interest rate, a larger capital expenditure implies greater upfront financing costs, while the effect of fuel savings throughout a plant's life cycle tapers off quickly because of discounting. Third, accounting for both localized and global externalities is essential if the LCOE is to reflect sustainable development concerns fully (i.e. the social cost); but, as seen above, it is debatable whether environmental costs are appropriately internalized and evaluated.[24]

Indicative figures for the LCOE across main technologies are provided, by cost element, in box 3.3 (baseline), along with two examples of the sensitivity of the computation to the above considerations. This highlights the critical importance of sensitivity analysis in the interpretation of the LCOE.

Figure 3.13

Worldwide trends in levelized cost of electricity, 2010–2015 (Ranges and capacity-weighted average)



Source: IRENA Renewable Energy dashboard, http://resourceirena.irena.org/gateway/dashboard/?topic=3&subTopic=33.

Even aside from these considerations, “a static analysis of LCOEs of different power generation technologies alone cannot identify their optimal role… in a country’s energy mix” (IRENA, 2016a: 24). While its exclusive focus on private costs is in line with private investment decisions, it neglects key policy issues, including (unpriced) environmental externalities, system-wide considerations (notably the time profile of generation) and energy security. Energy-security concerns underline the importance of attention to resource endowments and geographical factors as well as the relative climate resilience of different energy sources (highlighted by the slump in hydro-based electricity generation following the 2016 drought in Southern Africa).

Policy decisions related to the generation mix thus need to go beyond narrow cost-effectiveness criteria to encompass the full range of sustainable-development considerations, including sustainability, inclusivity and structural transformation.

2. System-wide considerations

While different generating technologies may be alternatives at a project level, a systemic perspective requires attention to their interactions and complementarities, given their different time profiles of generation, location, cost structures and resilience to shocks. Such considerations are essentially ignored in LCOE metrics (IEA, 2016c). Anticipating growing complexity as systems develop, and enhancing system flexibility from the planning and design phases for newly built electricity infrastructure, could offer significant leapfrogging opportunities to LDCs, by reducing the need to retrofit existing infrastructure (Welsch et al., 2013).

Electricity demand (load) needs to be continuously matched with supply in real time to avoid outages and load shedding. This requires sufficient generating capacity to serve peak demand, while leaving part of this capacity idle in off-peak periods. Some generating technologies, notably gas- and oil-based generators and hydro plants, are better able than others to vary output according to demand fluctuations. Under appropriate topological conditions, hydro plants can be combined with additional reservoirs for pumped hydro, thereby allowing energy from other sources to be stored.

The roles of different technologies in matching supply with demand can be illustrated by a typical daily electricity supply curve from the Bangladeshi grid operator (figure 3.14), which shows the use of oil-

Box 3.3. An illustration of the levelized cost of electricity from a societal perspective

This box presents an indicative illustration of the distinctive cost structures of the major power generation technologies from a societal perspective, and their implications for LCOE computation in the face of apparently “technology-neutral” changes in the underlying assumptions, using the Danish Energy Agency’s Levelized Cost of Energy calculator (Danish Energy Agency, 2016).[a] In line with a societal approach, relevant cost elements encompass system costs, air pollution and climate externalities, in addition to the private cost elements included in the LCOE. The latter elements comprise other costs (i.e. decommissioning), fuel costs, operation and maintenance costs, and capital costs. The underlying data, based on typical values for generic international power production plants, allow LCOE computation for seven different technologies: coal (with and without flue gas desulphurization), combined cycle gas turbine, nuclear, solar PV, wind and biomass. Unless otherwise stated, the default settings are applied (box figure 3.2).

A comparison of the different technologies in the baseline scenario highlights three important considerations.[b] First, accounting for environmental externalities (“air pollution”, mainly of SO2, NOx and PM2.5, “climate externalities” in the form of GHG emissions and “other costs”, including radioactivity) significantly alters the cost comparison across different technologies, especially for coal-based generation. Second, solar- and wind-based generation (and to a lesser extent nuclear) are characterized by relatively high capital expenditure, with negligible marginal operating costs. Third, unlike fully controllable technologies, variable renewable technologies have positive system costs, reflecting the need to balance their variable temporal profile and enhance grid flexibility. These costs increase with the unpredictability of the energy source, so are higher for wind than for solar.

The second scenario features higher prices for fuels and CO2, consistent with a maximum global temperature increase of 2°C.[c] This has significant effects on combustible fuels technologies, increasing the LCOE for coal-based generation sharply, due to its high emission intensity, and to a lesser extent for natural gas and biomass. These results underscore the extreme sensitivity of the relative LCOEs of renewable and fossil-fuel technologies to accounting for fuel costs and environmental externalities.

The third scenario repeats the baseline scenario, but raising the weighted-average cost of capital of 10 per cent, to reflect LDCs’ tighter financing conditions. While this increases the LCOE across all technologies, the rise is much greater for solar PV, wind, biomass and nuclear, reflecting their greater capital intensity.

a The LCOE Calculator modelling tool is available at no charge at: https://ens.dk/en/our-responsibilities/global-cooperation/levelized-cost-energy-calculator.

b The baseline scenario applies the default settings, including fuel prices consistent with the “2015 new policies scenario”, and a 4-per-cent weighted-average cost of capital.

c This corresponds with the “450 ppm” fuel and CO2 price scenario, all other parameters remaining at their default values.

Box 3.3 (contd.)

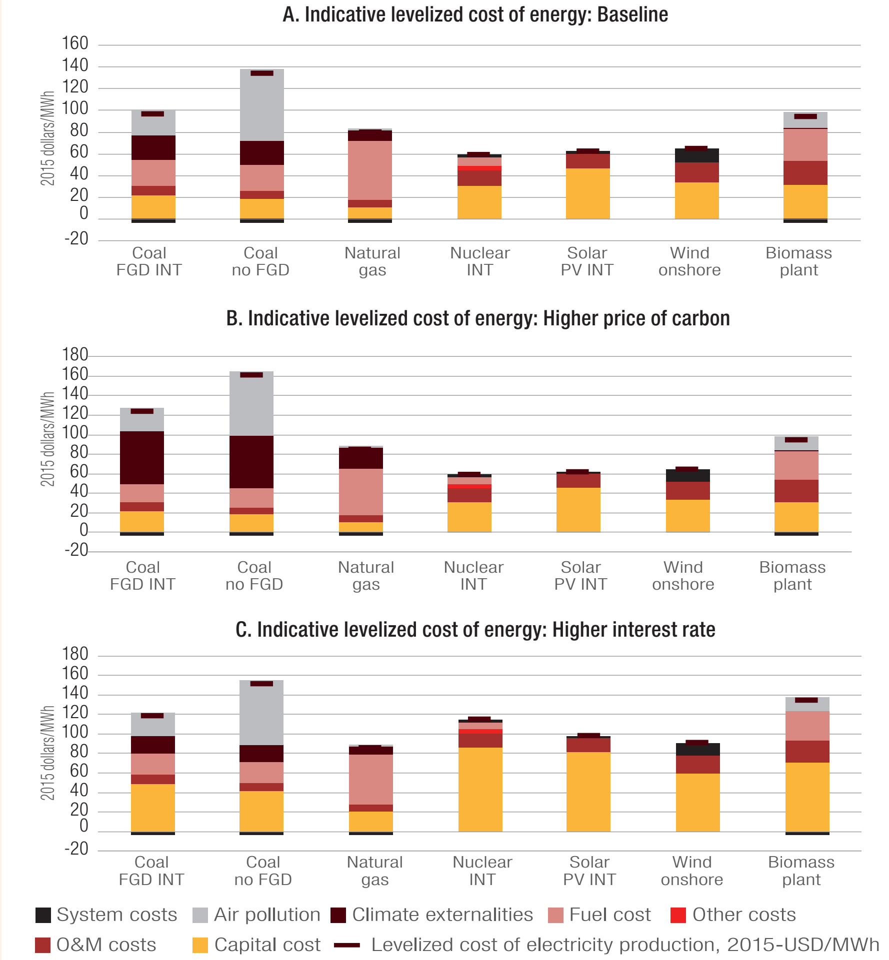
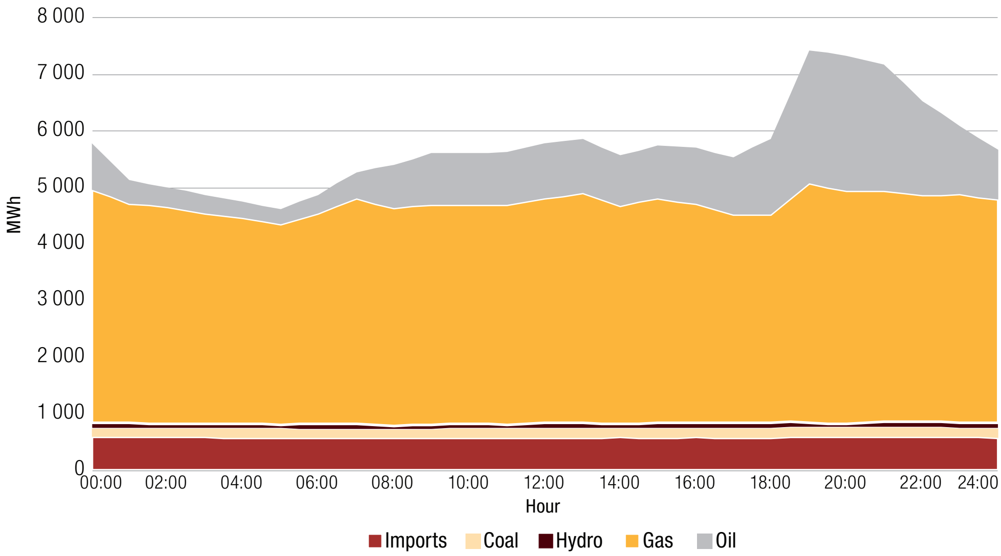


Figure 3.14

Typical daily electricity supply curve in Bangladesh, 13 March 2017



Source: UNCTAD secretariat estimates, based on the operational daily report by the Power Grid Company of Bangladesh Ltd., https://www.pgcb.org.bd/PGCB/?a=user/home.php (accessed May 2017).

based power generation for peak load, while other technologies complemented by imports provide the baseload.[25] While daily supply curves and power generation mixes vary widely across countries and seasons, this example highlights the crucial importance of rapidly dispatchable peak-load capacity and/or storage, in order to match the time-varying profile of electricity demand.[26] The need for such system flexibility is likely to become even more pronounced in the future, with an increasing penetration of variable renewables.

Furthermore, the distinct cost structures of the various technologies (illustrated in box 3.3) will gradually play a deeper role in LDCs' energy markets, as the integration of variable renewables – nowadays largely off-grid – will advance; and such a development could create additional challenges for LDC grid operators. The negligible marginal costs of solar and wind generators, once installed, means that they can outcompete centralized conventional plants, especially if they are located close to users (as in mini-grids operating in "islanding mode"). However, while this could help to reduce overall electricity prices and foster greater access, the partly unpredictable fluctuations of solar and wind generation may result in additional ramping costs and lower capacity factors for conventional backup generators (Boccard, 2010; IEA, 2016a). As the penetration of variable renewables increases, system flexibility thus plays a more and more fundamental role in supporting the decarbonization of the power sector, while limiting price fluctuations.

These issues may appear somewhat distant for LDCs, given the generally limited role of non-hydro renewables in grid generation; but anticipating such systemic challenges and fostering the emergence of a diversified and flexible electricity system is important to smooth and sustainable development of the sector. Past energy transitions highlight the critical importance of technological interrelatedness and infrastructure needs in supporting the widespread adoption of innovative technologies for energy supply (Grubler, 2012; Sovacool, 2016). Fully exploiting the potential of technological innovations in renewable energy and storage involves the co-evolution of the energy demand (end-use) and supply systems; and this requires a systemic approach to energy policy, geared towards transformational energy access.

From an LDC perspective, this suggests four priorities. First, once the initial phase of technological experimentation has been completed, LDCs could reap significant benefits from becoming "early followers", adopting advanced energy technologies to the extent possible.[27] As energy transitions typically take several decades, accelerating technology diffusion from the "core" (early adopters) to the "rim" (early followers) and "periphery" (late adopters) could minimize the risk of locking in less efficient technologies (Lund, 2010; Grubler, 2012).

Second, diversifying the power generation mix, while taking account of each country's resources and comparative advantages, is essential to system resilience. Progressive investment in appropriate renewable and hybrid technologies could thus help to redress LDCs' dependence on a narrow range of energy sources (figure 3.3), as well as exploiting complementarities across different technologies.[28] Geographical diversification may also help to smooth output variability in the case of wind, and to a lesser extent solar (IEA, 2016c).

Third, strengthening grid flexibility and upgrading monitoring and control capabilities, to ensure interoperability and manage the increasing complexity of power flows, could offer considerable opportunities for leapfrogging (Welsch et al., 2013; IEA, 2016a). However, it would also entail significant investment costs, and take considerable time, especially in light of the ICT-intensive nature of "smart grids". Interconnection of electricity network infrastructures internationally could further promote diversification (chapter 4), especially where resource potential and technological portfolios are complementary (Africa Progress Panel, 2015; IEA, 2016c).

Finally, systemic approaches to electricity markets in LDCs need to address the role of energy-efficiency practices and demand-side management (IPCC, 2014; Ouedraogo, 2017). The greater capital stock in downstream and end-use sectors than in generation highlights the need for a bottom-up, design-driven approach to end-use technologies (Grubler, 2012).

E. Scope and challenges for energy technology transfer

As recognized by the international community (e.g. in the 2030 Agenda and the Istanbul Programme of Action), access to technology is a fundamental enabler of LDC structural transformation; and facilitating the development and transfer of environmentally sound technologies is a key pillar of the global fight against climate change (under UNFCCC and its Technology Mechanism, Technology Transfer Framework and Poznan Strategic Programme on Technology Transfer). Thus, technology transfer is essential to the achievement of SDG 7.

Of the four main channels for technology and knowledge transfer (trade, foreign direct investment (FDI), licensing and labour mobility), trade is by far the most relevant to energy-related technologies. The expansion of LDC electricity generating capacity over the past 20 years has been reflected in a major increase in imports of generating machinery and equipment and of electrical end-use machinery and appliances (figure 3.15). Around half of LDCs' imports of power-generating machinery and 70 per cent of electrical end-use machinery and appliances are from ODCs, highlighting the growing importance of South-South trade as a vehicle for energy-related technology transfer. While China has been the main driver, increasing its market share spectacularly since the mid-2000s, several other ODCs are also involved, especially for end-use appliances.[29]

Burgeoning trade flows confirm the dynamism of investment in LDC energy sectors, but assessing the effectiveness of technology transfer is much more complex. The process of technology transfer encompasses not only the "discovery" of the technology, but also the acquisition of related knowledge and capabilities and viable economic application of the

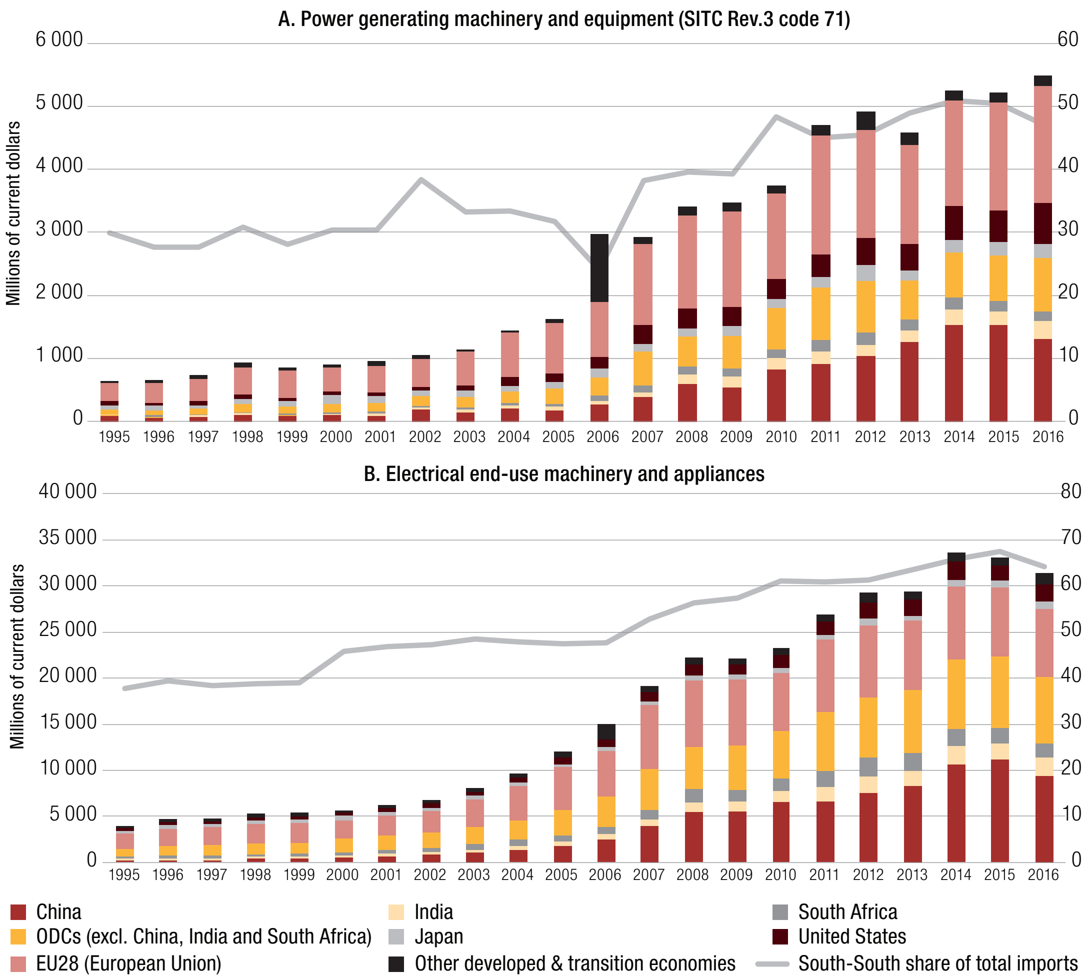
South-South trade is an important means of energy technology transfer to LDCs, but local absorptive capacities need to be strengthened

discovery in the recipient country's context (UNCTAD, 2011a, 2014b). From this perspective, technology-transfer measures in favour of LDCs have a rather inadequate track record, reflecting vague and non-binding formulation, lack of adequate funding, fragmentation and limited political will (UNCTAD, 2016b).

Local absorptive capacities and innovative capabilities are thus particularly critical in the energy sector, given its complexity and the importance of context-specific conditions to technology design, its integration in the broader electricity system and the viability of

Figure 3.15

LDC imports of electricity-related capital goods, by origin, 1995–2016



Source: UNCTAD secretariat estimates, based on data from UNCTAD, UNCTADstat database (accessed June 2017).

Notes: The SITC Rev. 3 items considered as a proxy for electrical end-use machinery and appliances include chapters 72 to 77, excluding those items which are non-electric or explicitly related to transport, namely 722, 723, 744, 745, 746, 747 and 748.

the underlying business model. However, LDCs have relatively weak local innovation systems, reflecting their structural vulnerabilities (UNCTAD, 2014b). Despite overall improvements in secondary and tertiary enrolment ratios, skilled workers with science, technology, engineering and mathematics backgrounds remain scarce, women being particularly underrepresented (UNCTAD, 2011b). Moreover, LDCs invest barely 0.3 per cent of GDP in research and development (R&D) activities, and only one tenth of this in engineering and technology.[30]

This highlights the need for:

- A strong emphasis on capacity development in the design, implementation and monitoring of energy-related projects;
- A robust science, technology and innovation (STI) policy framework, ranging from use and adaptation to technology production and innovation;
- Greater involvement of local universities and research institutions in energy-related activities;
- Concerted efforts to promote experience-sharing, mutual learning and regional collaboration in energy-related research.[31]

F. Conclusions

Achieving sustainable structural transformation and universal access to modern energy by 2030 will require a momentous increase in LDCs' power generation, faster than the expansion witnessed over the past 20-25 years. Relative to 2014, LDCs' combined electricity generation needs to be scaled up by a factor of between 3.4 and 6.8 to be adequate for productive use, and by a factor of 13.5 to meet modern energy needs.

Meeting this challenge will require harnessing all available energy resources and technologies, according to local circumstances, coupled with energy efficiency measures, especially to upgrade grids and reduce transmission losses. As well as reflecting local endowments and resource potential, the energy mix should evolve in such a way as to kick-start the structural transformation process, while maximizing the development opportunities within the energy value chain. If complementarities across technologies are effectively harnessed, the wider range of options for grid-connected generation offered by the increasing competitiveness and technological improvements in non-hydro renewables could foster more diversified, more reliable, and less import-dependent electricity systems, with additional benefits for the national economy and energy security. While fossil-fuel-based generation is likely to play a continuing role where substantial sunk costs have already been incurred and in countries with significant reserves, a progressive move towards renewable technologies could offer substantial development opportunities as well as environmental co-benefits.

In rural areas, while grid extension still has a role to play (especially in view of the higher demand resulting from structural transformation), the emergence of off-grid technologies has the potential to accelerate electrification. In this respect, the modularity of off-grid renewable technologies makes them particularly suitable to incremental deployment. Renewable and hybrid off-grid solutions can also contribute to diversification of LDCs' power generation mix, system reliability and energy security.

However, in contrast with the relatively smooth roll-out of small-scale off-grid systems in some LDCs, the deployment of mini-grids still faces a number of technical, economic and institutional challenges. Moreover, the ambiguity as to whether off-grid solutions represent an alternative to, or a stepping stone towards, grid extension gives rise to potential tensions and time inconsistencies between support for off-grid solutions and grid extension, which would be more conducive to more sophisticated productive uses of energy.

These circumstances highlight the need for a systemic approach to the energy sector, exploiting the synergies and complementarities between technologies and energy sources in support of structural transformation, while maintaining flexibility to respond to rapidly evolving technologies and cost structures and avoiding locking in technologies that may prove inappropriate as structural transformation proceeds. This includes a carefully planned and forward-looking approach to transformational energy access, including transparent plans for grid extension, with clear strategic guidelines to ensure the early adoption of mutually compatible standards to allow mini-grid interconnection as appropriate at a later stage; a proactive policy framework that supports and facilitates progressive technological upgrading; and conducive STI policies, fostering a greater involvement of local research institutions in efforts towards adaptation and innovation in energy technologies and their wider use.

Notes

1 United Nations Statistics Division (UNSD) data comprise under the label "combustible fuels" all fuels that can be ignited or burnt, hence fossil fuels (oil, coal and natural gas) but also bioenergy products such as biofuels, biogas, agricultural waste, wood, charcoal, etc. While a detailed breakdown of the electricity generated from each fuel is unavailable (partly due to the possibility of "cofiring", i.e., using different fuels in the same plant), this can be estimated on the basis of country-level data on fuel inputs and their corresponding efficiency. Box 3.1 provides some basic explanations of the main features of various combustible fuel technologies.

2 Data limitations are particularly acute in relation to non-hydro-renewable technologies due to their use in off-grid energy systems, which are more difficult to monitor.

3 Available at http://www.world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx (accessed September 2017).

4 Due to limitations in UNSD data coverage of renewable off-grid energy systems, this subsection uses data from the International Renewable Energy Agency (IRENA).

5 Afghanistan, Bangladesh, Bhutan, Burkina Faso, Cambodia, the Comoros, Democratic Republic of the Congo, Ethiopia, the Gambia, Haiti, Kiribati, Madagascar, Malawi, Nepal, the Niger, Rwanda, Senegal, South Sudan, the Sudan, Timor-Leste, Tuvalu, the United Republic of Tanzania, Vanuatu and Yemen.

6 Box 3.1 provides some basic explanations of the main features of different generating technologies.

7 Solar and wind technologies are often jointly referred to as variable renewables, because of the fluctuating nature of their output.

8 Equally, no LDC has yet sought to deploy marine power, suggesting that LDCs tend to prioritize commercially viable technologies over less mature alternatives whose success requires greater research and development.

9 Notwithstanding the lack of a universal definition of "utility scale", the expression typically refers to large-scale projects (often with a capacity of 10 MWe or larger), to be connected to the national grid.

10 Benin, Burkina Faso, Cameroon, Cape Verde, Kenya, Madagascar, Malawi, the Niger, Senegal, South Africa, Uganda and United Republic of Tanzania.

11 The Intergovernmental Panel on Climate Change (IPCC) finds "robust evidence" and "high agreement" that "Efficiency enhancements and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development, are a key mitigation strategy in scenarios reaching atmospheric CO2eq concentrations of about 450 to about 500 ppm by 2100" (IPCC, 2014: 20).

12 In the absence of an agreed definition and classification of off-grid systems, this Report uses the term to refer to a broad suite of technologies for local generation and distribution, which *typically* operate disconnected from the national grid (IEA, 2011; Kempener et al., 2015).

13 "Islanding" refers to the temporary isolation of a portion of the grid to enable it to operate independently.

14 In the case of solar PV, for example, small- and large-scale plants differ significantly, utility-scale applications having higher capital costs but also better performance (IEA, 2016b).

15 Another example of intervention aimed at building the market for SHSs is the World Bank's Lighting Global platform, which supports market development in 18 developing countries (including 13 LDCs) through market intelligence, quality assurance, business support services and consumer awareness-raising.

16 Cultural norms and age appear to be important determinants of gender differences in education effects: in Rwanda, for example, study time was not significantly affected for secondary school children, and increased only for boys in primary school, whereas girls of the same age just shifted their study time from the afternoon to the evening (Grimm et al., 2014).

17 Energy demand is generally contingent on the availability of appropriate end-use machinery and devices, indispensable to make use of related energy services, be it for residential or productive purposes (Grubler, 2012; Sovacool, 2016). A firm recently connected to the grid, for instance, needs also to invest in electrical machinery before being able to harness electricity for productive purposes.

18 Given their less sophisticated nature and potential backward linkages with the local economy, bioenergy-based mini-grids could potentially offer significant developmental benefits (UNCTAD, 2011a). However, their sustainable-development impact depends on a host of context-specific considerations, including changes in crop patterns, pressure on natural resources, local pollutants and land-based investment issues.

19 Unlike diesel, biofuels are often not readily available, making the viability of biofuel-based mini-grids dependent on the suitability and scalability of the local upstream supply chain for bioenergy products.

20 While long-term sustainability warrants some emphasis on cost recovery, this does not necessarily imply an unfettered emphasis on profit maximization on the part of mini-grid operators: subsidized tariffs and cross-subsidization measures are standard practice in community- and utility-based mini-grid business models.

21 These figures may be biased downwards by the lack of systematic geological prospecting in some regions.

22 More formally, the LCOE is defined as the ratio between expected lifetime expenses and total expected electricity generation, both in net present value terms. It thus represents the minimum average electricity price consumers would have to pay to recover all costs, including a rate of return equal to the discount rate.

23 The global average LCOE of concentrating solar power and offshore wind could witness similar trends, dropping

by 43 per cent and 35 per cent respectively by 2025 (IRENA, 2016a).

24 Accounting for CO_2 emissions in LCOE computations is seriously complicated by the absence of a global mechanism for carbon pricing and uncertainties about climate-change impacts.

25 Although Bangladesh is the leading LDC in the deployment of SHSs (figure 3.6), the absence of solar power in figure 3.14 reflects the fact that electricity generated from solar PV is not fed into the grid but rather used for off-grid systems.

26 Whether different technologies are substitutes or complements thus depends on their time profiles of generation as well as relative costs (Ambec and Crampes, 2012). Some practitioners anticipate that storage may become the next disruptive technology, if cost reductions and performance improvements continue, allowing still faster deployment of variable renewable technologies (Frankel and Wagner, 2017).

27 Examples include low-wind speed mills, solar modules allowing for orientation and tilt, or even solar towers with integrated storage components (IEA, 2016c).

28 For example, hybrid PV/wind plants may benefit from higher efficiency and partly complementary time profiles of generation (Ludwig, 2013).

29 According to Comtrade data, the one segment where China has emerged as the undisputed market leader is solar PV, scale economies and declining production costs allowing it to supply nearly three quarters of all LDC imports of photosensitive semiconductor devices and light-emitting diodes in 2015 (SITC Rev.3 basic heading 77637).

30 These figures are based on a simple average of the latest observations for the 12 LDCs for which data are available from the United Nations Educational, Scientific and Cultural Organization (UNESCO), UIS.STAT database.

31 India's Barefoot College represents an insightful example of South-South collaboration for skills transfer. Barefoot College and Vocational Training Centres provide illiterate or semi-literate rural women from several LDCs with training and skills to install, maintain and repair solar home systems, as well as basic business, financial and digital literacy (Roy, 2016).

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