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Towards **universal electricity access** in Sub-Saharan Africa

A quantitative analysis of technology and investment requirements

Policy Report

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Contents

MAIN FINDINGS

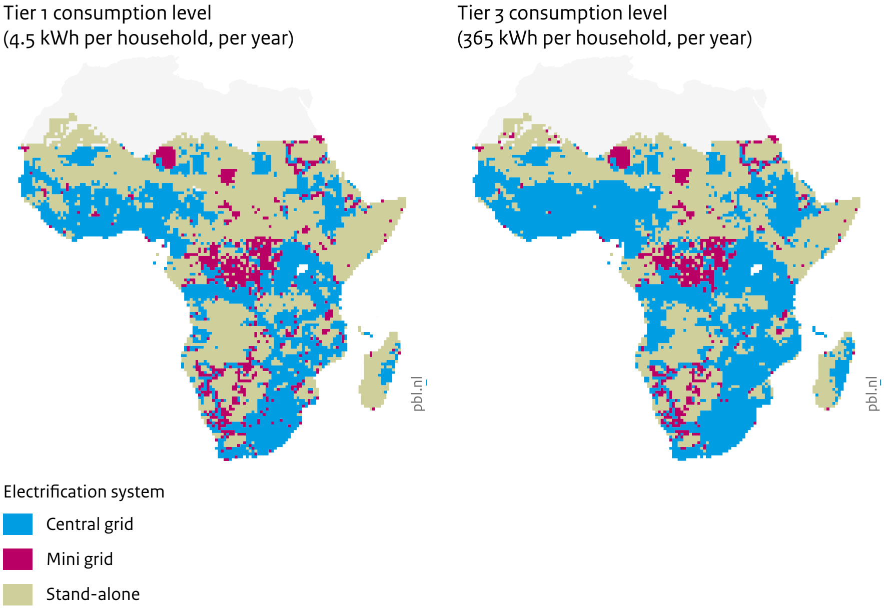
Summary

Achieving universal electricity access is of vital importance for human development, but poses severe challenges for the electricity sector
Two in every three people in Sub-Saharan Africa, more than 600 million people, currently do not have access to electricity. Improving access is an essential component of accelerating human development, for example through the greater use of energy technologies for irrigation and water pumping, creating employment and enhancing conditions for study, work and leisure, modern health services and better educational services. With the adoption of Agenda 2063 and the UN 2030 Agenda for Sustainable Development, not only African leaders but the global community too have committed to achieving universal access to electricity by 2030. Largely due to expected strong economic growth in many parts of Sub-Saharan Africa, 530–600 million additional people are projected to have gained access by 2030, with total household electricity demand at least tripling between 2010 and 2030. The total corresponding cumulative 2010–2030 investment in production capacity and transmission and distribution infrastructure is estimated at USD 300–350 billion, or USD 15–19 billion per year. However, without explicit new and additional policies, the projected infrastructure development will probably not be enough to keep pace with the rapidly growing population. Achieving universal electricity access requires connecting the remaining 350–600 million people that, by 2030, are projected to otherwise have no access to electricity, 90% of whom live in rural areas.

Decentralised electrification systems are key to reaching out to remote rural areas
To achieve universal electricity access in Sub-Saharan Africa, further expansion of generation capacity and transmission and distribution networks is required. Traditionally, national governments have focused on extending the central grid to benefit from economies of scale. However, grid-based electrification is only attractive for densely populated areas, an expected high demand for electricity, and/or within reasonable distance of existing high voltage power lines. Rural areas, constituting by far the largest share of the population without access to electricity, are sparsely populated, with many households on very low income levels. In these areas, off-grid systems, including mini-grids and stand-alone systems, could play a vital role in improving electricity access (Figure 1). This could bring electricity to the millions of people that live in areas too remote to be connected to the grid at a reasonable cost, especially as the electricity demand of these people is expected to be relatively low. Their incomes might only allow the use of very low-power appliances, such as basic lighting and mobile phone charging (Tier 1), but higher incomes could potentially also allow the use of low (Tier 2) or medium (Tier 3) power appliances, including televisions, fans, refrigerators and rice cookers. However, most of the current funding goes to centralised medium- and large-scale projects or to the maintenance and operation of the existing power infrastructure. Energy providers that do focus on off-grid electrification are faced with a range of barriers that will not be resolved by more finance alone. Therefore, innovative policies, an enabling environment for the energy market and human and institutional capacity building all need due attention.

Renewable energy production becomes increasingly competitive, but fossil fuels continue to play a significant role in future electricity production
Even when universal access to electricity is not achieved, current electricity production can only meet around 35% of the consumption projected for 2030, and for 2050 this is less than 15%. Although not evenly distributed across the region, most Sub-Saharan African countries are well endowed with both fossil fuel and renewable energy resources. Coal is abundant in countries in southern Africa, while many countries in Sub-Saharan Africa, but especially in western Africa, are endowed with large natural gas resources. The potential for solar PV is huge all over Sub-Saharan Africa, large- and small-scale hydropower potential is large in all regions except for the Republic of South Africa, and wind power and geothermal

Figure 1
Least-cost electrification systems under SSP2 baseline scenario with universal electricity access, 2030



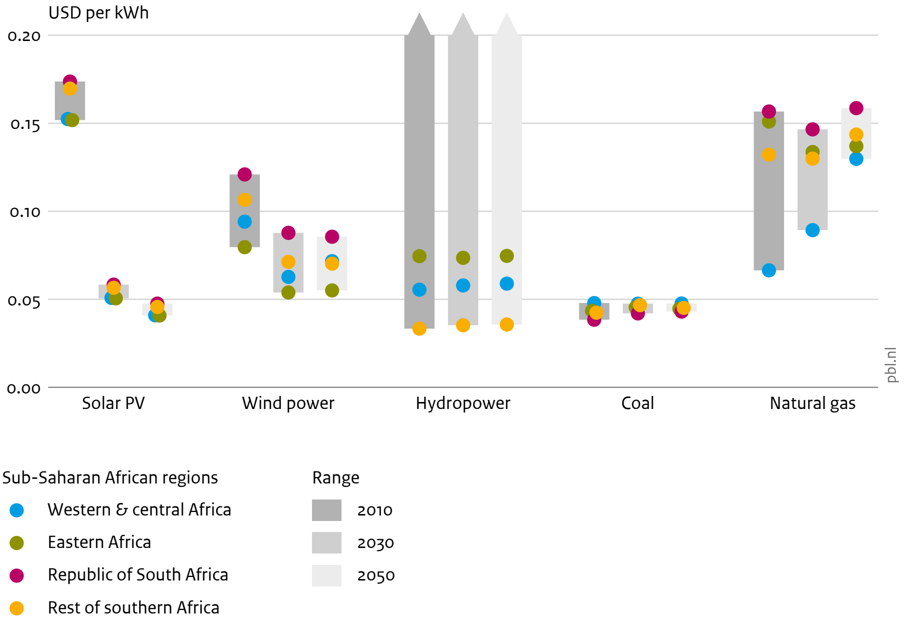
Source: PBL

potential is especially large in eastern Africa. Driven by technological innovation and renewable energy policies, the cost of renewable power generation technologies, primarily solar PV and wind energy, has decreased significantly. Our model projections show a continuation of this trend, with renewable energy technologies becoming increasingly competitive with fossil fuels for electricity generation (Figure 2). Thus, being a latecomer with respect to electrification not only comes with challenges, but also with opportunities, as a large part of the generation capacity still needs be built and the region can potentially profit from the global renewable energy revolution. Under business-as-usual assumptions, around half of the capacity growth between 2010 and 2030 is projected to come from renewable energy sources, with very small but increasing shares of solar PV in the Republic of South Africa and large shares of hydropower in the rest of Sub-Saharan Africa. After 2030, the scenarios also project a significant increase in the use of solar PV and wind power in electricity production, as most hydropower potential is already deployed. However, the overall renewable energy share remains relatively constant. It should be noted that there are significant controversies around the development of large-scale hydropower, especially with respect to its adverse environmental and related social impacts. These controversies are not included in our projections.

Total additional annual investment requirements for achieving universal electricity access projected at USD 9–33 billion

Achieving universal electricity access requires a significant expansion in electricity generation capacity and transmission and distribution networks. However, access is not only about having electricity or not. It is also about fulfilling the needs of households within their financial capacity and therefore links to the development status of a household or community. For very low-income households, access can already mean being able to charge a mobile phone and turn on lights in the evening. For high-income households, access is about being able to use medium to high power appliances, but also about the reliability and quality of the network. The most cost-efficient electrification system (grid-based, mini-grid or stand-alone) and the related investment requirements strongly depend on the level of household electricity demand. Higher levels of demand can profit from the economies of scale of capital-intensive on-grid infrastructure. For low levels of demand, off-grid systems can be much more cost-efficient, saving significantly on expensive high voltage power lines, especially when people live far from the central grid. Our model projections conclude total cumulative 2010–2030 investment requirements to achieve universal electricity access to be USD 480–970 billion (Figure 3), or USD 24–49 billion

Figure 2
Levelised cost of electricity (LCOE) for central grid, per technology, under SSP2 baseline scenario



Source: PBL

per year. This is USD 9–33 billion per year, on top of our business-as-usual projection in which universal electricity access is not targeted. It should be noted that these investment requirements only include generation capacity, transmission and distribution. Aspects such as research and development, planning, policies and regulations are excluded, but could also be significant.

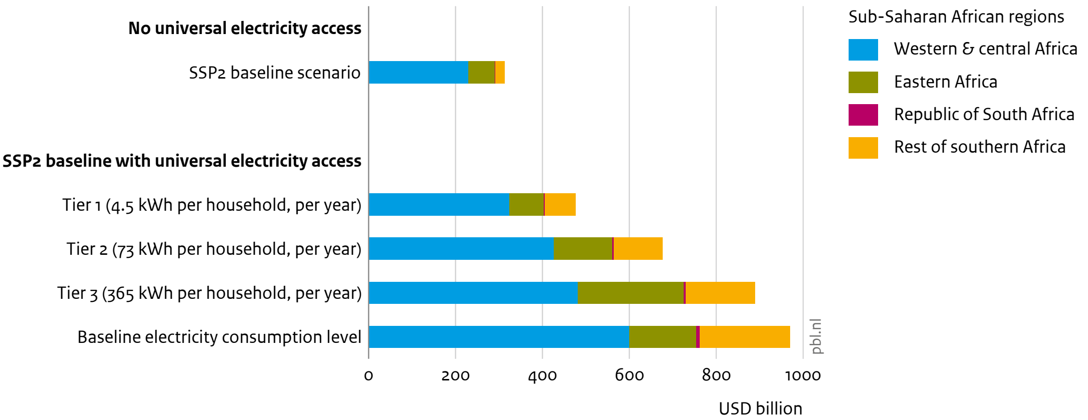
Achieving universal electricity access is not in conflict with the 2 °C climate target, while climate policy can become a driver of renewable electricity access

Achieving universal electricity access will have only a small impact on the electricity mix. Under optimistic assumptions on the electricity demand from the additional number of connected households, grid-based electrification based on fossil fuels might increase slightly. Assuming low levels of electricity demand from the additional number of connected households, off-grid renewable energy use, especially solar home systems, play a much more important role in providing many households with electricity, but the additional demand is too small to have a significant impact on the total electricity mix. Our model projections show an increase in household electricity-related CO_2 emissions of 0.2% to 27% by 2030, compared to a situation in which universal access is not targeted. This increase is negligible, as it is only 0.001% to 0.2% of the global electricity-related emissions. Global coordinated climate policy can stimulate Sub-Saharan African countries to take a renewable energy pathway when pursuing universal electricity access. The global carbon price that we use in our analysis makes renewable energy technologies more competitive due to higher fossil fuel prices. Furthermore, energy savings policies improve the energy efficiency of appliances, thereby making electricity use more affordable for poor households while lowering the required expansion in generation capacity. Global climate finance can help fuel this transition. Governments of developed countries have committed to mobilise USD 100 billion, annually, in public and private sources by 2020 to help developing countries mitigate and adapt to climate change. The energy sector is already a big recipient of climate finance, but the share that goes to decentralised systems is still small. Policymakers and practitioners could thus improve the targeting of international climate finance for decentralised electricity access.

A long-term electricity access strategy

Low-carbon options can only scale-up and play a substantial role if they are cost-competitive and make sense in the context of countries' broader development objectives. Severe lack of financial resources and related low electricity demand of communities in remote rural areas could call for the use of stand-alone systems. Even the transition from a kerosene lamp to basic electricity services provided by solar home systems may significantly affect a household's welfare. However, the ultimate goal is to supply electricity at a scale that can support

Figure 3
Cumulative investments in electricity generation capacity, transmission and distribution, 2010 – 2030



Source: PBL

community development and income-opportunity development, while taking into account social, economic and environmental effects related to climate change, air pollution, employment opportunities and energy security issues. This calls for a long-term strategy on electricity access that takes into account long-term objectives, including climate change, health impact and energy security objectives, while at the same time building on local knowledge and capacity and addressing short-term constraints related to finance and governance. This may be difficult to achieve given the currently weak institutions and low governance capacity. Still, governments can make a good start by including off-grid electrification as an essential component of power sector plans, by supporting the market development of mini-grid and stand-alone systems, and by making electricity affordable for the poorest households. Furthermore, as there is a clear need to speed up the transition, governments could facilitate emerging bottom-up electrification processes while keeping track of long-term targets and broader energy system challenges.

A clear role for Dutch renewable energy ambitions
With its renewed target of providing 50 million people with access to renewable energy by 2030, the Dutch Government can significantly contribute to achieving the SDG target of ensuring universal access to electricity by 2030. Our quantitative analysis provides insights into the technology and investment requirements for achieving this target in Sub-Saharan Africa. The challenge could be the largest for poor, rural communities – not in terms of absolute investment requirements but with respect to many socio-economic and institutional barriers to starting off-grid projects. Building on these insights, added value for Dutch development cooperation could be found in providing support for market development for off-grid systems, targeting international climate finance towards decentralised electrification projects and help strengthen the national enabling environment to incentivise decentralised electricity access.

FULL RESULTS

FULL RESULTS

Introduction

Improving access to electricity in Sub-Saharan Africa requires a significant scale-up of electricity infrastructure
Access to electricity is an essential component of accelerating human development. It allows greater use of energy technologies for irrigation and water pumping, creating employment and enhancing conditions for study, work, leisure, modern health services and better educational services (Karekezi et al., 2012).
However, although Sub-Saharan Africa is rich in energy resources, it currently lacks the required infrastructure to ensure access to affordable, reliable, sustainable and modern energy for all its citizens (IEA, 2014). Two in every three people in Sub-Saharan Africa – around 634 million in total – have no access to electricity (IEA, 2016), while in many African countries the power sector is confronted with an unstable and unreliable electricity supply, low generation capacity, low efficiency and high costs (Sokona et al., 2012). Furthermore, the expected large population growth and strong economic development could result in a high increase in demand for energy services (Lucas et al., 2015). Increasing access to electricity thus requires a significant scale-up of electricity infrastructure, including generation capacity and transmission and distribution networks.

Scaling-up of electricity infrastructure also affects other energy-related challenges
The challenge of increasing electricity access is highly interlinked with other energy system challenges (Van Vuuren et al., 2012; Van Vuuren et al., 2015). Depending on the technology choice, increasing access could affect local and regional air pollution (Liousse et al., 2014), as well as add to global climate change by increasing greenhouse gas emissions (Pachauri, 2014). Furthermore, while several countries in Africa – including Nigeria, Libya and Algeria – are endowed with large fossil fuel resources and are net exporters of oil and natural gas (UNECA, 2011), most other countries are net importers and faced with serious energy security issues (Bacon and Mattar, 2005). Finally, while the upfront capital costs of energy infrastructure – in particular renewable infrastructure – are generally high, investment decisions are often driven by concerns of a shorter timeframe.
As energy infrastructure stands for decades, choices made today have long-term consequences, including the possibility of lock-ins.

The broader energy system challenge is high on political agendas – nationally, regionally and globally
Almost all African governments emphasise the critical role that electricity services play in human development (Parshall et al., 2009) and are making electrification a development priority (Deshmukh et al., 2013; Scott and Seth, 2013; APP, 2015). The broader energy system challenge is recognised by the African Development Bank's Energy Sector Policy for Africa, which has a dual objective: (i) to support Regional Member Countries (RMCs) in their efforts to provide all of their populations and productive sectors with access to modern, affordable and reliable energy services; and (ii) to help RMCs develop their energy sector in a socially, economically and environmentally sustainable manner (AfDB, 2012).
Furthermore, providing universal access to modern energy services is at the heart of Agenda 2063 (African Union Commission, 2015) and the 2030 Agenda for Sustainable Development (UN, 2015), and is strongly related to the Paris climate agreement (UNFCCC, 2015). Together, these agendas provide a key opportunity for tackling the interlinked twin challenges of sustainable development (including poverty eradication) and climate change mitigation (Care and WWF, 2016).

Improving access to renewable energy is also a priority in Dutch development cooperation
Dutch renewable energy policies are linked to international global challenges such as poverty alleviation and combating

international cooperation. In 2004, the Dutch government adopted a target of providing 10 million people with access to energy by 2015, as a condition for achieving the Millennium Development Goals (EZ, 2016). Since then, the focus has shifted from poverty alleviation to adaption to climate change. It is estimated that by 2014, 16.7 million people had gained access to energy due to Dutch financed interventions, of which two thirds through improved cooking technologies and one third through access to electricity (IOB, 2015). Building on this success, the Dutch government has adopted a new target of providing 50 million people with access to renewable energy by 2030 (BZ, 2015). This target is repeated in the Dutch energy vision of December 2016 (EZ, 2016), with climate finance playing an important role.

We analyse the technology and investment requirements for achieving universal electricity access in Sub-Saharan Africa in the context of global climate policy

The analysis focuses on the role of renewable energy technologies and infrastructure development. It is based on goals and targets from international agreements such as the 2030 Agenda for Sustainable Development and the Paris Agreement, and uses an energy system model and scenarios analysis (Chapter 2). More specifically, we address the following research questions:

- What progress has been made since 1990 and what is the potential future progress under different socio-economic developments, assuming that no new intervention policies will be implemented? (Chapter 3)
- What are the technology and investment requirements for achieving electricity access for all, and what is the role of climate change mitigation policy? (Chapter 4)
- What are key issues for driving the transition? (Chapter 5)

TWO

Analysing the challenges

Increasing access to electricity is a development priority in many countries in Sub-Saharan Africa and is part of recent global and continental agreements and action plans that define goals and targets for 2030 and beyond. This chapter discusses the role of energy in these agendas, the selection of targets and indicators from these agendas for our study, and the quantitative modelling and scenario approach applied.

2.1 Global and regional goals and targets

Most African governments have made electrification a development priority (Scott and Seth, 2013). The broader energy system challenge – including climate change, air pollution and energy security – is addressed by a range of global and regional agreements that have been developed over the last few years, including the Sustainable Energy for All initiative (SE4All; Yumkella and Holliday, 2012), the Paris Agreement (UNFCCC, 2015), the 2030 Agenda for Sustainable Development (SDGs; UN, 2015) and Agenda 2063 (African Union Commission, 2015). Together, these agreements describe *The Future We Want*, and in the context of this study, *The Africa we Want*, formulated by targets for 2030, 2063 and 2100. Here, we briefly discuss the different agreements, with a focus on the role of energy.

Sustainable Energy for All

The Sustainable Energy for All (SE4All) initiative is a multi-stakeholder partnership between governments, the private sector and civil society, launched by the UN Secretary-General in 2011 (AGECC, 2010; Yumkella and Holliday, 2012). It addresses the twin challenge of providing energy access for all and combating climate change, through three interlinked objectives, together to be achieved by 2030: ensuring universal access to modern energy services, doubling the global rate of improvement in energy efficiency and doubling the share of renewable energy in the global energy mix. The three objectives are conceived of as global objectives, applying to both developed and developing countries, with individual nations setting their own domestic targets in a way that is consistent with the overall spirit of the initiative, depending on where they can make the greatest contribution to the global effort.

The Paris Agreement

The Paris Agreement is a legally binding instrument within the United Nations Framework Convention on Climate Change (UNFCCC, 2015). It provides a top-down global climate target, coupled with a long-term framework for periodic adjustment and ratcheting up of national bottom-up commitments. National governments have agreed on *holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change* (UNFCCC, 2015). This has to be achieved through combined national efforts under 'nationally determined contributions' (NDCs). All Sub-Saharan African countries submitted intended nationally determined contributions (INDCs) in the run-up to the Paris climate summit. Top priority mitigation areas are energy, agriculture and forestry (Mbeva et al., 2015). Furthermore, the countries place strong emphasis on taking climate action within the context of sustainable development, including access to electricity.

The 2030 Agenda for Sustainable Development

The 2030 Agenda for Sustainable Development is a plan of action for people, planet and prosperity (UN, 2015). Set for the 2016–2030 period, the 2030 Agenda offers a reference for international sustainable development.

Table 2.1
Selected indicators for this study

Targets	Official indicators	Selected indicators
By 2030, ensure universal access to affordable, reliable and modern energy services (SDG 7.1) By 2030, ensure universal access to modern energy services (SE4All)	Proportion of population with access to electricity (SDGs and SE4All)	1. Proportion of population with access to electricity
By 2030, increase substantially the share of renewable energy in the global energy mix (SDG 7.2) By 2030, double the share of renewable energy in the global energy mix (SE4All)	Renewable energy share in total final energy consumption (SDGs and SE4All)	2. Renewable energy share in total residential electricity consumption
Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels (Paris Agreement)	-	3. CO_2 emissions from household electricity use

Source: Based on Banerjee et al. (2013) and IAEG-SDG (2016)

It is a key outcome of the 2012 UN Conference on Sustainable Development (Rio+20) and builds on the Millennium Development Goals (MDGs) and other international agreements. Keywords are transformation, integration and universality. At the heart of the 2030 Agenda are the 17 Sustainable Development Goals (SDGs) and the associated 169 targets that operationalise the goals and guide the process of sustainable development (*transformation*). The goals and targets integrate the three dimensions of sustainable development: economic, social and environmental (*integration*). Whereas the MDGs mainly aimed to reduce poverty in developing countries (with developed countries committing to a Global Partnership for Development), the 2030 Agenda is a broad sustainability agenda for *all* countries, both developing and developed (*universality*).

While energy was completely absent in the MDGs, it is included as a stand-alone goal in the SDGs: Ensure access to affordable, reliable, sustainable and modern energy for all (SDG7). Moreover, the goal includes the three SE4All targets, as well as two targets addressing means of implementation, including research for clean energy technologies and infrastructure development. Furthermore, several other goals include targets that directly relate to the energy challenge, most notably the SDG on climate change (SDG13: Take urgent action to combat climate change and its impacts). The targets under SDG13 are more procedural than the targets under the other goals. However, the goal acknowledges that the United Nations Framework Convention on Climate Change is the primary international, intergovernmental forum for negotiating the global response to climate change. It thereby links directly to the Paris Agreement, including its long-term climate target.

Agenda 2063
Agenda 2063, adopted by African leaders in 2015, is a strategic framework for the socio-economic transformation of the continent for the next 50 years (African Union Commission, 2015). Its builds on, and seeks to accelerate, the implementation of past and existing continental initiatives for growth and sustainable development. Agenda 2063 is both a vision and an action plan. It is a call for action to all segments of African society to work together to build a prosperous and united Africa based on shared values and a common destiny. Agenda 2063 defines seven aspirations for Africa for 2063 and commits African countries to 17 actions, of which action g on infrastructure includes a sub-target on energy: *harnessing all African energy resources to ensure modern, efficient, reliable, cost effective, renewable and environmentally friendly energy to all African households, businesses, industries and institutions, through building the national and regional energy pools and grids, and PIDA[1] energy projects.*

2.2 Selected targets and indicators

Both Agenda 2030 and Agenda 2063 place the energy challenge in a broader sustainable development context, integrating it with the much broader social, economic and environmental challenges that the world and the continent are facing. Agenda 2063 provides an overarching goal on energy for Sub-Saharan Africa, while SE4All and Agenda 2030 provide more specific targets for energy access, renewable energy and energy efficiency, as well as for means of implementation, including finance and technology development. Finally, the Paris Agreement links to both Agenda 2030 and Agenda 2063 and provides a long-term climate target.

Table 2.2
Multi-tier matrix for measuring access to household electricity services and consumption

		TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Electricity services	Typical household electric appliances	Very low-power appliances	Low-power appliances	Medium-power appliances	High-power appliances	Very high-power appliances
		Task lighting, phone charging and radio	Multipoint general lighting, television, computer and fan	Air cooler, refrigerator, food processor, rice cooker	Washing machine, iron, hairdryer, toaster and microwave	Air conditioning units, space heater, water heater, electric cooker
Electricity consumption	Annual consumption levels (kWh)	>4.5	>73	>365	>1,250	>3,000
	Daily consumption levels (Wh)	>12	>200	>1,000	>3,425	>8,219

Source: ESMAP (2015)

Providing universal electricity access, while mitigating climate change
The selected targets for our analysis build on the overarching energy goal of Agenda 2063. More specifically, we look at the energy access target of SE4All and the SDGs and the long-term climate target as formulated in the Paris Agreement. This results in the twin challenge of providing electricity access for all, while mitigating climate change:
- ensuring access to electricity for all Sub-Saharan African households by 2030;
- holding the global average temperature increase well below 2 °C above pre-industrial levels.

We analyse the technology and investment requirements of achieving these targets, with a focus on the role of renewable energy (SE4All and SDG7) and infrastructure development (SDG7).

Tracking progress through internationally agreed indicators
The World Bank has developed the Global Tracking Framework to track progress towards the SE4All targets, which includes rigorous technical definitions (Banerjee et al., 2013). These technical definitions are now also included in the global indicator framework for tracking progress towards SDG achievement (IAEG-SDG, 2016). We used some of these indicators in our analysis. As the analysis focuses on household electricity access only, we selected the indicators that apply to the electricity sector, or adapted specific indicators in such a way that they only apply to the residential electricity sector (Table 2.1).
The SDG indicators for Goal 13 (climate action) only include process indicators[2], while the Paris Agreement only includes a global target. To track progress on the climate target, we added a third indicator on carbon dioxide (CO_2) emissions from household electricity use.

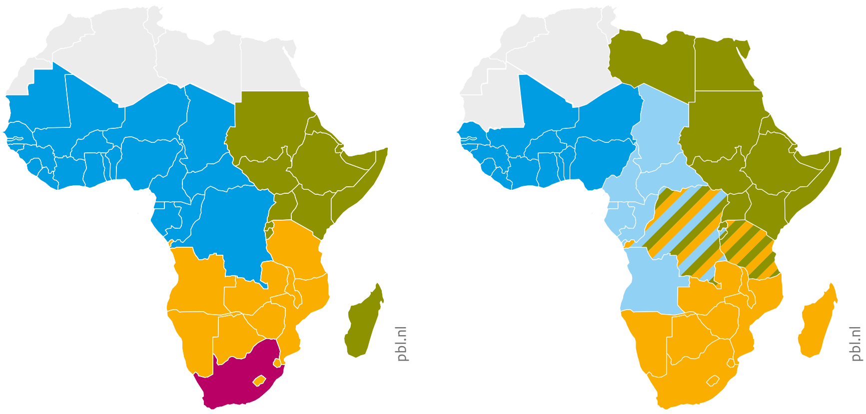
Using multi-tier measurement of electricity access
While the selected indicator presents electricity access in a binary manner (yes or no), a more refined set of categories is desirable to assess its relevance for human development. The multi-tier framework, developed by the World Bank, defines access to electricity based on technology-neutral multi-tiered standards, where successive thresholds for supply attributes allow increased use of electricity appliances (ESMAP, 2015; Table 2.2).
A gradually improving electricity supply enables increased and improved access to electricity services, and subsequently increased electricity consumption. In our analysis, we use the annual consumption levels of the multi-tier framework to assess the technological and financial implications of providing different levels of electricity access.

2.3 A model-based approach

The two overarching targets of achieving universal access to electricity and mitigating climate change are highly interlinked. Providing electricity access inevitably pushes up electricity demand and, depending on fuel choice, also CO_2 emissions. At the same time, climate policies increase the preference for renewable energy sources and induce energy efficiency measures. Energy system models can be used to allow a consistent exploration of the electrification challenges and the efforts needed to realise specific targets, and to gain insight into the synergies and trade-offs with other energy system challenges. Here, we use the energy systems model TIMER, which is part of the integrated assessment model IMAGE3.0 (Stehfest et al., 2014). The applied TIMER model version used includes the recently developed Sub-Saharan Africa electrification

Figure 2.1
Regional grouping of African countries

This report | African power pools



This report:
- Western & central Africa
- Eastern Africa
- Republic of South Africa
- Rest of southern Africa

African power pools:
- West African Power Pool
- Central African Power Pool
- Eastern African Power Pool
- Southern African Power Pool

Source: PBL

model (Dagnachew et al., submitted; Appendix).
The electrification model allows the exploration of household electrification in urban and rural areas, taking into account grid extension, mini-grid and stand-alone systems. It applies a least-cost methodology, taking into account local characteristics such as distance to the central grid, population dynamics, resource availability and prices of different technologies. The model includes four regions that largely overlap with the four regional power pools in Sub-Saharan Africa (Figure 2.1).

To understand the nature of the challenges posed by the targets, we constructed two sets of scenarios: a set of explorative scenarios that describe baseline or business-as-usual developments, and a set of normative or goal-based scenarios in which the universal electricity access and climate change mitigation targets are achieved.

Explorative baseline scenarios: three alternative socio-economic futures
Explorative scenarios are an important method to explore uncertainty in future societal conditions. They describe societal futures which can be combined with, for example, climate change projections and climate policy assumptions to explore mitigation, adaptation and residual climate impacts in a consistent framework. In our study, we take into account uncertainty in socio-economic developments by using the shared socio-economic pathways (SSPs; O'Neill et al., 2017). The SSPs are a set of five scenarios developed in the climate change research community to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation and mitigation.
The SSPs describe different future developments of key aspects of society and are designed to span a range of uncertainty in future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and the environment and natural resources (see Box 2.1).

The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation and vulnerability analyses. Along with the qualitative storylines, the developers of the SSPs have produced quantitative projections for population by age, sex and education (KC and Lutz, 2017), urbanisation (Jiang and O'Neill, 2017) and economic development (Dellink et al., 2017) for over 200 countries. We use three of the five SSP scenarios: SSP1, SSP2 and SSP3 (Box 2.1). They provide insight into future progress towards the agreed targets without targeted policies for achieving them.
The baseline scenarios used in our analysis build on the IMAGE implementation of the SSP scenarios (Van Vuuren et al., 2017).

2.1 Qualitative storylines for three shared socio-economic pathways (SSPs)

SSP1 (sustainability): This scenario describes a world that makes relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. Elements that contribute to this are rapid development in low income countries, reduced inequality (globally and within economies), rapid technology development and a high level of awareness regarding environmental degradation. The world is characterised by an open, globalised economy, with relatively rapid technological change directed towards environmentally friendly processes, including clean energy technologies.

SSP2 (continuation): In this middle-of-the-road scenario, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. The development of low income countries proceeds unevenly, with some countries making relatively good progress while others are left behind. Most economies are politically stable with partially functioning and globally connected markets. A limited number of comparatively weak global institutions exist.

SSP3 (fragmentation): This scenario portrays a world fragmented into regions characterised by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. Regional blocks of countries have re-emerged with little coordination between them. This is a world failing to achieve global development goals and making little progress in reducing resource intensity and fossil fuel dependency, or addressing local environmental concerns such as air pollution. Countries focus on achieving energy and food security goals within their own region. The world has de-globalised, and international trade, including energy resource and agricultural markets, is severely restricted.

Source: O'Neill et al. (2017)

Universal access scenarios: different levels of household electricity consumption

The explorative baseline scenarios are set against the results of normative universal access scenarios in which 100% household electricity access by 2030 is induced in the model. In these universal access scenarios, access to electricity grows linearly from the regional 2010 level to 100% in 2030. Based on cost assumptions for different technologies, distance to the central grid, demand density (population density and household electricity demand) and local resource availability, the model determines a least-cost distribution of electrification technologies (grid extension, mini-grids and stand-alone systems) and the related technology mix (see Dagnachew et al., submitted, and Appendix).

The universal access scenarios focus on providing access to electricity for those households not connected in 2030 in the baseline scenarios. The technology choice (grid extension, mini-grid or stand-alone system) and thereby the required transmission and distribution network, as well as additional generation capacity, largely depends on the expected electricity consumption level of these additional households. Most households that gain access to electricity for the first time are likely to start with relatively low consumption levels, but actual data is missing (Szabo et al., 2011; IEA, 2014). To take this uncertainty into account in our assessment of technology and investment requirements, we look at different levels of electricity consumption. We constructed three tier-based scenarios, in which the additional households are assumed to have electricity consumption levels in line with Tier 1, Tier 2 and Tier 3 as defined by the World Bank's multi-tier framework (Table 2.2). These three tiers are generally lower than current average electricity consumption levels in Sub-Saharan Africa.
Multi-tier measurement of electricity access allows governments to set their own targets and ambitions depending on the local situation, for example the development status, the needs of the population and the available budget (Bhatia and Angelou, 2016). In addition, we constructed a scenario in which we assumed that the additional households have the same electricity consumption level as households that already had access in the baseline scenario in 2030.

Universal access with climate policy scenario: staying below 2 °C temperature increase compared to pre-industrial levels

In addition to the baseline and universal access scenarios, we also developed a universal access scenario that includes climate policy. This scenario aims to achieve

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universal access to electricity while also keeping the global average temperature increase well below 2 °C, above pre-industrial levels. The scenario builds on the SSP2 universal access scenario, assuming baseline electricity consumption levels for the additionally connected households. With respect to climate policy, for the sake of simplicity, we applied a global carbon tax, so that the long-term climate target can be achieved with more than 66% probability. The carbon tax is taken from the IMAGE implementation of the SSPs (Van Vuuren et al., 2017). It is used to increase the preference for renewable energy carriers and to induce energy efficiency measures. In reality, the same effect may be achieved through other policy measures, such as specific energy efficiency policies.

Notes

1 Programme for Infrastructure Development in Africa.

2 For example, indicator 13.2.1: Number of countries that have communicated the establishment or operationalization of an integrated policy/strategy/plan which increases their ability to adapt to the adverse impacts of climate change, and foster climate resilience and low greenhouse gas emissions development in a manner that does not threaten food production (including a national adaptation plan, nationally determined contribution, national communication, biennial update report or other).

Historical progress and future developments without new policies

Global poverty has decreased since 1990, mainly due to the tremendous progress made in China and other emerging economies. At the same time, global environmental problems, including climate change, have worsened. In this chapter, we provide an overview of progress made since 1990 regarding access to electricity in Sub-Saharan Africa, including the use of renewable energy and CO_2 emissions in the residential sector. We also discuss future progress towards achieving universal and renewable electricity access under different socio-economic developments, assuming no specific policies to achieve universal electricity access will be implemented.

3.1 Progress since 1990

Despite strong population growth, Sub-Saharan Africa has made considerable progress towards achieving the Millennium Development Goals

While most developing countries outside Africa have fertility rates approaching replacement levels, women in Sub-Saharan Africa still give birth to on average five children (UNDESA, 2015). The resulting strong population growth induces severe challenges for poverty eradication. The Sub-Saharan African population has almost doubled since 1990 (Figure 3.1; left). At the same time, the region has made considerable progress towards achieving the MDGs (UNECA, 2015). Universal primary education is now well within reach, impressive progress with respect to child mortality is being made, and the region is leading the way in women's representation in national parliaments. However, progress with respect to extreme poverty and hunger has been slow and many people still live without access to safe drinking water and improved sanitation.

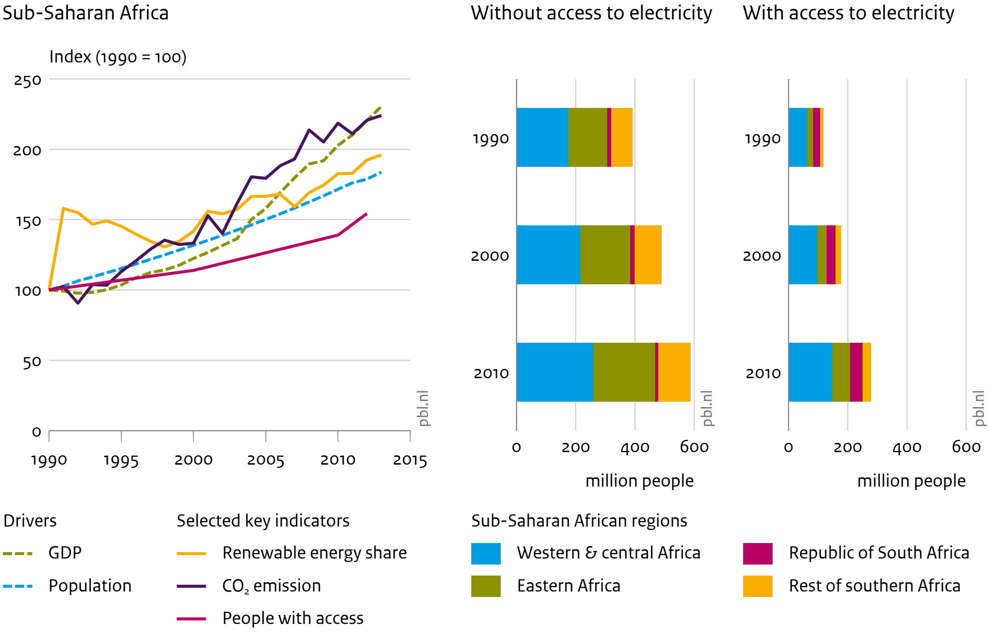
Access to electricity has increased, but more people live without electricity today than 25 years ago

In 1990, around 77% of the population of Sub-Saharan Africa (around 400 million people) had no access to electricity. In relative terms, access to electricity has improved significantly, with even a slight acceleration since 2010 (Figure 3.1; left). However, in absolute terms, the number of people without access has increased, as population growth has outpaced infrastructure development (Figure 3.1; right). As a result, 632 million people had no access to electricity in 2014 (IEA, 2016). Electrification rates differ largely between countries. For instance, in 2014 the Republic of South Africa had an electrification rate of 86%, while in South Sudan only 1% of the population had access. Furthermore, lack of access to electricity is a particular problem in rural areas. Around 63% of the population in Sub-Saharan Africa is rural, of which only 19% has access to electricity, compared to 63% of the urban population.

Share of renewable energy sources in the electricity mix has doubled

The power generation capacity has barely kept pace with the strong population growth. The total installed capacity grew from 58 gigawatts (GW) in 1990 to 68 GW in 2000 and almost 80 GW in 2010 (Eberhard et al., 2016). Currently, the region's total generation capacity is just over 90 GW, comparable to the installed capacity of the United Kingdom – a country with less than 7% of the population of Sub-Saharan Africa (IEA, 2014). Although most of the additional capacity was installed outside the Republic of South Africa, this country is still responsible for more than 40% of electricity generation in Sub-Saharan Africa, and is almost completely dominated by coal-fired power plants. In contrast, the electricity mix of eastern Africa and the rest of southern Africa depends for almost 50% on hydropower and other renewable energy technologies. As the share of the Republic of

Figure 3.1
Historical developments in drivers and selected key indicators for the residential electricity sector



Source: IEA 2015; World Bank 2016

South Africa in the Sub-Saharan African electricity system has declined, the share of renewable energy technologies in its total electricity mix has doubled since 1990.

Africa's share in global electricity-related CO_2 emissions is very small

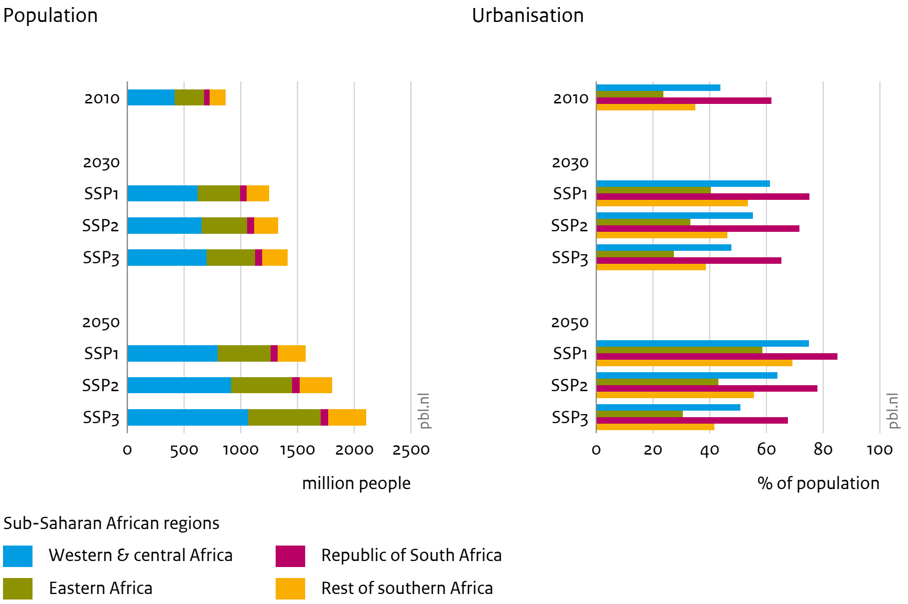
Total CO_2 emissions from residential electricity use in Sub-Saharan Africa have almost doubled since 1990. In 2010, these emissions accounted for around 25% of the total electricity-related CO_2 emissions in Sub-Saharan Africa. Although the growth in CO_2 emissions has been much larger than in most other world regions, Sub-Saharan Africa residential electricity use still accounts for only around 0.5% of global electricity-related CO_2 emissions, of which two thirds are from the Republic of South Africa. Climate change, resulting from increasing global greenhouse emissions, brings significant risks of damage to unique ecosystems and human well-being, and the associated impacts could be disproportionately large for Africa (CDKN, 2014). To mitigate the negative impacts, deep reductions in global greenhouse gas emissions are thus necessary, which is also agreed upon in the Paris Agreement. However, given the relatively low emission levels, climate change mitigation is currently not an important issue for most African countries in their electricity system planning.

3.2 Future developments without new policies

3.2.1 Population and economy

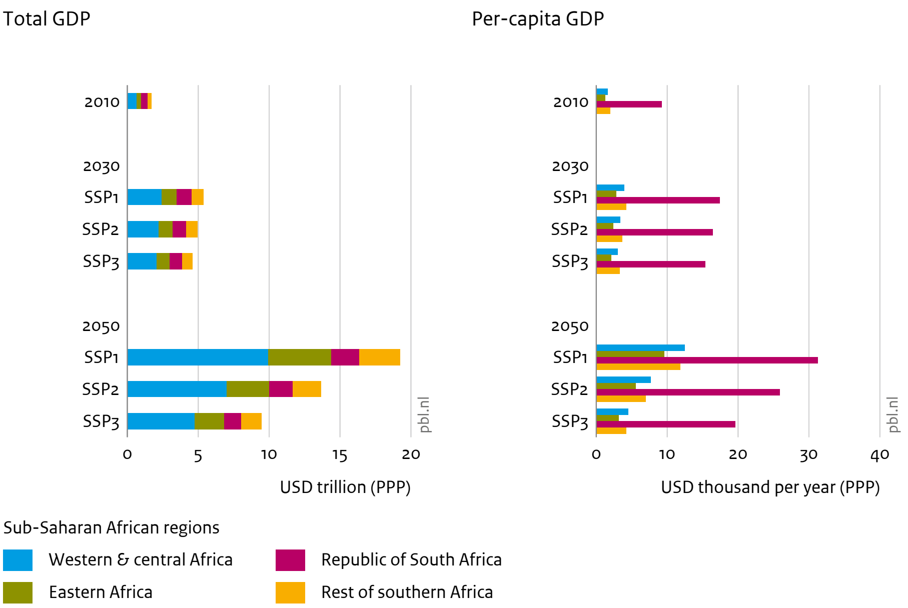
To take into account uncertainties in future socio-economic developments, we use three distinct baseline scenarios: SSP1, SSP2 and SSP3 (Section 2.3). According to these scenarios, the strong population growth of the last 25 years is projected to continue, with the total population growing from slightly over 850 million people in 2010 to around 1.2–1.4 billion by 2030 and 1.6–2.1 billion by 2050 (Figure 3.2). More than half of this increase is projected in western & central Africa. Furthermore, most of the population growth is projected in urban areas. Currently, less than 40% of the Sub-Saharan African population is urban, which is the lowest share of all world regions. Eastern Africa has the lowest urbanisation level, with less than 25% of the population residing in urban areas. Towards 2030, the share of the urban population in Sub-Saharan Africa is projected to increase, reaching 41% to 54% by 2030 and 44% to 70% by 2050. It is generally easier to provide access to electricity for the higher concentrations of people in urban areas.

Figure 3.2
Population and urbanisation, per baseline scenario



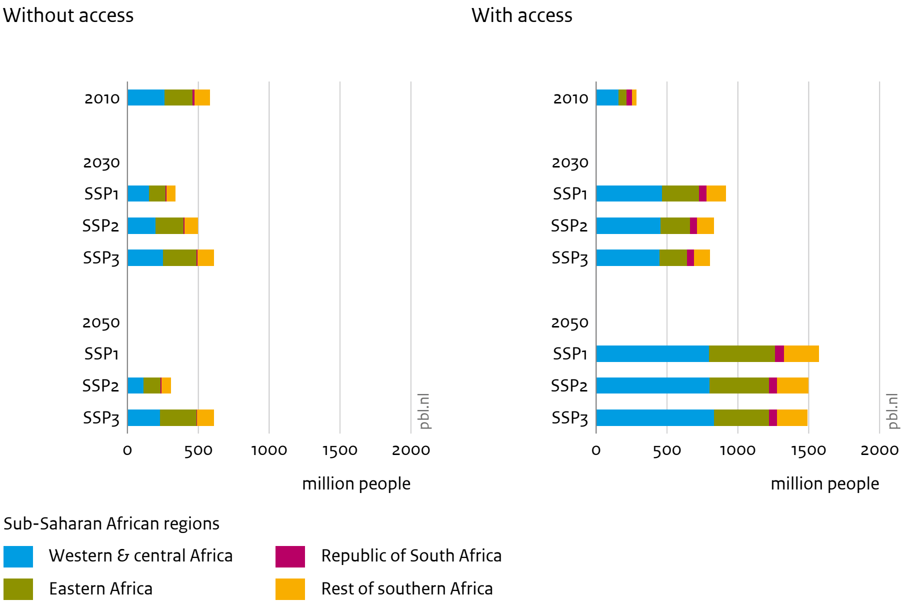
Source: KC and Lutz 2017; Jiang and O'Neill 2017

Figure 3.3
Total and per-capita GDP, per baseline scenario



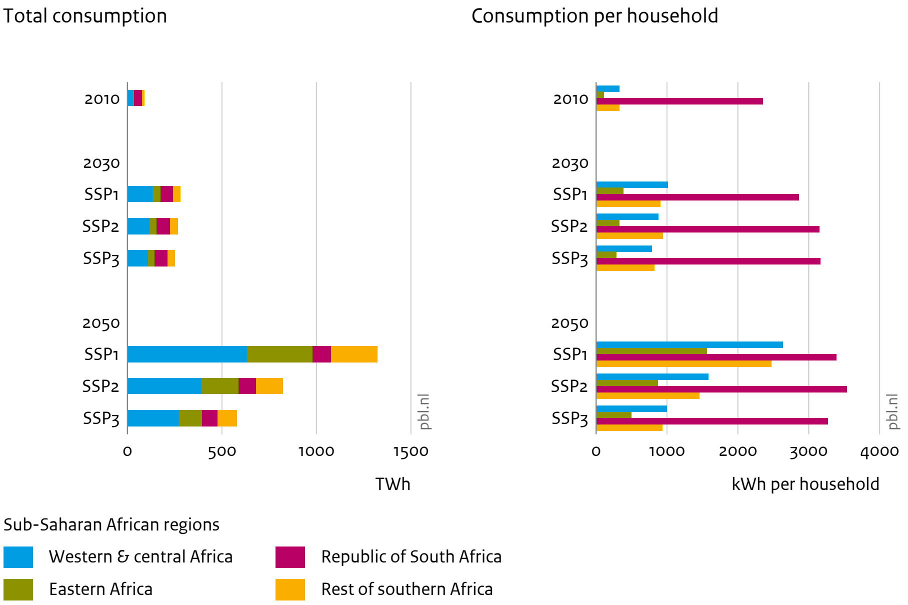
Source: Dellink et al. 2017

Figure 3.4
Access to electricity, per baseline scenario



Source: PBL

Figure 3.5
Electricity consumption, per baseline scenario



Source: PBL

Table 3.1
Urban and rural population and electrification rate in 2010 and 2030

Region	2010			2030								
				SSP1			SSP2			SSP3		
	Urb. (%)	Rur. (%)	Tot. (%)	Urb. (%)	Rur. (%)	Tot. (%)	Urb. (%)	Rur. (%)	Tot. (%)	Urb. (%)	Rur. (%)	Tot. (%)
Western & central Africa	65	16	38	86	58	75	87	41	69	89	41	64
Eastern Africa	54	12	23	90	55	69	95	30	52	100	25	45
Republic of South Africa	88	56	76	95	78	91	93	76	88	94	73	87
Rest of southern Africa	52	6	22	81	55	69	82	33	56	86	27	50
Sub-Saharan Africa	63	14	33	87	57	73	88	36	63	91	33	57

Although the economy more than doubled between 1990 and 2015, due to rapid population growth per capita income grew by only around 25%. Future trends in total and per capita GDP (in purchasing power parity terms) differ largely between the three scenarios (Figure 3.3). For Sub-Saharan Africa as a whole, per capita GDP more or less doubles between 2010 and 2030 and again between 2030 and 2050. Per capita GDP largely determines household electricity consumption, as purchasing power determines the type of electricity services people use. These services range from lighting and phone charging at low income levels to the use of medium power appliances such as televisions and rice cookers when incomes grow, and eventually very high power appliances, such as washing machines and air conditioning units, for very high income households.

3.2.2 Electricity access

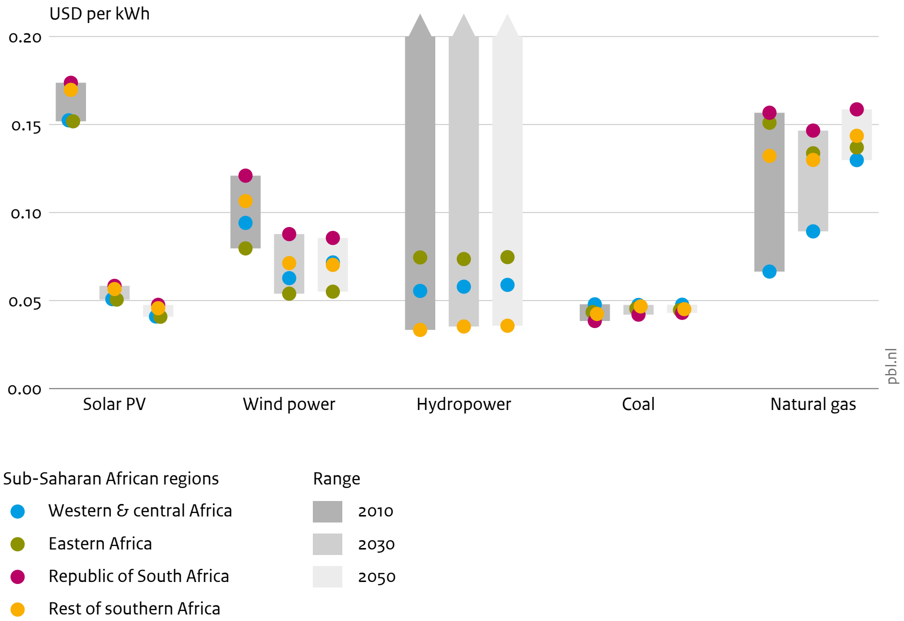
All three baseline scenarios project a considerable increase in the number of people with access to electricity (Figure 3.4). In total, 530–600 million people are projected to have gained access in 2030, still leaving 350–600 million people without access to electricity. These numbers are comparable to the projections of IEA (2014) and Pachauri et al. (2013). There are significant differences between the four regions, as well as between rural and urban areas (Table 3.1). In the middle-of-the road SSP2 baseline scenario, almost 90% of the population in the Republic of South Africa is projected to have gained access to electricity by 2030, compared to only 52% in eastern Africa. Furthermore, electricity access will remain a particular issue in rural areas. While 12% of the urban population is projected to not have access to electricity in 2030, in rural areas this is 64% of the population. The other two baseline scenarios have similarly large disparities.

Most of the households that currently have access to electricity are connected to the central grid. Single-Wire Earth Return (SWER) systems are used in many countries to connect communities in low consumption areas. In these systems, the earth (or sometimes a body of water) is used as the return path for the current, to avoid the need for a second wire. As a result, their installation costs are about 30% to 50% of the costs of alternative systems (Iliceto et al., 1999; Mayer, 2009), and can reach households up to 50–60 kilometres away from the grid (Kashem and Ledwich, 2005; Trojanowska, 2014).

In 2010, around 50% of the population lived within 50 kilometres of the central grid, with around two thirds of this population actually being connected. Furthermore, a study on rural Kenya concluded that a substantial portion of the population without electricity access lives 'under grid', meaning that they are close enough to connect to a low voltage line at a relatively low cost (Lee et al., 2016). This is reflected in the three baseline scenarios. More than 99% of the newly connected population in the Republic of South Africa, a country that already has an extensive network of high voltage power lines, is projected to be connected to the grid. In western & central Africa and in eastern Africa, where the current network of high voltage power lines is less extensive, this is around 90% to 95%.

Strong population growth, a significant increase in electricity access and higher household incomes push up electricity demand. Even without achieving the universal access target, total residential electricity demand is projected to increase from 90 TWh in 2010 to 250–280 TWh in 2030 (Figure 3.5; left). After 2030, the range over the three scenarios widens, largely due to diverging socio-economic trends. The differences in projected household consumption levels between the four regions are large (Figure 3.5; right). For example, in 2030, average electricity consumption in the Republic of South Africa is projected to be ten times greater than in eastern Africa.

Figure 3.6
Levelised cost of electricity (LCOE) for central grid, per technology, under SSP2 baseline scenario



Source: PBL

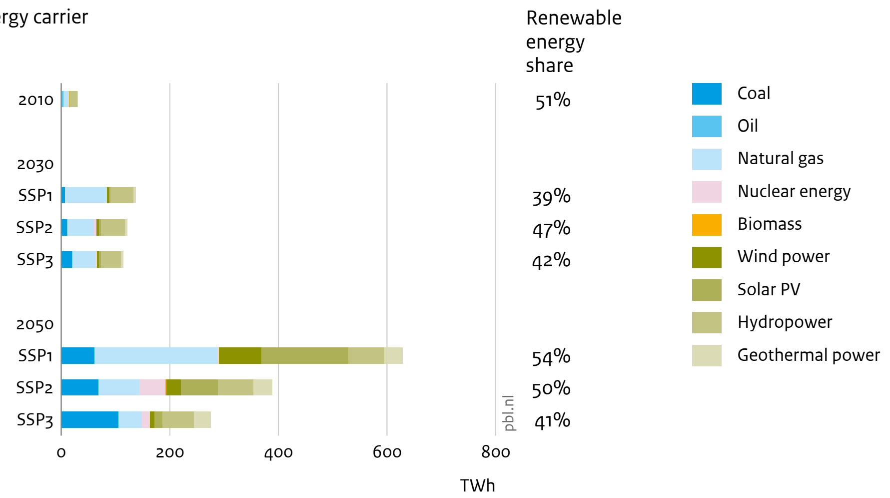
3.2.3 Renewable energy shares

The energy mix is largely determined by the relative prices of different technologies. A good indicator for comparing the cost of electricity generation is the levelised cost of electricity (LCOE); in other words, the ratio of discounted lifetime costs of a technology to discounted lifetime electricity generation. The LCOE is the average price per unit of output needed for the plant to break even over its operating lifetime, and depends on the technology, the location, the type of energy source, capital and operation costs, and the efficiency of the technology (IRENA, 2016). Prices of renewable power generation technologies, in particular solar PV and wind power, have decreased significantly over the past decades, largely driven by innovation in technology and policy (IRENA, 2017). The model projection shows a continuation of this trend, with renewable energy technologies, especially solar PV and wind power, becoming increasingly competitive with fossil fuels for electricity generation over the coming decades (Figure 3.6). Wind energy prices are especially low in eastern Africa, where the largest single wind power project in Africa, the Lake Turkana Wind Power Project, is being built. Hydropower and coal-based electricity production remain cheap, while prices of oil- and gas-based electricity production are projected to increase over time.

Although the 2010 electricity mix differs significantly between the regions, fossil resources are prominent in all four. Coal is the dominant fossil fuel in the Republic of South Africa, natural gas in western Africa, and oil in eastern Africa and the rest of southern Africa. Next to fossil fuels, hydropower also takes a significant share of the electricity production in all regions, except for the Republic of South Africa. Towards 2030, oil is almost completely phased out, while the use of coal, natural gas and hydropower increases significantly, with large differences over the four sub-regions (Figures 3.7–3.10).

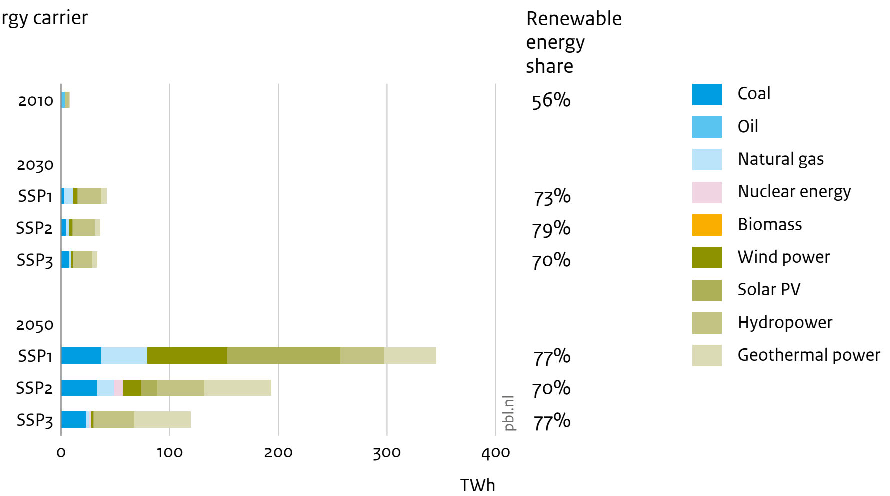
The construction of large dams for hydropower or water supply has contributed significantly to the socio-economic development of some African countries (Alhassan, 2008). However, there are also significant controversies around their development, especially with respect to potential adverse environmental and related social impacts (Ledec and Quintero, 2003). Large dams can change the ecological and physical characteristics of a river. Furthermore, reservoirs may cover important natural, agricultural and cultural areas and may result in the relocation of people. The physical impacts of a dam and reservoir, the operation of the dam, and the use of the water can change the environment over a much larger area than the area covered by a reservoir, including downstream communities and countries. Furthermore, insufficient compensation to people adversely affected or dislocated and the subsequent lack of economic perspectives to many rural communities have been among the most common

Figure 3.7
Electricity production for the residential sector in western & central Africa, per baseline scenario



Source: PBL

Figure 3.8
Electricity production for the residential sector in eastern Africa, per baseline scenario



Source: PBL

socio-economic problems (Nüsser, 2003). These controversies are not included in our projections.

The differences between the three baseline scenarios are relatively small. The SSP1 baseline scenario, which aims for sustainable development, shows slightly stronger growth in the use of natural gas. The SSP3 baseline scenario, which is heading towards a more fragmented world, shows stronger growth in coal use. Towards 2050, the growth in electricity consumption accelerates, with increasing differences between the three baseline scenarios. The large growth in electricity demand in the SSP1 baseline scenario is more than compensated by a strong growth in solar PV and wind power. Developments in renewable energy shares differ largely over the four sub-regions.

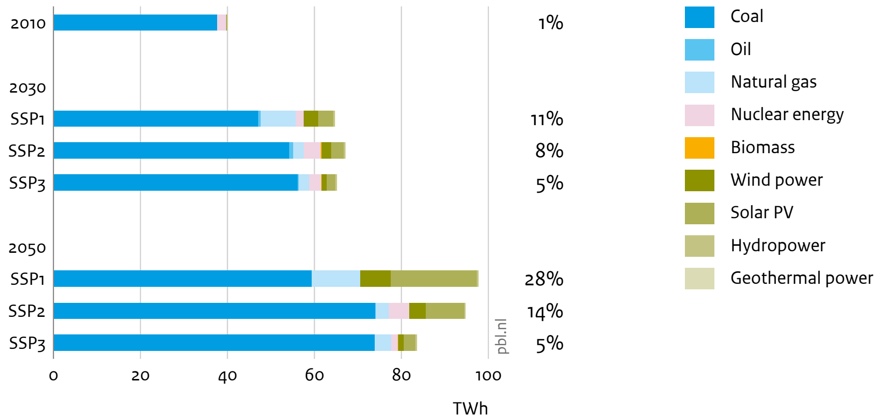
Western & central Africa

Western & central Africa currently relies for 51% on fossil fuels, particularly natural gas. Nigeria and Equatorial Guinea are amongst the top five natural gas producers in Sub-Saharan Africa, while Ghana and Côte d'Ivoire also have significant gas reserves. However, the region also

Figure 3.9
Electricity production for the residential sector in the Republic of South Africa, per baseline scenario

Per energy carrier

Renewable energy share

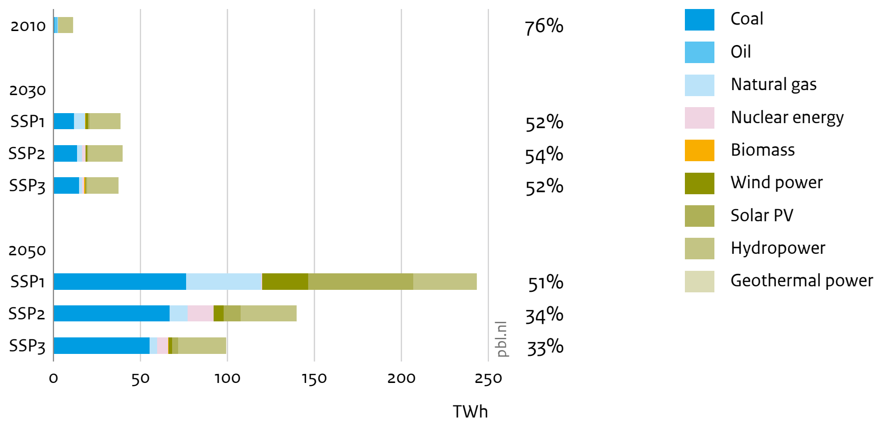


Source: PBL

Figure 3.10
Electricity production for the residential sector in the rest of southern Africa, per baseline scenario

Per energy carrier

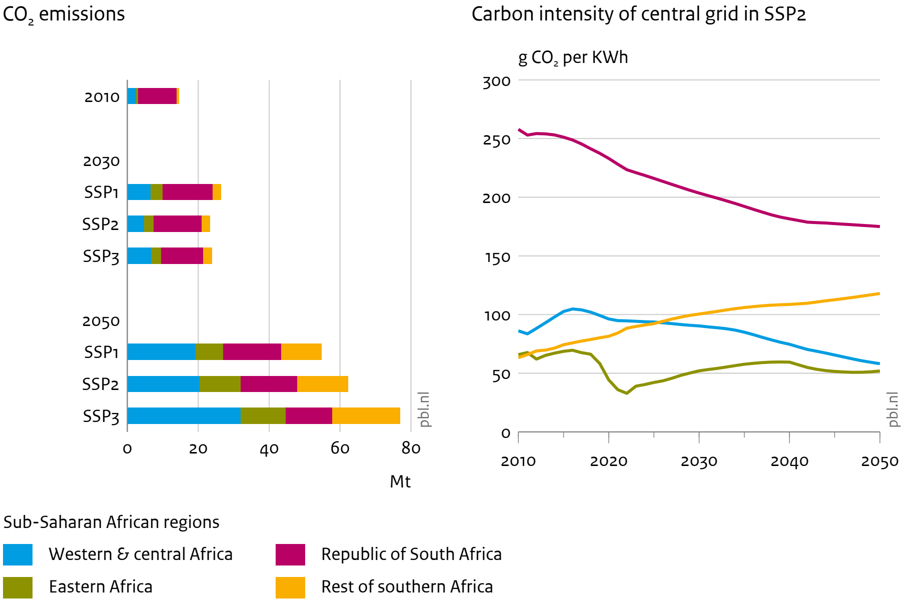
Renewable energy share



Source: PBL

has high potential for renewable energy production, including hydropower, solar PV and wind power.
The Democratic Republic of Congo is building the huge Grand Inga hydropower station, estimated to add 44GW to the region's installed capacity. Many other countries have large untapped hydropower potential. The large potential for both natural gas and hydropower shape the projected future of the electricity sector. However, the shares of coal (mostly imported), solar PV and wind power are projected to increase, starting from a very low level. Overall, the share of renewable energy in the total electricity production is projected to decrease, from 51% in 2010 to between 39% and 47% by 2030, mainly due to a higher share of natural gas. Towards 2050, the renewable energy share increases again, largely due to an increased use of geothermal energy. The installed capacity of hydropower does not increase much after 2030 as most of its potential is already being exploited by 2030. Solar PV and wind energy only become prominent in the SSP1 baseline scenario, in which a large increase in demand takes place with a focus on more sustainable electricity production.

Figure 3.11
Electricity-related CO_2 emissions and carbon intensity in residential sector, per baseline scenario



Source: PBL

Eastern Africa

Eastern Africa is one of the regions with the highest renewable energy potential in Sub-Saharan Africa, especially with respect to hydropower. The planned and ongoing hydropower projects in Ethiopia alone are estimated to add up to 15GW to the region's installed capacity (for example, the installed capacity of the two hydropower projects GERD and Koysha is 8.2GW combined). Several countries in the region, particularly Ethiopia, Tanzania, Kenya and Uganda, have a high proportion of hydropower in their generation mix.
The share of renewable energy in the total electricity production is projected to increase significantly, from 56% in 2010 to between 70% and 79% by 2030. Hydropower provides the lion's share of additional electricity generation, accounting for more than 50% of the electricity generation mix in 2030. At the same time, the use of coal and especially natural gas also increases fast, starting from a very low base level. The recent natural gas discoveries in Kenya and Uganda are the main cause of this. Towards 2050, the increase in installed capacity of hydropower is projected to slow down, while geothermal becomes a prominent source.

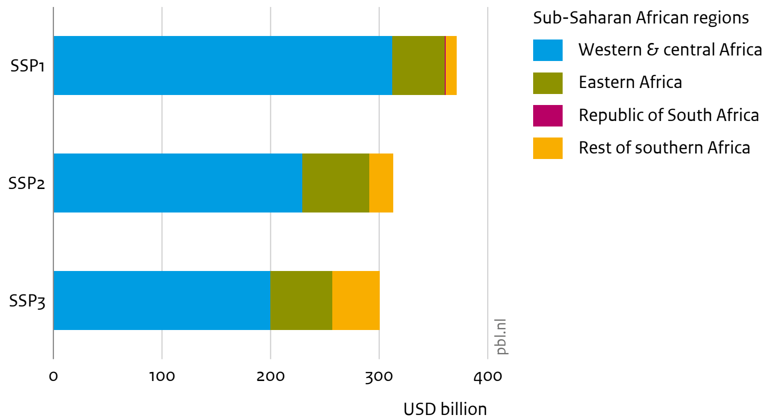
Republic of South Africa

Around 95% of the proven coal reserves in Sub-Saharan Africa are situated in the Republic of South Africa. This is also reflected in its electricity generation mix. In 2010, 99% of total electricity production was based on coal. Although this share is projected to decline, by 2030 around 90% of total electricity production is still projected to come from coal. Overall, the share of renewable energy in total electricity production is projected to increase significantly, from less than 1% in 2010 to between 5% and 11% by 2030, mainly due to a large increase in the use of solar PV and wind power. Hydropower is almost non-existent in the region's current and projected future generation mix.

Rest of southern Africa

The rest of southern Africa is well endowed with both fossil and renewable energy resources. Mozambique and Botswana have large coal reserves, while Mozambique, Tanzania, Angola and Namibia have large natural gas reserves. New coal-fired power plants are either under construction or proposed in Tanzania, Mozambique, Namibia, Zimbabwe and Botswana. However, most countries, especially Malawi and Zimbabwe, also have large solar PV and wind energy potential.
Furthermore, Angola, Mozambique, Zambia and Zimbabwe have considerable untapped hydropower potential. In 2010, 76% of the total electricity production came from renewable energy sources, primarily large-scale hydropower, with the remainder being a mix of coal, oil and natural gas. Towards 2030, the model projections show a phase-out of oil, similar to in the other regions, while the share of natural gas and coal increases much faster than that of renewable energy sources. As a result, the share of renewable energy in the total electricity production is projected to decrease to between 52% and

Figure 3.12
Cumulative investments in electricity generation capacity, transmission and distribution, per baseline scenario, 2010 – 2030



Source: PBL

54% by 2030. This trend continues towards 2050, with a large increase in coal use in particular. Only in the SSP1 baseline scenario, which focuses more on sustainable development, does the renewable energy share remain around 50%. In the other two scenarios, the further increase of coal use results in a further decrease of the use of renewable energy resources to around one third of total production.

3.2.4 CO_2 emissions

As a result of the increasing share of renewable energy in the electricity mix, a switch from oil to gas and the use of more efficient coal- and gas-fired power plants, the carbon intensity of grid-based electricity production is projected to decrease in western & central Africa and the Republic of South Africa. In the rest of southern Africa, the increasing use of coal pushes the carbon intensity up. As residential electricity demand is projected to grow faster than improvements in the carbon intensity, total residential electricity-related CO_2 emissions are projected to increase by 60% to 80% between 2010 and 2030 and by 100% to 220% between 2030 and 2050 (Figure 3.11). After 2030, western & central Africa is projected to overtake the Republic of South Africa as the largest emitter of CO_2 emissions from residential electricity use in Sub-Saharan Africa. Despite this relatively large increase in CO_2 emissions, the share of Sub-Saharan Africa in global electricity-related emissions remains very small: 0.5% in 2030 and 0.8% to 1.4% in 2050.

3.2.5 Investment requirements

The projected expansion in installed capacity and transmission and distribution networks requires large infrastructure investments. Total 2010–2030 cumulative investments are projected in the order of USD 300–350 billion, representing an average of USD 15–19 billion, per year (Figure 3.12). This is about twice the current level of annual infrastructure investment (Brahmbhatt et al., 2016). Recurring costs such as for fuels and operation and maintenance are projected to be on average USD 5 billion, per year. By far the highest investment requirements are for western & central Africa, where 55% of the newly connected population lives. The region requires investments for the refurbishment of existing power plants, significant capacity addition to meet the growing electricity demand, and an extension of the high voltage transmission and distribution network to provide electricity to more than 50% of the newly connected population. In contrast, total investment requirements in the Republic of South Africa are relatively low. The country already owns an extensive grid, to which a large share of the population is connected; therefore, the projected investments are mostly for expanding generation capacity.

3.3 Projected progress towards achieving the targets

Universal access to electricity in 2030 is not achieved
Our model projections show a significant improvement in the number of people who gain access to electricity towards 2030 and 2050, mostly by extending the central grid. Between 2010 and 2030, around 530–600 million people are projected to gain access. During the same period, total electricity demand is projected to triple. The required 2010–2030 cumulative investment in generation capacity and transmission and distribution networks is projected to be around USD 300–350 billion,

representing an average of USD 15–19 billion, per year. Despite these investments, 350–600 million people are projected to still have no access to electricity by 2030, 90% of whom in rural areas. Thus, the target of universal electricity access by 2030 is projected not to be met without additional policies.

A doubling of renewable energy shares in 2030 is not achieved

Sub-Saharan Africa is well endowed with both fossil and renewable energy resources, with significant differences between the four sub-regions. The model projections show large increases in electricity production from both fossil fuels (coal and natural gas) and renewable resources such as large-scale hydropower and, after 2030, solar PV and wind power. Renewable energy shares are projected to increase only slightly in eastern Africa – primarily due to larger than average growth in hydropower capacity – and the Republic of South Africa, where solar PV and wind energy become more prominent. In western & central Africa and the rest of southern Africa, the renewable energy shares are projected to remain constant or even decrease due to a strong increase in the use of natural gas and coal, respectively. In short, the target of doubling the share of renewable energy in total residential electricity consumption is projected not to be achieved, with some regions even showing a decline.

Electricity-related CO_2 emissions at least double between 2010 and 2050, but remain very small on a global scale

Despite the large increase in renewable energy production, electricity-related CO_2 emissions in the residential sector are projected to grow by 60% to 80% between 2010 and 2030 and by 100% and 220% between 2030 and 2050. The largest increase is projected for western & central Africa, with 290–310 million people gaining access to electricity, primarily through a grid connection, and with electricity predominantly being generated by natural-gas-fired power plants.
Overall, the Sub-Saharan African share of residential electricity emissions in global electricity-related emissions increases, but remains very small: only around 0.5% in 2030 and less than 0.8% to 1.4% in 2050.

FOUR

Universal and renewable electricity access

Providing electricity access to an additional 350–600 million people is a big challenge, requiring further expansion of generation capacity and extension of transmission and distribution networks. In this chapter, we assess the technology and investment requirements for achieving a universal and renewable electricity system in Sub-Saharan Africa. We discuss important determinants for selecting the most appropriate electrification technology, either fossil or renewable and grid-based or off-grid, and assess the role of global climate policy.

4.1 Determinants for on-grid or off-grid electrification

Traditionally, electrification in developing countries has largely been regarded as the responsibility of governments and has been implemented by national utilities with natural monopolies (Scott and Seth, 2013). Governments have focused on extending the central grid to benefit from economies of scale (Banerjee, 2006; Pachauri and Brew-Hammond, 2012). However, the emphasis on the grid has caused alternative off-grid solutions (mini-grids and stand-alone systems) to be overlooked, which has hampered the rapid spread of electricity infrastructure to large parts of the developing world (Pachauri and Brew-Hammond, 2012). As a result, and despite substantial efforts to extend central grids, the electrification rate in Sub-Saharan Africa has barely kept up with population growth (Ahlborg and Hammar, 2014). The diversification of electrification solutions could play an important role in increasing access, especially in sparsely populated rural areas far from the central grid (Pachauri and Brew-Hammond, 2012).

Choice of electrification system depends on a range of, mostly local, factors

Grid-connected and off-grid systems have their own advantages and disadvantages (Table 4.1). Given the limited financial resources and the many competing priorities in most Sub-Saharan African countries, the choice between systems strongly depends on the price per kWh and maintenance requirements (Palit and Chaurey, 2013). Regional electricity prices reflect the costs of building, maintaining and operating power plants, transporting the electricity from the power plant over long distances (requiring a transmission network which includes high voltage transmission lines and step-up transformers), and distributing electricity to and within communities (requiring medium and low voltage distribution networks, sub-stations, step-down transformers and household wiring and metering). Electricity prices are influenced by a range of factors, including the type of fuel used for electricity generation, the type of power plant (fossil combustion turbines, for instance, have lower capital costs but higher operation and maintenance costs compared to a large-scale hydropower facility) and the required transmission and distribution network. Key determinants for choosing between electrification systems include – in addition to the costs of the individual technologies themselves – distance to the central grid, demand density (population density, household electricity demand) and local resource availability, in particular renewable energy potential for wind power, solar PV and hydropower (including mini-hydropower).

Off-grid electrification systems are most relevant in remote areas, far from the grid …

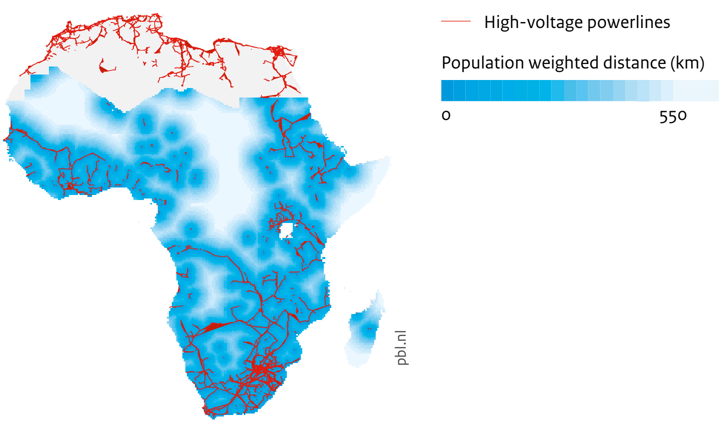
Transmission and distribution costs are an important factor in the choice between off-grid and on-grid electrification (Table 4.2). High voltage transmission lines are responsible for the bulk of the grid investments.

Table 4.1
Definitions of electrification systems

Type	Definition	Advantages	Disadvantages	Technologies included in analysis
On-grid system	All network or sub-grid or generating systems that are connected to the grid and run by national utility	High degree of reliability, cheaper USD/kWh[1] than other options when density and/or consumption is high	High initial investment, very high USD/kWh in low population density or consumption areas	Oil, coal, natural gas, nuclear, biomass, hydropower, solar PV, concentrated solar power, onshore wind, offshore wind
Mini-grid system	System where all or a portion of the produced electricity (by any source) is fed into a small distribution grid which provides several end users with electricity. A mini-grid system can be either isolated or connected to the centralised grid	Enhance local-level ownership of O&M, social control over power theft, better reliability than stand-alone systems, easy adaptability, more cost-effective than grid extension over large distance, reduced distribution loss	Frequent technological failure from lack of maintenance, untested technology, lack of local skills for maintenance. Insufficient capacity due to poor assessment, increasing demand, seasonal resource fluctuation, demand management	Diesel generator, solar PV, wind power, small hydropower, hybrid PV- diesel, hybrid wind- diesel
Stand-alone system	Isolated power system that usually supplies one rural user without a distribution grid (e.g. household, community infrastructure, battery charging station, multifunctional platform, water pumping station)	User-managed on day-to-day basis, blackouts affect only one user	Limited capacity, lack of maintenance capacity at household level	Solar home systems, diesel generator

[1] Kilowatt-hour
Source: DFID (2013)

Figure 4.1
Distance from central grid, 2010



Source: PBL; OpenStreetMap 2015

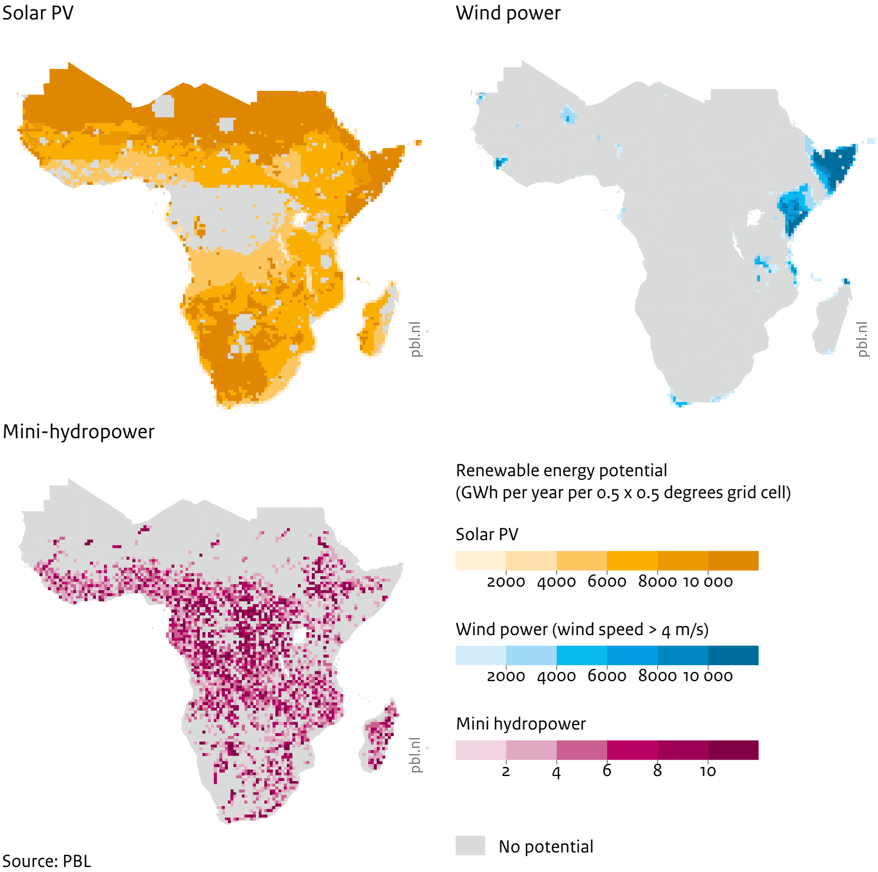
Distance to the central grid is thus an important determinant for choosing between electrification systems (Figure 4.1). If the distance is low, delivering electricity through the established grid is often cheaper than off-grid options. In addition, central power plants benefit from economies of scale. Extending high voltage transmission lines could be attractive in high density, high electricity-demand countries like Nigeria, but less economically feasible in countries with a low population density and electricity demand, such as Ethiopia. IEA projections show that annual investments in transmission and distribution in Sub-Saharan Africa will significantly increase by 2040 and, in total, could outpace those for new power generation capacity over the same

Table 4.2
Cost assumptions for transmission and distribution

	Cost (in USD)
High voltage transmission lines (132 kV line)	28,000 per kilometre
Medium voltage transmission lines (33 kV line)	9,000 per kilometre
Low voltage transmission lines	5,000 per kilometre
Transformers	5,000 per unit
Metering and wiring	100 per household

Source: Levin and Thomas (2016); Nerini et al. (2016); Taliotis et al. (2016)

Figure 4.2
Renewable energy potential in Sub-Saharan Africa



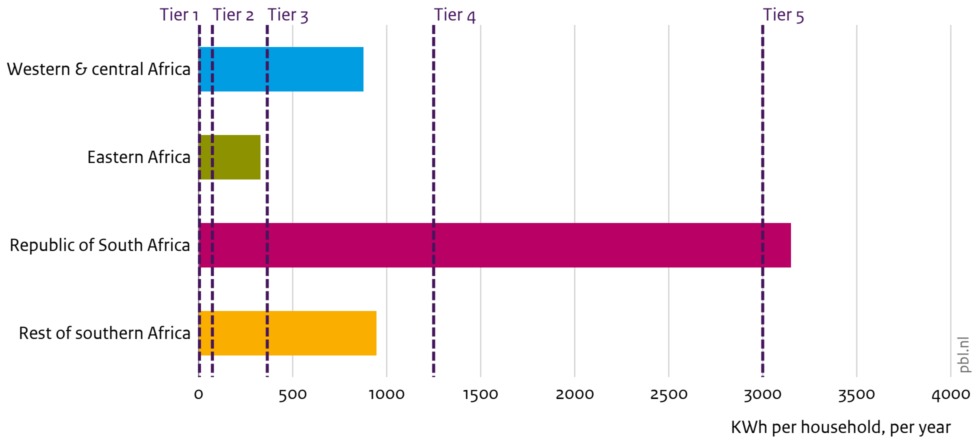
Source: PBL

For solar PV and wind power potential, agricultural areas are partly excluded, while protected areas, forest areas and urban areas are fully excluded.

period (IEA, 2014). However, extending the grid to remote areas can be very expensive and long distance transmission lines can experience high technical losses (IEA, 2011). Mini-grid systems do not require expensive transmission lines but they do require distribution networks involving medium voltage and low voltage lines, as well as household wiring and metering. Stand-alone systems, on the other hand, require only household wiring and metering.

… in locations where the demand density is low …
Population density and household electricity demand together determine the electricity demand density (defined as total demand per square kilometre), which is another important factor in the relative attractiveness of off-grid electrification options. Communities with a high population density have in general low transmission and distribution costs per square kilometre, making grid extension more

Figure 4.3
Annual household electricity consumption, under SSP2 baseline scenario, 2030



Source: PBL

attractive than off-grid options (Nerini et al., 2016). In low population density areas, electricity transmission and distribution costs are shared by relatively few people, resulting in higher costs per unit of electricity consumed (World Bank, 2010). Most rural communities, as well as many peri-urban areas, are characterised by low population density. The average population density in Sub-Saharan Africa was 41 inhabitants per km² in 2014 (ranging from 3 in Namibia to 440 in Rwanda). Moreover, average electricity demand is often low in rural areas, due to socio-economic factors such as household income, age structure, standard of living, dwelling type and size, the cost of competing or substitute services, and the cost of appliances (Bhattacharjee and Reichard, 2011). Low electricity demand makes off-grid options, and specifically stand-alone systems, more attractive. Mini-grids fall between on-grid and stand-alone systems and are an attractive option for communities far from the central grid but with a relatively high population density and/or household electricity demand.

... and in areas with high energy resource availability
Off-grid systems are smaller in size compared to grid-connected systems and do not need extensive transmission and distribution networks for transporting power. Off-grid systems use locally available resources to avoid reliance on imported/transported fuels and are deployed close to the load centre. Local resource availability thus plays an important role when choosing an off-grid technology. Sub-Saharan Africa is richly endowed with renewable energy resources (Figure 4.2). The technical potential for solar PV exceeds 100PWh per year (Hoogwijk, 2004) and the highest potential for wind energy is located in eastern Africa, with a total capacity more than 300 times its current electricity consumption (Hoogwijk, 2004). Similarly, the whole of Sub-Saharan Africa has a significant potential for hydropower, with the ratio of available generation capacity to technically feasible capacity ranging from 8% in eastern Africa to 19% in western & central Africa (IRENA, 2012). Finally, the region has many rivers and streams with great potential for mini-hydropower development (<10MW), with less than 15% already installed (Liu et al., 2013).

4.2 Technology and investment requirements for achieving universal electricity access

4.2.1 On-grid and off-grid electricity access

As discussed in Section 4.1, the future level of household electricity demand is highly relevant for infrastructure planning and development. For the middle-of-the-road SSP2 baseline scenario, the average household electricity demand in Sub-Saharan Africa is projected to increase significantly, reaching 2030 levels halfway between Tier 3 and Tier 4, with large differences over the four regions (Figure 4.3). Average household electricity demand in eastern Africa is projected to reach 2030 levels around Tier 3, allowing for the use of medium power appliances, including televisions and rice cookers. In western & central Africa and the rest of southern Africa, electricity demand reaches 2030 levels halfway between Tier 3 and Tier 4, allowing the use of medium power to high power appliances, including washing machines and microwaves. Finally, the Republic of South Africa reaches 2030 demand levels of around Tier 5, allowing the use of very high power appliances, including electric cookers and air conditioning units.

Table 4.3

Total residential electricity demand in 2030 with universal electricity access under different assumption of household electricity demand, based on SSP2 baseline scenario

Scenario variant	Household electricity demand from the additionally connected households (kWh/hh/year)	Total electricity demand from the additionally connected households (TWh/year)	Total residential electricity demand (TWh/year)
SSP2_Tier-1	4.5	0.6	267
SSP2_Tier-2	73	9	275
SSP2_Tier-3	365	49	315
SSP2_UA	328–3150[1]	64	330

[1] Range over the four regions of the SSP2 baseline scenario. The low value is for eastern Africa and the high value for the Republic of South Africa

Table 4.4

Additionally connected population (in millions) with an off-grid connection in 2030 for the SSP2 baseline scenario with universal access and different levels of household electricity demand

Scenario variant	Western & central Africa	Eastern Africa	Republic of South Africa	Rest of southern Africa	Sub-Saharan Africa
SSP2_Tier-1	51 (47)	36 (33)	1 (0)	22 (18)	110 (98)
SSP2_Tier-2	26 (23)	17 (15)	0 (0)	9 (8)	53 (46)
SSP2_Tier-3	5 (3)	1 (0)	0 (0)	0 (0)	6 (3)
SSP2_UA	5 (3)	13 (11)	0 (0)	2 (1)	19 (15)

Numbers between brackets are the total population connected with stand-alone systems.

Households connected for the first time are likely to have much lower consumption levels. Earlier studies used household consumption levels of 250 kWh per household per year in their analyses, which is in between Tier 2 and Tier 3 (Szabo et al., 2011; IEA, 2014). In our analysis of the technology and investment requirements, we focus on providing access to electricity for households that were not connected in 2030 in the SSP2 baseline scenario. We account for the uncertainty in the electricity consumption of these additionally connected households by including different levels of consumption: the SSP2 baseline consumption level and tier-based consumption levels (see also Section 2.3). The tier-based analysis is limited to the first three tiers as the projected household electricity consumption in three of the four regions does not reach a Tier 4 consumption level by 2030 in the SSP2 baseline scenario.

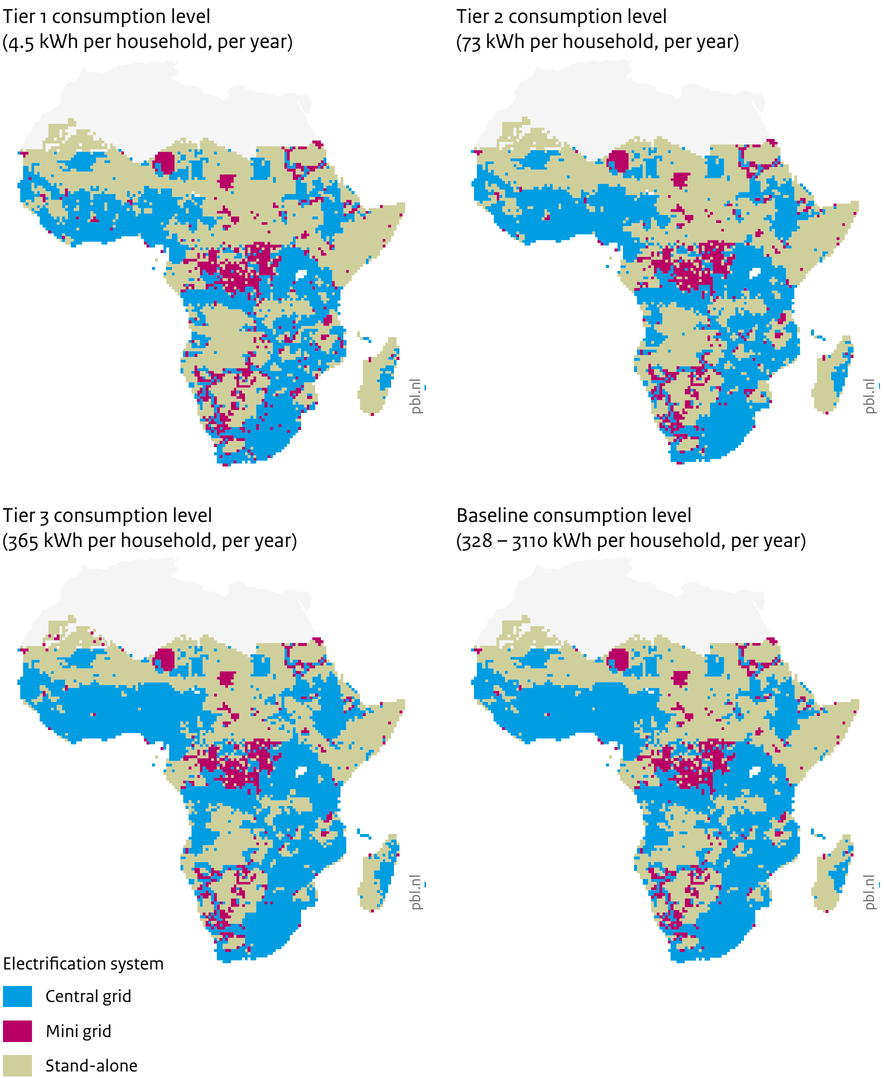
Depending on the assumed electricity consumption level for the additionally connected households, total 2030 residential electricity consumption increases by 0.25% for Tier 1, and 18% for Tier 3, compared to the levels under the SSP2 baseline scenario (Table 4.3). Assuming very optimistic consumption levels for the additionally connected households, similar to those of households already connected under the SSP2 baseline scenario, the total 2030 residential electricity demand increases by 25%.

Off-grid electrification systems are projected to be the least-cost option for 1% to 22% of the additionally connected population, depending on the assumed electricity consumption level (Table 4.4 and Figure 4.4). It should be noted that, in the SSP2 baseline scenario, 500 million people are already projected to gain access to electricity in 2030, including 5% to 10% through off-grid systems (Section 3.2.2). Furthermore, the projected extension of the grid brings the population that does not gain access in the SSP2 baseline scenario closer to the grid. In eastern Africa and parts of western & central Africa, where people live relatively dispersed, the projected share of off-grid systems is larger than in the other regions. Assuming Tier 1 levels of consumption, solar home systems are the least-cost option for almost 90 million people in these two regions. Although they do not allow the use of high power appliances, solar home systems provide a cleaner and better-quality alternative to kerosene lanterns, and also allow mobile phone charging.

4.2.2 Renewable energy, CO_2 emissions and the role of climate policy

The choice of electrification system largely determines the additional generation capacity. Off-grid electrification technologies include mini-grid systems based on mini-hydropower, solar PV and wind power, potentially in combination with a diesel generator, and stand-alone systems based on solar PV panels or diesel generators

Figure 4.4
Least-cost electrification systems under SSP2 baseline scenario with universal electricity access, 2030



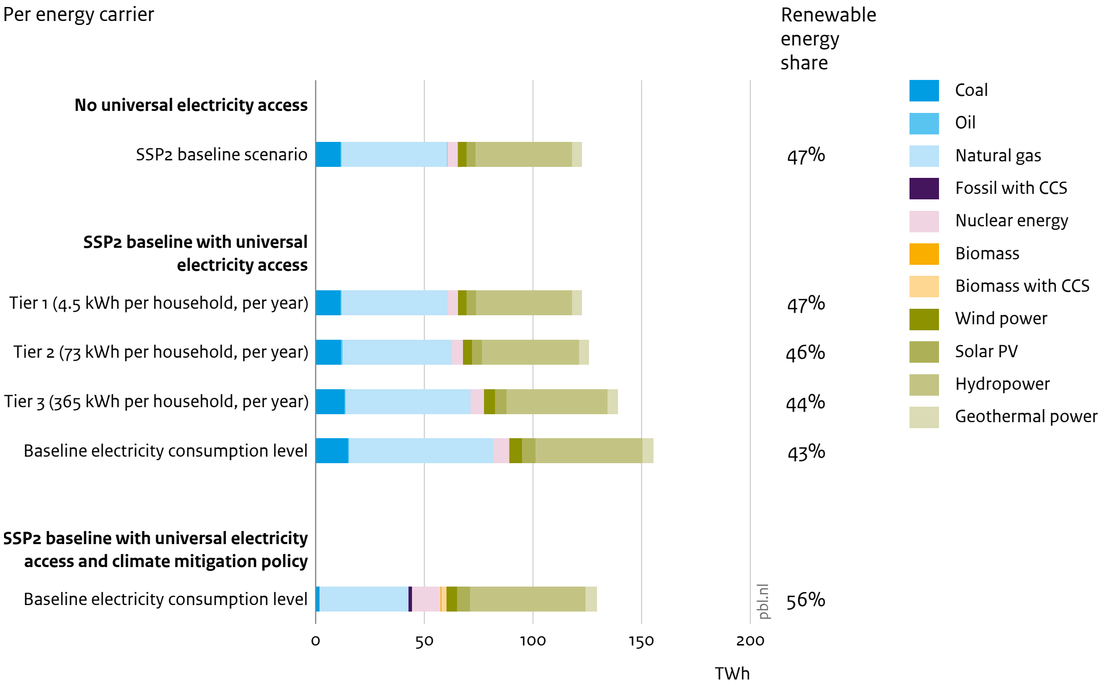
Source: PBL

Decentralised electrification systems play a crucial role in providing access to electricity to poor communities far from the central grid.

(Table 4.4). Renewable-based off-grid generation is largely dependent on local resource potential, which is not the case for grid-based systems. For those households that gain on-grid access, which is the largest share of the population in our projections, additional generation capacity is mostly a scaling-up of existing capacity. For western & central Africa, this is primarily natural gas and hydropower; for eastern Africa hydropower, coal and natural gas; for the Republic of South Africa, primarily coal; and in the rest of southern Africa, coal and hydropower.

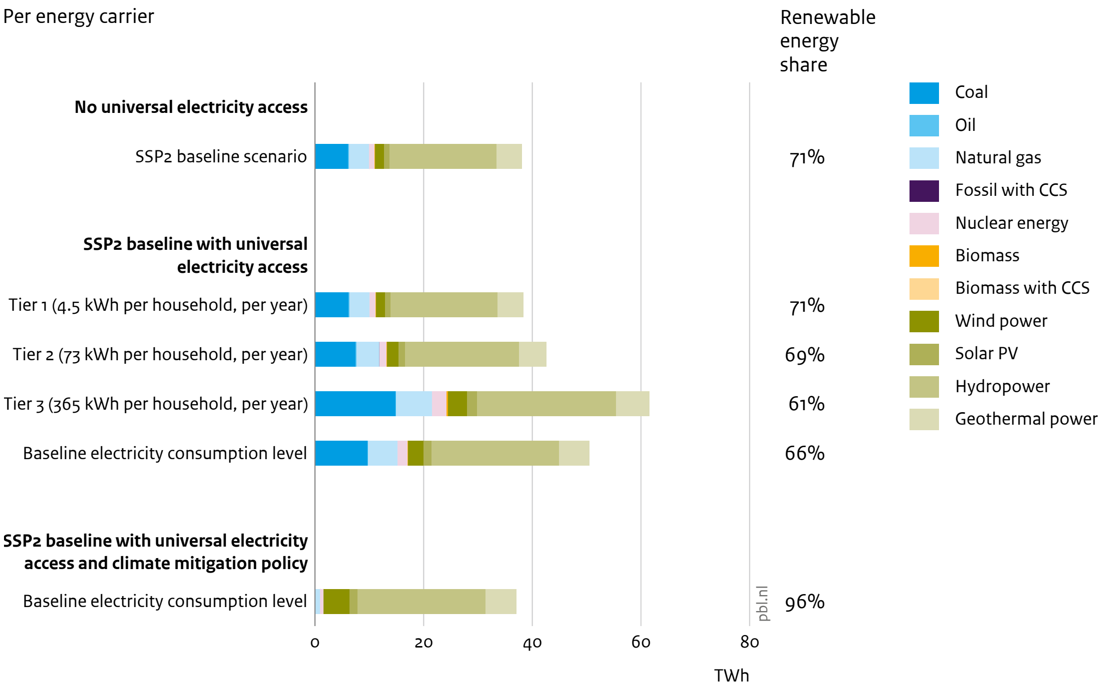
The electricity mix is highly dependent on the level of household electricity consumption (Figures 4.5 to 4.8). At Tier 1 levels of consumption, where the off-grid share (consisting mostly of solar home systems) is relatively large, additional demand is very small. Therefore, the renewable share is only marginally different from a situation in which universal access is not targeted. Assuming the very ambitious SSP2 baseline level of consumption for the additionally connected households, the share of renewable energy in the electricity mix is projected to decrease in all regions, on average, by five

Figure 4.5
Electricity production for the residential sector in western & central Africa, 2030



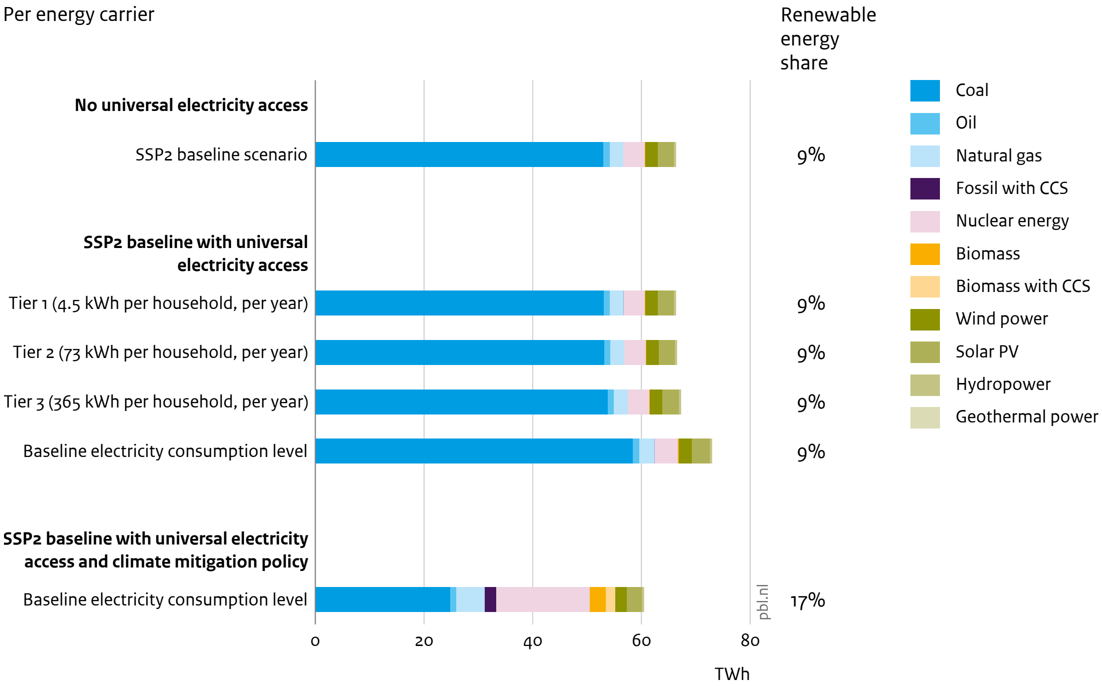
Source: PBL

Figure 4.6
Electricity production for the residential sector in eastern Africa, 2030



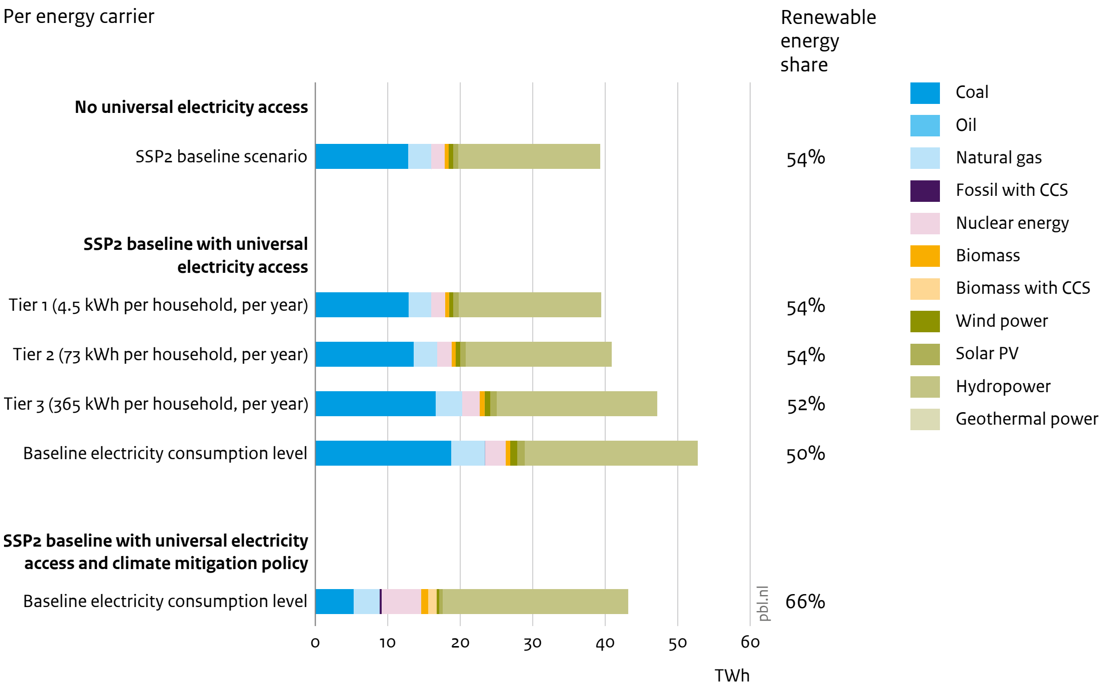
Source: PBL

Figure 4.7
Electricity production for the residential sector in the Republic of South Africa, 2030



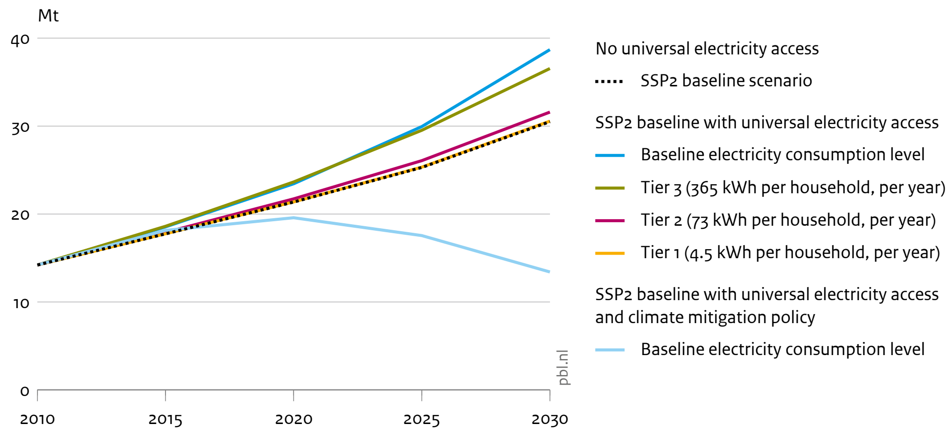
Source: PBL

Figure 4.8
Electricity production for the residential sector in the rest of southern Africa, 2030



Source: PBL

Figure 4.9
Electricity-related CO_2 emissions in residential sector



Source: PBL

percentage points. Only in the Republic of South Africa does the electricity mix not change much, as the projected additional electricity demand is relatively small and the energy mix is already dominated by coal.

Overall, achieving universal electricity access is projected to lead to an increase in total CO_2 emissions from residential electricity consumption of 0.2% to 27% by 2030 (Figure 4.9). This increase is negligible, as it is only 0.001% to 0.2% of global electricity-related emissions.

In the climate policy scenario, we assume for simplicity that carbon emissions are taxed globally, in order to achieve the long-term climate target of holding the global average temperature increase to well below 2 °C above pre-industrial levels with a probability of more than 66%. The tax trajectory is taken from the IMAGE implementation of a 2 °C scenario (SSP2-2.6), and amounts to 43 USD/tCO_2 by 2020, increasing to 110 USD/tCO_2 by 2030 (Van Vuuren et al., 2017). The carbon tax induces a reduction in the use of fossil fuels and a more rapid development of low carbon electricity generation technologies, including renewable energy. Furthermore, it stimulates energy savings in the form of improved appliance efficiency, resulting in decreased electricity demand.

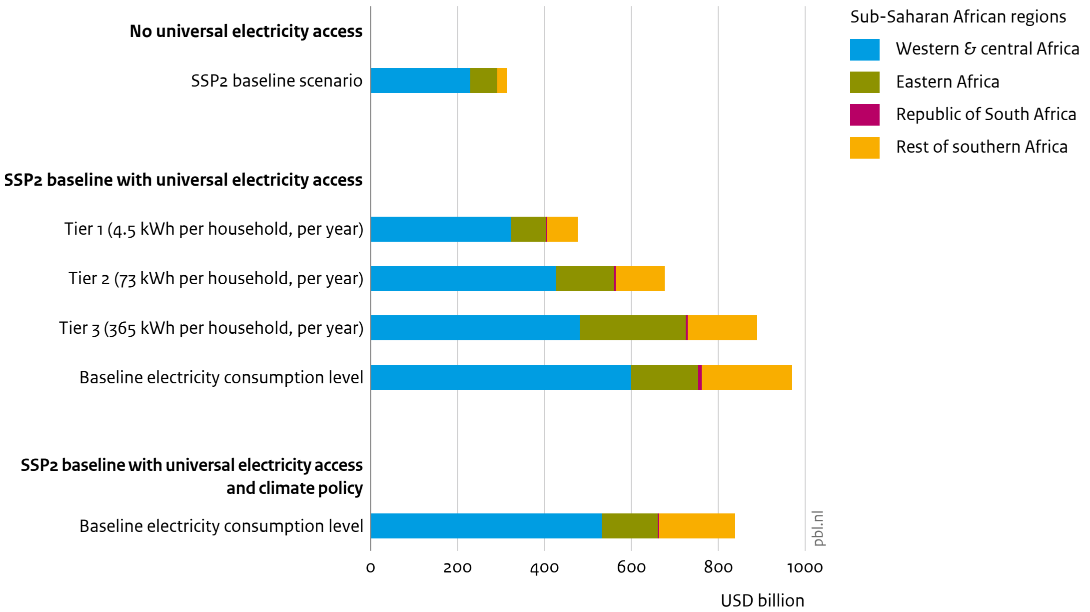
Assuming universal electricity access in 2030 with SSP2 baseline levels of consumption for the additionally connected households, a total electricity saving of around 20% in 2030 is projected. Furthermore, the role of natural gas and especially coal in the electricity mix is projected to decrease significantly, while total electricity production from renewable energy sources does not change much in this scenario. The model also projects a significant increase in nuclear energy, especially in the Republic of South Africa. Several countries in Sub-Saharan Africa have considerable uranium reserves and the Republic of South Africa has two nuclear power plants providing approximately 5% of its total electricity use. Still, due to its very high upfront capital costs and significant global security issues, nuclear power might not be the preferred low carbon technology. Therefore, nuclear power could be interpreted here as any other low-carbon energy technology, depending on regional availability.

Overall, the global carbon tax pushes Sub-Saharan Africa (back) onto a renewable energy pathway, especially when interpreting the projected nuclear energy shares as solar PV or wind power. In eastern Africa, where the renewable energy share is already high, it is projected to reach almost 100% in 2030, up from 58% in 2010. In the Republic of South Africa, the renewable share is also projected to increase significantly, from only 1% in 2010 to 17% by 2030. In western & central Africa and the rest of southern Africa, the global carbon tax compensates the projected decline in the renewable energy share when no global carbon tax is applied. Together, the electricity savings from improvements in the end-use efficiency of appliances and the phasing-out of fossil fuels, induce a total CO_2 emission reduction of 65% in 2030, bringing total residential emissions from electricity use back to 2010 levels (Figure 4.9).

4.2.3 Investment requirements

Achieving the universal access target will require a significant expansion in installed capacity and transmission and distribution networks. The corresponding investment requirements strongly depend on the level of household

Figure 4.10
Cumulative investments in electricity generation capacity, transmission and distribution, 2010 – 2030



Source: PBL

electricity consumption and the electrification system used (grid-based, mini-grid or stand-alone). Extending high voltage transmission and distribution networks requires large investments and is economically feasible only for high density and/or high consumption settlements. The total cumulative 2010–2030 investment requirements, including achieving the universal electricity access target, is projected at USD 480–970 billion, or USD 24–49 billion, per year (Figure 4.10). This includes generation capacity and transmission and distribution for the 500 million people that are projected to gain access to electricity without specific policies.

The largest investment requirements are projected for western & central Africa. Assuming a SSP2 baseline consumption level for the additionally connected households, an extension of the high and medium voltage transmission and distribution network is required for more than half of the additionally connected population, which involves large investment costs. In eastern Africa, around 20% of the additionally connected population requires an extension of the high and medium voltage transmission and distribution network. Assuming lower levels of consumption for the additionally connected households results in lower investment requirements in all regions, as less additional capacity is required. Furthermore, more off-grid systems, especially solar home systems, are the least-cost electrification option. They do not require capital-intensive high and medium voltage transmission and distribution networks.

In the global climate policy scenario, total investment requirements for achieving universal electricity access are projected to be 10% lower than under a universal access scenario without climate policy. This is mainly the result of the large energy savings from significant efficiency improvements in household appliances and more efficient electricity production. It should be noted that these reduced investment requirements do not take into account the costs from energy saving programmes, or the impact of a carbon tax on the economy itself.

FIVE

The way forward

The previous chapters analysed the technology and investment requirements for achieving universal and renewable electricity access in Sub-Saharan Africa. Here, we recap the main conclusions from this quantitative analysis and link them to governance and institutional challenges by discussing key issues for driving the transition.

5.1 Main conclusions from the quantitative analysis

Achieving universal electricity access in Sub-Saharan Africa requires significant scaling-up of power sector investments
The African electricity system is still in its infancy, with 65% of the population (more than 600 million people) not having access to electricity and a total generation capacity of just over 90 GW (comparable to that of the United Kingdom). However, due to projected economic progress, 530–600 million additional people are projected to have gained access to electricity by 2030, with total household electricity demand at least tripling between 2010 and 2030. The corresponding total investment in production capacity and transmission and distribution infrastructure is estimated at USD 15–19 billion, per year. Despite the projected increase in electricity access, achieving universal access requires connecting an additional 350–600 million people by 2030, who would otherwise remain unconnected. The total additional annual investment requirements for achieving universal electricity access are projected at USD 9–33 billion, depending largely on the assumed level of electricity consumption by the additionally connected households. These investment estimates are in line with the lower range of estimates in similar studies (Rai et al., 2016).

Decentralised electrification systems are key to reach out to remote rural areas
Of the 350–600 million people that are projected as not having access to electricity by 2030, more than 90% live in rural areas. Traditionally, national governments have focused on extending the central grid to benefit from economies of scale (Banerjee, 2006; Pachauri and Brew-Hammond, 2012). However, grid-based electrification is only an attractive option in densely populated areas, with an expected high demand for electricity, and/or within reasonable distance of existing high voltage power lines. Large parts of Sub-Saharan Africa do not satisfy these criteria, with large, sparsely populated rural areas in which many households have a very low income. Off-grid systems, including mini-grids and stand-alone systems, could play a vital role in bringing electricity to millions of people that live in areas that are too remote to be connected to the grid at a reasonable cost, especially as the electricity demand of these people is expected to be relatively low.
However, extending the transmission and distribution systems to cities and communities for which on-grid electrification is cost-effective also brings the grid closer to remote communities, thereby increasing the cost-effectiveness of grid connection compared to off-grid systems.

International climate policy can help Sub-Saharan African countries take a renewable energy pathway

Although not evenly distributed across the region, several Sub-Saharan African countries are well endowed with fossil fuel resources. For example, there is an abundance of coal in the Republic of South Africa as well as in the rest of southern Africa (Botswana, Mozambique and Zimbabwe), and there is natural gas in western Africa (Nigeria) and recently also in eastern Africa (Mozambique and Tanzania) and the rest of southern Africa (Angola). The same holds for renewable energy resources, with huge potential for PV all over the region, for large- and small-scale hydropower in all regions except the Republic of South Africa, and for wind power, especially in eastern Africa. Driven by technological innovation and renewable energy policies, the costs of renewable power generation technologies, in particular solar PV and wind power, have decreased significantly. Our model projections show a continuation of this trend, with renewable energy technologies becoming increasingly competitive with fossil fuels for electricity generation. Being a latecomer with respect to electrification not only comes with challenges, but also with opportunities, as a large part of the generation capacity still needs be built and the region can potentially profit from the renewable energy revolution (Collier and Venables, 2012). Even so, under business-as-usual assumptions, our model projections show large increases in both renewable and fossil electricity production. Such multiple energy trajectories are already being observed in several countries in Sub-Saharan Africa, such as Mozambique and the Republic of South Africa (Power et al., 2016).

Overall, around half of the projected growth between 2010 and 2030 will come from renewable energy sources, mostly large-scale hydropower. It should be noted that there are significant controversies around the development of large-scale hydropower, especially with respect to its adverse environmental and related social impacts. These controversies are not included in our projections. Achieving universal electricity access will further increase the use of fossil fuels, especially under optimistic assumptions on the electricity consumption of the additionally connected households. However, international climate policy – which in our analysis takes the form of a global price on carbon – can push the region onto a more renewable energy pathway. Apart from increased fossil fuel prices, international climate policy also induces energy savings through the improved end-use efficiency of appliances, thereby lowering the required expansion in generation capacity.

Achieving universal electricity access does not have to interfere with the 2 °C climate target

Sub-Saharan Africa's share in global CO_2 emissions is currently small. With 14% of the global population, the region is responsible for only around 5% of global CO_2 emissions (World Bank, 2016). Achieving universal electricity access increases total household electricity-related CO_2 emissions by 0.2% to 27% by 2030, depending on the electricity consumption level of the additionally connected households. This increase is negligible, as it is only 0.001% to 0.2% of global electricity-related emissions. Furthermore, access to electricity could also provide climate benefits. For example, switching from kerosene to electric lighting could reduce related climate forcing by a factor of ten due to the avoided black carbon emissions (Alstone et al., 2015). All in all, achieving universal electricity access hardly impacts global climate change, especially not when combined with a transition to a renewable energy electricity system.

5.2 Key issues for driving the transition

5.2.1 Targeting international climate finance for decentralised electricity access

Finance is an important piece of the puzzle in achieving universal access to electricity. In 2013, an estimated USD 13.1 billion in capital investment was directed towards improving access to modern sources of energy globally, 97% of which was directed at improving electricity access (IEA, 2016). Our model calculations project total investment requirements of USD 27–47 billion, annually, for the next 15 years, to achieve universal electricity access in Sub-Saharan Africa alone, which includes generation capacity and transmission and distribution for the 500 million people that are projected to gain access to electricity without specific policies. A significant scale-up of investments is thus required.

Public funding, both international and domestic, is an important source of finance in the initial stage of electrification projects (Glemarec, 2012). A significant proportion of the public funding goes to capacity development (such as research and development, planning, policies and regulations), community mobilisation and market creation. Private finance is relevant, among other things, for equity loans, consumer credit and micro-finance. However, low income energy markets carry high risks with low returns for the private sector. Public finance can reduce these risks and thereby attract additional sources of private finance, as well as fill in the funding gaps that the private sector cannot reach, such as very poor populations who cannot afford to pay a commercial rate for energy services. This is especially the case for many off-grid electrification projects.

The IEA estimates that around 45% of the future investment requirements will come from bilateral and multilateral sources (IEA, 2013). There is a broad range of international funding sources that could be channelled for electricity access, including Official Development Assistance, Multilateral Development Banks and climate-related funds (Glemarec, 2012; Gujba et al., 2012; UNEP, 2012). Governments of developed countries have committed to mobilise USD 100 billion, annually, from public and private sources by 2020, to help developing countries mitigate and adapt to climate change. Our model projections show that linking electricity access policies with international climate policy can help countries take a low carbon trajectory. The energy sector is already a big recipient of climate finance, but only a very small share (about 3%) has been allocated for decentralised electricity access (Rai et al., 2016). This is mainly due to challenges in the approval processes, the transaction costs associated with small projects, the need to achieve significant carbon savings, and the collapse in the price of carbon (Wilson et al., 2014). To increase the role of climate finance for electricity access, policymakers and practitioners could improve the targeting of international climate finance for decentralised energy access, strengthen the national enabling environment to incentivise decentralised energy access, and fill knowledge gaps and share lessons among low income countries in Sub-Saharan Africa (Rai et al., 2016).

5.2.2 Addressing the barriers to off-grid electrification projects

Achieving universal electricity access requires significant roll-out and scale-up of decentralised electrification options. Current shares of mini-grids and stand-alone systems in Sub-Saharan Africa are very small. In most African countries, the basis for development of the electricity system (generation capacity and transmission and distribution) has been a vertically integrated state-owned utility, with little or no autonomy to operate commercially (Scott, 2015). Furthermore, many countries have significant fossil fuel reserves and/or huge hydropower potential that deter national governments from pursuing renewable off-grid electrification options. Most of the current funding goes to medium and large-scale projects or to the maintenance and operation of existing power infrastructure (UNEP, 2012; Bhattacharyya, 2013; Tessama et al., 2013; IEA, 2016). Energy providers that do focus on off-grid electrification experience a range of partly overlapping financial barriers, as described below.

Lack of level playing field: New technologies and systems are seldom on an equal footing with established technologies. Rules, laws and systems have been built up over the last century primarily based on fossil fuel/centralised/large-scale systems. The lack of a clear national strategy for the energy sector, unequal tax burdens, a lack of incentives for renewable energy technologies and significant subsidies for fossil fuel-based energy technologies are factors that need to be addressed to create a level playing field for investors in medium and small-scale decentralised energy systems (Bhattacharyya, 2013; Rai et al., 2016). Governments need to have a clear vision on the future energy path of the country, including the expected role of renewable technologies. From the perspective of private sector financiers, setting clear and legally binding national targets for renewable energy technologies is crucial (UNEP, 2012). Such targets are a clear indicator for the private sector of the direction the country's energy future is heading in.

High risk perception: High risk perceptions make investment in decentralised electricity systems unattractive to private investors. These risks relate to sudden policy changes, unclear permitting procedures and off-grid investments becoming needless due to grid extension (Hussain, 2013). Uncertainties about the continuation of subsidies and around government support of renewable energy as well as fossil-based energy technologies strengthen the reluctance of financial institutes to fund decentralised systems. Similarly, uncertainties in grid extension plans and regulatory requirements are also challenges for private investors. Experience in India shows that extension of the grid to rural areas has often led to end-users abandoning the use of micro-/mini-grids (CLEAN, 2015). Furthermore, prior experiences with poor off-grid renewable energy products have made financial institutes concerned about the bankability of decentralised renewable energy technologies (CLEAN, 2015).

Low investment returns: Most decentralised electricity systems lack the ability to earn high returns (Hussain, 2013). As many poor households are dependent on seasonal harvest and/or ad hoc remittances, they have very irregular incomes and therefore are not able to guarantee pay back in instalments, let alone afford the high upfront cost of new technologies (Rai et al., 2016). Furthermore, poor households lack the financial capacity to purchase appliances and equipment, therefore initially consuming very low levels of electricity when gaining access.

High transaction costs: Most decentralised renewable energy projects are small scale. Investing in large-scale on-grid projects involves lower transaction costs compared with funding large numbers of small decentralised projects. In addition, microfinancing institutions offer loans at very high interest rates that scare off small-scale investors. Often, investments in decentralised renewable energy projects require complex deal structures that drive up transaction costs.

5.1 The concept of swarm electrification

With increasing development, stand-alone systems could be scaled up and connected to each other to create a diverse regional grid that eventually could be connected to the central grid. In this way, a central grid is built bottom-up in three stages. In the first stage, households with for example solar home systems connect to each other to make use of each other's surplus power, and potentially also battery capacity. Together they form a swarm system (Groh and Koepke, 2014). In a second stage, neighbouring swarm systems connect to each other, forming a regional grid. Alternatively, the swarm system is connected to a mini-grid that serves as additional capacity when consumption increases. Instead of increasing the generation capacity for high consumer households, the swarm grid uses the surplus production of neighbouring solar home systems, while stimulating innovation and entrepreneurship once the total neighbourhood's electricity demand exceeds the existing swarm capacity. Integration with neighbouring swarm systems or mini-grids could increase the security of supply by allowing diversification of the generation sources. In the third and final stage, the regional grid can be connected to the central grid, thereby allowing for the full range of electricity services (Hollberg, 2015). Such a transition from solar home systems to swarm systems and eventually a central grid connection does not require the same speed for all households in a neighbourhood or community but can start with early adopters, followed by high consumers and eventually the rest of the community. Finally, the system can benefit from electrification projects in local health centres and schools.

All the above barriers will not be resolved by more finance alone, but rather by complementing the additional finance with innovative policies, an enabling environment for the energy market and human and institutional capacity building. Addressing the barriers includes supporting the market development of mini-grids and stand-alone systems. Furthermore, electricity should be made affordable for the poorest households, for example by targeting electricity consumer subsidies and credit schemes to these households (Scott, 2015).

5.2.3 Creating a long-term electricity access strategy

The better we understand the local benefits and constraints of specific technologies in a broader socio-economic and long-term perspective, the better equipped we will be for providing universal electricity access (Jürisoo et al., 2014). Low-carbon options can only scale-up and play a substantial role if they are cost-competitive and make sense in the context of countries' broader development objectives.

Low income levels and the related low electricity demand of communities in remote rural areas could call for the use of stand-alone systems. Even the transition from a kerosene lamp to a basic electricity service as low as Tier 1 can significantly impact a household's welfare. Switching from kerosene to electric lighting allows mobile phone charging, could reduce greenhouse gas emissions (including black carbon), improve indoor air quality and, as total electricity costs are generally lower than total costs for kerosene, save on recurring fuel costs (Alstone et al., 2015). However, the ultimate goal is to supply electricity at a scale that can support community development and income-opportunity development, while taking into account social, economic and environmental effects related to climate change, air pollution, employment opportunities and energy security issues.

This calls for a long-term strategy for electricity access that takes into account long-term objectives, including climate change, health impact and energy security objectives, while at the same time building on local knowledge and capacity and working with short-term constraints related to finance and governance. This may be difficult to achieve given the currently weak institutions and low governance capacity. Still, governments could make a good start by including off-grid electrification as an essential component of power sector plans. Furthermore, as there is a clear need to speed up the transition, governments can facilitate emerging bottom-up electrification processes – for example by building on the concept of swarm electrification (see Box 5.1) – while keeping track of long-term targets and broader energy system challenges.

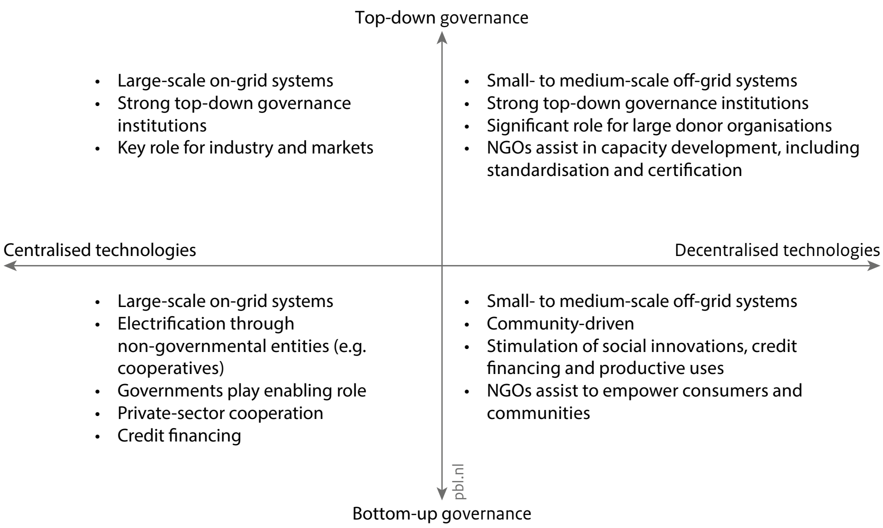
5.2.4 Including a broad range of actors beyond national governments

Grid-based and off-grid electrification not only differ in the type of technology used, but also in the actors involved (Tenenbaum et al., 2014). Grid-based electrification relies on electricity generation at large-scale centralised facilities and distribution through a transmission network. These are usually built by a national government-owned utility, a rural electrification agency, or a large private operator (World Bank, 2012). Off-grid systems generate electricity at or near demand sites and do not require significant distribution networks, and are implemented through non-governmental entities such as cooperatives,

5.2 Four distinct storylines that discuss the roles of actors in different electrification tracks

Based on a series of workshops with people and institutes involved in the Sub-Saharan Africa electricity sector in different capacities, four alternative storylines were developed. These storylines describe the roles of different actors in the transition to sustainable and universal access to electricity in Sub-Saharan Africa. Key actors and their roles were identified, as well as driving forces and key uncertainties. The main characteristics of the storylines are organised along two axes: a governance axis and a technology axis (see Figure 5.1). The governance axis is about the dominance of large top-down actors or more dispersed bottom-up actor, while the technology axis is about the dominance of large-scale on-grid systems or decentralised off-grid technologies. Every country has its own governance model, which is not purely top-down or bottom-up, and there is not a 'best electrification' model that can be applied. The context of the community, country and the region is of key importance. One storyline might be more appropriate for one country than another and, in most cases, a combination of the governance models might apply.

Figure 5.1
Role of actors involved in providing electricity access, in four distinct storylines



Source: PBL

community user groups, or smaller private sector companies. Achieving universal access to electricity requires action on both tracks, with attention for multiple actors at multiple scales, that is regional, national and local governments, the private sector, international donors and financial institutions, and civil society.

Governments are responsible for identifying development priorities and allocating resources, and are expected to perform key steering and convening functions (UN-OHRLLS, 2014). The role of the public sector is essential in enabling the right environment, creating effective regulatory frameworks, and developing implementation strategies. Furthermore, the public sector plays an important role in reaching out to communities where the private sector is absent (Sanchez and Tozicka, 2013). However, political leadership and a clear vision are crucial. Local communities and community organisations could be involved in the planning and implementation of electrification projects, thereby creating a sense of belonging within the community and increasing the long-term sustainability of the project.

There is an urgent need to develop local technical and institutional capacity and to coordinate efforts among non-state actors who can play a role in electricity sector planning. These non-state actors range from local entrepreneurs to large international utilities, and could help find new and innovative solutions and scientific advancements that match local resources and characteristics. An excellent example is the wind turbine built from scrap metal and car parts in Kenya, a project set up by Yale University and the EngineerAid network, which generates power for fifty rural homes for less than the equivalent in solar PV panels (Samantar, 2012). Bilateral collaboration with the private sector, rather than the traditional path of supporting governments and large-scale utilities, could help to develop the local technical and institutional capacity that is needed. In fact, the European Union is already financing local energy initiatives and developing innovative co-financing instruments.

The role that actors play not only depends on the type of electrification technology, but also on the country's governance tradition or governance model used for driving the transition (see also Box 5.2). Having a clear overview of the active and desired actor landscape can help national governments and international donors in targeting their resources, including financing, training and institutional capacity building.

5.3 Suggestions for Dutch development cooperation

The Dutch target of providing 50 million people with access to renewable energy by 2030 would represent a significant contribution to the challenge of achieving the SDG target of ensuring universal access to electricity by 2030. Our quantitative analysis provides insights into the technology and investment requirements for achieving the SDG target in Sub-Saharan Africa. However, more robust evidence is needed on the synergies and trade-offs between climate change mitigation, energy access and broader sustainable development goals. Furthermore, a clearer picture of the role of different actors under different electrification tracks and governance styles could help to better target available resources. Nevertheless, the analysis suggests that the challenge of achieving universal electricity access could be the largest for poor, rural communities – not in terms of absolute investment requirements but with respect to socio-economic and institutional barriers to starting off-grid projects. Dutch development cooperation policies could be targeted at financing, capacity building and training, supporting market development for off-grid systems, targeting international climate finance to decentralised electricity projects, and helping to strengthen the national enabling environment to incentivise decentralised energy access.

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Appendix

Household electrification model

The residential electrification model is a multiannual bottom-up model that determines the least-cost electrification technology on a 0.5° x 0.5° grid cell basis. The model distinguishes between three electrification options: (a) extending the central grid; (b) mini-grid systems (photovoltaic panels, diesel generator, wind power, mini-hydropower and hybrid technologies); and (c) stand-alone systems (diesel generators and solar home systems). For a full description of the model and the data used, see Dagnachew et al. (submitted).

The least-cost calculations are based on grid cell data on the costs of electricity generation for different technologies, the technical potential of renewable energy sources, the cost of transmission and distribution networks, the distance of a grid cells population from existing high voltage power lines, population density and household electricity demand. The model uses the levelised cost of electricity (LCOE) to compare costs across the different system and technology options. The total LCOE of a system is a combination of the LCOEs of electricity generation, the transmission system and the distribution network. The transmission system is required only for extending the central grids, while both extending the central grid and mini-grid systems require a distribution network. Stand-alone systems are installed close to the load and therefore require neither a transmission system nor a distribution network. The LCOE for power generation ($LCOE_g$) for different technologies is calculated according to the following formula:

$$LCOE_g = \frac{\sum_{i=1}^{m}[Annuity * I_i + C_{FC,i} + \beta_i I_i]}{\sum_{i=1}^{m} E_i} \qquad (1)$$

Where i = the power generating plant (1, 2,...., m)
m = the total number of power generating plants
E_i = the annual electricity output of plant i (kWh)
$Annuity$ = the present value annuity factor = $\frac{1-(1+r)^{-1}}{r}$
I_i = the capital cost of plant i (USD)
$C_{FC,i}$ = the fuel cost (USD per MJ) of plant i calculated as $E_i * \emptyset_{HR,i} * P_{fuel}$
$\emptyset_{HR,i}$ = the heat rate of plant i (MJ per kwh)
P_{fuel} = the price of fuel (USD per MJ)
r = the interest rate
β_i = the fraction of the capital cost for the annual operation and maintenance of plant i

The required transmission system and distribution network for a grid cell is calculated according to the methodology discussed in Van Ruijven et al. (2012). The cost of the transmission systems becomes relevant when choosing between on-grid and mini-grid systems, as discussed below. The LCOE of the distribution network ($LCOE_n$) is the same for both grid-based and mini-grid electrification and is calculated according to the following formula:

$$LCOE_n = \frac{Annuity * Inv_n}{\sum_{i=1}^{m} E_i} \qquad (2)$$

Where Inv_n = the cost of the required distribution network for a grid cell (USD)

Accordingly, the LCOE for delivery of electricity (generation and distribution) from a system ($LCOE_d$) is given as:

$$LCOE_d = LCOE_g + LCOE_n \quad (3)$$

The $LCOE_g$ of the grid-based technologies is calculated in the TIMER model (de Boer and van Vuuren, 2016). The model calculates the LCOEs of off-grid technologies based on total system cost, lifetime and technical potential of the technology (Dagnachew et al., submitted). Technical potential of renewable technologies per grid cell is based on Hoogwijk (2004) and Dagnachew et al. (submitted). The costs of transmission and distribution lines, transformers and household metering and wiring are taken from the literature (Deichmann et al., 2011; Nerini et al., 2016).
The distance from existing power lines is the population weighted distance in 2010, based on power line data from OpenStreetMap (2015) and gridded population data from Landscan (Bright et al., 2013). Population density is based on Landscan data for 2010, with future projections based on van Vuuren et al. (2007). Household electricity demand is either determined in the TIMER model (Daioglou et al., 2012) or based on exogenous assumptions.

The least-cost technology is based on two main model decisions: 1) selecting between grid extension and off-grid electrification and, for off-grid electrification, 2) selecting between mini-grid and stand-alone options (Figure A1).

The first decision is made based on the $LCOE_d$ of the central grid and off-grid technologies and the population weighted distance of the grid cell from existing power lines. If the $LCOE_d$ of the central grid (generation and distribution) is lower than that of the off-grid options, the choice between central grid and mini-grid system depends on the distance of the grid cell from the existing power line. Grid extension is favourable if the distance from the power line does not exceed a certain threshold value. This value is represented by the economical distance limit (EDL) (Kemausuor et al., 2014):

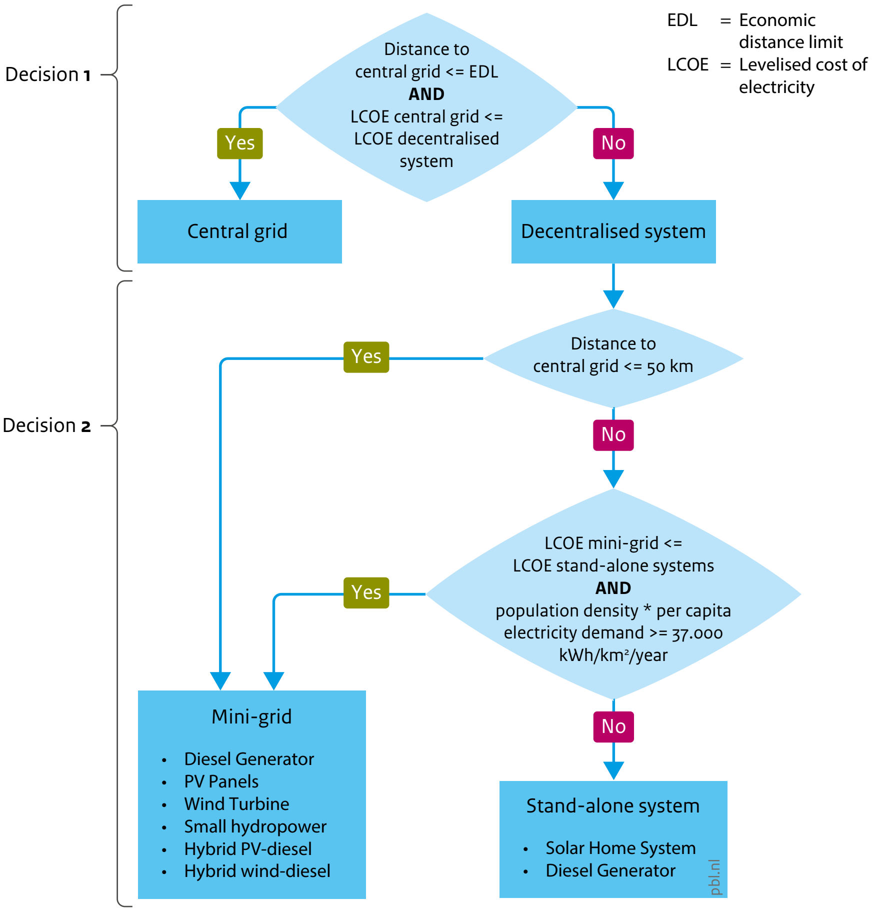
$$EDL = \frac{(LCOE_{alt} - LCOE_{cg}) * \sum_{t=Baseyear}^{Baseyear+Lifetime} E_{t(t)}}{C_{HV\&MV}} \; km \quad (4)$$

Where $LCOE_{cg}$ = the levelised cost of electricity generation per grid cell from central power plants (USD per kWh)
$LCOE_{alt}$ = the levelised cost of electricity generation per grid cell for off-grid electrification (USD per kWh)
$E_{t(t)}$ = the total annual electricity consumption per grid cell (kWh per year)
$C_{HV\&MV}$ = the transmission network cost (high voltage and medium voltage lines) required to link households a grid cell to the centralised power grid (USD per km)

The EDL is the critical distance between households/communities and the main power line for which the total $LCOE_d$ (generation, transmission and distribution) for grid extension is greater than the $LCOE_d$ (generation and distribution) for off-grid electricity supply (IEA, 2010). If the distance to the existing power line is larger than the EDL, off-grid electrification is more cost-effective.

The second decision is based on the $LCOE_d$ of the off-grid technologies, population density and household electricity demand. Stand-alone systems are the least-cost systems only if the average demand density is lower than 37,500 kWh per km^2 per year. This demand density is a factor of population density and electricity demand per capita. For example, if the grid cell has a population density of less than 250 persons per km^2 (equivalent to about 50–100 households per km^2) and electricity demand is less than 150 kWh per person per year, stand-alone is favoured over other systems (DFID, 2013; Nerini et al., 2016). To reduce the revenue risk of stand-alone technologies, mini-grids are always selected as the least-cost option within 50 km distance of an existing power line.

Figure A1
Decision tree to determine the lowest-cost electrification system



Source: PBL

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