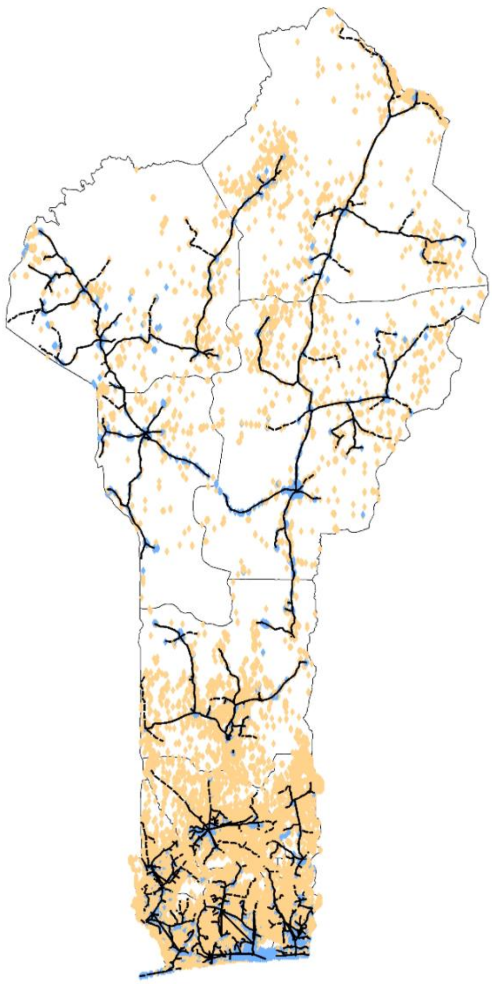
ELECTRIFICATION PATHWAYS FOR BENIN

A spatial electrification analysis based on the Open Source Spatial Electrification Tool (OnSSET)



Prepared by the division of Energy Systems Analysis at KTH in collaboration with SNV
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Cover map: KTH dESA.

Contents

Foreword by DGRE

This document is the outcome of research conducted on the OnSSET decentralised electrical planning model commissioned by SNV Netherlands Development Organisation in partnership with the General Direction of Energy Resources of Benin and carried out by the Royal Institute of Technology (KTH). It was commissioned to demonstrate that energy service planning requirements can be met with increasingly powerful tools. This electrification planning software is one such tool, developed to address the challenges of electrification, including rural and off-grid electrification, focused on dedicated online databases and designed to solve issues related to the availability and updating of data.

The research report is based on experiences gained by the Ministry of Energy during the planning of rural and urban electrification and in the deployment of Energy Information Systems (EIS), sometimes based on Geographic Information Systems. It is also based on data collected from energy sector stakeholders or from the Directorate General of Energy Resources, and from online data by the World Bank, the International Agency for Renewable Energy, the African Development Bank through "Africa Energy Portal" (launched in November 2018), and the United Nations Development Programme (UNDP), as well as a number of additional institutions that place planning at the heart of sustainable development, including the achievement of SDG 7 or the Sustainable Energy for All initiative (SEforALL).

The project "Electrification Pathways for Benin" takes advantage of the tremendous success of the deployment of this planning tool by KTH, particularly in Afghanistan, Nigeria, Tanzania and Zambia.

I thank SNV and KTH for their noble ambition and would also like, on behalf of the Government of Benin, to express my deep gratitude to all the Development Partners and people who have worked tirelessly in the field of energy services planning for several years.

Also, it is worth noting that the capacity strengthening of stakeholders, as identified by SNV with the support of KTH, is the foundation required to achieve the goals of the energy sector and reach the targets identified in the 2016-2021 Government Action Programme.

We hope that you will enjoy reading this report.

Dona Jean-Claude HOUSSOU,

Minister of Energy of Benin.

Foreword by SNV

At SNV, we are committed to ending energy poverty, and providing clean energy for the billions of people that currently do not have access to electricity and/or clean cooking facilities. In order to achieve universal access to affordable, reliable and sustainable energy by 2030 (Sustainable Development Goal 7), comprehensive energy planning is key to help guide the development of a country's energy system. Integrated energy and electrification planning tools, such as the Open Source Spatial Electrification Tool (OnSSET), can be used to ensure a customer-driven approach that takes account of not only the technology issues, but also the growth of demand (including productive uses) and social, environmental and health aspects.

Traditional, supply-driven energy systems (based on centralised power production and extensive transmission and distribution grids) are often not the most suitable or economical electrification option for developing countries, especially for rural areas. Small-scale decentralised, off-grid energy systems, such as mini-grids and stand-alone solar for households, businesses and institutions, play a vital role in providing access to electricity for the millions of people living in remote areas.

The choice between grid extension and decentralised electrification depends largely on remoteness, and how much electricity newly connected households and businesses are expected to use. The cost-effectiveness of grid extension decreases significantly in less densely populated and remote areas with relatively low electricity demand compared to urban areas. With the ever-declining costs for renewable technologies, renewable energy systems are expected to become the least costly option in more and more locations.

However, most financiers still perceive off-grid renewables as high-risk options with low return on investment. At the same time, established technologies mainly based on fossil fuels often benefit from favourable laws, regulations, subsidies and tax incentives. A level playing field for renewable off-grid options is important to reduce investment risks. This requires a conducive enabling environment for renewable energy technologies, and more certainty about future energy policies. The development of a long-term energy vision, resulting in national energy plans that outline the role of renewables, is a prerequisite to improve the energy investment climate, and to ensure that the poorest communities get access to clean and affordable energy. Innovative public-private sector financial approaches will often be needed, combining commercial finance with incentives such as targeted subsidies and credit schemes for the poorest consumers.

With the application of the Open Source Spatial Electrification Tool (OnSSET) to explore different electrification pathways for Benin, SNV intends to contribute to the national energy plan of the country. By utilising local data and involving key stakeholders from government, private sector and academia in the process, we aim to ensure that this tool provides realistic assessments, which can be translated into concrete implementation projects.

We would like to stress that this report is not an end in itself. At the level of KTH, the outcomes of the modelling will be continuously reviewed, and will be updated with the further development of the OnSSET tool, when for example the incorporation of productive uses has advanced. Also in-country, the assessments can be updated at any time by local stakeholders. Representatives in Benin from government, universities and the private sector have been trained in using the OnSSET tool and are able to adapt the planning assessment according to new needs identified or to changes in the context observed.

With the positive experiences in using OnSSET and collaborating with KTH and in-country stakeholders in Benin, SNV is now very well-placed to apply its learnings to develop concrete projects for off-grid electrification in Benin and other countries with similar needs.

Tom Derksen

SNV Netherlands Development Organisation

Global Managing Director Energy

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This report was prepared by Andreas Sahlberg (KTH), Babak Khavari (KTH), Alexandros Korkovelos (KTH) and Mark Howells (KTH) under the KTH/SNV collaboration. The study benefited greatly from valuable comments and suggestions from Rianne Teule (SNV), Martin van Dam (SNV) and Dean Cooper (SNV). Important contributions were made also by Edouard Fagnon (SNV), who organized the local data gathering and the workshop in Benin. The data support from the Direction Générale des Ressources Energétiques du Bénin (DGRE) is gratefully acknowledged as well. Finally, many thanks to the participants of the workshop and the high-level meeting who provided valuable inputs and discussions. None of these individuals should be held responsible for any remaining errors in the study, for which the authors are solely responsible.

Abbreviations

CBE	Communauté Electrique du Bénin
DGRE	Direction Générale des Ressources Energétiques du Bénin
ESMAP	Energy Sector Management Assistance Program
EUEI	EU Energy Initiative
GDP	Gross Domestic Product
GIS	Geospatial Information System
HV	High voltage
IRENA	International Renewable Energy Agency
km	Kilometre
KTH	Royal Institute of Technology in Stockholm
kWh	Kilowatt-hour
LCOE	Levelized Cost of Electricity
LV	Low voltage
META	Model for Electricity Technology Assessment
MTF	Multi-Tier Framework
MV	Medium voltage
MW	Megawatt
OnSSET	Open Source Spatial Electrification Tool
PV	Photovoltaic
SBEE	Société Béninoise d'Energie Electrique
TEMBA	The Electricity Model Base for Africa
USD	United States Dollar
Wp	Watt-peak

Key Terminology

Centralized electricity generation: Refers to the large-scale generation of electricity at centralized facilities, located usually away from end-users and connected to a network of high-voltage transmission lines [1].

Distributed electricity generation: Refers to a variety of technologies that generate and distribute electricity at or near where it will be used. It may serve selected loads in the vicinity or it may be part of a greater system (regional and/or national grid) [2] [3].

Under this perspective and for the purposes of this report we define the following:

National grid (or grid): A system of centralized and distributed electricity generation facilities that are inter-connected through an extensive transmission network spreading throughout the country.

Mini-grids: Isolated power generation-distribution systems that are used to provide electricity to local communities (power output ranging from kilowatts to multiple megawatts) covering domestic, commercial and/or industrial demand.

Stand-alone systems: Small power systems that are not tied to the national grid, operate autonomously on island mode, and can satisfy on site, low electricity demand for a limited time.

Abstract

Access to electricity is strongly linked to social- and economic development [4]. As of 2016 in Benin, residential access to electricity was limited to 29%. Targeting universal access to electricity by 2030 – as per SDG7[1] mandates – requires a combination of grid expansion and deployment of off-grid technologies. In this study, the Open Source Spatial Electrification Tool (OnSSET) was used to examine 21 electrification pathways for Benin. The tool leverages geo-spatial information and uses a least-cost approach to identify the most cost effective electrification solution in each settlement.

The selected scenarios, study the effects and implication of targeting different levels of access to electricity as well as sensitivity to technology costs. Results show that 58-92% of the population in 2030 is expected to receive electricity from the grid. The remaining 8-42% is expected to gain electricity access through mini-grids or stand-alone systems. The total investment cost required to achieve universal electrification in Benin by 2030, ranges from 1.2 to 5.9 billion USD, depending on the level of service provided and technology cost developments. Stand-alone technologies are favoured at lower electricity access targets and in remotely or sparsely located areas; mini-grids and grid-connections are observed at higher demand levels and in more densely populated areas.

[1] Sustainable Development Goal 7 (SDG7) of the 2030 Agenda for Sustainable Development [5]

1. Introduction

1.1 Background of the study

Benin is located in West Africa, surrounded by Togo in the West, Nigeria in the East, Burkina Faso and Niger in the North and the Atlantic Ocean in the South. The population in 2015 was 10,58 million people, of which 44% lived in urban areas. With a poverty rate[2] of 49,6% in 2015, Benin lags slightly behind the rest of Sub-Saharan Africa which has reduced poverty rates to 41,1% in 2015 [7]. Furthermore, with a GDP per capita of 830 USD (2017 estimate), the country falls behind the average of 1 554 USD/capita in Sub-Saharan Africa [7]. Access to modern fuels, especially electricity, is often considered a pre-requisite for development [8]–[10] . Currently, only 29% of the population in the country has access to electricity [11]. In urban areas this number is higher, 71%, while adversely in rural areas merely 18% of population has access to electricity [12]. As per the *Reflection group on the State vision of the electricity sector* (GRVSE) the electrification target is 95% in urban areas and 65% in rural areas by 2025 [13].

Benin's power sector is closely tied to its neighbour Togo. The power system of both countries has been under the control of Communauté Electrique du Bénin (CEB). A large majority of the electricity consumed in the country is imported. Currently Benin is highly dependent on imports of electricity from Nigeria and Ghana from where they get approximately 90% of their electricity supply. The domestic power generation is also dependent on imports of Natural gas from neighbouring countries. CEB supplies the only power distribution utility, Société Béninoise d'Energie Electrique (SBEE), in the country with electricity. The dependency on other countries has proven to be challenging. Fluctuations in the electricity supply from the supplying countries results in severe black outs and power shortages [14]. To mitigate the effects of these challenges, SBEE relied on inefficient thermal generators and expensive emergency power rentals to meet the demand. In addition, the transmission and distribution network is of poor quality with losses of approximately 24%. Finally, SBEE has set low electricity tariffs (on average US₵ 22.1 / KWh); this is not reflective of average cost of generation (US₵ 26 / KWh, thus damaging for the long term economic sustainability of the utility [15].

1.2 Energy Policy and Plans

In response to these challenges, the government of Benin has put forward an Action Plan for the electricity sector. The plan pledges to increase the domestic production of electricity and therefore decrease import dependency. A number of different actions are to be undertaken such as [14]:

- Expansion of domestic thermal electricity plants
- Increase the share of renewables in the mix, focusing on hydro, solar PV and biomass
- Restructure the power distribution and open it to the private sector
- Increase the energy efficiency in the public and residential sector

The government has also received financial support from international donors. In 2015, a 375 million USD contract was signed with Millennium Challenge Corporation (MCC) including actions aimed at strengthening the power sector through [14]:

[2] The international poverty line defined as 1.90 USD a day (2011 purchasing power parity) [6].

- Increasing generation capacity by building an additional 60 MW from renewable and thermal sources
- Strengthening the grid network and connecting and increasing the connectivity rate
- Increase the accessibility to off-grid technologies for electricity generation

As part of the project, there is also an Electricity Distribution project that aims to strengthen the grid in several areas of the country. These changes aspire to reduce technical losses in the transmission and distribution networks and decrease the severity of power outages [16].

1.3 Scope and objective

KTH – in collaboration with SNV – examined a number of electrification pathways aiming at universal electricity access in Benin by 2030. The overall scope of the assignment entailed:

1. **Gathering and validation of data:** This activity included collection of datasets that are necessary for the geospatial electrification analysis. Such data include socio-economic parameters (population density and distribution, existing and planned infrastructure, resource availability etc.), and techno-economic parameters (types of power systems, technology costs, technical properties etc.). All collected and derivative data are publicly available on Energydata.info
2. **Preparation of an electrification model for Benin:** This activity included the development of a customized OnSSET electrification model for Benin. A number of scenarios were created to examine how residential demand, technology costs and other parameters affect the optimal electrification mix. The impact of the cost of diesel, solar PV technology costs and grid electricity price was examined in particular as part of a sensitivity analysis. An up-to-date version of the electrification model developed and used in this activity is publicly available on GitHub[3].
3. **Result dissemination:** This activity included the analysis of the electrification results and preparation of assisting material (maps, tables) to support policy design and strategy development for electrification. Further, a one-week training workshop was held in Benin with the participation of stakeholders from different sectors.

2. Geospatial electrification analysis for Benin using OnSSET

2.1 What is OnSSET

The 2030 Agenda for Sustainable Development [17] has set the goal of universal electricity access by 2030. The challenge is significant. It involves reaching populations with limited income, often living in sparsely populated areas, mostly in developing and least developed countries. The choice of which technology to use for increasing electricity access depends on a number of parameters, from social to techno-economic including e.g. target level of energy access, local population density, distance to the national grid and local resource availability. These parameters are spatial in nature, making geospatial information very useful for their evaluation on regional, national and sub-national scale.

[3] https://github.com/KTH-dESA/PyOnSSET/tree/Benin-differentiated-costs/pyonsset2018/Benin

Over the past few years, the division of Energy Systems Analysis at KTH has been embracing the advancements in the geospatial field, by developing together with partners[4] an open source, geospatial electrification toolkit – the Open Source Spatial Electrification Tool (OnSSET). OnSSET is a Geospatial Information System (GIS) based tool developed to identify optimal electrification pathways for a region under certain timeframes.

OnSSET calculates the optimal split between grid-connection, stand-alone and mini-grid systems for electrification. The selection process is carried out on the premise of minimizing levelized cost of electricity (LCOE), which allows for easy comparison of the cost of providing electricity using different generation technologies [18]. Seven electricity generation technologies are taken into account (Table 1).

Table 1. The seven technology configuration options considered in OnSSET for increased access to electricity. The seven technologies are divided into three categories; grid, mini-grid and stand-alone systems.

<table>
<tr><th>Category</th><th>Definition</th><th>Supply technology</th></tr>
<tr><td>Grid-connection (Grid)</td><td>Connection to the national grid.</td><td>National Grid</td></tr>
<tr><td rowspan="4">Mini-grid systems (MG)</td><td rowspan="4">A system with its own distribution network operating independently of the national grid serving multiple customers [19]</td><td>Diesel generator</td></tr>
<tr><td>Hydropower</td></tr>
<tr><td>Solar PV</td></tr>
<tr><td>Wind turbine</td></tr>
<tr><td rowspan="2">Stand-alone systems (SA)</td><td rowspan="2">An energy system serving one single customer.</td><td>Diesel generator</td></tr>
<tr><td>Solar PV</td></tr>
</table>

OnSSET divides the study area into a mesh of square grid cells. The user can define one household electricity access target (kWh/year) for urban households and one for rural households. This division comes from the notion that electricity demand may often be higher in urban areas. In each cell, the total electricity demand is calculated based on the population in 2030 and the assigned electricity access targets.

LCOE for generating electricity in each cell is calculated for the six off-grid technologies based on factors such as renewable energy resource availability, diesel cost and techno-economical information of generation technologies [10]. For mini-grid systems, an additional cost for the distribution network is added. Then for each cell, the most cost effective off-grid technology is chosen. LCOE for grid-connected electricity is based on the cost of generating electricity for the grid-connected power plants plus the marginal cost of grid extension to reach each cell. The grid-extension algorithm determines where grid-extension is the economically preferred alternative to off-grid technologies based on population densities, length and cost of transmission network and comparisons to the off-grid LCOEs [20]. The algorithm considers all cells within 50 km from the current and planned network to be built by 2030 to determine which cells should be grid-connected in an iterative process where connection of one cell may lead to economical connection of neighbouring cells as well. The algorithm stores the additional length of medium and low voltage lines required to be built as well as the additional reinforcements requirements of the current grid. At each iteration, the reinforcement cost increases by a default value of 10%. Extensions further than 50 km from the main grid may be significantly more expensive due to techno-economic aspects and are therefore not considered in the algorithm [20].

[4] United Nations, The World Bank, International Energy Agency, ABB, Swedish International Development Agency (SIDA) etc.

The results indicate the technology mix, capacity and investment requirements for achieving universal access in a modelled country, within certain time periods (usually until 2030). The findings can be presented in various formats such as interactive maps, graphs, images, tables etc. (Figure 1).

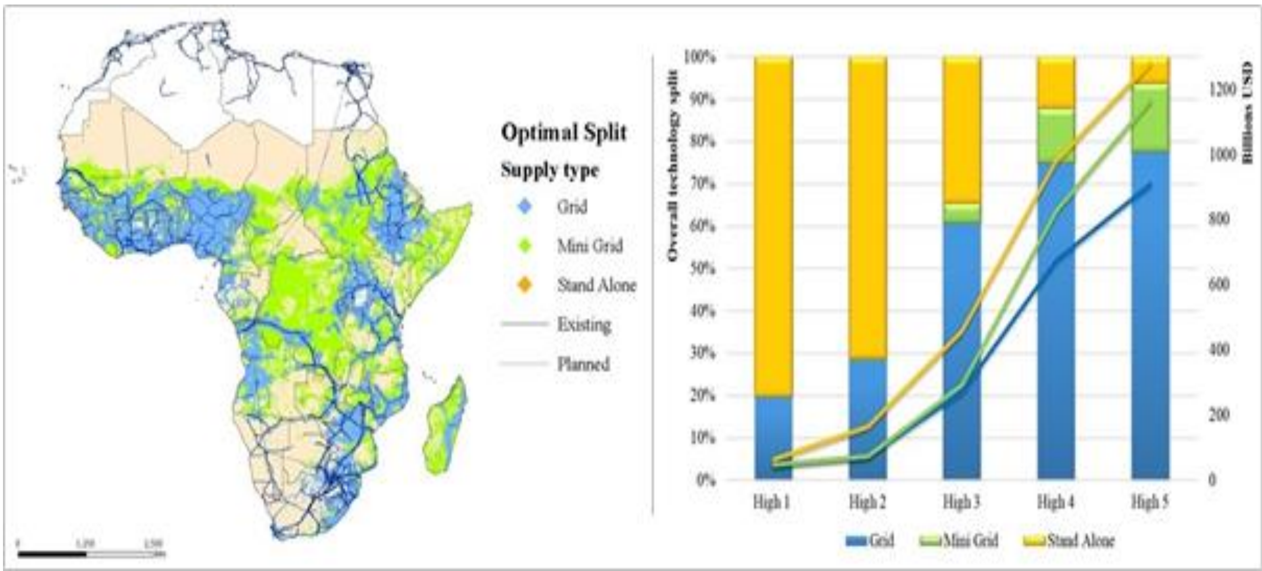

Figure 1. Optimal electrification mix for 44 Sub-Saharan African countries, based on certain electricity access targets, diesel price and grid electricity cost per country. Results indicate that achieving universal electrification in the Sub-continent will require between $50 billion to $1,2 trillion by 2030, with investment targeted towards small off-grid systems or grid extension for low and high access targets respectively[10].

Input data to the electrification model have been collected under a fourfold approach:

- Peer reviewed data from previous geo-spatial electrification analyses undertaken [21] [22]
- Data collected via literature review
- Data collected by SNV in collaboration with local stakeholders in Benin, in particular the (DGRE)
- Data discussed with local stakeholders during a training workshop on geospatial electrification modelling using OnSSET. The workshop was held in October 2018 in Calavi, Benin with participants from the public and private sector as well as universities.

Data were cross validated and selected to best reflect the local conditions. In general, data provided by local stakeholders and data where there was a consensus during the workshop were prioritized. The notable exception is the mini-grid hydro capital cost, where the value provided by the local stakeholders was more than three times higher than the value derived from literature; the latter value was used as it was considered more realistic. The following sections describe in detail the datasets and input parameters used in the electrification model.

2.2 Geospatial datasets

OnSSET relies on the collection and preparation of 14 GIS layers. Table 2 provides a brief description of those along with their functionality and source for the case of Benin.

Table 2. The 14 geospatial datasets included in the OnSSET analysis for Benin. The use of each dataset in the model is described briefly in the table.

Dataset	Purpose of use in the OnSSET analysis	Source
Population density & distribution	Spatial identification and quantification of the current (base year) population. This dataset sets the basis of the OnSSET analysis as it is directly connected with the electricity demand and the assignment of energy access goals.	[23]
Administrative boundaries	Includes information (e.g. name) of the country(s) to be modelled and delineates the boundaries of the analysis.	[24]
Existing grid network	Used to identify and spatially calibrate the currently electrified/non-electrified population.	DGRE
Substations	Current substation infrastructure used to identify and spatially calibrate the currently electrified/non-electrified population. It is also used in order to specify grid extension suitability.	DGRE
Roads	Current road infrastructure may be used to identify and spatially calibrate the currently electrified/non-electrified population. It is also used in order to specify grid extension suitability.	[25]
Planned grid network	Represents the future plans for the extension of the national electric grid. It also includes extension to current/future substations, power plants, mines and queries.	DGRE
Nighttime lights	Dataset used to identify and spatially calibrate the currently electrified/non-electrified population.	[26]
GHI	Provide information about the Global Horizontal Irradiation (kWh/m^2/year) over an area. This is later used to identify the availability/suitability of Photovoltaic systems.	[27]
Wind speed	Provide information about the wind velocity (m/sec) over an area. This is later used to identify the availability/suitability of wind power (using Capacity factors).	[28]
Hydro power potential	Points showing potential mini/small hydropower potential. Dataset developed by KTH dESA including environmental, social and topological restrictions and provides power availability in each identified point. Other sources can be used but should also provide such information to reassure the proper model function.	[29]
Travel time	Visualizes spatially the travel time required to reach from any individual cell to the closest town with population of more than 50 000 people.	[30]
Elevation Map	Filled DEM maps are used in a number of processes in the analysis (Energy potentials, restriction zones, grid extension suitability map etc.).	[31]
Slope	A sub product of DEM, used in forming restriction zones and to specify grid extension suitability.	Generated from the elevation map.
Land Cover	Land cover maps are used in a number of processes in the analysis (Energy potentials, restriction zones, grid extension suitability map etc.).	[32]

2.3 Socio-economic parameters

Socioeconomic parameters are used to describe the current status of the country in terms of population and electricity access, to properly calibrate the model. Future projections are also required in order to estimate the future demand for electricity. Key socioeconomic parameters are presented in Table 3

Table 3. Socio-economic parameters used in the electrification model for Benin

Parameter	Metric	Value 2016	Value 2030
Population total	Million persons	10,872 [7]	15,507 [14]
Urban population	Percent of total population	44,395% [14]	51,3% [14]
Electricity access	Percent of total population	29% [11]	100%
Urban household size	People per household	Only value of 2030 used	4[5]
Rural household size	People per household	Only value of 2030 used	6[4]

2.4 Techno-economic parameters

As explained in Section 2.1, LCOE for grid-connected electricity is based on the cost of generating electricity for the grid-connected power plants plus the marginal cost of grid extension to reach each cell. The cost of generating electricity for the centralized grid does not simply reflect the tariff the customers pay at the moment, but the estimated average cost of producing 1 kWh of electricity by the centralized grid (under its most probable mix) in 2030 taking into account capital investment, fuel and operation and maintenance costs of the centralized power plants. The centralized generation mix can be defined either by studies, the plans of the government or by the optimization model TEMBA (see here). Table 4 presents the grid-related costs that are common for all scenarios in this study. Further information on the cost of generating electricity for the centralized grid and losses in the transmission and distribution network, which varies between scenarios, is described in the paragraphs below. The grid capacity-weighted investment cost in Table 4 represents the average capital investment cost per kW for the plants to be installed during the modelling period. Note that transmission and distribution network costs are treated separately.

Table 4. Transmission and distribution costs used in the electrification model of Benin.

Transmission and distribution parameters in the model		
Parameter	**Default values**	**Unit**
Life	30	Years
HV line cost	53 000 (108 kV)	USD/km
HV line cost	28 000 (69 kV)	USD/km
MV line cost	9 000 (33kV)	USD/km
LV line cost	5 000 (0,2 kV)	USD/km
Transformers	5 000	USD/50 kVA
Additional connection cost per household connected to grid	150 [33]	USD/HH
Additional connection cost per household connected with mini-grid	100	USD/HH
O&M costs of distribution	2%	of capital cost/year
Grid capacity investment cost	2 000	USD/kW
Base to peak load ratio	0,50	

[5] Estimated projection based on discussions with participants attending the OnSSET workshop in Benin

Four combinations of grid electricity generation costs and grid losses have been reported, calculated and optimized. First of all, DGRE reports that the current grid electricity generation cost amounts to 0,19 USD/kWh, and that the transmission losses are 23%. These values were also reported in a World Bank study as the current cost and losses [14]. In the OnSSET model, it is the grid cost and losses by the end year that are used as input for comparison with the off-grid technologies. However, in this study the current cost and grid losses have been used as part of the sensitivity analysis to examine the effect if no improvements to the grid take place.

The base scenarios in this analysis build on grid electricity developments until 2030 reported in a study by the World Bank [14]. These developments are based on the actions proposed by the *Action Programme* [34]. The World Bank scenario considers instalments of 80 MW of solar farms, 360 MW heavy fuel oil (HFO) and 194 MW hydropower installed by 2030. 60 MW of temporary rentals is also considered in the start, but phased out in the first years of the scenario. By 2030, this would result in a grid electricity generation cost of 0,1022 USD/kWh. Further, the grid losses are assumed to decrease to 20% until 2030.

The second grid generation cost for 2030, used for sensitivity, of 0,06 USD/kWh is based on a long-term optimization model, OSeMOSYS. The grid costs are retrieved from The Electricity Model Base for Africa [35] (TEMBA). The model considers all countries on the African continent and potential power trade between them. In this analysis the projected electricity demand in Benin was modelled to be higher than what was considered in the World Bank study, and therefore also the new capacity requirements. The new generation capacity until 2030 would consist of 900 MW coal, 257 MW solar PV and 7 MW natural gas plants. The grid electricity generation cost would be 0,06 USD/kWh and the grid capacity investment cost 2 219 USD/kW. The grid losses are assumed to reach 20% by 2030 also in this scenario. The key information on the two grid cost scenarios from the World Bank and TEMBA are summarized in Table 5.

Finally, the last grid electricity generation cost and losses for 2030 are based on discussions held during the workshop in Benin[6]. In this case, the grid electricity generation cost reflects a situation where all electricity is imported, at a cost of 0,10 USD/kWh. Also, the transmission losses were assumed to decrease to 15% by 2030. These costs are also treated as part of the sensitivity analysis.

Table 5. Cost of generating electricity for the grid-connected power plants by 2030 under two scenarios; one based on a World Bank report and one based on the optimization model TEMBA.

	World Bank scenario	TEMBA scenario
New capacity (MW)		
HFO/Dual fuel plants	360	0,07
Solar PV	80	257
Coal	-	900
Natural gas	-	-
Hydro	194	-
Total generation 2030 (GWh)	3 368	6 258
Grid costs		
Grid electricity generation cost (USD/kWh)	0,1022	0,06
Grid capacity investment cost (USD/kW)	2 000	2 000

[6] OnSSET workshop Benin

Off-grid technologies

Default values are based on literature review (ESMAP, IRENA and IEA) or previous electrification exercises of the KTH team. Furthermore, country-specific information provided for Benin through SNV have been used when available. A summary of the values is presented in Table 6. One should notice however, that the capital costs, in terms of USD/kW, for the off-grid technologies vary depending on system size. Stand-alone PV system costs highly depend on the electricity service they aim to provide. In the OnSSET analysis, electricity consumption relates to the targeted access tier (Tier 1 to Tier 5). The cost of different sizes of stand-alone PV systems in Benin were based on values provided from the private solar sector during the workshop in Benin (Table 7). Notably, the two smaller system ranges are DC systems, explaining the lower cost per kW compared to the two following larger systems sizes which are AC systems.

Table 6. Electricity generation technology parameters used in the OnSSET model.

	System capacity (kW)	Investment cost (USD/kW)		O&M costs (% of investment cost/year)	Efficiency (%)	Life (years)
Plant type	**Default**	**Default values**	**Benin values (DGRE)**	**Default values**	**Default values**	**Default values**
Mini-grid Diesel	100	721*	-	10	33	15
Mini-grid Hydro	1 000	5 000*	16 440	2	-	30
Mini-grid Solar PV	100	4 300	5 280*	2	-	20
Mini-grid Wind	100	3 000*	-	2	-	20
Stand-alone Solar PV	0,3	5 500	5 870*	2	-	15
Stand-alone Diesel	1	938*	-	10	28	10

* These values have been used as the basis for capital investment costs for the base scenarios.

Table 7. Changes in type and cost of stand-alone PV system with different capacities. The first column presents the indicative peak power capacity of the solar panel, which varies depending on the solar resource. The investment cost per kW for these systems is presented in the following column.

Type of System	Investment Cost (USD/kW)[7]
<20 Wp	5 000
<50 Wp	3 400
<100 Wp	8 000
<200 Wp	4 580
>200 Wp	3 330

The investment costs of the mini-grid systems are differentiated with regards to the system size to be installed in each location. The system size in this case depends not only on the target tier, but also on the population in each location that share the system. The total demand to be supplied by the mini-grid system in each grid cell is determined by the population multiplied by the targeted electricity access level per capita. Using this number together with local energy resource availability the required system capacity is calculated.

Drawing on available data IRENA and ESMAP for different technologies, a relationship between installed system size and investment cost is seen. This relation has been applied to the mini-grid investment costs presented in Table 6 to derive differentiated mini-grid investment costs applicable for Benin. For each of the four mini-grid technologies the differentiated costs found in the literature and the corresponding costs

[7] Reported by local actors in the PV market attending the OnSSET workshop Benin

calculated for this project are presented in Tables 8 – 11 below. The costs presented in Table 8 – 11 include battery costs when applicable.

The costs of mini-grid PV follow the same pattern as found in data for various African countries from IRENA [36]. The other three mini-grid technologies follow the patterns found in ESMAPs Model for Electricity Technology Assessment (META) database[8].

In the scenarios where the differentiated costs are used, this refers to the values in the rightmost column in tables 8 – 11.

Table 8. Differentiated costs for mini-grid PV systems. A reference relationship between system size and investment cost from IRENA has been applied to the cost presented in Table 6 to derive differentiated costs following the same pattern depending on system size. For PV mini-grids, systems larger than 200 kW are estimated to be 42% less expensive per kW compared to 100 kW systems, while smaller systems are up to 181% more expensive per kW compared to 100 kW systems.

Mini-Grid PV		
Maximum Capacity (kW)	Cost adjustment factor based on data from IRENA using 100 kW system as a base	Costs based on Benin value of 5 280 USD/kW for 100 kW
50	2,81	14 827
75	1,80	9 498
100	1	5 280
>200	0,58	3 081

Table 9. Differentiated costs for mini-grid wind systems. A reference relationship between system size and investment cost from META has been applied to the cost presented in Table 5 to derive differentiated costs following the same pattern depending on system size. For wind mini-grids, systems up to 1 000 kW and mare are estimated to be 4% less expensive per kW compared to 100 kW systems, while systems up to 10 000 kW and mare are estimated to be 41% less expensive per kW.

Mini-Grid Wind		
Maximum Capacity (kW)	Cost adjustment factor based on data from META using 100 kW system as a base	Costs based on default value of 3 000 USD/kW for 100 kW
100	1	3 000
1 000	0,96[9]	2 889
>10 000	0,59	1 773

Table 10. Differentiated costs for mini-grid hydro systems. A reference relationship between system size and investment cost from META has been applied to the cost presented in Table 5 to derive differentiated costs following the same pattern depending on system size. For hydro mini-grids, systems up to 5 000 kW and mare are estimated to be 39% less expensive per kW compared to 1 000 kW systems, while systems below 1 kW are estimated to be 69% more expensive per kW compared to 1 000 kW systems.

Mini-Grid Hydro		
Maximum Capacity (kW)	Cost adjustment factor based on data from META using 1 000 kW system as a base	Costs based on default value of 5 000 USD/kW for 1 000 kW
1	1,69	10 556
1 000	1	5 000
>5 000	0,61	2 457

[8] Available at: https://www.esmap.org/node/3629

[9] Interpolated using linear interpolation to provide useful break-points in the model.

Table 11. Differentiated costs for mini-grid diesel systems. A reference relationship between system size and investment cost from META has been applied to the cost presented in Table 5 to derive differentiated costs following the same pattern depending on system size. For diesel mini-grids, systems up to 1 000 kW are estimated to be 6% less expensive per kW compared to 100 kW systems, while systems up to 5 000 kW and 25 000 kW are estimated to be 35% and 46% less expensive per kW compared to 100 kW systems respectively.

Mini-Grid Diesel		
Maximum Capacity (kW)	Cost adjustment factor based on data from META using 100 kW system as a base	Costs based in default value of 721 USD/kW for 100 kW
100	1	721
1 000	0,94[10]	674
5 000	0,65	467
>25 000	0,54	392

Stand-alone diesel generators already have a low capital cost and are assumed to operate at a smaller range of capacities, and have therefore been left to a constant value in terms of USD/kW of installed capacity.

Diesel price

The diesel pump price (USD/l) in the country is based on a projection of the current price to 2030. It is assumed that the price will follow the same trajectory as the crude oil price. A high and a low diesel price have been used as seen in Table 12.

Table 12. Current and future diesel prices. It is assumed that the price of diesel will increase at the same rate as the crude oil price projections.

Parameter	Value	Unit
Crude oil current price	44,23 [37]	USD/barrel
Crude oil future low price	96 [35]	USD/barrel
Crude oil high future price	115 [35]	USD/barrel
Litre per barrel	158,99	
Diesel current price	1,04 [37]	USD/litre
Diesel future low price	2,25	USD/litre
Diesel future high price	2,70	USD/litre

2.5 Population

Population is a key driver of electricity demand in OnSSET. The magnitude and the distribution of the population as well as the demographics are all important factors affecting to a greater extent, the results of the electrification analysis.

2.5.1. Population distribution

Population distribution in OnSSET is usually derived from GIS data and – where geospatially available – national statistics. In this case, the Global Human Settlement Layer was used and calibrated so that the population it indicated for Benin reflects the official population value (presented in Table 3). The settlements were divided into urban and rural based on population density. The most densely populated settlements, together containing the same amount of people as the official urban population rate in Table 3, were defined

[10] Interpolated using linear interpolation to provide useful break-points in the model.

as urban in the model. In practice, this meant all settlements with more than 3 100 people per km² were considered urban in this study. Finally, growth rates were applied to urban and rural settlements in order for the total population in 2030 to match national population projections (Figure 2).

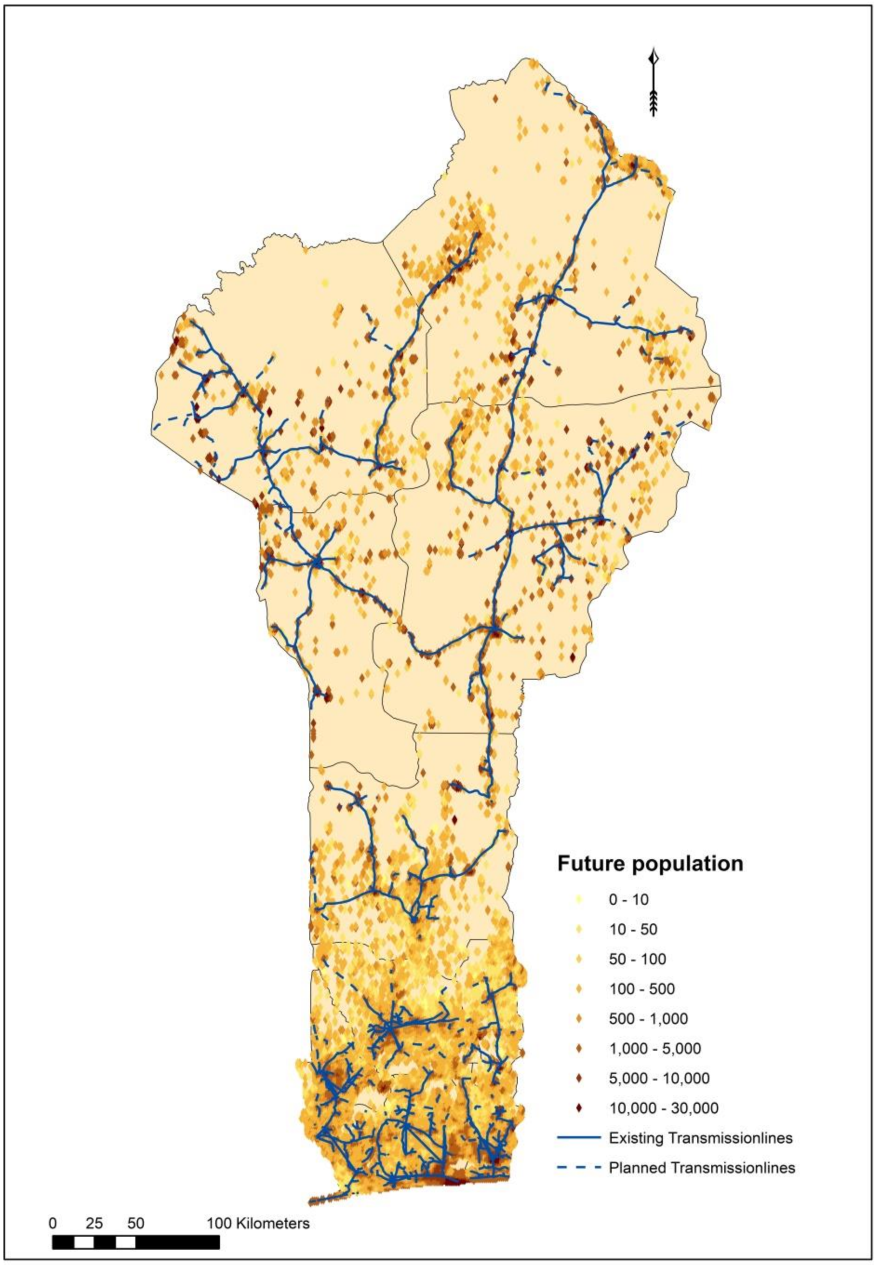

Figure 2. Population distribution in Benin 2030. The populated settlements are overlaid with the existing and planned transmission network. Darker colours indicate more densely populated areas, which may be more suited for grid-connection or mini-grids compared to stand-alone systems.

2.5.2. Population living in proximity to grid network

The economic viability of grid-extension versus off-grid technologies depends largely on the current extent of the grid network and how the population is distributed in relation to it. Long distances from a settlement to the grid may result in high network extension costs, making grid connection more costly than off-grid solutions. Conversely, settlements located in close proximity to the grid can often be connected at a lower cost. Other factors (e.g. population density, resource availability, technology costs) may also affect the choice of the least-cost electrification technology. However, an analysis of the population distribution in relation to the grid network gives an indication to which extent grid connection can increase electrification rates in a country in the short- to medium term. The share of the population living within 5 and 15 km of the current and planned grid network is summarized in Table 13. This information is also visualized in Figure 3.

Table 13. Population living in proximity of the current and planned transmission network by 2030. The majority of the population (93,2%) live within 5 km from the network. Another 5,3% live between 5 to 15 km of the grid network. This means that there is a large potential to increase electrification rates by grid-connection in Benin.

Proximity to grid network	
Population within 5 km from existing or planned grid by 2030	**Population within 15 km from existing or planned grid by 2030**
14 458 000 (93,2%)	15 280 000 (98,5%)

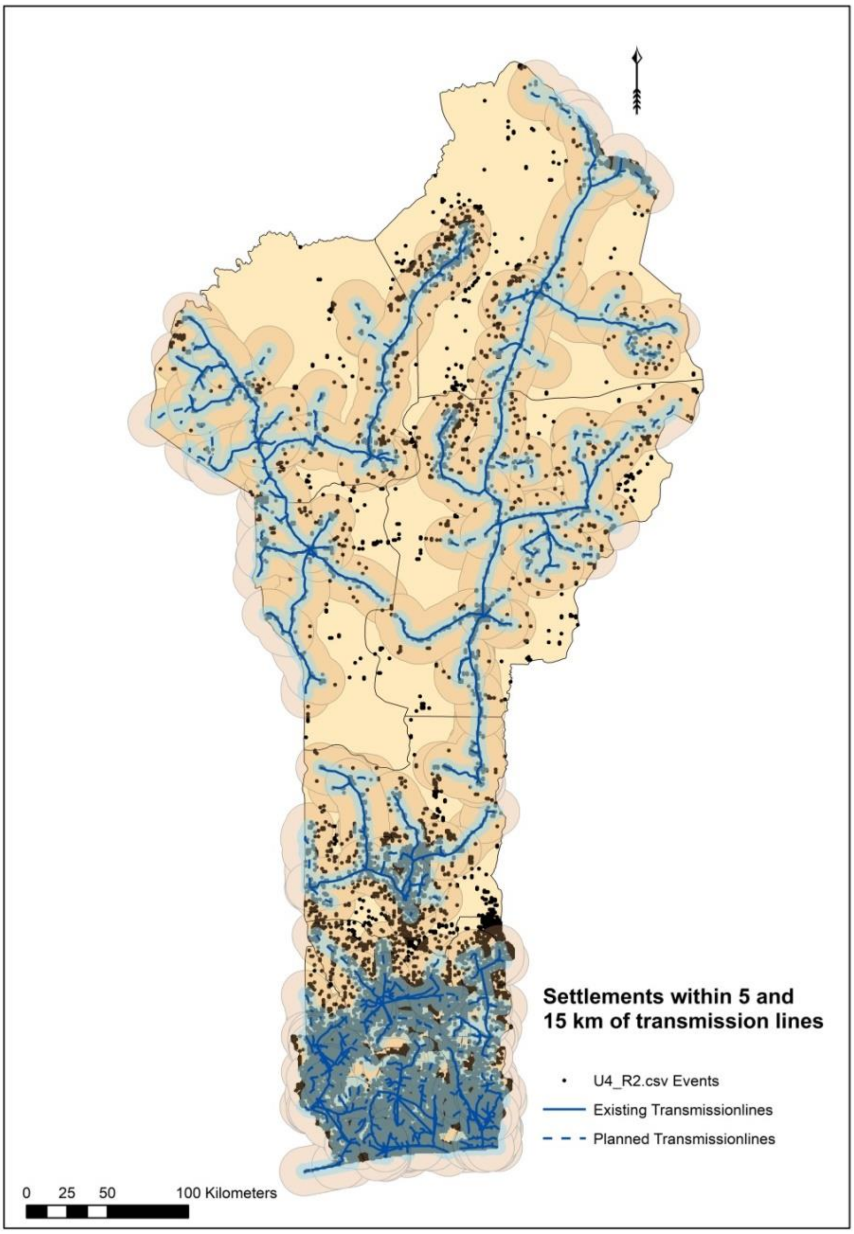

Figure 3. Population living in proximity of the current and planned transmission network by 2030. In southern Benin, the most densely populated area of Benin, virtually all of the population lives close to the grid. Some settlements are located further than 15 km from the grid, mainly in central and northern Benin.

2.5.3. Calibration of electrified settlements in the base year

A pre-condition for any electrification modelling effort is to determine who already has access to electricity, and who is yet to be electrified. Detailed data on this is often scarce or scattered in many countries [38]. OnSSET is therefore equipped with a flexible calibration module making use of remote sensing data to estimate where there is access to electricity in the base year. The settlements from the GIS data were considered to be electrified if they a) were within 20 km from the grid network and b) had a high population density above 50 people/km² and c) had night-time lights detected by the VIIRS satellite [26]. The settlements fulfilling all three of the above conditions, therefore considered to be electrified, are seen in Figure 4.

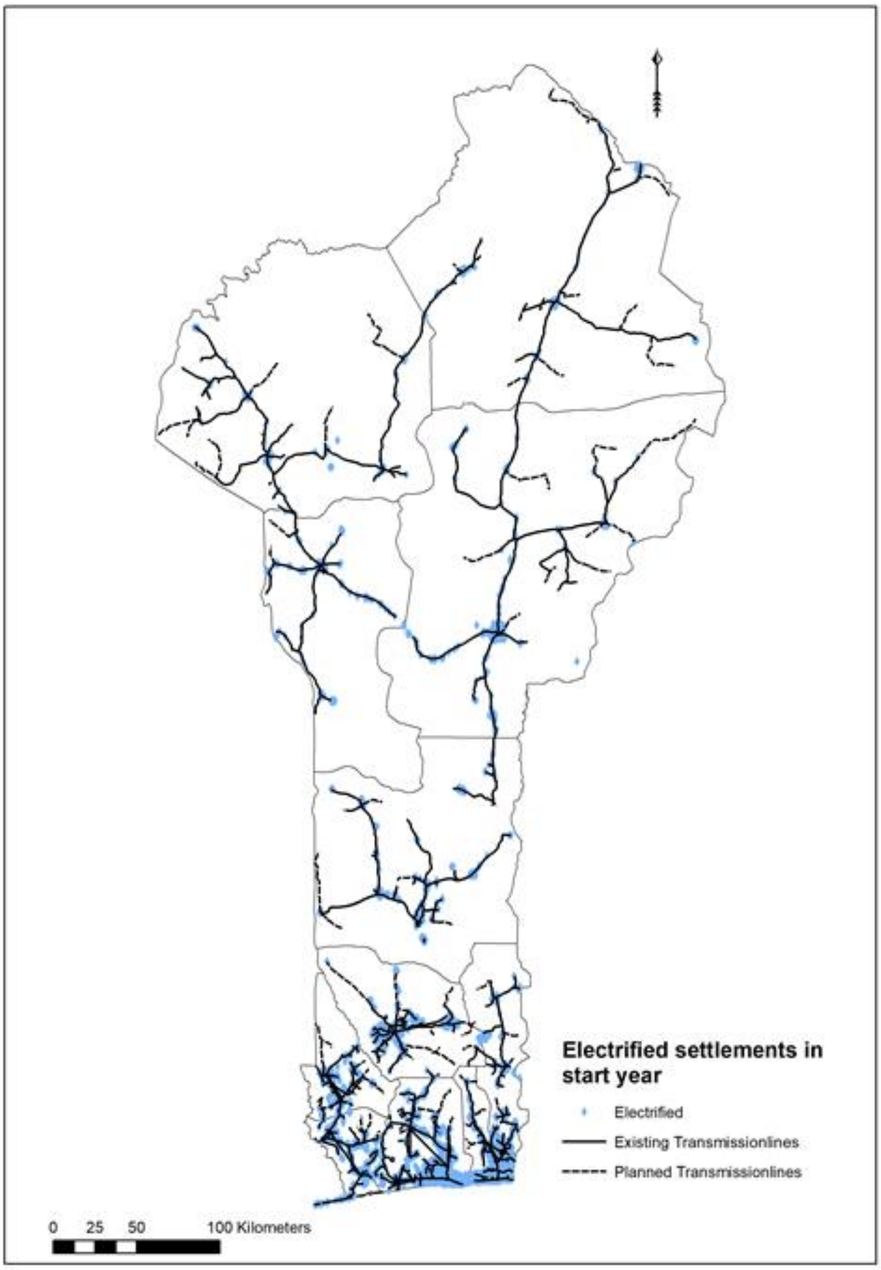

Figure 4. Electrified settlements in 2016. The light blue settlements were found to be electrified in the OnSSET model based on night-time lights, population density and distance to the grid network. The rest of the settlements in Benin remain to be electrified by 2030.

2.6 Electricity access target

The residential electricity access targets in the study are adopted from ESMAPs Multi-Tier Framework (MTF) for measuring energy access for households [39]. Five tiers with different electricity consumption levels, power capacity requirements and reliability measures etc. are presented in the framework. Each tier relates to the different electricity services that can be provided. A summary of the five tiers are seen in Table 14.

Table 14. Electricity access tiers of the Multi-Tier Framework. The table describes the power requirements, reliability levels, hours of supply and services that can be provided at each tier. The values are given per household.

		Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Peak capacity	**Power capacity (W)**	Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
	Daily power capacity (Wh)	Min 12 Wh	Min 200 Wh	Min 1 kWh	Min 3,4 kWh	Min 8,2 kWh
Availability (duration)	**Hours/day**	Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours/evening	Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
Reliability					Max 14 hrs disruption/ week	Max 3 hrs disruption/ week
Services	**Service level**	Task lighting and phone charging	General lighting and phone charging and television and fan	Tier 2 and any medium-power appliances	Tier 3 and any high-power appliances	Tier 3 and any very high-power appliances

Energizing Development (EnDev) has also developed a tier-based framework aiming at identifying key aspects of energy poverty in the residential sector, in which they define different levels of access in terms of service provision and level of consumption. Based on this framework a household with access to 220 kWh per person and year would have the ability to use electricity for productive uses in the household [40]. This falls under Tier 4 of ESMAPs MTF. Further discussions on the MTF also suggest that some level of productive uses in the household could be sustained at Tier 4 and above [39].

3. Model outputs, results and analysis

Three base scenarios were developed with different electricity access targets, reflecting a “Low”, “Medium” and “High” consumption scenario. These examine electrification pathways for Benin to achieve universal access to electricity by 2030. Furthermore, 18 additional scenarios were developed as part of a sensitivity analysis to examine the effect of different development paths. These included a variation of technology costs as well as different levels of electricity access targets. The sensitivity analysis covers grid cost and losses, mini-grid and stand-alone PV capital costs and electricity demand for health and education facilities.

3.1 Base scenarios

In 2016, total residential electricity consumption amounted to 411 GWh in Benin [41]. With a population of 10,3 million people and an electricity access rate of 29%, the average consumption per capita with electricity access was 138 kWh. This is in the lower range of Tier 3 of the MTF. Three base scenarios have been developed based on variations of target electricity access tiers.

Scenario 1, the lowest consumption scenario, considers a case where all the urban population would receive a similar amount of electricity as the current national average. The rural population would get access only to enough electricity for the most basic electricity services.

Scenario 2 considers electricity services that are one tier higher in both urban and rural areas compared to Scenario 1. In the highest consumption scenario.

Scenario 3, the urban population would reach the highest Tier of the MTF, 5, and the rural population would gain access to today’s average level of electricity consumption.

A summary of the three scenarios is seen in Table 15. Scenarios 1, 2 and 3 have been examined using the differentiated off-grid technology costs presented in Table 7-11. These scenarios reflect a “Low”, “Medium” and “High” consumption scenario.

Table 15. Description of scenarios 1, 3 and 5, serving as the base scenarios in this report. These reflect a low, medium and high electricity consumption scenario for universal access to electricity in Benin by 2030.

Scenario	Urban access target tier	Rural access target tier	Grid cost (USD/kWh)	Grid losses (%)
1	3	1	0,1022	20
2	4	2	0,1022	20
3	5	3	0,1022	20

3.1.1. Least-cost technology split

In all three scenarios, grid-extension provides the least-cost electrification option for a majority of the population. At the lowest electricity target tiers, 61% of the population would live in areas where grid-intensification or grid-extension is the most cost-effective option. This number increase to 67 and 78% for Scenario 2 and Scenario 3 respectively (Figure 5), as the higher electricity access targets economically justifies the cost of grid-extension to more locations. The remaining population gets electricity from one of the off-grid technologies. In Scenario 1, 7% of the population would most affordably get electricity by PV or hydro mini-grids and the remaining 33% by stand-alone PV systems. The mini-grids in this scenario are only deployed for the urban population, as the rural electricity access target is too low to economically justify min-grids in rural areas.

In Scenario 2, a mere 1% of the population receive electricity at the lowest cost from mini-grids. As the urban electricity access target increases, grid-extension in the areas where mini-grids are found to be most affordable in Scenario 1 is motivated. In this scenario, all urban population will get their electricity from the centralized grid. The increased rural electricity access target justifies PV and hydro mini-grids in some rural areas. In Scenario 3, grid-extension is again the least-cost option for all of the urban population. At Tier 3 levels of electricity consumption in rural areas, PV and hydro mini-grids are the most economic option for 7% of the total population. These are divided into 121 hydro mini-grids and 538 PV mini-grids.

Figure 6-8 display the spatial distribution of least-cost technologies considering the differentiated costs. Mini-grids are mainly found in the northern parts of the country, in areas where the population density, and therefore demand, remains adequately high for these technologies to be deployed. Some of these mini-grids are found in close proximity to the grid-connected settlements. Considering the small distances from these mini-grids to the grid, technical specifications and policies should be put in place to ensure that these can later be connected to the grid, ensuring that there is a viable business case for mini-grid deployment.

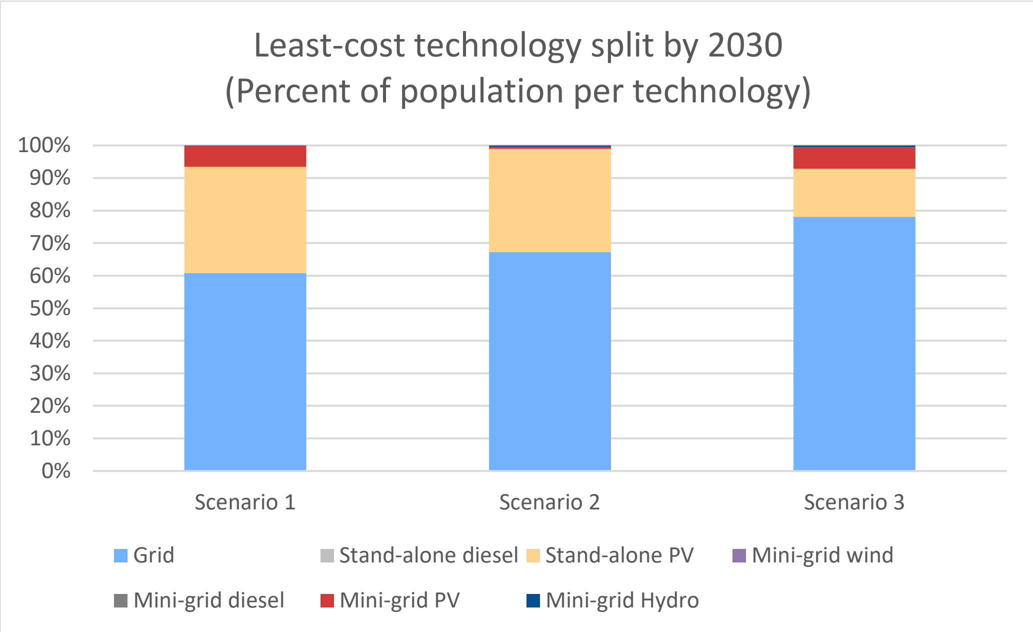

Figure 5. Least-cost technology split for the three base scenarios. The different colours show how large share of the total population in Benin by 2030 will be served by each of the seven generation technologies. In all scenarios, grid-connection (light blue) will be the most deployed technology. Stand-alone PV (yellow) will be the most utilized off-grid technology, followed by PV mini-grids (red). A small share of hydro mini-grids (dark blue) will also be deployed for less than 1% of the population. In Scenario 1, the PV mini-grids will be utilized in urban areas, but as demand increases, grid-extension becomes favourable in these areas. In Scenario 2 and 3 the PV mini-grids are instead found in rural areas.

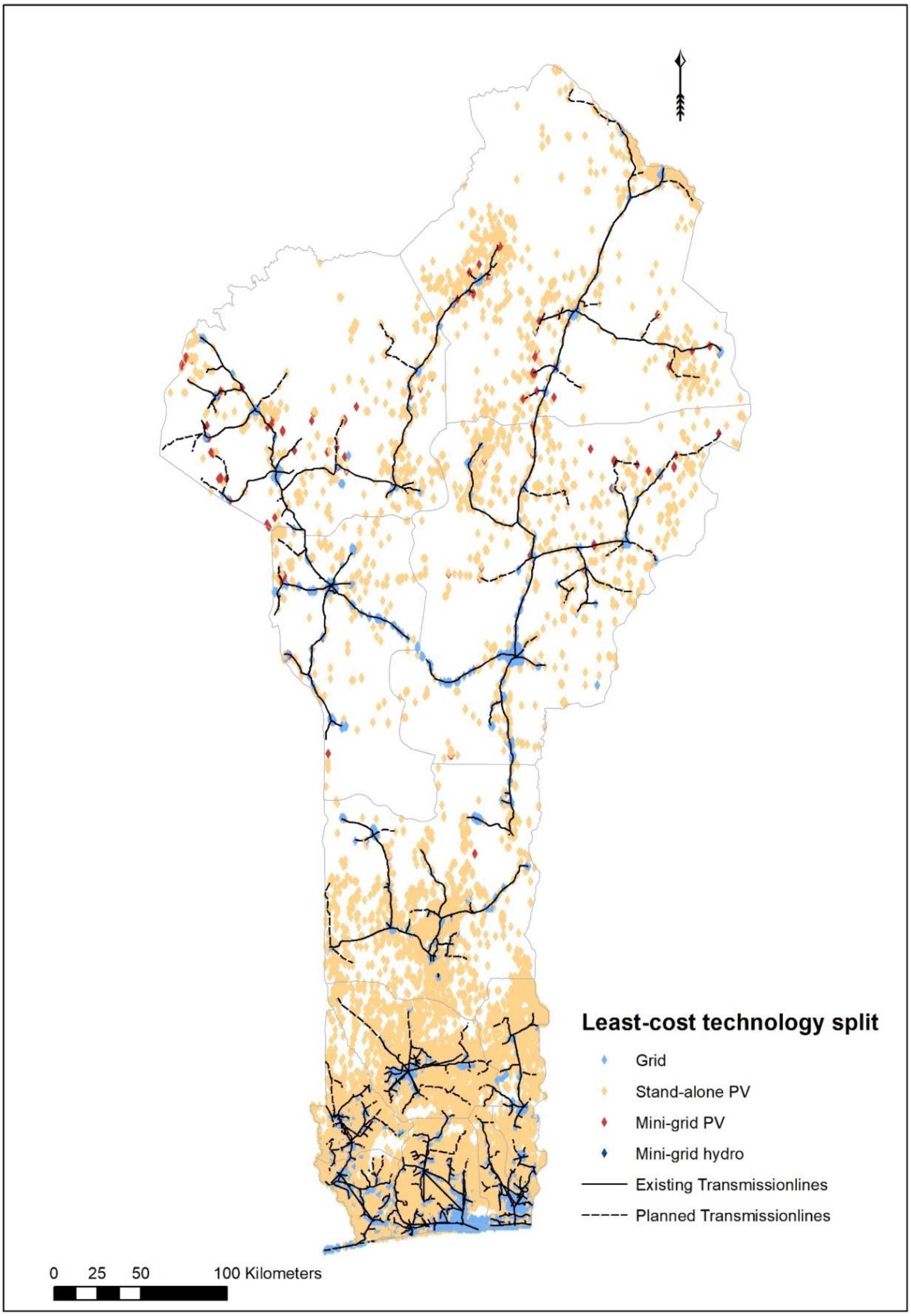

Figure 6. Distribution of least-cost electricity generation technologies in Benin by 2030 for Scenario 1 (Tier 3 target level of electricity access in urban areas and Tier 1 target level of electricity access in rural areas). Grid-connection (light blue) will be deployed around the larger cities, and the rest of areas will be supplied by stand-alone PV (yellow) or mini-grids. Despite covering a smaller area than stand-alone PV, grid-connection serves the majority of the population as it is deployed in the most densely populated areas.

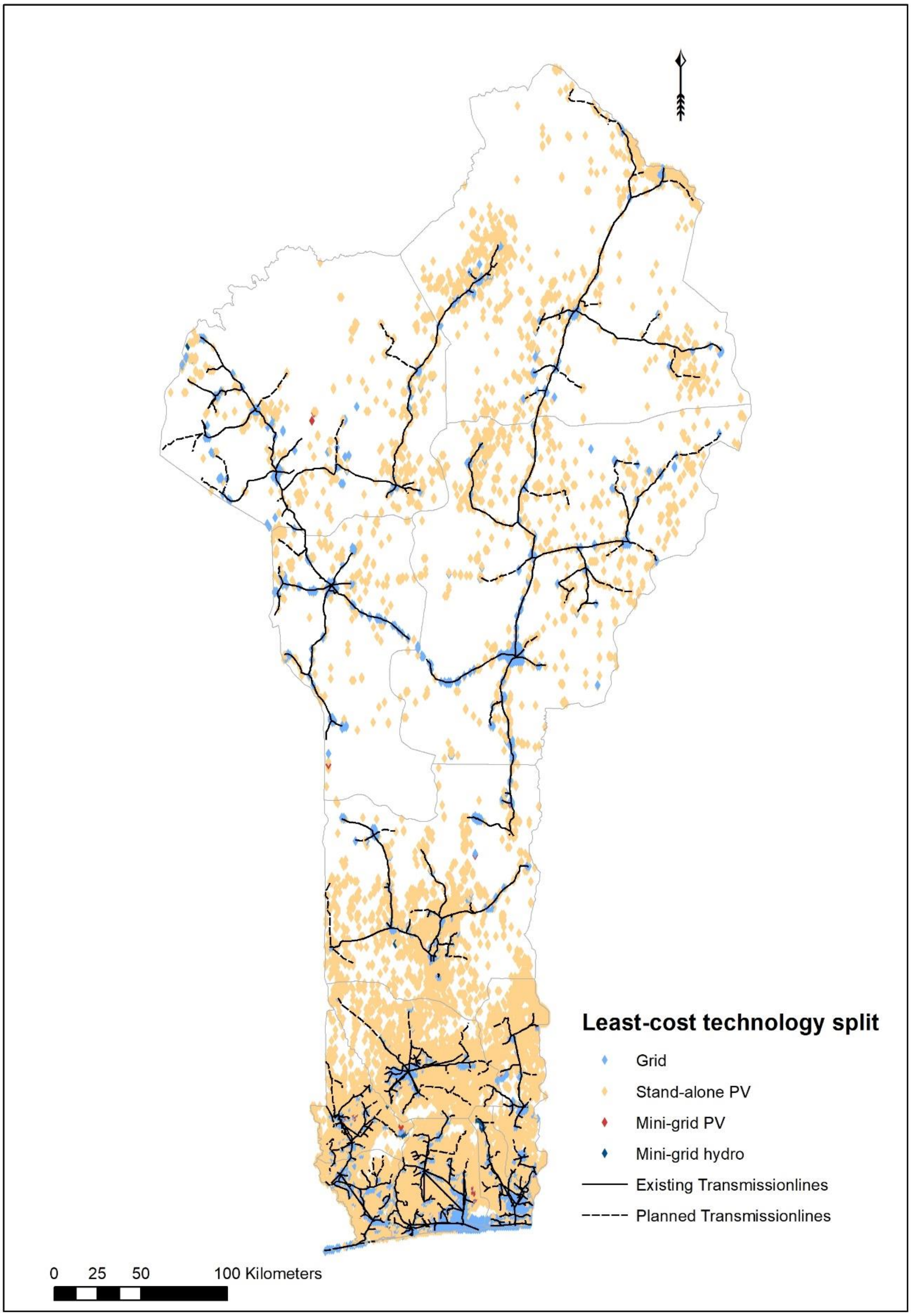

Figure 7. Distribution of least-cost electricity generation technologies in Benin by 2030 for Scenario 2 (Tier 4 target level of electricity access in urban areas and Tier 2 target level of electricity access in rural areas). Grid-connection (light blue) is deployed around the larger cities and roads, and the rest of areas are to be supplied by stand-alone PV (yellow) or mini-grids. Mini-grids are to a large extent found close to grid-connected areas. Despite covering a smaller area than stand-alone PV, grid-connection would serve the majority of the population as it is deployed in the most densely populated areas.

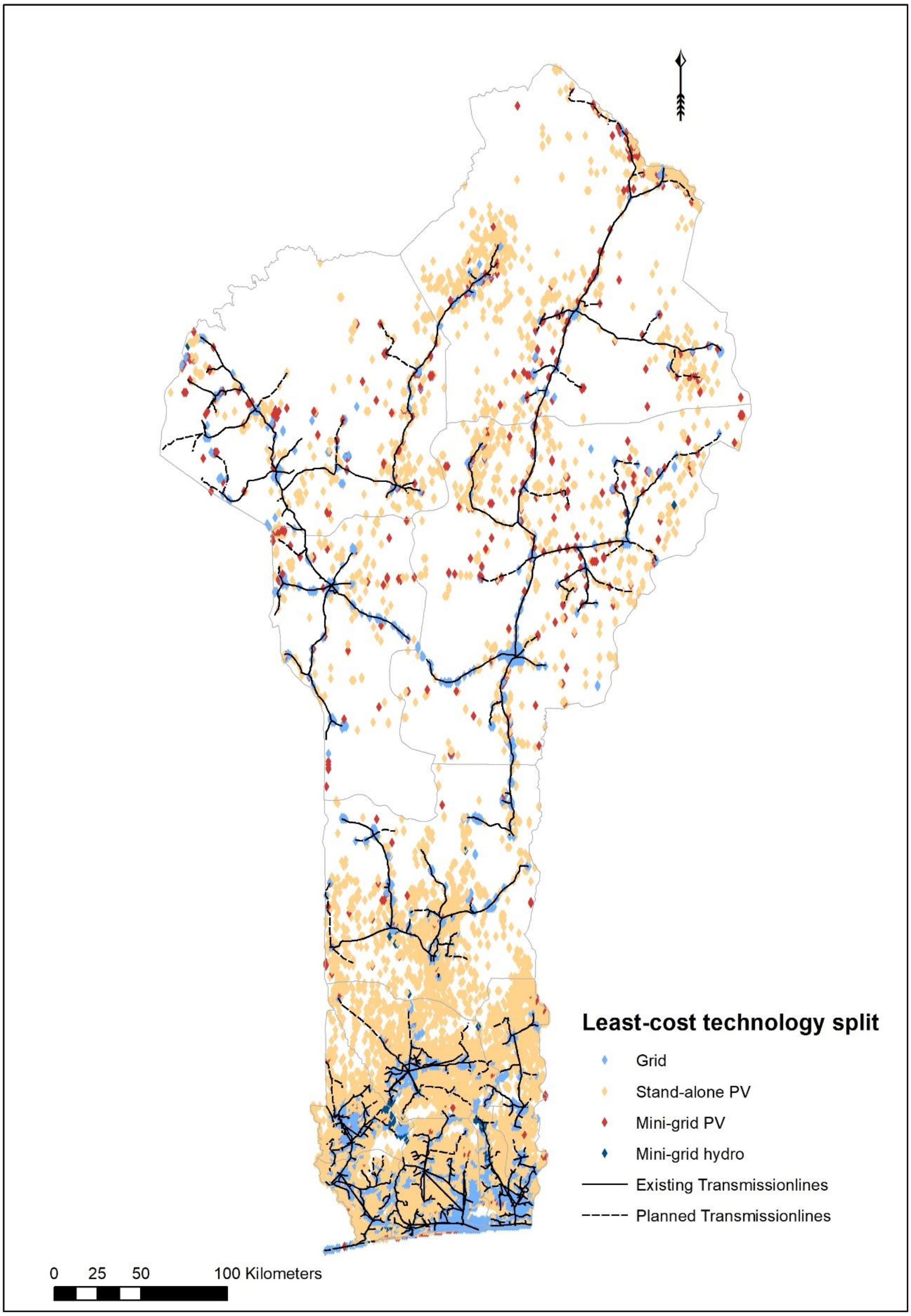

Figure 8. Distribution of least-cost electricity generation technologies in Benin by 2030 for Scenario 3 (Tier 5 target level of electricity access in urban areas and Tier 3 target level of electricity access in rural areas). Grid-connection (light blue) will be deployed around the larger cities, and the rest of areas would be supplied by stand-alone PV (yellow) or mini-grids. Mini-grids are to a large extent found close to grid-connected areas where the population density is sufficiently high, while stand-alone PV is deployed in more sparsely populated areas.

3.1.2. Capacity and investment needs

The new electricity generation capacity required to achieve higher electricity access targets increases for each scenario. In total 329 – 1 428 MW is required, depending on scenario. New generation capacity connected to the national grid varies between 211 MW for Scenario 1 and 1 103 MW for Scenario 3 (Figure 9). In the high consumption scenarios, these generation capacity additions require significant investments and upgrades both for the power plants and for the transmission and distribution network. It should be noted that extending the grid network and centralized grid generation capacity requires significant investments. The costs for grid-connected power plants and the T&D network range from 1,0 to 3,6 billion USD (Figure 10). Furthermore, the transmission network must have the capacity to accommodate the increased electricity demand and supply. The financial troubles of SBEE and currently high losses in the grid indicate that this poses large challenges, which must be taken into account especially for the high consumption scenario. The total cost to provide universal access to electricity in Benin in these scenarios, including off-grid technologies, range from 1,4 billion USD to 4,7 billion USD depending on electricity access target.

Stand-alone PV capacity is 25 MW in Scenario 1, supplying electricity at the lowest cost for 5,1 million people (33% of the population in 2030). In Scenario 2, the higher rural demand justifies grid-extension in favour of stand-alone PV for 1 million additional people compared to Scenario 1. In addition, capacity requirements for stand-alone PV in this case increase to 131 MW, at a cost of 602 million USD. This is caused by the larger systems required per household to provide additional electricity services. In Scenario 3, both capacity and investment costs for stand-alone PV increase further as system size increases, despite stand-alone PV deployment dropping down to supply 15% of the population.

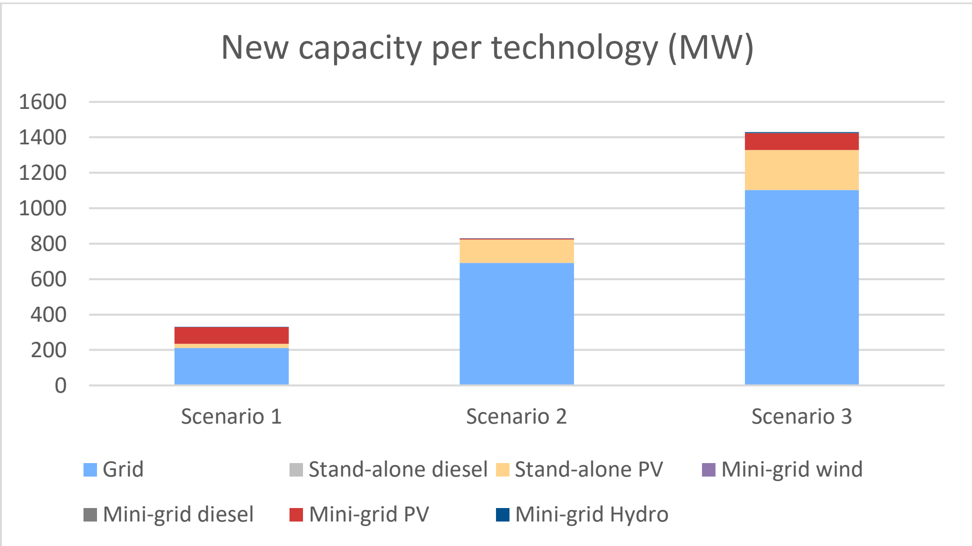

Figure 9. New capacity instalments required by technology in the three base scenarios. The new generation capacity will be directed mainly towards the grid-connected power plants (light blue) in all scenarios. In Scenario 1, the majority of the off-grid capacity is required for PV mini-grids, which are located where the per capita demand is highest. In Scenario 2 and 3, stand-alone PV requires more capacity as the rural electricity access target is higher, where these systems are mainly deployed. The highest electricity access target scenario requires approximately four times as much generation capacity as the lowest one.

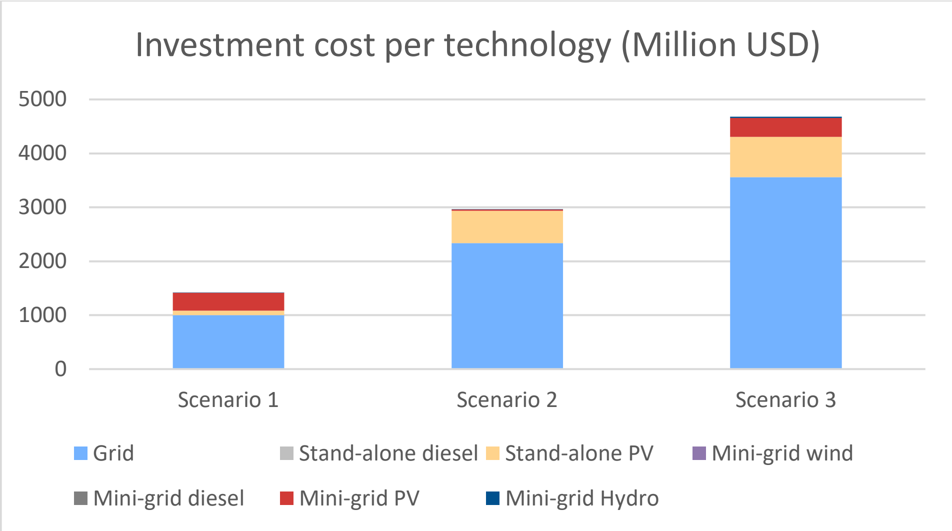

Figure 10. Investment costs required by technology in the three base scenarios with differentiated off-grid costs. The majority of investments will be directed towards the grid-connected power plants and T&D network (light blue) in all scenarios. In Scenario 1, the majority of the off-grid investments is required for PV mini-grids, which are located where the per capita demand is highest. In Scenario 2 and 3, stand-alone PV requires more investments as the rural electricity access target is higher, where these systems are mainly deployed.

3.2 Grid cost sensitivity analysis

The cost at which electricity can be generated for the centralized grid network and the performance of the transmission and distribution network are important factors in the choice of least-cost electricity generation technology. Nine scenarios have been developed examining three different developments for the centralized grid (Table 16). Scenarios 1a, 2a and 3a examine the effect of the grid generation cost and transmission levels remaining at today's level of 0,19 USD/kWh and 23% respectively. Scenarios 1b, 2b and 3b on the other hand examine what would be the least-cost options of a strong development in the centralized grid generation. In this case, the value of 0,06 USD/kWh from the optimization model TEMBA is used, with grid losses at 20% as projected in the World Bank study. Finally, scenario 1c, 2c and 3c consider a grid cost of 0,10 USD/kWh and future transmission losses reduced to 15% as discussed with local stakeholders during the OnSSET modelling workshop in Benin.

Table 16. Description of the nine scenarios using alternative grid generation costs presented in Chapter 2.3.

Grid generation cost scenarios				
Scenario	Urban target tier	Rural target tier	Grid cost (USD/kWh)	Grid losses (%)
1a	3	1	0,19	23
2a	4	2	0,19	23
3a	5	3	0,19	23
1b	3	1	0,06	20
2b	4	2	0,06	20
3b	5	3	0,06	20
1c	3	1	0,10	15
2c	4	2	0,10	15
3c	5	3	0,10	15

3.2.1. Least-cost technology split

In Scenarios 1a, 2a and 3a the grid is deployed for 59% of the population (Figure 11). This means grid-connection is only utilized in the areas where some of the population is already connected by the grid in 2016. In this case, intensification is considered the most affordable option in the model by default. The remaining 41% of the population receive their electricity from off-grid technologies. Hydro mini-grids are utilized by 0,2-0,5% of the population, while PV mini-grids will be deployed for 9-25% of the population. Mini-grid deployment will increase at the higher electricity access targets. The remaining population (16-33%) find stand-alone PV to be the cheapest alternative.

If the cost of electricity for the centralized grid improve, and the transmission losses decrease as in the base scenarios, grid-connection can play a significantly larger role in increasing electricity access in Benin at the lowest cost. In Scenarios 1b, 2b and 3b, 67-92% of the population receive their electricity by grid-connection. In these scenarios, hydro- and PV mini-grids supply energy to a mere 0,2-1,0% of the population. For the remaining population, living in too remote or sparsely populated areas, stand-alone PV provide the least-cost option.

In Scenarios 1c, 2c and 3c, the cost of grid electricity is only marginally lower than in the base scenarios. The transmission losses on the other hand are reduced significantly. In this case, grid-connection is used by 65-82% of the population respectively. This is lower than in scenarios 1b, 2b and 3b, but still 0,2 - 4,1% higher than in the three base scenarios. Hydro- and PV mini-grids are limited to 1-5% of the population, and stand-alone PV to 13-33% of the population.

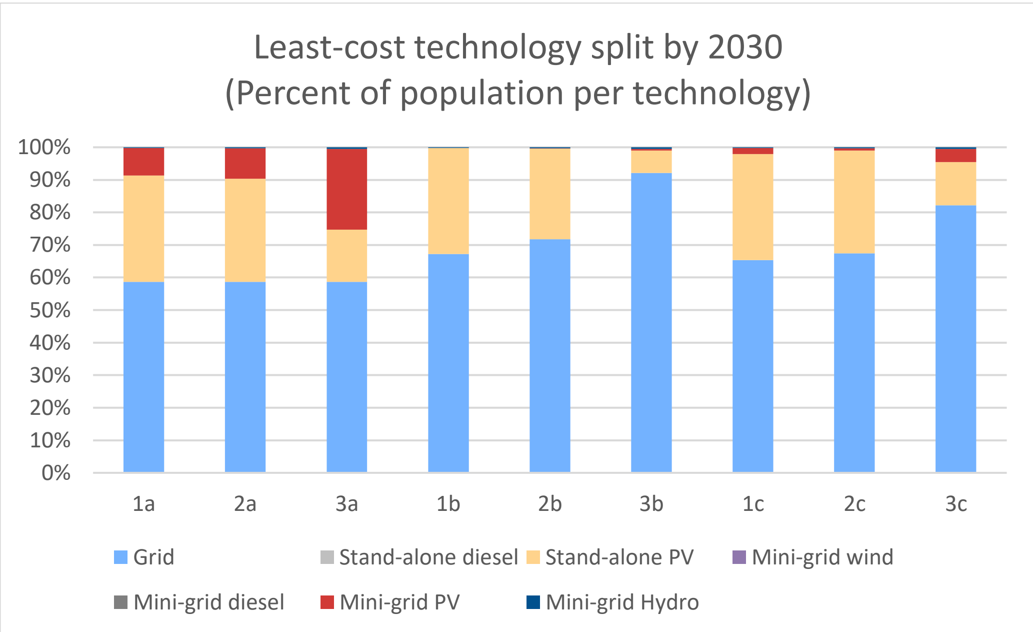

Figure 11. Least-cost technology split for the nine scenarios modelled using varying grid electricity generation cost and transmission losses. The different colours show how large share of the total population in Benin by 2030 will be served by each of the seven generation technologies. In all scenarios, grid-connection (light blue) is the most deployed technology, followed by stand-alone PV (yellow) or PV mini-grids (red). A small share of hydro mini-grids is also present in all scenarios. PV mini-grids are mainly found in urban areas in the low consumption scenarios (Scenario 1a, 1b and 1c) and in rural areas in the higher consumption scenarios where the higher rural electricity access targets justify the deployment of these systems.

3.2.2. Capacity and investment needs

The new capacity requirements and investment costs are higher in the scenarios where grid costs are high and off-grid systems are deployed to a larger extent. The centralized power plants are not expected to be renewable-based to the same extent as the mini-grids found in the model. As such, the grid power plants are expected to have a higher average capacity factor, and do not need as many MW of installed capacity to meet the demand[11]. In the low consumption scenarios (1a-1c), the total generation capacity ranges from 267 MW in Scenario 1b where grid penetration is highest up to 355 MW in Scenario 1a where grid penetration is lowest (Figure 12). Similarly, in Scenarios 2a-2c and 3a-3c total capacity ranges from 776-1 025 and 1 246-1 810 MW respectively.

Furthermore, renewable mini-grids may be costlier per kW of installed capacity compared to fossil-fuel based grid-connected power plants. Therefore, the total investment cost required increases by 5-26% for scenarios 1a, 2a and 5a, where renewable mini-grids are deployed to a larger extent, compared to scenarios 1, 3 and 5. It should be noted however, that the running costs decrease, as the renewable mini-grids do not have any fuel costs. Similarly, the total investment costs can be decreased by 9-13% if the grid cost is lower as in Scenario 1b, 2b and 3b. Also in Scenarios 1c, 2c and 3c the investment costs are reduced by 6-10%. As the transmission losses are significantly lower in these scenarios, a lower amount of new power plants are required to supply the same amount of electricity to the customers.

Total new capacity required only for the electrification component of the grid-connected power plants ranges from 204 up to 1 131 MW, at a cost of 962-3 854 million USD (Figure 13). Similarly, for off-grid technologies 25-981 MW are required at a cost of 88-906 million USD. The main driver of new capacity requirements and investment cost is the electricity access target levels, but the split between grid- and off-grid technologies also has a large impact. Furthermore, this split may also affect who will bear the investment, depending on the policies and regulations in Benin.

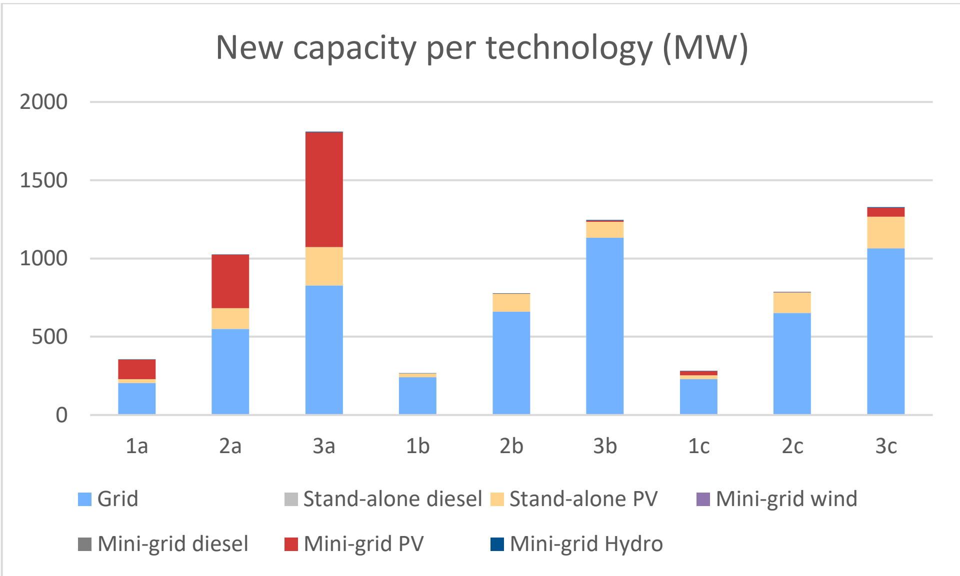

Figure 12. New capacity instalments required per technology in the nine scenarios modelled using varying grid electricity generation cost. The split between grid-connected power plants (light blue), stand-alone PV (yellow) and mini-grids vary significantly depending on targeted electricity access tier and the grid electricity generation cost. The higher electricity access target scenarios require significantly larger generation capacity instalments.

[11] See Annex B for a more detailed description of the capacity factors used in the model.

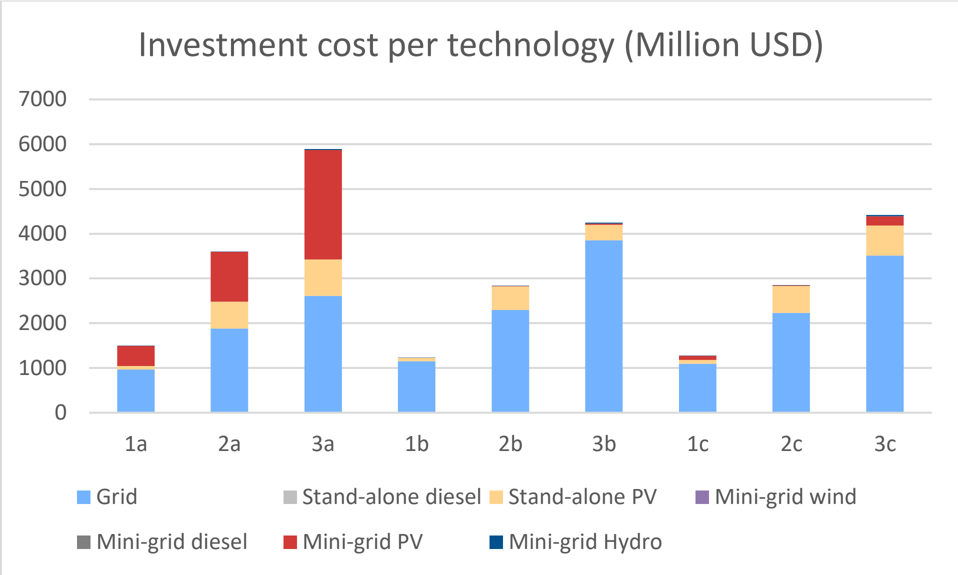

Figure 13. Investment costs required by technology in the nine scenarios modelled using varying grid electricity generation cost. A half or more of investment is directed towards the grid-connected power plants and T&D network (light blue) in all scenarios. The higher electricity access targets require significantly larger investments.

3.3 Sensitivity analysis on PV mini-grid PV cost reductions

Three additional scenarios are developed to examine the effect of lower PV mini-grid investment costs, which can come as a result of technology improvements or a larger deployment of these kinds of systems in Benin. For these scenarios, the lower cost in Table 6 was applied. This means 4 300 USD/kW for a 100 kW system as a base (Table 17). A summary of the three scenarios if found in Table 18.

Table 17. PV mini-grid costs used in the model for Scenario 1d, 2d and 3d. The values in the center columns are used as reference for the relationship between system size and cost, to find the values in the right-hand columns, which are used in the model for Benin.

Mini-Grid PV		
Maximum Capacity (kW)	Costs from IRENA (Reference)	Costs based on Benin value of 4 300 USD/kW for 100 kW (For use in the model)
50	8 964	12 076
75	5 742	7 735
100	3 192	4 300
>200	1 863	2 510

Table 18. Description of the three scenarios examining the effect of lower PV mini-grid investment costs.

Reduced PV mini-grid investment cost scenarios				
Scenario	Urban access target tier	Rural access target tier	Grid cost (USD/kWh)	PV mini-grid investment cost for 100 kW system (USD/kW)
1d	3	1	0,1022	4 300
2d	4	2	0,1022	4 300
3d	5	3	0,1022	4 300

3.3.1. Least-cost technology split

As expected, PV mini-grids can be economically competitive in more areas if the investment cost is reduced. In Scenario 1d, PV mini-grids is the least-cost option for 8,5% of the population (Figure 14). This is an increase from 6% in Scenario 1. Again, mini-grid deployment only occurs in urban areas, as the rural electricity access target is too low to justify mini-grids. This increase in mini-grid deployment comes on behalf of grid-extension, in locations where the electricity demand is not enough to justify the extension of the grid compared to the more affordable PV mini-grids. In Scenario 2d, PV mini-grids is the least-cost alternative for 8,8% of the population. In this scenario, the higher demand leads to a small deployment also in rural areas, for 0,6% of the total population. In Scenario 3d, PV mini-grids can play its largest role for electrification. At this demand target, almost a quarter of the population, 24,4%, find PV mini-grids to be the least-cost alternative. One third of this population is located in urban areas.

In all three scenarios, stand-alone PV remains at the same level as in the base scenarios, deployed in areas too sparsely populated to justify either grid-extension or mini-grids. In Scenario 1d, grid-connection is the least-cost option only in areas where some of the population is already connected to the grid. As electricity access targets increase in Scenario 2d and 3d, grid-connection increases only marginally by 80 000 – 270 000 people. This is significantly lower than in the base scenarios, and high demand areas would instead be served at a lower cost by mini-grids when considering the cost reduction examined in these scenarios.

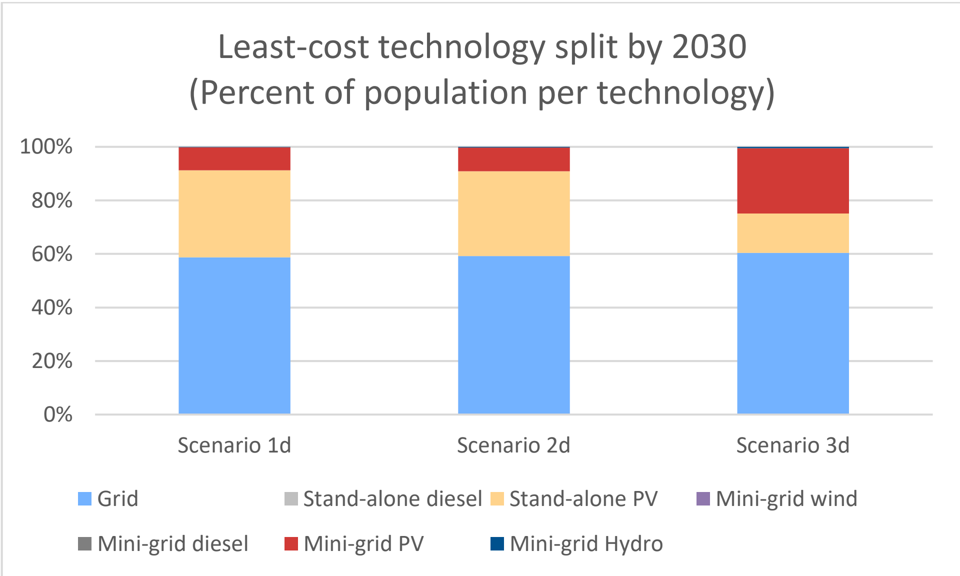

Figure 14. Least-cost technology split for the three scenarios examining the effect of lower PV mini-grid investment cost. The different colours show how large share of the total population in Benin by 2030 that is served by each of the seven generation technologies. In all scenarios, grid-connection (light blue) is the most deployed technology. Stand-alone PV (yellow) will be the most utilized off-grid technology in Scenario 1d, while PV mini-grids (red) will be in Scenario 2d and 3d. A small share of hydro mini-grids (dark blue) are also deployed for less than 1% of the population. In Scenario 1d, the PV mini-grids are utilized in urban areas, but as demand increases, grid-extension becomes favourable in these areas. In Scenario 2d and 3d, the PV mini-grids are found in rural areas.

3.3.2. Capacity and investment needs

Compared to the three base scenarios, both new electricity generation capacity and investment costs increase with lower cost of PV mini-grids. Both of these increases are driven by the transition from grid-extension to mini-grids. Again, the generation capacity increase is caused by the fact that the renewable mini-grids have a lower capacity factor than the mainly fossil-fuel based grid-generation power plants. The investment cost also increasesmainly due to higher investment cost of renewables compared to fossil-fuelled plants, but this is compensated by lower running costs, making the off-grid renewable options overall the lowest cost option in these scenarios. The exception is Scenario 1d, where PV mini-grids are deployed at the same ratio as in Scenario 1, but with a lower investment cost per kW of installed capacity. In total, new capacity requirements increase by 18, 162 and 316 MW for Scenario 1d, 2d and 3d (Figure 15) respectively compared to Scenario 1, 2 and 3. The investment cost decreases by 15 million USD in Scenario 1d, and increase by 358 and 637 million USD in Scenario 2d and 3d respectively (Figure 16).

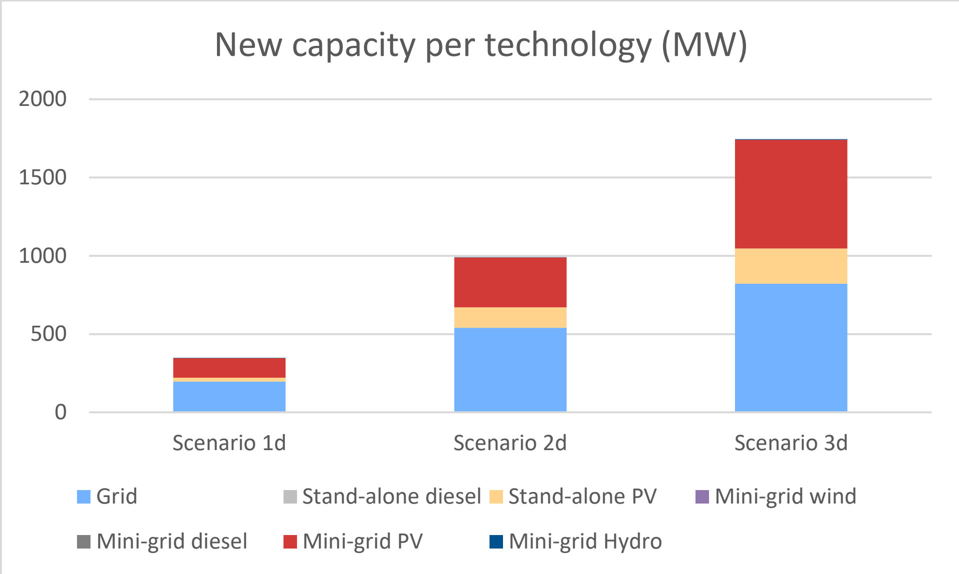

Figure 15. New capacity instalments required by technology in the three scenarios examining the effect of lower PV mini-grid investment cost. The new generation capacity is directed mainly towards the grid-connected power plants (light blue) in all scenarios. Also, in all scenario the majority of the off-grid capacity is required for PV mini-grids, which are located where the per capita demand is highest. New capacity requirements increase by 18, 162 and 316 MW for Scenario 1d, 2d and 3d respectively compared to Scenario 1, 2 and 3.

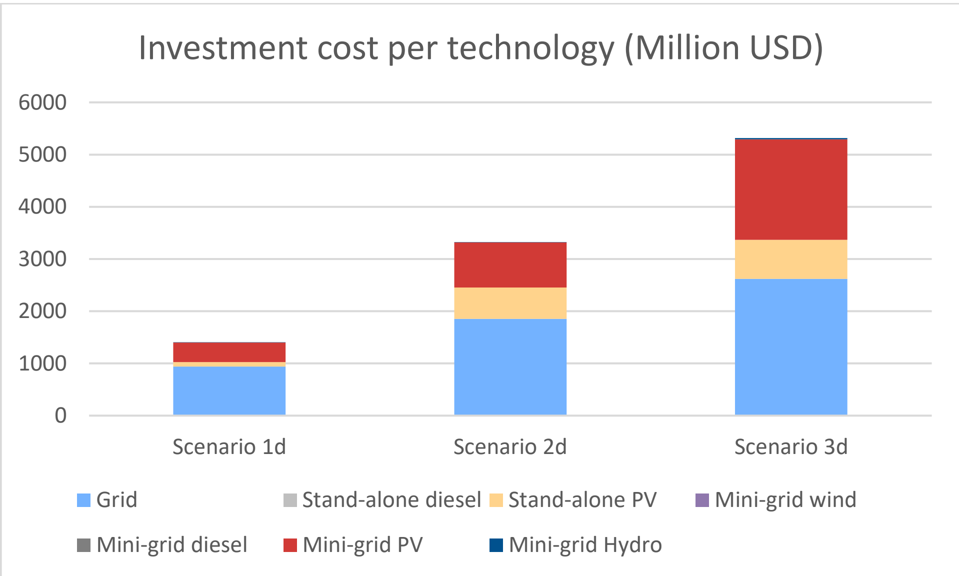

Figure 16. Investment costs required by technology in the three scenarios examining the effect of lower PV mini-grid investment cost. The majority of investments will be directed towards the grid-connected power plants and T&D network (light blue) in Scenario 1 and 2. In Scenario 3, 51% of the investment is required for off-grid technologies. In all scenarios, the majority of the off-grid investments is required for PV mini-grids, which are located where the per capita demand is highest. The investment cost decreases by 15 million USD in Scenario 1d, and increase by 358 and 637 million USD in Scenario 2d and 3d respectively compared to the three base scenarios.

3.4 Sensitivity analysis on stand-alone PV cost reductions

Three additional scenarios have been developed to examine the effects of future stand-alone PV investment cost reductions (Table 19). In these scenarios, the cost of all stand-alone PV systems is reduced by 30%. In all other aspects, the scenarios are identical to the three base scenarios.

Table 19. Description of the three scenarios examining the effect of lower stand-alone PV investment costs.

Differentiated costs				
Scenario	Urban access target tier	Rural access target tier	Grid cost (USD/kWh)	Stand-alone PV investment cost reduction
1e	3	1	0,1022	30%
2e	4	2	0,1022	30%
3e	5	3	0,1022	30%

3.4.1. Least-cost technology split

In the three scenarios, stand-alone PV systems play a significantly larger role than in the base scenarios. 40-41% find stand-alone PV systems to be the least-cost technology in the three scenarios (Figure 17). In Scenario 1e, no grid-extension occurs. This means grid-connection (intensification) only appears in areas where some of the population already has access to grid-electricity at the start year. In Scenario 2e and 3e, grid-extension would have a marginal effect as 0,2 and 0,8% of the population would be served by grid-extension. PV mini-grids are not competitive in any areas in any of the three scenarios at the investment cost of 5 280 USD/kW for a 100 kW system. Hydro mini-grids are only deployed only for 0,1-0,3% of the population in these scenarios.

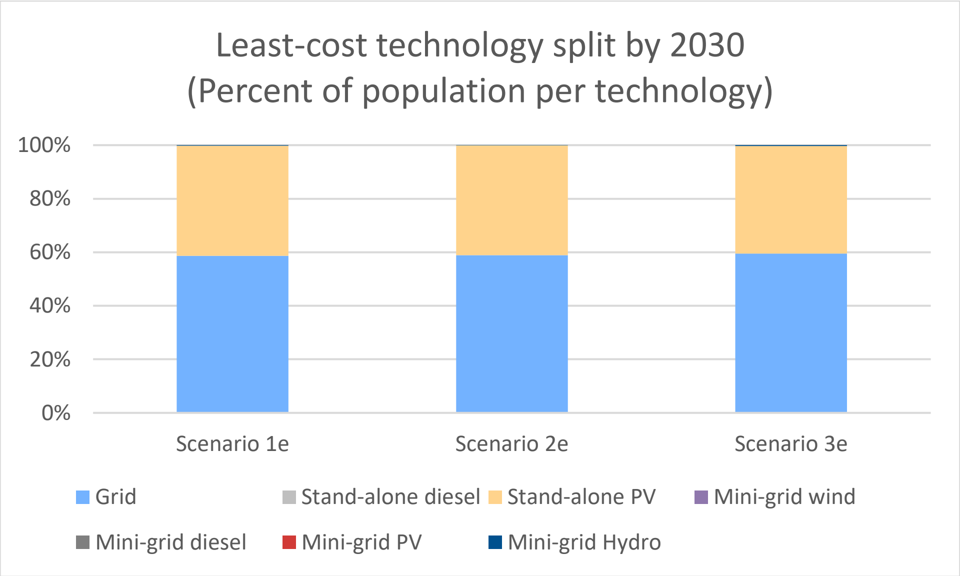

Figure 17. Least-cost technology split for the three scenarios examining the effect of lower stand-alone PV investment cost. The different colours show how large share of the total population in Benin by 2030 would be served by each of the seven generation technologies. In all scenarios, grid-connection (light blue) is the most deployed technology. Stand-alone PV (yellow) is utilized for almost all of the off-grid electrification. A small share of hydro mini-grids (dark blue) are also deployed for less than 1% of the population. Grid-extension is limited to below 1% of the population, the remaining grid-connection occurring in locations where some of the population already has access to the grid in 2016.

3.4.2. Capacity and investment needs

As in the scenarios with lower PV mini-grid investment costs, the trend is higher capacity requirements and investment costs with lower stand-alone PV investment costs compared to the three base scenarios. An additional 12, 153 or 289 MW of electricity generation capacity is required for Scenario 1e, 2e and 3e (Figure 18) compared to Scenario 1, 2 and 3 respectively. In Scenario 1e, the investment cost is reduced by 15 million USD as the stand-alone PV systems are less expensive than in Scenario 1. In Scenario 2e and 3e the cost instead increases by 35 and 17 million USD respectively (Figure 19). This is caused by the fact that stand-alone PV systems replace grid-extension to a larger extent, which has lower investment costs but higher running cost.

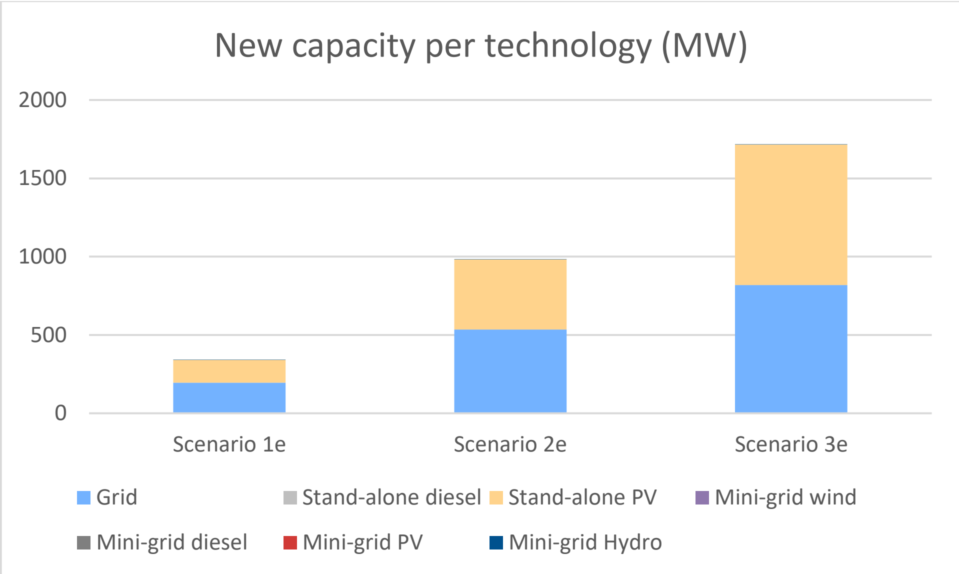

Figure 18. New capacity instalments required by technology in the three scenarios examining the effect of lower stand-alone PV investment cost. The new generation capacity is directed mainly towards the grid-connected power plants (light blue) and stand-alone PV in all scenarios. An additional 12, 153 or 289 MW of electricity generation capacity is required for Scenario 1e, 2e and 3e compared to Scenario 1, 2 and 3 respectively.

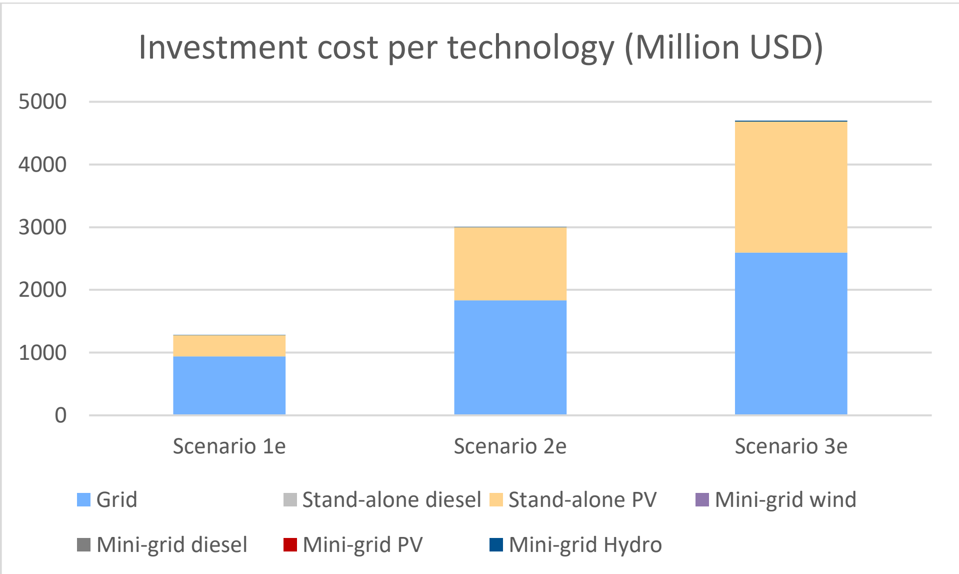

Figure 19. Investment costs required by technology in the three scenarios examining the effect of lower stand-alone PV investment cost. The majority of investments are directed towards the grid-connected power plants and T&D network (light blue) and stand-alone PV in all scenarios. In Scenario 1e, the investment cost is reduced by 15 million USD as the stand-alone PV systems are less expensive than in Scenario 1. In Scenario 2e and 3e the cost instead increases by 35 and 17 million USD respectively.

3.5 Sensitivity analysis including productive uses electricity demand estimate

The above scenarios examine pathways for universal access to electricity considering residential demand. Productive and social uses of electricity are also important. Electricity usage in these sectors can improve socio-economic development. Taking into account also these uses of electricity, the higher demand can also shift the least-cost electricity generation technologies. Two types of productive uses are considered at this point, using a population-based method for estimating demand for health and educational facilities in three scenarios (Table 20). This method is further described in Appendix A.

Table 20. Description of the three scenarios including electricity demand estimates for health and education facilities.

Scenario	Urban target tier	Rural target tier	Health and education demand (GWh)	Residential demand (GWh)	Grid cost (USD/kWh)
1f	3	1	307	1 332	0,1022
2f	4	2	444	3 695	0,1022
3f	5	3	587	5 963	0,1022

3.5.1. Least-cost technology split

The electricity demand for education and health facilities increases the total electricity demand by 23%, 12% and 10% in Scenario 1f, 2f and 3f respectively compared to the three base scenarios. This increase in electricity demand causes a slight shift up the technology ladder, towards mini-grids and grid-extension. In Scenario 1f, grid-connection increases to be the least-cost option for 61,4% of the population (Figure 20), compared to 60,8% of the population in Scenario 1. This increase comes at the expense of mini-grids, as the higher demand justifies the cost of grid-extension for an additional share of the urban population. The effect of the electricity demand for productive uses is seen to a larger extent in Scenario 2f, where mini-grid deployment increase to 5,1% compared to 0,7% in Scenario 2. Grid-connection also increases marginally to 67,4% from 67,3% in Scenario 3. These changes result in a drop in stand-alone PV from 31,7 to 27,3% as mini-grids and grid-extension is favoured in more places due to the higher demand. In Scenario 3f the changes are smaller, grid-connection increase by 0,4% compared to Scenario 3 while stand-alone technologies decrease by 0,4% and mini-grids remain unchanged. The impact of the productive on the total electricity demand is relatively smaller in this scenario; hence, the changes are not as significant.

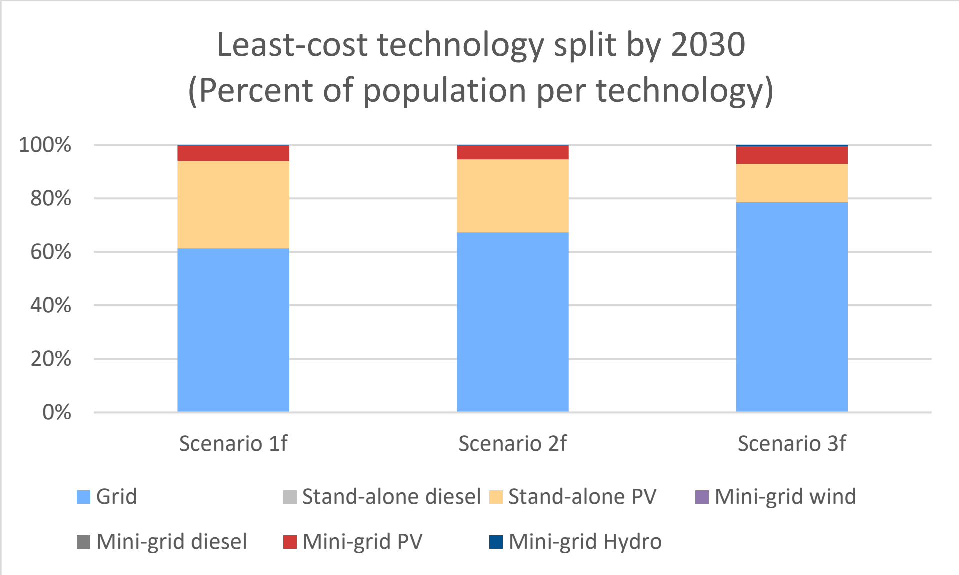

Figure 20. Least-cost technology split for the three scenarios electricity demand estimates for health and education facilities. The different colours show how large share of the total population in Benin by 2030 would be served by each of the seven generation technologies. In all scenarios, grid-connection (light blue) is the most deployed technology followed by stand-alone PV (yellow). In Scenario 1f, the PV mini-grids will be utilized in urban areas, but as demand increase grid-extension becomes favourable in these areas. In Scenario 2f and 3f the PV mini-grids are instead found in rural areas.

3.5.2. Capacity and investment needs

The capacity requirements and investment costs increase across all three scenarios compared to the base scenarios as a result of the higher electricity demand. In total, the capacity requirements increase by 98, 139 and 174 MW in Scenario 1f, 2f and 3f (Figure 21) compared to Scenario 1, 2 and 3 respectively. The majority of this increase is for the grid-connected power plants. As electricity demand for both health and education facilities are population driven the biggest demand increases are found in the most densely populated areas, where grid-extension is utilized to the largest extent in all scenarios. A similar pattern is seen for the investment cost, which increases by 440, 488 and 538 million USD in Scenario 1f, 2f and 3f (Figure 22) respectively compared to Scenario 1, 2 and 3. Of this increase, 371, 387 and 493 million USD is targeted for grid-connection.

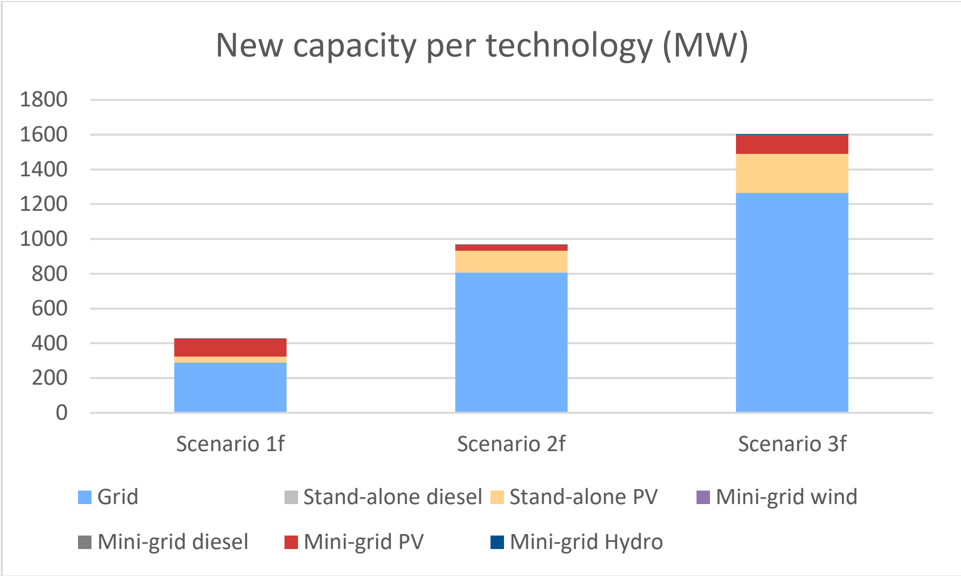

Figure 21. New capacity instalments required by technology in the three scenarios electricity demand estimates for health and education facilities. The new generation capacity is directed mainly towards the grid-connected power plants (light blue). The additional electricity demand for productive uses increase the electricity generation capacity by 98, 139 and 174 MW in Scenario 1f, 2f and 3f compared to Scenario 1, 2 and 3 respectively.

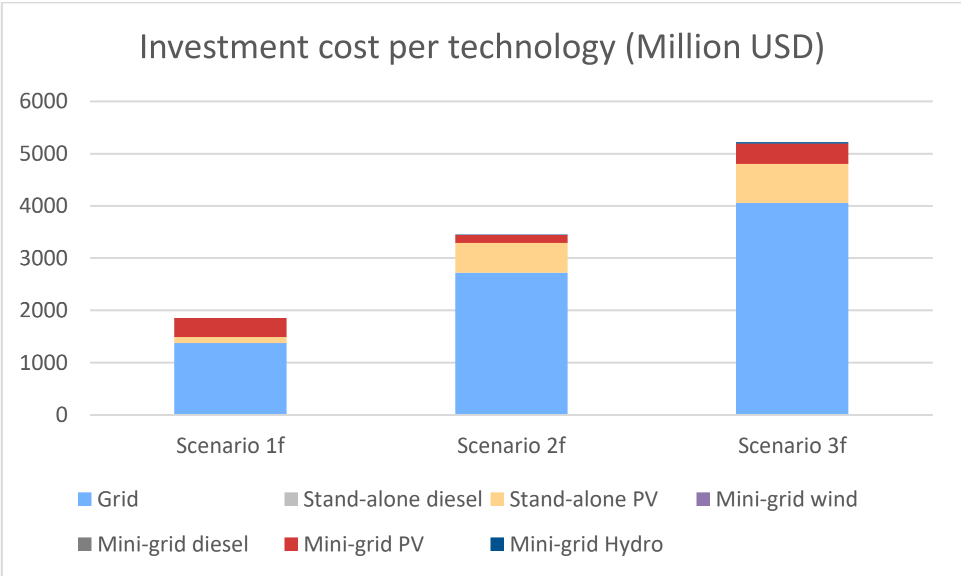

Figure 22. Investment costs required by technology in the three scenarios electricity demand estimates for health and education facilities. The majority of investments is directed towards the grid-connected power plants and T&D network (light blue) in all scenarios. The additional electricity demand for productive uses increase the investment cost by 440, 488 and 538 million USD in Scenario 1f, 2f and 3f respectively compared to Scenario 1, 2 and 3.

4. Conclusion and recommendations

Achieving universal access to electricity in Benin by 2030 in a cost-effective manner requires a combination of grid-connection and off-grid technologies. Across the scenarios examined, grid-connection is the least-cost alternative for 58-92% of the population in Benin by 2030. This corresponds to 47-90% of the new connections required by 2030. The remaining 8-42% of the population (10-53% of new connections) is electrified by mini-grids and stand-alone technologies. These are mainly PV based systems, but a small share of hydro mini-grids also appears in the mix. Stand-alone PV systems play an important role in providing electricity mainly for rural population and at low electricity targets. With higher access targets and the addition of productive loads (schools, health clinics), the optimal electrification technology solution motivates more mini-grids and grid-extension. In this case, stand-alone PV systems are only deployed in the most sparsely populated and remotely located population. The investment cost required to achieve universal access ranges from 1 236 million USD up to 5 895 million USD.

The cost at which electricity is generated for the centralized grid as well as the transmission losses have a significant impact on the role of grid. If grid electricity generation costs and transmission losses remain at today's levels, the economic viability of grid-extension compared to off-grid technologies is limited. In many of the scenarios, PV mini-grids are found to be the least-cost alternative also in close proximity to the grid. It is likely that these will be connected to the grid at some point. Development need to be undertaken in such a way that will allow the deployment of mini-grids that are compatible with grid in these areas and will allow interconnection. This might however, require additional capital, which is something that was not considered in this analysis. Furthermore, policies and regulations need to ensure that there is still a viable business case for mini-grid developers to invest in these areas, even if these are later connected to the grid.

Mini-grid deployment in urban areas can be important if a) a low urban electricity access targets is considered, b) if the grid costs remain high or c) the PV mini-grid capital costs decrease. In rural areas, the most important aspect for the viability of mini-grids is the level of electricity demand. At low demands, the cost of the distribution network is too high in relation to the amount of electricity supplied. At higher rural electricity access targets, the role of mini-grid deployment increase. Considering additional demand for health and education facilities, mini-grid deployment in rural areas increases from 1,4 up to 10,5% of the rural population for the medium electricity access target. Other productive uses of electricity not considered in this report could potentially further increase the role of mini-grids, or alternatively grid-extension. A more comprehensive analysis of electricity demand for productive uses should be included in further studies.

It should be noted that the OnSSET tool simply select the technology that indicates the lowest LCOE in each location. It does not however consider affordability issues. That is, different policies and incentives may also affect the technology mix. E.g., grid tariff subsidies can make grid-connection more favourable for the customers in areas where another technology may be less costly to deploy. Furthermore, the tool also does not consider who bears the cost of deployment for different technology options. Considering the substantial import dependency, high transmission losses and financial challenges for SBEE, mini-grids and stand-alone technologies may provide a means to attract investments from private and international actors to increase electrification rate in the short to medium term. This would shift some of the costs away from the governmental organizations involved in the centralized grid, and can increase the rate at which electricity access increases. Finally, it should be noted that the centralized grid is based to a large extent on fossil-fuelled power plants, compared to the PV and hydro mini-grids, which are renewable. As such, scenarios with high mini-grid deployment can potentially lead to a higher share of renewables in the electricity generation mix in Benin. However, this also depends on the developments of the centralized grid.

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Annex A. Estimating electricity demand for productive uses

Data on electricity access for health and educational facilities in developing countries may often be lacking or incomplete [38]. The use of Geospatial Information Systems (GIS) and geospatial data can help fill data gaps where data are unavailable and national statistics are lacking. Over the past few months the division of Energy Systems Analysis at KTH (KTH dESA) has been developing a methodology that aims to quantify electricity demand for educational and health facilities based on publicly available geo-spatial information. The output can be included in electrification studies and add useful information for decision-makers. The methodology considers the electricity demand in health facilities to be driven by the population that may utilize the service in each location, as well as the type of settlement that is expected. Better-equipped and more electricity-demanding facilities are expected to be found in e.g. towns and cities compared to more sparsely populated rural areas.

A.1 Education facilities

Starting with a geospatial population dataset, containing information of the number of people living in each sub-location, the electricity demand for education facilities is determined in four main steps:

In the first step of the analysis, the population of primary and secondary education[12] age by 2030 in each cell is determined based on national demographic statistics. These statistics reflect the proportion of the population in the country that is in the primary and secondary school age. This value is multiplied by the population in the cell from the population dataset, to find the total population of primary and secondary education.

When the population of school age in the cell has been determined, the number of school areas in each cell is determined by dividing the population of school age by the average classroom size and average number of students in a class in the country, plus an additional area for non-classroom facilities.

Finally, the annual electricity demand for educational purposes in the cell is determined as the product of the school area (m^2) and the annual electricity demand per area ($kWh/m^2/year$, Table 21) (average value for primary and secondary education) which is divided into five tiers (Table 21). In this study, the electricity demand tier for education facilities has been assumed to follow the residential electricity access tier.

Table 21. Electricity demand per school area for five tiers[13].

Tier	School area electricity demand (kWh/m^2)
1	1,05
2	3,15
3	6,3
4	9,45
5	12,6

Table 22. Key input values for educational demand.

Indicator	Value	Reference
Average size of class in Benin (students/class)	50	[42]
Classroom size (m^2)	50	[43]

[12] 6-18 years old

[13] These values are estimates based on data for various countries.

Proportion of population in primary education age in Benin (share)	0,17	[44]
Proportion of population in secondary education age in Benin (share)	0,17	[44]

Figure 23 displays a preliminary demand assessment using this method for education facilities. The results are for Tier 3 target of school electricity access (6,3 kWh/m²) as described above. As can be expected, the demand is higher in densely populated areas.

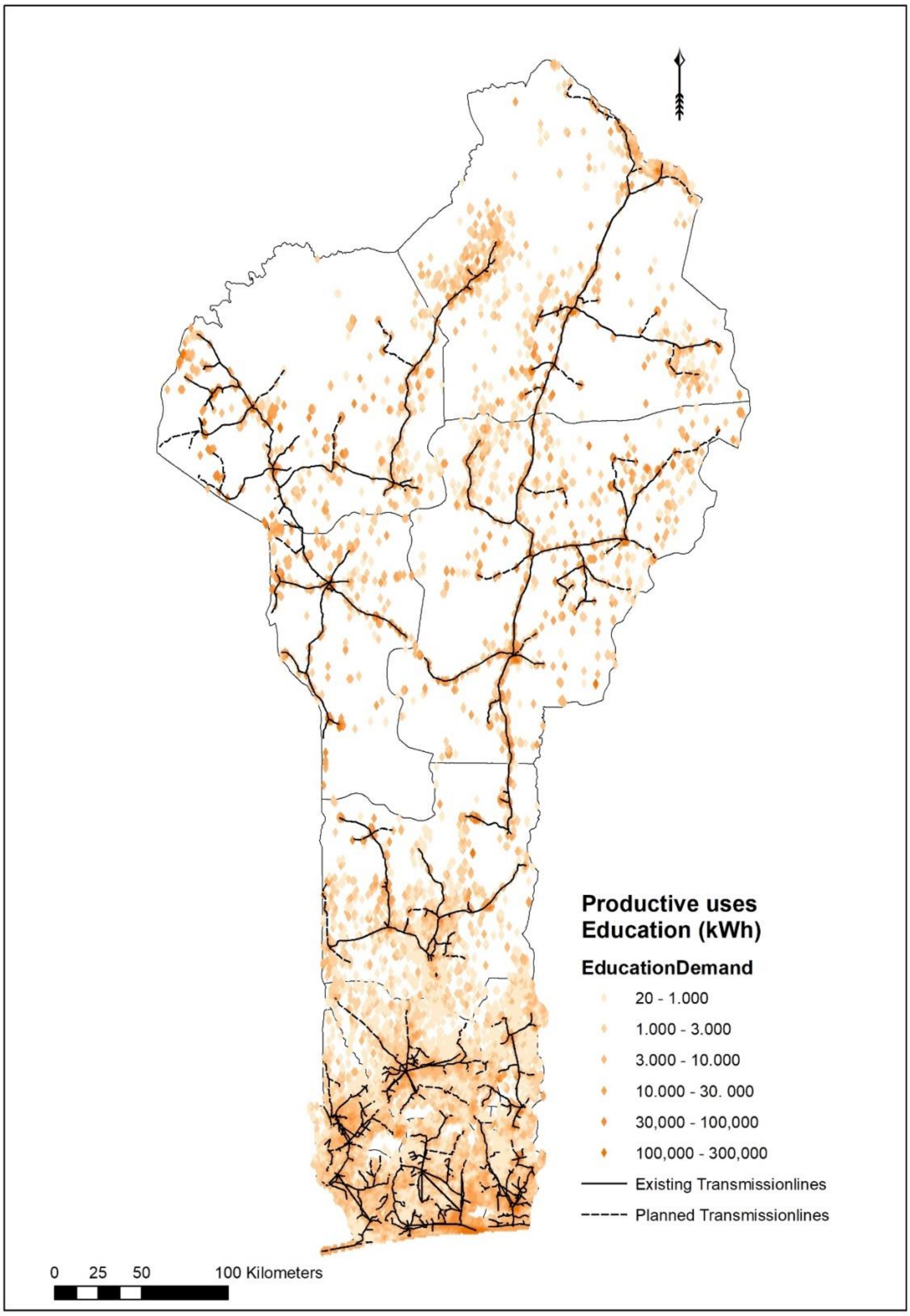

Figure 23. Estimated annual electricity demand per cell for education facilities for Tier 3 level of electricity access target.

A.2 Health facilities

Starting with a geospatial population dataset containing information of the number of people living in each location the electricity demand for health facilities is determined in five main steps:

1. In the first step, the target hospital beds to population ratio is chosen by the user from five target tiers (see Table 23 below). In this study, the target has been assumed to follow the residential electricity access target tier.
2. When the beds-to-population tier has been chosen, the number of hospital beds in each cell is calculated from the population and the target hospital beds to population ratio.
3. The type of health facility in each cell is determined from the settlement type based on population density as seen in Table 24 below.
4. The average energy requirements per hospital bed (kWh/hospital bed/year) for the four types of health facilities considered have been derived from [45] and [46].
5. Finally, the electricity demand for health facilities in each cell is calculated as the product of the target number of hospital beds in the cell and the average energy requirements per hospital bed in the cell for the expected health facility type.

Table 23. Ratio of hospital beds to population for five tiers

Tier	Number of beds per 10 000 people
1	10
2	20
3	30
4	40
5	50

Table 24. Electricity demand per hospital bed depending on settlement type. The hospital is assumed to be a fully equipped modern hospital found in urban centres, thus the significantly higher electricity demand per hospital bed compared to the health clinics.

Settlement type	Estimated maximum population density (pop/km^2)	Type of health clinic	Energy demand per hospital bed (kWh/year) [35, 36]
Hamlet	50	Health clinic type 1	90
Village	880	Health clinic type 2	60
Town	2 000	Health clinic type 3	43
City	>2 000	Hospital	9 844

Figure 24 displays a preliminary demand assessment using the above method for electricity demand in health facilities. The results are for Tier 3 target of health access, corresponding to 30 hospital beds per 10 000 people.

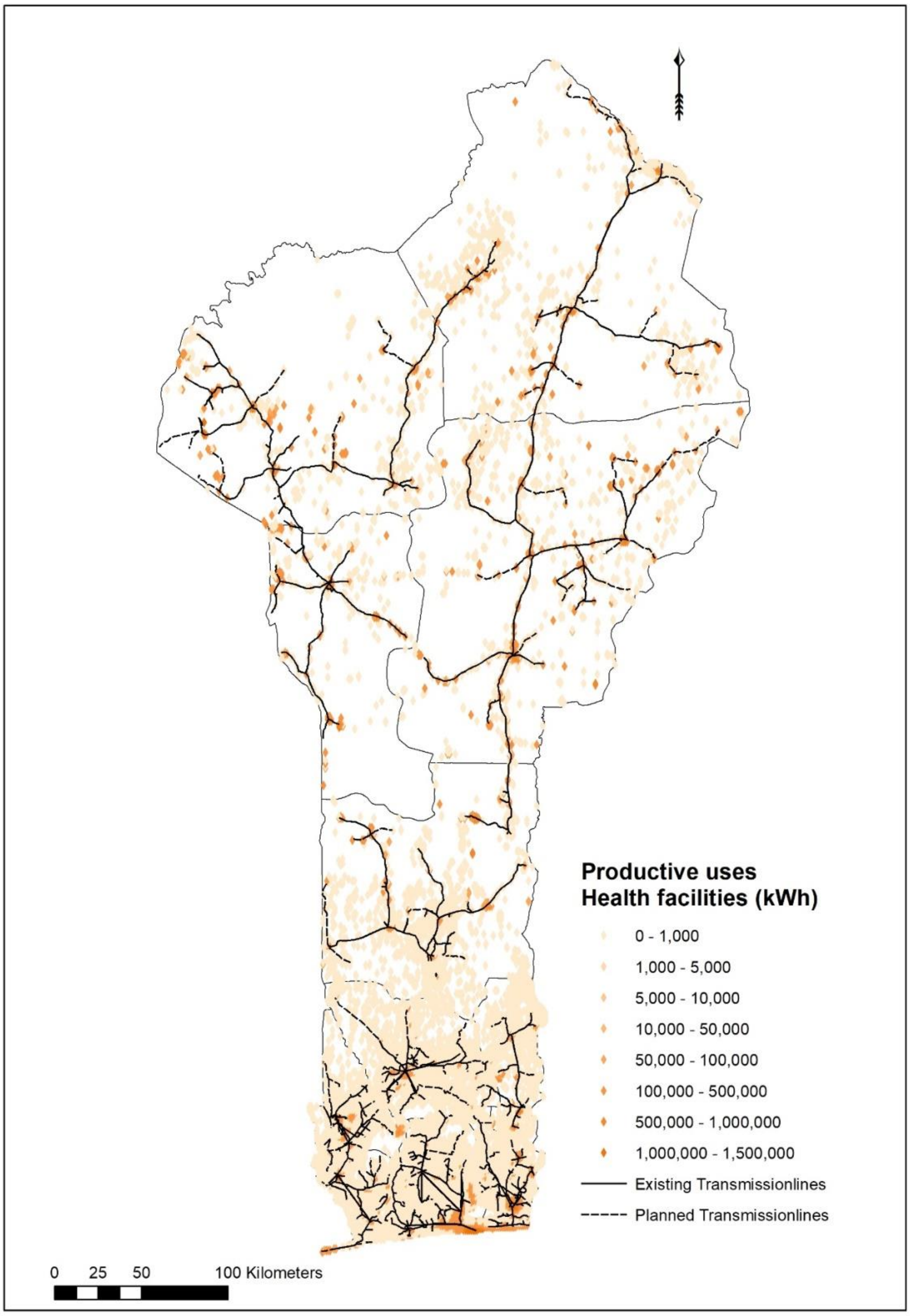

Figure 24. Estimated annual electricity demand per cell for health facilities for Tier 3 level of electricity access target.

A.3 Limitations of the methodology

There are some important limitations of the proposed methodology. First and foremost, all cells in the population dataset are assigned an electricity demand for health and education facilities. In reality, this may not be the case, since the population may receive their education or health services in a neighbouring location. Rather, demands should be aggregated for all neighbouring cells using the same health or education facility. This may increase settlements with higher demand intensity that may be suitable for mini-grids or grid-extension. Future developments of the methodology will include such an option, either by adding the exact locations of all health and education facilities where feasible or by aggregating (creating clusters) based on some other conditions.

Furthermore, this methodology is used to estimate the electricity demand based on five target tiers. This means that the method can generate an estimation of the electricity demand if those targets are reached. It does not examine if the targets are realistic and should not be used to determine the exact demand in a specific location, but give a general idea of the demand throughout the country for a specified target.

Finally, much of the data in this method is based on general values that have been gathered from various reports and databases. Where such data can be found, it should be replaced by national values. There are several important improvements that should be further researched. As previously mentioned the possibility of clustering electricity demand for health and educational facilities should be included. Furthermore, methods to estimate the electricity demand for other productive uses such as agriculture and enterprises should be developed.

Annex B. Capacity factors in the OnSSET model

The capacity factor is a measurement of the output energy output from an electricity generation technology in relation to its power capacity:

$$Capacity\ factor = \frac{Actual\ annual\ energy\ generation\ of\ a\ power\ generation\ source}{Potential\ annual\ energy\ generation\ if\ operating\ at\ rated\ power\ all\ year}$$

The capacity factor takes a value between 0 and 1, as the electricity generation technologies deployed cannot operate at full capacity during every hour of the year. This is due to various reasons, including maintenance and energy resource availability. Renewable energy technologies that depend on intermittent energy resources may only generate electricity when the resource is available, and may therefore have lower capacity factors. In the OnSSET model, the capacity factor is modelled in every location based on the local annual resource availability values for wind- and PV off-grid technologies. For hydro- and diesel, off-grid technologies as well as the centralized grid the capacity factor is instead an input to the model as these are not depending on geo-spatial characteristics to the same extent. A summary of the capacity factors used in this study is seen in Table 25.

Table 25.Capacity factors used in the OnSSET model for Benin

Plant type	Capacity factor
Diesel mini-grid	0.7
Hydro mini-grid	0.5
Solar mini-grid	Obtained for each grid point depending on solar availability
Wind mini-grid	Obtained for each grid point depending on wind availability
Diesel stand-alone	0.7
PV stand-alone	Obtained for each grid point depending on solar availability
Centralized grid	0.9