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The role of decentralized systems in providing universal electricity access in Sub-Saharan Africa – A model-based approach

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ABSTRACT

Poverty and lack of access to electricity are highly correlated. In Sub-Saharan Africa, one of the poorest regions in the world, two in every three people have no access to electricity. This paper describes a purpose designed model to explore and project the development in the Sub-Saharan African electricity sector in Baseline and Universal access scenarios. The results provide insight into the role of different systems and technologies in providing access to electricity in the region and associated investment requirements. We project that Baseline developments do not lead to universal access to electricity, especially in Eastern Africa and the rural areas. The results show that central grid extension should be complemented with off-grid systems (mini-grid and stand-alone) to increase access in Sub-Saharan Africa. At the same time, the targeted level of consumption has large implications on the preferred electrification technology and associated investment requirements. For low levels of consumption, off-grid technologies are the most important technologies to increase access rate, while for high levels of consumption, extending the central grid is more economical. Total cumulative investment in the period 2010-2030 amount to 22 billion USD for low levels of consumption and exceed 2.5 trillion USD for high levels of consumption.

1. Introduction

Access to electricity is crucial for human development [1]. Still, in Sub-Saharan Africa 621 million people (i.e. two in every three people) have no access to electricity [2]. The total generation capacity in Sub-Saharan Africa is just 90 GW (GW), i.e. comparable to the total installed capacity of United Kingdom - a country with less than 7% of the population of Sub-Saharan Africa [3]. Moreover, electricity systems often function poorly with an unstable and unreliable electricity supply, low generation capacity, and low efficiency and high costs [4].

Through the adoption of the Sustainable Development Goals (SDGs), the global community has committed to achieving universal access to electricity by 2030 [5]. Scenario studies show that without dedicated policies, this target is unlikely to be reached [6]. Achieving the target would require a significant expansion of the grid and a strong increase in generation capacity [7]. In addition to central grid-extension, off-grid options, such as mini-grids and stand-alone systems, will be required to provide electricity to smaller or remote communities [8]. Energy models can help to evaluate the future challenges of achieving full electricity access. In particular, they can capture the complex interactions between various factors influencing future energy systems, such as long-term investments, operational planning, and electricity distribution.

Yet there are only few models that focus on African countries with their specific characteristics. A notable exception is Zeyringer et al.[9] who developed a model to analyze cost-effective electrification solutions for Kenya, comparing grid extension with stand-alone Photovoltaic (PV) systems. Mentis et al. also applied a GIS based methodology to inform electrification planning and strategies in Nigeria [10] and Ethiopia [11], taking into account grid extension, mini-grid and stand-alone electrification options [3]. presented a projection and analysis of Sub-Saharan Africa's energy system to 2040, using its World Energy Model (WEM).

In this paper, we use an extended stand-alone version of the rural electrification model developed by Ref. [12] to explore future

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Table 1
Definitions of electrification systems [17].

Type	Definition		Advantages	Disadvantages
On-grid system	All network or sub-grid or generating systems that are connected to the grid and run by national utility		High degree of reliability, lower price per kWh than other options when population density and/or consumption is high	High initial investment, very high price per kWh in low population density or consumption areas
Off-grid system	All distribution networks that are isolated from the main grid, supplied by independent source(s) of power, and managed by any kind of operator. This includes both mini-grid and stand-alone options.			
	Mini-grid system	System where all or a portion of the produced electricity (by any source) is fed into a small distribution grid that provides several end-users with electricity A mini-grid system can be either isolated or connected to the central grid	Enhance local level ownership of operation & maintenance, social control over electricity theft, better reliability than stand-alone, easy adaptability, more cost effective than grid extension over large distance, reduced distribution loss	Frequent technological failure from lack of maintenance, untested technology, lack of local skills for maintenance Insufficient capacity from poor assessment, increasing demand, seasonal resource fluctuation, demand management
	Stand-alone system	Isolated power system that usually supplies one rural customer without a distribution grid (such as household, community infrastructure, battery charging station, multifunctional platform, water pumping station, etc.)	User-managed on day to day basis, blackouts affect only one user	Limited capacity, lack of maintenance capacity at household level, seasonal resource fluctuation

developments in the electricity sector in Sub-Saharan Africa. The model was designed to assess the costs of rural electrification in developing countries, focusing on extension of the central grid to areas with no access to electricity. Unlike van Ruijven et al [12]; who only looked at the central grid to provide access to electricity, the extended model includes eight off-grid electrification technologies (mini-grid and stand-alone options). Furthermore van Ruijven et al [12], focused only on rural electrification, while the extended model allows assessing both rural and urban areas. This means that the extended model is able to evaluate a broad range of options for household electrification in both urban and rural areas. The model takes into account local characteristics, including population dynamics, resource availability and the prices of different technologies at a 0.5° × 0.5° grid-cell. We used the model to address the following research questions:

1. What is the potential development in access to electricity and the related technology mix in Sub-Saharan Africa until 2030?
2. What is the role of decentralized systems in providing universal access to electricity in Sub-Saharan Africa in 2030?
3. How does changing the level of electricity consumption affect the technology mix and the required investment in the electricity sector?

The structure of the paper is as follows. Section 2 presents the key strengths and weakness of the various electrification systems and the main factors determining the choice between these systems. Then, section 3 explains the methodology, including model structure, the different electrification technologies being considered, the methodology for calculating the costs of the different technology options and model assumptions. After that, section 4 presents model results for different scenarios, as well as a sensitivity analysis of the main model parameters. Finally, section 5 provides conclusions and discussion on model performance, policy implications and suggestions for further research.

2. Key factors determining the choice of different electrification systems

Almost all governments in developing countries are emphasizing the crucial role of electricity services for human development [13] and have put electrification as a development priority [14]. Traditionally, electrification in developing countries has been regarded as the responsibility of governments and has been implemented by national utilities with natural monopolies [15]. Governments have been focusing on extending the central grid to benefit from economies of scale [8]. However, the emphasis on the central grid, while overlooking alternative off-grid solutions has hampered a rapid spread of electricity infrastructure to large parts of developing countries Ref. [8]. As a result, despite substantial efforts at extending central grids, the electrification rate in Sub-Saharan Africa has barely kept up with population growth [16]. Diversification of electrification solutions could play an important role in increasing access, especially in rural Sub-Saharan Africa [8].

Broadly, three different electrification options can be considered: 1) central grid extension, 2) mini-grid systems, and 3) stand-alone systems (see Table 1). Even though both grid-connected and off-grid systems have their own advantages and disadvantages, in the end, the choice between these systems strongly depends on costs per KWh and associated maintenance requirements [18]. This is particularly the case for a lot of countries in Sub-Saharan Africa, given the limitations in financial resources and the presence of other competing priorities.

In addition to the costs of the electricity supply technologies themselves, the distance to the central power line, the population density, household electricity consumption, and resource availability are key determinants of the costs per kWh of electricity.

The *distance of the area from existing power line* is a crucial factor for choice of an electrification system. Delivering electricity through an established grid is cheaper than off-grid options. However, extending the grid to remote and low populated areas can be very high and the long distance transmission lines can experience high technical losses [19]. In this situation, off-grid systems could be an attractive option for areas that are located far from the central grid [12].

Population density is also a key determinant. Most rural communities (as well as many peri-urban areas) are characterized by low population density. The average population density in Sub-Saharan Africa in 2014 was 41 inhabitants per km^2 (ranging from 3 in Namibia to 440 in Rwanda). In low population density areas, electricity distribution costs are shared by relatively few people, resulting in high costs for each unit of electricity consumed [20]. In such regions, off-grid options are relatively attractive, especially when the location is too remote to connect to the central grid.

Electricity consumption is another important determinant for the choice between electrification systems, as low levels of consumption imply high costs per KWh to cover the costs of transmission and distribution. Electricity consumption of any community depends on a number of factors ranging from income of consumers, tariff (price per kWh), cost of competing or substitute services, cost of appliances, socio-cultural factors and economic factors. Annual electricity consumption in Sub-Saharan Africa varies significantly between countries, ranging from 50 kWh per capita in Niger, to 4600 kWh per capita in South Africa [2].

Finally, *resource availability* plays an important role in choosing the electrification system and technologies. The whole of Sub-Saharan Africa is richly endowed with renewable energy resources [21]. The potentials of wind and solar energy are assessed in detail by Hoogwijk [22]; who estimated that the technical potential for solar energy in the region exceeds 100 PWh per year. The highest potential for wind power is located in Eastern Africa - with over 300 times more potential capacity than the current electricity consumption - while other parts of Sub-Saharan Africa have limited potential for wind [22]. Likewise, the whole of Sub-Saharan Africa has significant potential for hydropower, with the ratio of ‘available generation capacity’ to ‘technically feasible capacity’ ranging from 8% in Eastern Africa, to 19% in Western & central Africa [23].

3. Electrification model and model runs

In order to look at the technology options for electrification and use the information on key determinants presented in section 2, we have extended the electrification model developed by van Ruijven et al. [12] with eight off-grid electrification options. The model is designed to make projections for future electricity access rates, choice of electrification technology for rural and urban areas, and

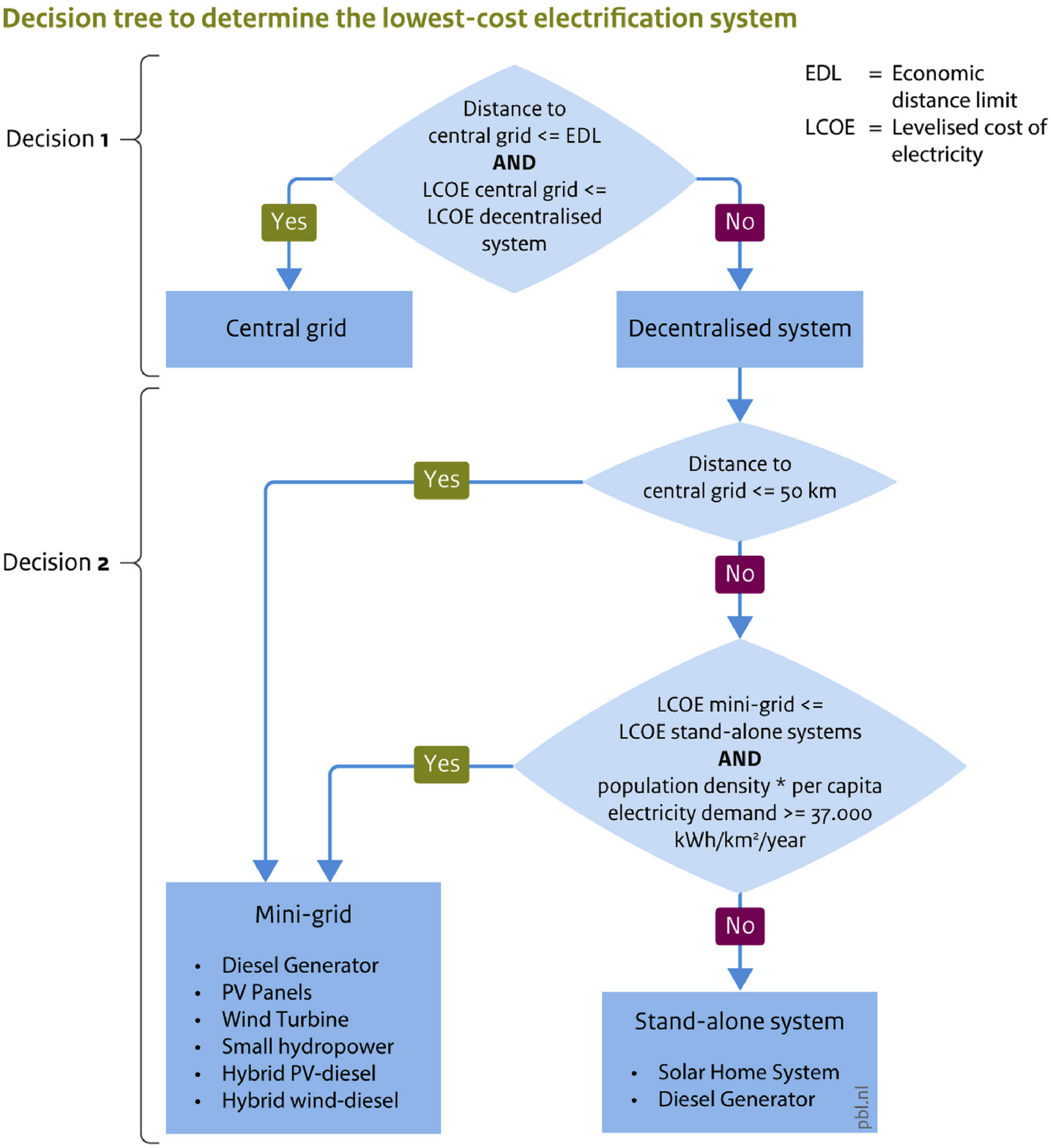
Decision tree to determine the lowest-cost electrification system

Fig. 1. Model decision-making process in choosing the least-cost options.

associated investment requirements under business-*as*-usual assumptions - as well as for achieving specific electricity access targets (such as universal access). The model can be used as a stand-alone tool (as used in this paper), and it can also be integrated into a more comprehensive energy-system model.

3.1. Choosing between electrification options

The extended model is a multi-year bottom-up electrification model that determines the preferred electrification technology for a grid-cell based on the least-cost option. Fig. 1 shows the model process in choosing the least-cost electrification technology for a given grid-cell. The model uses grid-cell data on cost of power generation (for different technologies), population density, cost of transmission and distribution networks, technical potentials of renewable energy sources, the distance of the grid-cell from an existing power line, and other socio-economic data. The data is used to project the cost of electrification and select the least-cost electrification technology from the following three electrification options:

a) extending the central grid,
b) mini-grid systems (photovoltaic (PV) panels, diesel generator, wind power, mini-hydro, and hybrid technologies), or
c) stand-alone systems (diesel generators and solar home systems - SHS).

The model makes two key decisions:

1. Central grid versus off-grid, and
2. Mini-grid versus stand-alone

These decisions are based on the cost of electricity at the grid-cell. The decision-making process is elaborated in section 3.1.1 and 3.1.2. In section 3.2, we discuss in detail the costs involved in the different electrification options and how these costs are calculated.

3.1.1. First decision: central grid versus off-grid options

The first decision is made based on the cost of power generation and the distance of the area from existing power lines. If the central grid has lower power generation costs than the off-grid options, the choice between connecting to the central grid or providing off-grid options depends on the distance to the existing power line. Grid extension is not favorable if the distance from the power line exceeds a certain threshold value. This value is represented by the Economical Distance Limit (EDL) Ref. [24]. EDL is calculated according to the following formula:

$$EDL_c = \frac{(LCOE_{alt,c} - LCOE_{cg}) * \sum_{t=Baseyear}^{Baseyear+Lifetime} E_{t,c(t)}}{C_{HV\&MV,c}}\ km \qquad (1)$$

$LCOE_{cg}$ *and* $LCOE_{alt,c}$ are the levelized costs of electricity generation per grid-cell from centralized power plants and alternatives, respectively (USD per kwh.$E_{t,c(t)}$ is the total annual electricity consumption per grid-cell (kwh per year) at year *t*, and.$C_{HV\&MV,c}$ is the cost of HV & MV lines required to extend the grid to a grid-cell (USD per km.

As such, the EDL is the critical distance between households/communities and the main power lines for which the levelized costs per kWh of grid extension ($LCOE_{ge}$) are greater than those for off-grid electricity supply [25]. If the distance to the existing power lines is smaller than the EDL, central grid extension is chosen as the electrification option. However, to reduce the revenue risk of a mini-grid, the model chooses central grid extension to provide access to electricity to the population within 50 km distance from the existing power line. Fig. 2 shows the distance to existing power lines as of 2010, based on power line data of [27] and Landscan population data Ref. [26]. The distance within each grid-cell is the population-weighted distance. First, the distance of every $30'' \times 30''$ grid-cell centroid from existing power lines was determined. This distance was then aggregated to a $0.5^\circ \times 0.5^\circ$ grid-cell using the population size as a weighting factor.

3.1.2. Second decision: mini-grid versus stand-alone options

The second key decision is to identify the least-cost off-grid electrification option for a grid-cell. If the mini-grid or stand-alone option has a lower power generation cost than the central grid, the model determines which of the decentralized systems is the least-cost electrification option. This is based on i) the LCOE of the

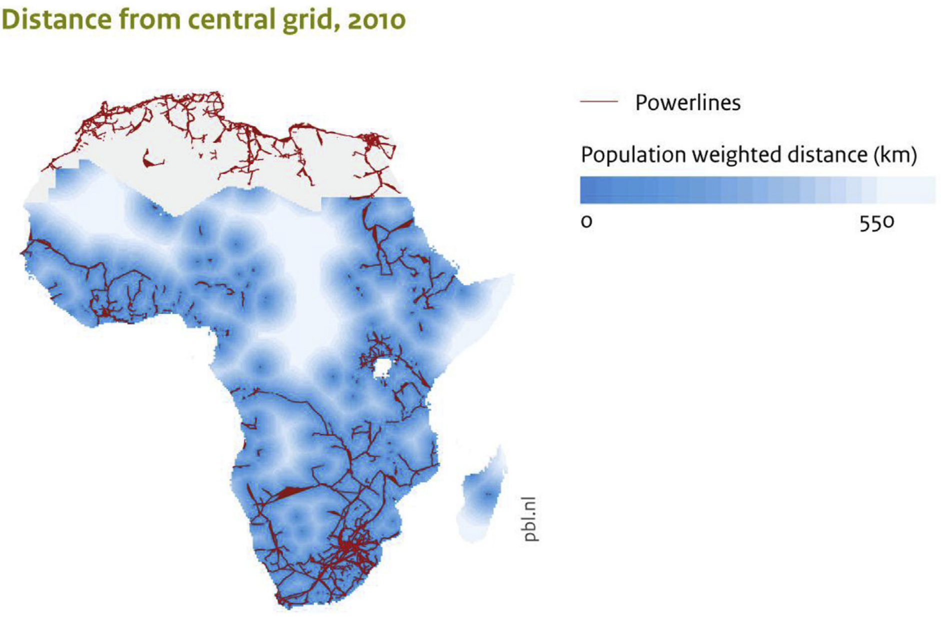

Fig. 2. Population-weighted average distance of the grid-cell centroid to the nearest existing power line (km) in 2010. Sources: population data [26] and power line data Ref. [27].

respective technologies, ii) population density, iii) the distance from the existing power lines of the grid-cell, and iv) household level of electricity consumption. If two or more of the following conditions are met, a stand-alone system is favored to other systems, provided that it is also the cheapest: (i) the grid-cell has a population density less than 250 persons per km^2 (equivalent to about 50 households per km^2) [28], (ii) electricity demand is less than 150 kWh per person per year [17], and (iii) the nearest power line is located further than 50 km away, in which case there is less chance of the grid expanding to the area in the near future.

3.2. Generation technologies & costs of electrification

The total annual and cumulative regional electrification investments are determined by aggregating required electrification investments of all grid-cells in a region. These investments depend on the cost of electrification, the projected population size, and the projected rate of electricity access at a grid-cell. The cost of electrification is the aggregate of the cost of four system components:

i. Power generation cost,
ii. Household wiring and metering cost,
ii. Internal component cost: the cost of Low-Voltage (LV) & Medium-Voltage (MV) distribution network, and
iv. External component cost: the cost of the required High-Voltage (HV) transmission lines and transformers.

For central grid extension, all four components are considered. For mini-grids, only i, ii and iii are relevant - and for stand-alone options, only i and ii are required.

A number of mini-grid and stand-alone options are considered in the model and are discussed in detail in the supplementary text. The levelized cost of electricity generation ($LCOE_g$) for all alternative technologies are calculated according to the following formula [29]:

$$LCOE_g = \frac{\sum_{i=1}^{m}\left[Annuity_i * I_i + C_{FC,i} + \beta_i I_i\right]}{\sum_{i=1}^{m} E_i} \tag{2}$$

where:

i = the power generating technology (1, 2, …. m.
m=the total number of power generating plants.
E_i=the annual electricity output (kWh.
$Annuity_i$= Present value annuity factor. $= \frac{1-(1+r)^{-1}}{r}$
I_i= the capital cost of plant i (USD.
$C_{FC,i}$=the fuel cost (USD/MJ) $= E_i * \varnothing_{HR,i} * P_{fuel}$
$\varnothing_{HR,i}$= the heat rate of the plant measured in (MJ/kWh.
P_{fuel}= the price of fuel (USD/MJ.
r= the rate of interest.
β_i= fraction of the capital cost for annual operation and maintenance of plant i.

The capital cost (I_i) includes the initial investment cost of power plants, including all components, replacement cost of the components, and the interest payment during construction.

The cost of distribution and household wiring and metering ($Inv_{tot,c}$) is calculated as follows:

$$Inv_{tot,c} = Inv_{w\&m,c} + Inv_{int,c} + Inv_{Ext,c} \tag{3}$$

where:

$Inv_{w\&m,c}$ is the cost of household wiring and metering for electrified households in a grid-cell (USD).
$Inv_{int,c}$ is the cost of the internal component of electrification for a grid-cell which includes the costs of low-voltage lines network for a grid-cell (USD).
$Inv_{Ext,c}$ is the cost of the external component of grid extension for a grid-cell which includes the costs of high-voltage and medium-voltage lines and transformers (USD).

$$LCOE_{dis,c} = \frac{\sum_{i=1}^{m}\left[Annuity_i * Inv_{i,tot,c}\right]}{\sum_{i=1}^{m} E_i} \tag{4}$$

Formula 2 is used to calculate the cost of electricity generation for selected mini-grid and stand-alone technologies, discussed in the next section. Formula 3 is used to calculate transmission and distribution costs for extending the central grid and mini-grid systems. The design and detail cost components of the transmission and distribution network is discussed in Ref. [12].

3.2.1. Mini-grid options

Mini-grids comprise a power generator and a low-voltage distribution network often serving a single community or small town. The most common technologies used for electrification with a mini-grid is the diesel generator, small hydro power, photovoltaics, wind power, and hybrid systems consisting of more than one of these technologies [30]. Mini-grids are not connected to the central grid. However, the ambitions and development policies of several countries in Sub-Saharan Africa to expand the central grid and central generation capacity implies that mini-grids are designed to facilitate future connectivity.

The model includes a range of mini-grid technologies:

1. Diesel generator mini-grid
2. Solar PV mini-grid
3. Wind power mini-grid
4. Small hydro power
5. Hybrid PV-diesel generator
6. Hybrid wind-diesel generator

The total capacity of the mini-grid technology i at a grid-cell level ($MG_{i,cap,c}$) depends on the annual electricity consumption of the grid-cell ($E_{t,c}$), the capacity factor of the technology (CF_i), annual load hours, and the distribution loss ($Loss_{dis}$):

$$MG_{i,cap,c} = \frac{E_{t,c}}{(CF_i * Annual\ load\ hours\ )*(1 - \ Loss_{dis})} \tag{5}$$

As mentioned above, the mini-grid technology also requires a distribution sub-system ($LCOE_{dis,c}$), which adds to the cost of the power plant. In line with Ref. [12]; we assume that Single Wire Earth Return (SWER) wires are used for the distribution network. Therefore, the cost of distribution involves the internal cost and the cost of wiring and metering as discussed in formula 3, with no external cost component. For the hybrid mini-grid, low and medium penetration levels are chosen to reduce complexity of the system, as these are mature technologies [31]. High penetration systems may require advanced power control systems, as discussed in Ref. [32] for micro-grid hybrid wind, photovoltaic, and fuel cell based power systems, and in Ref. [33] for systems containing solar power, wind power, and a diesel-engine. Tables 1, 2, 3 and 4 in the supplementary material present the specific parameters and assumptions for the mini-grid technologies considered by the model.

3.2.2. Stand-alone options

The stand-alone technology options are defined as decentralized systems in the form of a generator or solar home system (SHS) that can be adopted by individual households. A stand-alone system experiences less distance-related transmission losses. The capacity of the stand-alone technology i for a household ($StAl_{i,cap,c}$) depends on the annual electricity consumption of the household $E_{t,hh}$, the annual load hours, and the capacity factor of the technology (CF_i):

$$StAl_{i,cap,c} = \frac{E_{t,hh}}{(CF_i * Annual\ load\ hours\ )} \tag{6}$$

In the model, two stand-alone technologies are included:

1. Solar home systems (SHS)
2. Diesel generator

Tables 5 and 6 in the supplementary material present the specific parameters and assumptions for these stand-alone technologies.

3.3. Scenario assumptions

The model is used to explore two main scenarios: a baseline (BL) scenario and a universal access (UA) scenario. In the model, Sub-Saharan Africa is sub-divided in four regions: ‘Western and central Africa’, ‘Eastern Africa’, ‘Republic of South Africa’ and ‘the rest of southern Africa’ (see Table 1 and Fig. 1 in the supplementary text). The basic difference between the two main scenarios relates to the rate of regional electrification in 2030. In the BL scenario, the rate of electrification is based on business-*as*-usual developments (with no new policies or targets), and is calculated by the electrification model discussed in Ref. [12]. This model projects the rate of electrification based on GDP per capita, population density and the urbanization rate. In the UA scenario, the SDG target of full access to electricity by 2030 is imposed for the whole of Sub-Saharan Africa. Moreover, in addition to the projected baseline level of electricity consumption, five illustrative variants of the UA scenario are included, with varying levels of consumption according to the Multi-Tier Framework, to demonstrate the impact of changing consumption on the electrification system and the required cost of electrification (see Section 3.3.2).

3.3.1. Population and economic development

The main inputs for the model are projections of drivers of energy demand, e.g. population, economic activity, rate of technology change, and urbanization rate. For the purpose of this paper, these drivers are taken from the Shared Socioeconomic Pathway 2 (SSP2) as implemented in IMAGE [35]. SSPs provide narrative descriptions and quantifications of possible developments of the socioeconomic variables, mentioned above, that characterize challenges to mitigation and to adaptation Ref. [36]. SSP2 represents a middle-of-the-road scenario regarding population growth, economic growth, technology development and social acceptance for all energy conversion technologies. The population of Sub-Saharan Africa is projected to grow to over 1.3 billion in 2030, with the economy almost doubling during this period. The target population for each region is the projected population in 2030.

3.3.2. Electricity consumption levels

For both the BL scenario and the UA scenario, baseline household electricity consumption in 2030 is taken from the IMAGE implementation of the SSP2 scenario [37]. Electricity consumption level is provided for five different income classes, for both rural and urban households. Here, we only use the average levels of electricity consumption for urban and rural households, disregarding the income differences between individual households.

For the UA scenario, we introduce five illustrative variants according to the aspired level of household electricity consumption, as household electricity consumption is one of the key factors for determining the electrification system (see Section 2). The different *levels of electricity consumption* per *household* are based on the Multi-Tier Framework of the Global Tracking Framework (GTF) of the SE4ALL initiative Ref. [38], as summarized in Table 2. The levels used in our UA scenarios were set at the minimum consumption levels of the respective tiers. The Multi-Tier Framework gives a minimum threshold of different levels of electricity consumption, based on the indicative hours of use for selected appliances. Therefore, the tiers do not accurately reflect the diversity of appliances actually used by the household, nor appropriately account for energy efficiency. Instead, the tiers address the intensity of access, capture the amount of energy services that electricity connections provide, and emphasize that access should be beyond the mere existence of connections. The variations in levels allow for exploring the impact of the level of electricity consumption on the electricity system and cost of electrification in the region. Moreover, the multi-tier measurement of energy access allows governments to set their own targets and ambitions depending on the local situation, such as its development status, the needs of its population, and the available budget Ref. [39]. For each variant, the level of electricity consumption is kept uniform for all households that have acquired access to electricity after 2010, while baseline level of consumption were assumed for households that in 2010 already had access.

4. Results

4.1. Electrification rates and total electricity demand

4.1.1. Baseline scenario

A significant gap is projected between the BL electrification rate and universal access target in 2030, except for Republic of South Africa (Table 3). Furthermore, considerable differences are projected between regional electrification rates and between rural and urban electrification rates within the regions. Almost 90% of Republic of South Africa is projected to have access to electricity by 2030, while only 52% of the population in Eastern Africa is projected to have access. Likewise, nearly 75% of rural Republic of South Africa is projected to have access to electricity in 2030, while in Eastern Africa a mere 30% of the rural population is projected to have access. By 2030, an additional 550 million people are projected to have access to electricity in Sub-Saharan Africa. However, this still leaves 500 million people (more than 35% of the projected Sub-Saharan

Table 2
Multi-Tier framework for Access to household electricity supply [34].

		TIER-0	TIER-1	TIER-2	TIER-3	TIER-4	TIER-5
Annual consumption (kWh/Household)		<4.5	≥4.5	≥73	≥365	≥1250	≥3000
Duration	Minimum hours per day		4 hs	4 h s	8 h s	16 h s	23 h s
	Minimum hours per evening		1hr	2 h s	3 h s	4 h s	4 h s

Table 3
2010 and projected 2030 regional population and electrification rate (BL scenario).

Region	2010						2030					
	Total Regional Population (million)			Electrification rate			Total regional Population (million)			Electrification rate		
	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural	Total	Urban	Rural	Total
Western & central Africa	180	231	411	65%	16%	38%	361	294	655	86%	47%	69%
Eastern Africa	63	198	261	54%	12%	23%	135	267	402	96%	30%	52%
Republic of South Africa	31	19	50	88%	56%	76%	42	17	59	94%	75%	88%
The rest of southern Africa	47	89	136	52%	6%	22%	98	113	211	82%	33%	56%

Africa population in 2030) without access to electricity.

The total regional electricity demand is projected to increase from 90 TWh in 2010 to 270 TWh in 2030 – an increase of over 180 TWh. More than 140 TWh of the increase is to accommodate households connected after 2010. Western & central Africa accounts for more than 50% of the increase in residential electricity consumption in Sub-Saharan Africa.

4.1.2. Universal access scenario

In the UA scenario, all Sub-Saharan Africa households have access to electricity by 2030. The average level of electricity consumption of households connected before 2010 is taken from the baseline projection, while the average electricity consumption of all households connected after 2010 is determined by either the baseline projection or the five tiers, with the five tiers used for illustrative purposes. The projected baseline level of electricity consumption lies somewhere between Tier-3 and Tier-4 levels, while Tier-1 is considerably below, and Tier-5 is significantly above, the projected baseline level of consumption (see Table 4). Total residential electricity demand in 2030, at baseline level of consumption, is projected to reach 330 TWh (with 195 TWh for households connected after 2010). The tier-based projection shows total electricity demand in Sub-Saharan Africa ranging from 140 TWh for Tier-1 (with 1.1 TWh for households connected after 2010), to 920 TWh in Tier-5 (with 785 TWh for households connected after 2010).

4.2. Electrification systems and electricity costs

Fig. 3 shows the least-cost electrification system for each grid-cell in the UA scenario, including the five illustrative variants. At baseline level of consumption (which is between Tier-3 and Tier-4), projections show that 85% of the newly connected population in Sub-Saharan Africa will be connected to the central grid. At Tier-1 level of consumption, the electrification system is dominated by decentralized systems providing access to nearly 65% of the newly connected population in the UA scenario. In this scenario, in which all newly connected households are assumed to consume 4.5 kWh per HH per year, stand-alone systems and mini-grids provide access to 50% and 15%, respectively of the newly connected population. However, at the higher levels of consumption of Tier-4 or Tier-5, the economies of scale changes in favor of extending the central grid. As a result, at Tier-5 level of consumption, the central grid takes the lion's share of the electricity system, providing access to nearly 95% of the newly connected population (more than one billion people), while around 80 million people are connected through stand-alone systems.

Fig. 4 shows the share of the different systems in the BL scenario and the UA scenario, together with the illustrative variants (with consumption increasing from Tier-1 to Tier-5) in Sub-Saharan Africa in 2030. Under BL scenario, it is projected that the central grid provides access to more than 80% of the newly connected population, with the rest of the population getting access to electricity with mini-grid and stand-alone systems. For Tier-1 level of consumption, 80% of the stand-alone systems are solar home systems, providing access to 40% of the newly connected population. For Tier-5 level of consumption, 90% of the stand-alone systems are solar home systems (SHS), providing access to less than 5% of the newly connected population.

The projections show that the cost of electricity generation from a solar PV mini-grid starts from USD 0.09 per KWh in 2030, with the lowest LCOE in Eastern Africa and the highest in the Republic of South Africa. The LCOE for wind powered mini-grid starts from USD 0.11 per KWh in 2030, the cheapest being in Western & central Africa and the most expensive in Southern Africa. When there is enough technical potential available, mini-hydro is able to provide least-cost options in some parts of the region, with the LCOE starting from USD 0.14 per kWh. Eastern Africa and part of Western & central Africa have the highest hydropower potential, hence the lowest electricity generation cost. PV-Diesel Generator and Wind-Diesel hybrid systems also provide a very cost-effective electrification option in some parts of Sub-Saharan Africa. The LCOE of PV-Diesel hybrid mini-grid starts from USD 0.16 per kwh, whereas the cost of Wind-Diesel Generator mini-grid system starts from USD 0.15 per kwh. Extending the central grid to some remote low-density areas is projected to cost as high as USD 200 per KWh in 2030.

4.3. Electrification investments

Fig. 5 shows total 2010–2030 cumulative investment

Table 4
Total residential electricity demand in the UA scenario, including the illustrative variants in 2030.

Scenario Variant	Average level of electricity consumption of households connected after 2010	Projected Sub-Saharan Africa total residential electricity demand for households connected after 2010	Projected Sub-Saharan Africa total residential electricity demand
UA- Baseline consumption	Baseline level of consumption	195 TWh	330 TWh
Tier-1	4.5 kWh/HH/Year	1.1 TWh	140 TWh
Tier-2	73 kWh /HH/Year	18 TWh	155 TWh
Tier-3	365 kWh /HH/Year	95 TWh	230 TWh
Tier-4	1250 kWh /HH/Year	327 TWh	460 TWh
Tier-5	3000 kWh /HH/Year	785 TWh	920 TWh

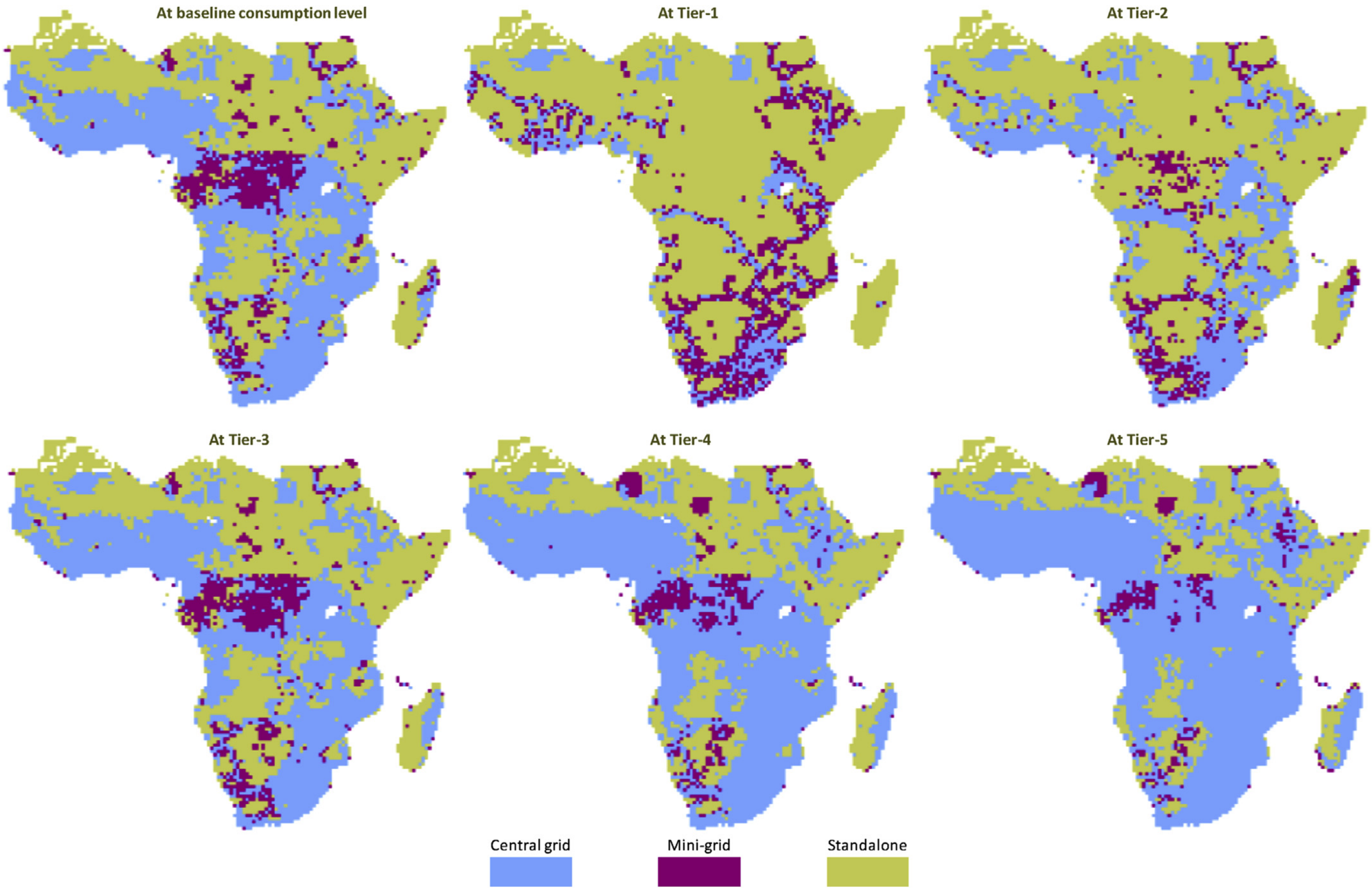

Fig. 3. The least-cost electrification system in 2030 for UA Scenario and the illustrative variants.

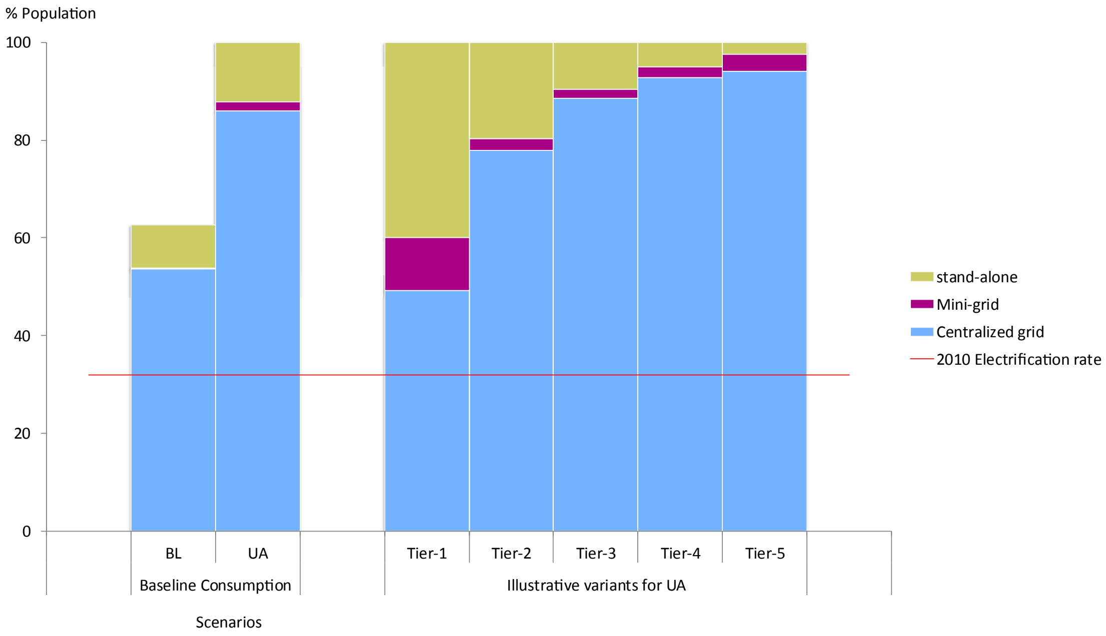

Fig. 4. Population distribution by system in 2030 for the BL scenario and UA scenarios, including illustrative variants.

requirements in the BL scenario and the UA scenario, together with the five illustrative variants. The cumulative investment is the capital expenditure required to provide households access to electricity. It does not include recurring annual costs such as fuel costs and operation and maintenance costs. Cumulative investments in the BL scenario are projected to amount to USD 310

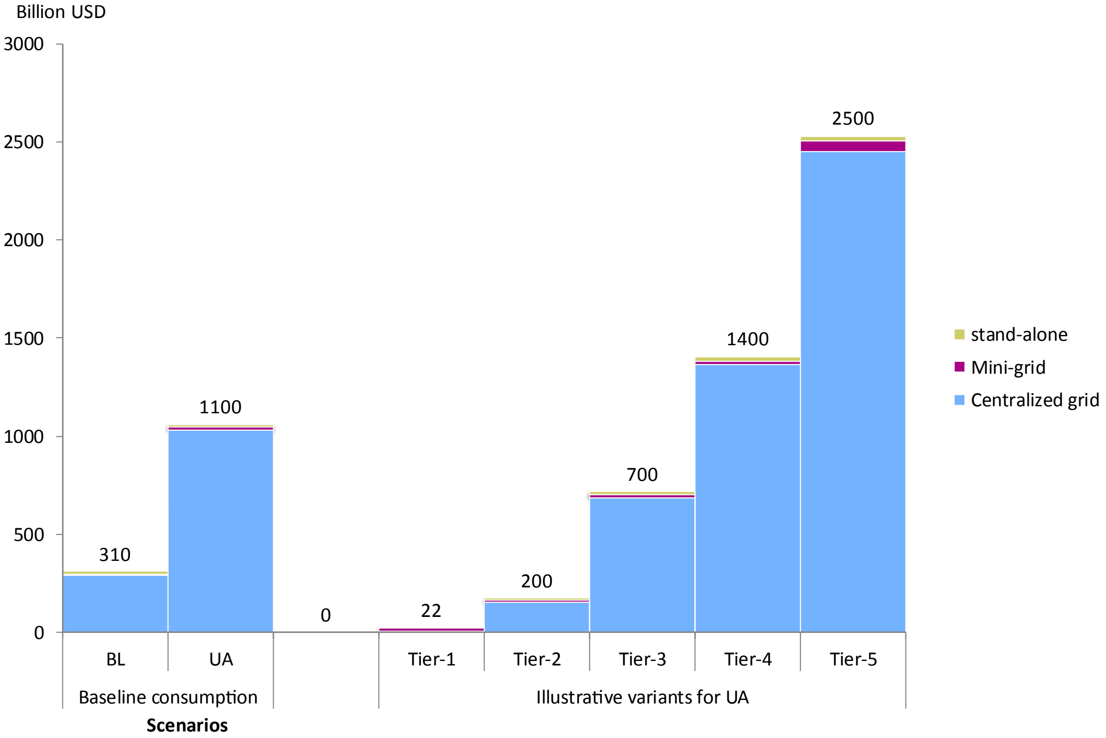

Fig. 5. 2010–2030 cumulative investments in the BL scenario and the five UA variants.

billion, an annual average of USD 16 billion. Under the BL scenario, more than 95% of the investment is projected to go toward extending the central grid. The highest cumulative investment is projected in Western & central Africa, as a large number of the population in that region is projected to get access by 2030, while the cumulative investment in Republic of South Africa is projected to be the lowest, since a large proportion of the population already has access to electricity.

The cumulative investment requirements for the UA scenario at baseline level of consumption is projected to exceed USD 1000 billion, with 95% of the investment projected to go toward extending the central grid. The cumulative investment requirements in the UA illustrative variants differ significantly between the lowest and the highest aspired levels of electricity consumption, with USD 22 billion at Tier-1 level of consumption, and USD 2500 billion at Tier-5 level of consumption. The Tier-1 requirement is much lower than the investments required in the BL scenario, due to the BL scenario having a much higher projected level of consumption. In other words, we project that full electricity access, at relatively low levels of consumption, could be achieved at lower costs than the projected costs required in the BL scenario, in which full access to electricity is not yet achieved.

The investment distribution of the different technologies at Tier-1 and Tier-5 levels of consumption is shown in Fig. 6. At Tier-1 level of consumption, decentralized systems are projected to require more than 75% of the total investment, while the rest goes toward extending the central grid. At Tier-5 level of consumption, on the other hand, more than 95% of the cumulative investment goes toward extending the central grid. At Tier-2 and Tier-3 level of consumption, the share of the decentralized system in the required cumulative investment is only 10% for Tier-2, and 5% for Tier-3.

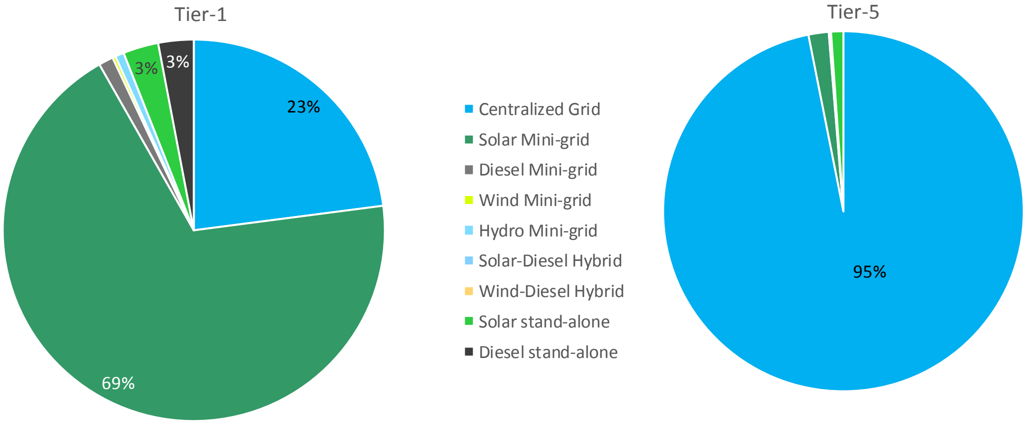

Fig. 6. 2010–2030 cumulative investment distribution at Tier-1 (left) and Tier-5 (right) illustrative level of consumption.

Our projections of required investments are in the same order of magnitude as other studies [12]. estimates that, in order to extend only the central grid, an investment of USD 180–320 billion between 2010 and 2030 is required to achieve the universal access target for rural Sub-Saharan Africa. Their estimates are based on consumption levels of 65 kwh per HH and 420 kwh per HH, which can be related to Tier-2 and Tier-3 of the Multi-Tier framework. Their estimates are somewhat higher for the lowest level of consumption, and marginally lower for the highest level of consumption, than in our projections (which are USD 115 and USD 360 billion). The higher estimates by Ref. [12] for low levels of consumption can be explained by the fact that extending the grid at the lowest level of consumption is quite expensive. At higher levels of consumption, the reason is that the estimated capital costs for grid extension in Ref. [12] are lower than reported in most recent literature, resulting in lower estimates than our study.

4.4. Sensitivity analysis

Several studies use different estimates for the cost of diesel fuel and transmission and distribution network. See, for example [21], for study on Kenya [28], for study on Ethiopia and Nigeria, and [24] for study on Ghana. Therefore, a sensitivity analysis was conducted to assess if the model results are sensitive to the assumptions regarding costs of diesel fuel and the transmission and distribution network, using the ranges of [21,28] as the lowest and highest estimates, respectively (see Table 5).

The cost of diesel has very little impact on the share of decentralized and centralized electrification systems for all levels of electricity consumption. However, the costs of the network components have a visible impact on the share of the different electrification systems at low levels of consumption, and a relatively smaller effect at higher levels of consumption. In the UA scenario, at the lowest level of consumption, off-grid systems provide access to 75% of the newly connected population, which is 10%-points (equal to 110 million people) higher than the share that assumes the low costs. At the highest level of consumption, the share of the decentralized systems is 7% of the newly connected population for the low value of the costs estimates, and 9% for the high value of costs estimates (see Fig. 7). In other words, at high network costs, decentralized systems are projected to provide access to an additional 20 million people than provided for at lower network costs.

The 2010–2030 cumulative investment requirement shows considerable increase at high costs of transmission and distribution. The projected cumulative investment for achieving the universal access target at the highest network costs is USD 55 billion for Tier-1 level of consumption (increasing from USD 22 billion at lowest network cost), and USD 8 trillion at the Tier-5 level of consumption (increasing from USD 2.5 trillion at lowest network cost). The investment requirements of the BL scenario are also projected to increase to nearly USD 600 billion (increasing from USD 310 billion at lowest network cost).

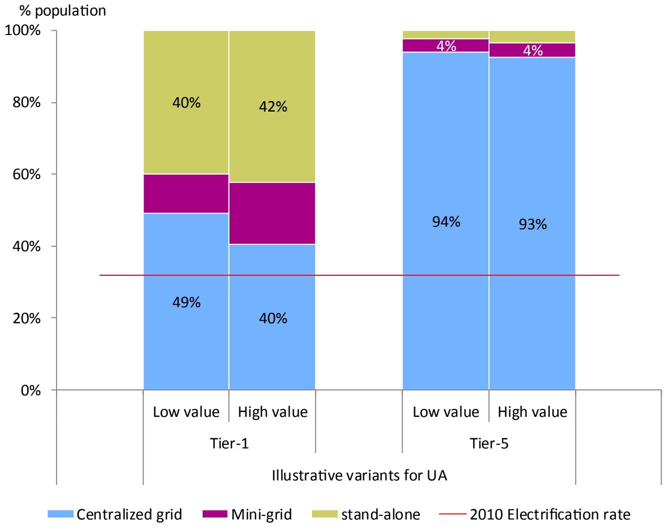

Fig. 7. The impact of high transmission and distribution cost on the share of the electrification systems.

5. Discussion and conclusion

This paper discussed an extended model that allowed exploration of the technological and financial developments for electricity access in Sub-Saharan Africa. More specifically, the model was used to explore future developments in the region's electricity sector, the technologies that will play a role, and investment requirements in different scenarios up till 2030. The model's results provide insight in the role of decentralized systems in achieving universal electricity access in Sub-Saharan Africa. In our analysis, we highlight the need for long term planning to address both the rapidly changing prices of various technologies and the increasing level of electricity consumption.

At the same time, it is important to understand the scope and limitations of the model and scenario assumptions:

1. With the aim of providing an overview of the role of different technologies in achieving universal electricity access and the associated investments, we have used a simple homogenous network design as discussed in Ref. [12]. Different network designs could result in different cost estimates.
2. For this paper, the focus was on the cumulative electricity consumption at grid-cell level, and not the different level of consumption of households. We assumed regional average urban and rural levels of electricity consumption, irrespective of the differences in income levels between individual households. Therefore, we recommend further research to explore the effects of linking the different levels of consumption to the different income categories in urban and rural areas.

Table 5
High [21] and low [28] values for transmission and distribution network costs in Sub/Saharan Africa.

Parameter		Low value	High value
Diesel fuel		USD 0.5 per liter	USD 0.8 per liter
Electricity network costs			
a	HV transmission lines (132 kV line)	USD 28000 per km	USD 90000 per km
b	MV transmission lines (33 kV line)	USD 9000 per km	USD 23000 per km
c	LV transmission lines	USD 5000 per km	USD 10600 per km
d	Transformers	USD 5000 per km	USD 35000 per km
e	Metering and wiring	USD 100 per HH	USD 250 per HH

3. The Multi-Tier Framework is used to demonstrate the impact of different levels of household electricity consumption on the technology mix, and on the investment needed to provide insight to planners and policy makers on the resources required. It is unlikely that in the short term everyone in Sub-Saharan Africa will reach Tier-5 level of consumption, considering that the average level of consumption at BL scenarios is projected to be much closer to Tier-3.
4. Climate policies will impact on the choice of electrification technologies and the total cost of electrification. We have not addressed this issue in this paper, but recommend further research.
5. The model is specifically designed to explore and project the developments in the Sub-Saharan Africa electrification system. At the current time, it has not been applied to other regions; however, it could be modified to study other regions, such as developing Asia.

The following conclusions can be drawn from the scenario analysis.

There is a significant gap between the projected electricity access rate in the BL scenario, and the target to provide universal access to electricity. By 2030, more than 550 million additional people are projected to have access to electricity in Sub-Saharan Africa, compared to 2010 levels. This still leaves over 500 million people without electricity access. The lowest levels of access are projected in Eastern Africa and in rural areas.

The model projections show a significant increase in total residential electricity consumption in most scenarios in Sub-Saharan Africa in 2030. For the baseline level of consumption, this is the result of rapid population growth and economic development projected in the SSP2 Scenario. For the tier-based variants, the electricity consumption is more illustrative, as it is determined by the targeted tier level. Tier-5 would lead to an enormous increase in electricity consumption in Sub-Saharan Africa, where the electricity consumption is projected to be 30% more than the current residential electricity consumption of China. The increase in most of the scenarios will inevitably have a serious consequence on the regions' electricity-related emissions, depending on the chosen energy source.

The technology mix for providing full access to electricity strongly depends on the targeted level of electricity consumption. Renewable mini-grid technologies are projected to have an especially large potential in providing universal access to electricity in Sub-Saharan Africa. At low levels of consumption, off-grid systems are projected to provide access to nearly 65% of the newly electrified population, with solar mini-grids and solar stand-alone technologies playing important roles. Large parts of rural Sub-Saharan Africa are sparsely populated, this makes extending the central grid only attractive at high levels of electricity consumption. At Tier-5 level of consumption, nearly 95% of the newly electrified population is projected to have access through the central grid. These results are sensitive to the cost of the transmission and distribution network. At high transmission and distribution cost, off-grid systems will play an even bigger role in providing electricity connection in Sub-Saharan Africa.

Achieving the universal access target in 2030 requires the integration of off-grid electrification options within the electrification systems. Extending the central grid requires a significant upfront investment and is not economically feasible at low levels of consumption and/or low population density. Decentralized systems, on the other hand, can be implemented with relatively low initial investment, gradually scaling up the capacity as the level of consumption increases. This involves a tradeoff between the initial investment and the level of electricity consumption, but with potentially lower costs over the long term as consumption increases. Therefore, there needs to be an emphasis on long term planning, and a strategy to integrate the stand-alone and mini-grid systems into the central grid, whilst providing for the increasing levels of consumption. Assuming that high levels of electricity consumption will not be achieved for all households in 2030, mini-grid and off-grid electrification options play a significant role in achieving universal access to electricity.

The level of ambition in achieving universal access to electricity also has a significant implication on the cumulative investment required in the region. The analysis shows the need to balance the tradeoff between the target electricity access rate and the level of consumption to provide for. While providing electricity access to the entire region at Tier-1 level of consumption is projected to cost around USD 22 billion, doing the same at Tier-5 level of consumption requires more than USD 2.5 trillion. It is projected to cost USD 310 billion to provide electricity access to nearly 65% of the Sub-Saharan Africa population at baseline levels of consumption, while it is projected that a little over half of that cost would suffice to provide access to everyone at Tier-2 level of consumption. As shown in the sensitivity analysis, these prices could be much higher at high transmission and distribution costs.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2017.07.144.

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