Perpetuating energy poverty: Assessing roadmaps for universal energy access in unmet African electricity markets

Benjamin Batinge[*, 1], Josephine Kaviti Musango[1], Alan C. Brent[2, 3]
* Corresponding Author, Email: benjaminb50@gmail.com
[1]School of Public Leadership, Urban Modelling and Metabolism Assessment (uMAMA), Centre for Complex Systems in Transition (CST), Stellenbosch University, South Africa
[2]Department of Industrial Engineering, Centre for Renewable and Sustainable Energy Studies (CRSES), Urban Modelling and Metabolism Assessment (uMAMA), Stellenbosch University, South Africa
[3]Sustainable Energy Systems, Engineering and Computer Science, Victoria University of Wellington, New Zealand

Highlights

- Infrastructure in Africa is inadequate for universal electricity access by 2030.
- A decline in the average GW unit cost of power would not yield universal access.
- Maximum utilisation of installed capacity alone would not yield universal access.
- Annual investment increment is needed for universal electricity access by 2030.
- Private sector finance is thus vital for universal electricity access in African.

Abstract

A growing number of people in Africa still do not have access to electricity. This phenomenon threatens the realisation of the United Nation's Sustainable Development Goal 7, pertaining to universal access to modern energy. Factors attributed to Africa's low electricity access include limited financial resources at the dispensation of governments to execute the capital-intensive infrastructure development required by the power sector. This paper examines different scenarios to ascertain roadmaps for universal energy access in unmet African electricity market. This was achieved by developing the Africa Electricity Access (AFELA) model, using system dynamics. AFELA comprises three sub-models, namely: Electricity Access, Electricity Capital Investment, and Electricity Supply Capacity. Four scenarios were examined to determine the fastest roadmap to universal electricity access in Africa. The scenarios were the Baseline scenario, Economies of scale scenario, Capacity utilisation factor scenario, and Electricity access investment scenario. The results show that the Electricity access investment scenario, which entails an increase in the annual power investment by two per cent of GDP, is the most viable way to universal electricity access. The budget constraints of national governments, who are mandated to provide electricity, and the limited funds available from multilateral and bilateral aids, imply that investment from the private sector is vital. The paper thus suggests private sector finance as a conduit to address the funding challenge, and expedite the attainment of universal access to electricity.

Keywords: Africa; electricity access; population without access; system dynamics.

1. Introduction

The main challenges of Africa's power sector include limited generation capacity, unreliable services, low electrification, high cost of electricity, low electricity consumption, and a large financing gap [1]. Others include deteriorating power plants, and the poor revenue collection in the electricity sector [2]. Nevertheless, the limited access to funds is the leading impediment to energy access [3-5]. The growing financing gap in the power sector is a priority for governments [6]. Though different studies [3, 7, 8] have reiterated the extent of energy poverty in Africa, and forecasted the trend of this problem until 2030, scanty findings are offered on how to navigate the finance barriers to accelerate energy access. The UN Secretary General in 2011 launched the Sustainable Energy for All (SE4All) initiative [9], a non-profit body to engage with governments and civil society groups, and collaborate with private entities to develop energy catalogues geared towards accelerating energy access. The African Energy Leaders Group, a community of leaders from both public and private sector also commits to champion sustainable energy transition in Africa, and promotes universal energy access through public private partnership and commercial regional power pools in support of the SE4ALL objectives. At the core of these initiatives, the issue of limited financial resources to pursue universal electricity access in Africa still lingers.

Modern and efficient infrastructure is a key component of growth and development [10]. Africa requires approximately $93 billion annually to finance its infrastructural gap [11]. Amid the financial challenges, there are also efficiency issues with the existing infrastructure across Africa. Briceño-Garmendia, Smits and Foster [12] assert that, one practical way to create resources for new infrastructure in Africa is by improving the efficiency the existing ones. In Africa, especially in the sub-Saharan region, infrastructure is most lacking, and providing it could potentially bring more transformation than anywhere in the world [13]. Unfortunately, governments still shoulder most of the infrastructure expenditure in sub-Saharan Africa [12].

According to the IEA [14], budgets allocated for energy access in developing countries are dominated by public finance, and multilateral and bilateral aids from development partners. In 2009, a paltry US$ 9.1 billion investment was made towards electricity access, of which the funding sources were: 30% public funding, 34% multilateral aid, 22% private finance, and 14% bilateral aid [15]. The total investment increased to US$13.1 billion in 2013, and were composed of: 37% public funding, 33% multilateral aid, 18% private finance, and 12% bilateral aid [15]. Since many Africans still do not have access to electricity, suggesting that funding from governments and aid have so far been insufficient for universal electricity, private sector financing as a potential source for driving universal electricity access is worth considering. Though investment increased between 2009 and 2013, the share of private finance declined by four per cent in the IEA [15] findings. This decline is of concern since the private sector is one of the pillars for developing a stable supply of power [16], and is expected to increase its contributions in infrastructural development amid governments' budgetary challenges and growing infrastructural deficits.

There are multiple factors that deter the private sector from investing in the African power sector. These factors comprise a regulatory dimension manifested in: issues of tariff settings, service standards, and private entry conditions [17]; conflicts with public agencies, which Brown, Stern, Tenenbaum and Gencer [18] proposed rules to pre-empt and govern the energy sector to promote private participation; the nature of incentive schemes available to private investors; and the corrupt acts perpetuated by state agents tasked to procure private finance. Corruption distorts financial investments, detracts state and business efficiency, and destroy the appeals of private investments [19].

Electricity losses through transmission and distribution also significantly undermine Africa's power sector efficiency. Transmission losses are often as a result of sub-standard transformers and cable lines while that of distribution losses are attributable to human conducts, including theft through meter tempering and illegal connections [20, 21]. The inability of public stakeholders to reduce these losses to an acceptable minimum, and effectively collect revenue from consumers to offset power sector expenditures has been a major obstacle to securing the necessary capital needed for infrastructural expansion. In order to address the perpetuating energy poverty in unmet African electricity market, there is the need to consider different roadmaps and how each measures towards universal electricity access in Africa.

The objective of the paper is to examine different scenarios to ascertain roadmaps for universal energy access in unmet African electricity market. The paper acknowledges the funding challenge in Africa's electricity sector, and contemplates on how to increase the power sector funding to bridge the gap and expedite the attainment of universal electricity access. To achieve this we explored the trend of investment in the power sector between 2001 and 2015, and quantified the amount of investment required for a universal electricity access in Africa by 2030. Based on the magnitude of the electricity access challenge, we postulated the kind of environment, through government and market policies, which would attract private investors to invest in the electricity sector, and consequently contribute to elimination of the finance barrier in the sector.

This study does not distinguish between electricity generation and distribution. The AFELA model is only focused on generation because of the challenge with delineating the complexities of both generation and distribution infrastructures. There are instances where households are connected to the grid but do not have access to electricity, and others with electricity tend to experience intermittent power outage resulting, largely, from fluctuation in generation, and in some cases technical issues with the transmission grid. Though the study does not investigate grid inadequacy in itself, it recognises the limited grid that exists across the continent to distribute electricity, if adequate generation capacity were to exist from a centralised system.

2 Method

The system dynamics modelling approach is not new to the electricity sector. Dyner and Larsen [22] applied the methodology to understand the changes required in the planning methods used in monopolistic, as against deregulated, electricity markets. The method has also been used to propose an improved mechanism for electric power capacity payment [23], assess the electricity access gap [24], and analyse the decentralisation and the network effect of electric power generation [25]. Ahmad, Mat Tahar, Muhammad-Sukki, Munir and Abdul Rahim [26] investigated the contributions system dynamics modelling made in the electricity sector and concluded that policy assessment (mainly at the national level), such as attracting investment from the private sector, and expanding generation capacity, are the two major electricity sector issues modelled using the system dynamics approach. A list of applications in the electric power sector is also found in the work of Ford [27].

In the broader energy sector, the application of system dynamics modelling is even more prominent. From understanding the energy market dynamics and economic indicators [28], to energy development and energy structure testing [29, 30] through the environmental aspect of energy and CO_2 emissions [31, 32], energy technology sustainability assessment [33], and energy security resulting from supply and demand in country specific cases [34, 35], this approach has proven useful. In fact, Andrew Ford, a forerunner in energy research using system dynamics modelling, points out that '…my experiences with energy industry modelling convinced me that the ability to simulate the information feedback in the system is a truly unique feature of the system dynamics approach' [27]. In a similar context, Bunn, Dyner and Larsen [36] noted: 'for markets in transition, where strategic imbalances exist, system dynamics has a useful role to play in developing a better understanding of processes, which might shape their evolution.' System dynamics methodology allows for a clear linkage and easy demonstration of the interactions among the key sub-sectors relevant for establishing the dynamics of the phenomenon the study investigates. This methodology fits with the nature of the electricity sector problem herein investigated; it is dynamic, with multiple stakeholders, variables, and different sectors with extensive interdependence. We subsequently constructed a simulation model using Vensim DSS version 6.3, developed by Ventana Systems Inc.

3 The African Electricity Access (AFELA) model

The African Electricity Access (AFELA) model was developed to assess the continent's power and electricity requirements. The model contains three sub-models, namely: (i) electricity access, (ii) electricity supply capacity, and (iii) electricity capital investment. The simulation period for the model is from 2001 till 2040. The results from 2001 to 2015 were compared with historical data to assess the model validity. Upon establishing confidence in the results through calibration, the simulation time was then extended to 2040 to understand the likely future pattern of electricity access, under business as usual (referred to as base run). The computation is done sixteen times (as time steps) in a year to enhance accuracy, and the results are saved annually. The Euler integration method is used in the model simulation, because it gives the simplest and fastest solution.

The causal loop diagram of the AFELA model captures the feedback processes among key variables in the model. The diagram in Figure 1 shows four key feedback loops: electricity supply capacity loop, investment loop, electricity access loss loop, and electricity access loop.

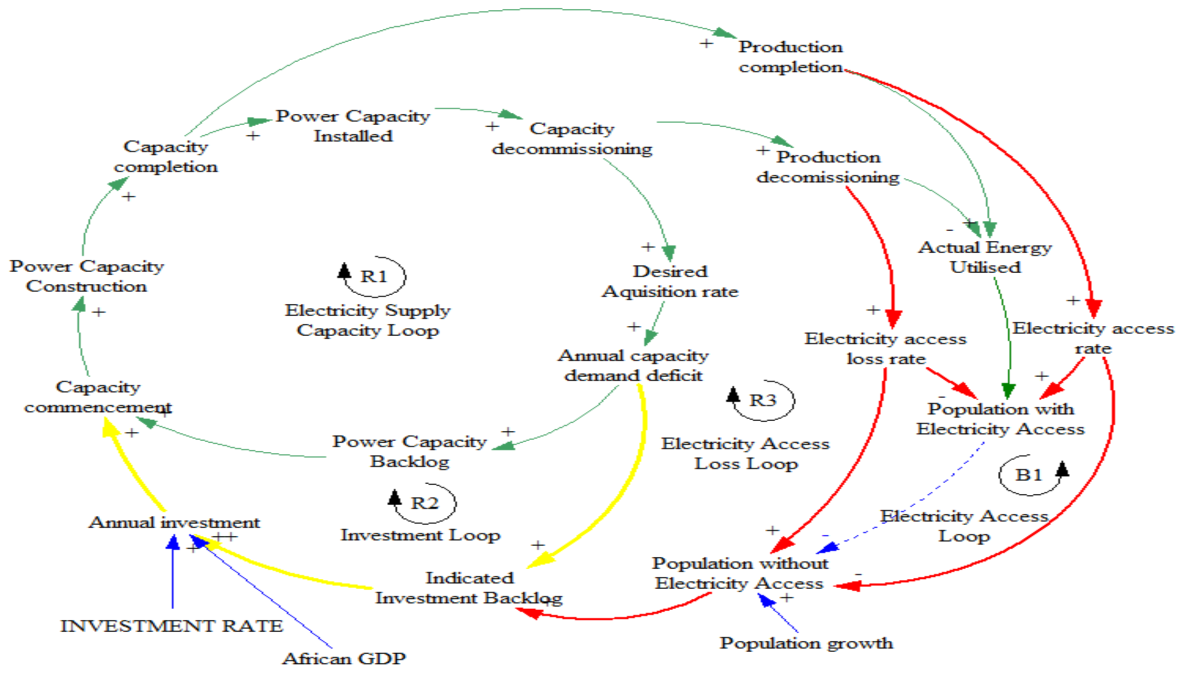


Figure 1: Causal loop diagram of Africa's power sector

A causal loop diagram is a useful tool for illustrating feedback structure; the relationships among model variables, with arrows from one variable (cause) to another (effect). A causal loop diagram presents a brief model boundary, with key feedbacks more essential than clouding in detailed specification of individual components [37].

The ***electricity supply capacity loop*** (R1) is core to the overall causal loop diagram. It takes into account the capacity backlog, capacity commencement, capacity construction, capacity installed, capacity decommissioning, desired acquisition rate, and annual capacity demand deficit, which ultimately accumulates in the capacity backlog. This sector interacts with the investment sector when new investments lead to capacity backlog depletion and with the access sector when population growth and access loss results in capacity backlog accumulation.

The ***investment loop*** (R2) is an extension of the power supply loop to show the feedback from the indicated annual demand deficit to the indicated investment backlog, annual investment, and then back to the capacity commencement. This loop captures the financial flow into infrastructural developments, and links the capacity sector to the access sector.

The ***electricity access loop*** (R3) builds on both the electricity supply capacity loop and investment loop. It extends from the capacity decommissioning to production decommissioning, through to the electricity access loss rate, population without electricity access, and then to the indicated investment backlog.

The ***electricity access loop*** (B1) is one of the key, and only counteracting, loops of the four main loops identified. Essentially, it is the outermost loop in the structure, extends upon the electricity supply capacity loop, the investment loop, and the electricity access loss loop. The key additional variables include the production completion, actual energy used, electricity access rate, population with electricity access, population without electricity access, and then to the indicated investment backlog. When more investment is made, the capacity availability increases, resulting in an increase in the population with electricity access, and a decrease in population without access.

3.1 Electricity access sub-model structure and equations

The sub-model comprises two key stocks, namely: population with electricity access, and population without electricity access. There are also three key flows: electricity access rate, electricity access loss rate, and population growth. The stock of population without electricity access decreases as more people gain access to electricity, and increases as population grows or people lose access to electricity. Population with access increases as people gain access to electricity, and decreases as assess is lost. The key parameters in the electricity access sub-model are the net population growth rate and the average consumption per access person.

The equations for the key sub-model variables include the electricity access rate (EAr):

$$\text{EAr} = Max\ [Min\ \left[\left(\frac{PCp}{AvCp}\right), \left(\frac{PwA}{TS}\right)\right], 0] \quad (1)$$

where PCp is the production completion, that is, the energy produced from new power capacity completed in a given year; TS is the time step; PwA is the population without electricity access; and AvCp is the average consumption per person. The maximum constraint in the equation ensures that the stock of population without electricity access remains non-negative, while the minimum constraint limits the flow rate to that group.

The average consumption per person in the model is not based on the conventional per capita income formulation. Africa's electricity consumption per capita is estimated as 620 kWh per year [38]. However, given that only a fraction of the total population have electricity access, using average per capita, which expresses access over the entire population, would understate the average electricity demand per person. The average electricity consumed per person is thus expressed as a function of the price effect on consumption, and the initial average consumption per person (this is calculated by dividing the population with access at start time by the energy used at the start time). This results in estimation of the average electricity consumption per capita over time, with an initial value of approximately 1,130 kWh per annum, a figure still far below the global average of 2,730 kWh in 2009 [38]. This formulation diminishes the error that arises from using population as the basis for estimating electricity needs for the entire economy (of which residential consumption constitutes a smaller fraction compared to industry and commercial sectors), and also caters for growth in consumption emanating from any change in the economic status of individuals. The electricity access loss rate (EALr) is:

$$\text{EALr} = Min\ \left[\left(\frac{PCd}{AvCp}\right), \left(\frac{PnA}{TS}\right)\right] \quad (2)$$

where PCd is the production decommissioning, the energy lost when power capacity is decommissioned in a given year, and PnA is the population with electricity access. The minimum constraint here ensures that when the population with electricity access is zero, no person be shown lose electricity. The population growth rate (Pg) is:

$$PGr = TP * nPgr \tag{3}$$

where TP is total population, and nPgr is the net population growth rate. The population without electricity access (PwA), a key variable of the model, depends on three key flows: the population growth rate, the population who lose electricity access, and the electricity access rate. The PwA is computed as:

$$PwA = PwAint + \int [(TP * nPgr) + Min\left[\left(\frac{PCd}{AvCp}\right), \left(\frac{PnA}{TS}\right)\right] - Max[Min\left[\left(\frac{PCp}{AvCp}\right), \left(\frac{PwA}{TS}\right)\right], 0]]dt \tag{4}$$

where PwAint is the initial population without electricity access, Pg is the population growth, EALr is the electricity access loss rate, and EAr is the electricity access rate. The population with electricity access (PnA) is formulated as:

$$PnA = PnAint + \int [Max[Min\left[\left(\frac{PCp}{AvCp}\right), \left(\frac{PwA}{TS}\right)\right], 0] - Min\left[\left(\frac{PCd}{AvCp}\right), \left(\frac{PnA}{TS}\right)\right]]dt \tag{5}$$

where PnA_{int} is the initial population with electricity access. These are the equations for the key stocks and flows in the electricity access sub-model. The stock and flow structure of this sub-model is shown under appendix A.

3.2 Electricity capital investment sub-model structure and equations

The electricity capital investment sector illustrates the financial requirements for the installation of power capacity in Africa. This sector determines how many new power projects are commissioned for construction, based on the financial resources/investment available. This sub-sector comprises two key stocks: indicated investment backlog, and African GDP. A third stock called cumulative investment was created to compute the total investment made during the simulation period. There are also two key flows: annual investment, and indicated annual investment. A third flow, GDP growth, calculates the yearly change in African GDP. The stock of indicated investment backlog calculates the total financial needs in US$ billions over the simulation period. It increases or decreases when there is a positive or a negative difference between the indicated annual investment and the annual investment, respectively. An essential focus of the model is the rate of annual investment (an outflow from the indicated investment stock), and how this rate would respond to policies such as change in regulations or incentives offered to private firms. It is expected that the annual investment would increase, resulting in increased cumulative investment. The key assumptions made on the parameters in this sub-model include learning rate, the initial cost per GW unit, and initial investment backlog.

The electricity capital investment sector of the AFELA model captures a core aspect of this study, namely: the finance gap of Africa's electricity sector, and how state and market policies can incentivise and increase the flow of private sector finance into the power sector.

The main sources of finance for investment in the energy sector are already identified as domestic governments, bilateral and multilateral aid, and private sector financing. The model assumes a limitation on the extent of foreign aid granted to Africa, and also on the national budgetary allocations for expanding electricity access. Private sector financing therefore becomes the focus area through which additional funding can be attracted into the energy sector. The size of investment from this private funding is a function of market conditions, and national policies including incentives to attract private investments.

The main equations used for this sub-model are those for the annual investment flow, the indicated annual investment flow, and the indicated investment backlog stock. One key variable of this sector is the annual investment rate (AIr) given as:

$$\text{AIr} = Min\ \left[\left(GdP * \left(Ir + step(Irs, 2020)\right)\right), \left(\frac{IiB}{TS}\right)\right] \qquad (6)$$

where GdP is African GDP, Ir is the investment rate, Irs is the investment rate sensitivity, a policy parameter to assess the effect of a change in the investment rate, and IiB is the indicated investment backlog. The indicated annual investment (IIr), the amount that ought to be invested into the electricity sector annually, is given as:

$$\text{IIr} = \text{CGu} * \text{CDd} \qquad (7)$$

$$\text{CGu} = \text{intCGu} + \text{step(CGWS, 2020)) *L} \tag{8}$$

where intCGu is initial cost per GW unit, CGus is the cost per GW unit sensitivity, L is the learning effect, and CDd is the annual capacity demand deficit. The cost per unit is a constant value representing an average cost of installing a GW unit of power. The average GW cost is not decoupled into the different energy sources. Instead it was attributed a value based on the average cost of the leading power sources from which electricity is generated in Africa. Since the electricity supply sub-model did not unbundle the different sources, this fixed unit cost improves consistency in the forecast. Differentiated unit pricing would require unbundling the generation mix to ensure accuracy, a task rather in-depth and demanding beyond the scope of this research.

The indicated investment backlog (IiB) is the stock of capital investment (in US$) that should have been made towards electricity access in Africa. Because of financial constraints, the investment deficit accumulates into a stock of indicated investment backlog. This stock is computed as:

$$\text{IiB} = \text{IiB}_{\text{int}} + \int \left[(intCGu + (step(CGus, 2020)) * L) * CDd - Min \left[\left(GdP * \left(Ir + step(Irs, 2020) \right) \right), \left(\frac{IiB}{TS} \right) \right] \right] dt \tag{9}$$

The amount of investment made annually throughout the simulation accumulates into the cumulative investment (CmI). While this is not a key stock in the model, it gives a clear insight of the total investment made in the power sector at any given point of the simulation. The formulation for this stock is:

$$\text{CmI} = \int Min \left[\left(GdP * \left(Ir + step(Irs, 2020) \right) \right), \left(\frac{IiB}{TS} \right) \right] dt \tag{10}$$

The amount of investment made in the power sector in Africa is assumed to be a fraction of the total Gross Domestic Product (GdP). The GdP changes annually, as the growth rate changes.

$$\text{GdP} = \text{GdPinit} + \int [GdPg]dt \qquad (11)$$

The GdPinit stands for the initial GdP, and GdPg is the annual GDP growth. The stock and flow structure of this sub-model is shown under appendix B.

3.3 Electricity supply capacity sub-model structure and equations

This sub-model contains five key stocks: power capacity backlog, which is the outstanding capacity needed at any given point in time of the simulation; power capacity construction - the total amount of power capacity that is under construction; power capacity installed, which is the total amount of power installed and generating energy; actual energy used - the total amount of energy consumed each year, not including transmission losses; and power capacity decommissioned, which is the capacity discarded and is no longer in use.

There are also six key flows, including the annual capacity demand deficit, the capacity commencement, capacity completion, production completion, capacity decommissioning, and production decommissioning. The annual capacity demand deficit is the annual capacity backlog as a result of the difference between the desired capacity and the actual capacity, after accounting for the supply line. The annual amount of new capacity initiated for construction as a result of investments made, is the capacity commencement. Capacity completion is the annual amount of power capacity that is completed and commissioned for use; the production completion calculates the amount of energy generated for the newly completed capacity; capacity decommissioning is how much capacity is written-off annually; and the production decommissioning is the amount of energy lost because of the capacity decommissioning. This also translates to loss of electricity access. Besides the key stocks and flows, assumptions are also made of some key parameters in this sub-model. The AFELA model's estimation of the utilisation factor takes cognisance of the losses from transmission and distribution. These losses are not separated, but rather embedded in the formulation, because of limited access to the information required for explicit presentation.

An increase in investment leads to increase in the total energy used, which amounts to an increase in the electricity access rate. The annual capacity demand deficit (CDd) is equivalent to the indicated capacity requirement, which is calculated as the maximum of the Supply line adjustment (Sla), and desired acquisition rate (Dar), expressed as a fraction of the supply line adjustment time (Slt). The CDd is therefore defined as:

$$\text{CDd} = \left(\frac{Max(Sla\ ,\ Dar)}{Slt}\right) \tag{12}$$

The capacity commencement (CCo) is a function of the power capacity backlog (PcB), the annual investment (AIr), and the cost per GW unit (CGu) and is given by:

$$\text{CCo} = Max\ [Min\left[\left(\frac{AIr}{CGu}\right), \left(\frac{PcB}{TS}\right)\right], 0] \tag{13}$$

Capacity completion (CCp) is a function of the power capacity construction [39] and the construction time (Ct):

$$\text{CCp} = \left(\frac{PcC}{Ct}\right) \tag{14}$$

The capacity decommissioning (PCd) is given as:

$$\text{PCd} = \left(\frac{PcI}{AvPl}\right) \tag{15}$$

where PcI is the power capacity installed, and AvPl is the average plant life. The production completion (PCp) is a function of the capacity completion (CCp), the GW to GWh conversion (Cf), the utilisation factor (Uf), and utilisation factor sensitivity (Ufs).

$$\text{PDn} = \left(\frac{EnU}{AvPl}\right) \tag{16}$$

Production decommissioning (PDn) is given as:

$$\text{PCp} = (CCp * Cf) * \left(Uf + step(Ufs, 2020)\right) \tag{17}$$

Where EnU is the actual energy utilised, which is also calculated as:

$$\text{EnU} = \text{EnUini} + \int \left[(CCp * Cf) * \left(Uf + step(Ufs, 2020)\right) - \left(\frac{EnU}{AvPl}\right)\right] dt \qquad (18)$$

The power capacity backlog (PcB) is a function of the initial power capacity backlog (PcBini), the power capacity commencement rate:

$$\text{PcB} = \text{PcBini} + \int \left[\left(\frac{Max(Sla\,,\; Dar)}{Slt}\right) - Min\left[\left(\frac{AIr}{CGu}\right), \left(\frac{PcB}{TS}\right)\right] dt \qquad (19)$$

The power capacity construction [39] is the sum of the initial power capacity construction (PcCini) at the start of simulation and the difference between the capacity commencement and capacity completion.

$$\text{PcC} = \text{PcCini} + \int \left[[Min\left[\left(\frac{AIr}{CGu}\right), \left(\frac{PcB}{TS}\right)\right] - \left(\frac{PcC}{Ct}\right)\right] dt \qquad (20)$$

Power capacity installed (PcI) accumulates the initial power capacity installed (PcIini), and the difference between capacity completion and capacity decommissioning.

$$\text{PcI} = \text{PcIini} + \int \left[\left(\frac{PcC}{Ct}\right) - \left(\frac{PcI}{AvPl}\right)\right] dt \qquad (21)$$

Power capacity decommissioned (PcD) only integrates the initial power capacity decommissioned (PcDini) and the capacity decommissioning rate.

$$\text{PcD} = \text{PcDini} + \int \left(\frac{PcI}{AvPl}\right) dt \qquad (22)$$

A key link between the access and supply sectors is the desired power capacity (DPC). This variable depends on the population growth, the average consumption per person, and the utilisation factor. The DPC is given by:

$$DPC = \left(\frac{AvCp * TP}{Uf}\right) * \left(\frac{1}{Cf}\right) + Ds \qquad (23)$$

Where Uf is the utilisation factor and Cf is the conversion factor. The stock and flow structure of this sub-model is shown under appendix C.

3.4 Model testing and validation

Model validation in system dynamics is an essential part of building confidence and reliability into the model. It is an exercise to establish that the model's structure and behaviour matches the knowledge of the actual system examined [40], and boosts confidence when using the model for the purpose for which it was developed [41]. There are different ways for validating a model. Some key validation techniques include those for structural validity, a dimensional consistency check, parameter assessment, behaviour reproduction, and a sensitivity test.

Structural validity is a multidimensional process of problem identification and representation, logical formulation of the structure, as well as the illustration of the mathematical and causal relationships [42]. Structural validation ensures that the formulations in the model conform to conventional and logical wisdom. In order to improve the general understanding of the model, the parameters were verified and the model validated through calibration (see: Table *1*).

Dimensional consistency is a form of validation that ensures that the units of all variables and parameters are indicated and are consistent throughout the model. The model was developed using the Vensim software, which contains a functionality for checking dimensional consistency [43], making this process less cumbersome.

Behaviour reproduction validation compares the result of data and simulation. The AFELA model used key variables such as the power capacity installed and the population without electricity to check consistency between model behaviour and data. Indeed, replication of the reference mode is not a guarantee that the model is correct, but it indicates that the model's validity is not questioned based on data.

Sensitivity analysis helps test the robustness of conclusions drawn in relation to parameters estimated [37], especially those parameters with high uncertainty, but greater impact. Sensitivity also helps identify high leverage points for policy interventions. The results of the sensitivity tests are extensively discussed under the results and analysis section. Other related validation tests were carried out, including how the model responds to extreme tests of both parameters and simulation duration. The model produces results consistent with the dynamics and feedback processes design within.

Data of certain parameters were not readily accessible, and different sources reported different figures for some parameters. The resulting base-run was thus noticeably distinct from the reference mode. To improve upon the model validity based on data, the model was calibrated to ensure that values that are more accurate could be obtained for parameters with high uncertainty surrounding them. The calibration results are shown in Table 1.

Table 1: Model parameters calibration and results optimisation

Initial point of search	**Maximum payoff**
AVERAGE PLANT LIFE = 60 INITIAL COST PER GW UNIT = 2e+009 CONSTRUCTION TIME = 3 INITIAL CAPACITY CONSTRUCTION = 10 LEARNING RATE = 0.05 Simulations = 1 Pass = 0 **Payoff = -86.0389**	*AVERAGE PLANT LIFE = 49.328 INITIAL COST PER GW UNIT = 2e+009 CONSTRUCTION TIME = 2.0015 *INITIAL CAPACITY CONSTRUCTION = 12.0521 LEARNING RATE = 0.1 Simulations = 601 Pass = 3 **Payoff = -15.1774**
Confirmatory search	Confirmation of Maximum payoff
*AVERAGE PLANT LIFE = 49.328 INITIAL COST PER GW UNIT = 2e+009 CONSTRUCTION TIME = 2.0015 *INITIAL CAPACITY CONSTRUCTION = 12.0521 LEARNING RATE = 0.1 Simulations = 601 Pass = 3 Payoff = -15.1774	AVERAGE PLANT LIFE = 49.328 INITIAL COST PER GW UNIT = 2e+009 CONSTRUCTION TIME = 2.0015 INITIAL CAPACITY CONSTRUCTION = 12.0521 *LEARNING RATE = 0.1 Simulations = 71 Pass = 3 Payoff = -15.1774
Parameter confidence bound defined	**Parameter confidence bound found**
20 <= AVERAGE PLANT LIFE = 49.328 <= 80 2e+009 <= INITIAL COST PER GW UNIT = 2e+009 <= 5e+009 2 <= CONSTRUCTION TIME = 2.0015 <= 7 10 <= INITIAL CAPACITY CONSTRUCTION = 12.0521 <= 30 0.01 <= LEARNING RATE = 0.1 <= 0.1	46.3782 <= AVERAGE PLANT LIFE = 49.328 <= 52.6256 2e+009 *<= INITIAL COST PER GW UNIT = 2e+009 <= 2.04846e+009 2 *<= CONSTRUCTION TIME = 2.0015 <= 2.17994 10.606 <= INITIAL CAPACITY CONSTRUCTION = 12.0521 <= 13.4996 0.0192344 <= LEARNING RATE = 0.1 <= 0.1 *
The final payoff is -1.517738e+001	

After conducting 601 simulations, as shown under the column "maximum payoff" (see Table 1), all the calibrated parameters recorded a change in value, except the cost per GW unit. The new values obtained are shown under the column; maximum payoff in Table 1. There was also an improvement in the final payoff from -86.0389 to -15.1774 indicating that these new parameter values resulted in a better fit between the simulated model results and the actual data. The calibrated values of the base run model were then loaded and simulated under a different name ‘baseline’. A total of 71 (see Table 1) simulations were done under the baseline and the payoff remained at -15.1774 as expected since the new values of the parameters were now initialised and run as the baseline. The simulation runs also offer a confidence bound for the parameters that were calibrated. The baseline model therefore becomes the final model used for assessing different scenarios and policy options through sensitivity analysis.

3.5 Scenarios developed

The AFELA model examines four scenarios, namely: the Baseline scenario, which represents the business as usual; Economies of scale scenario, which entails a decline in average unit cost through learning effect; Capacity utilisation factor scenario, which entails an improvement in the capacity utilisation factor; and Electricity access investment, which represents an increase in annual investment. These scenarios were assessed by conducting sensitivity analyses of three key parameters: the unit GW cost, the capacity utilisation factor, and the investment rate. This was to ascertain what must happen to achieve universal access to electricity in Africa by 2030, the target set by the UN Sustainable Development Goals. Whether a decline in the baseline scenario is enough, or a decline in cost per GW unit, or is an improvement in the efficiency of presently installed power plants to optimal capability, or is an increase in the annual investment rate. The simulation timeline extended to 2040, in part, to validate the model and ensure that the policy options that led to universal access by 2030 were robust beyond that timeline. It was also to understand how long it would take for universal access to be attained under the baseline scenario.

Key model parameters (see Table 2) identified as potential leverage points for policy actions to address the problem of lack of electricity access, were varied independently to ascertain the impact on the behaviour of model variables. The baseline scenario shows the pattern of development of the variables if no policy interventions are implemented. The economies of scale scenario reduces the GW unit cost by half a billion dollars (US$). This conceptualisation is based on the likely outcome from employing economies of scale, research and development, and the learning effect.

Table 2: Scenario assessment parameters

Scenarios / Parameters	GW unit Cost (US$)	Utilisation factor	Investment rate
Baseline	2,000,000,000	0.48	0.01
Economies of scale	1,500,000,000	0.48	0.01
Capacity utilisation factor	2,000,000,000	0.80	0.01
Electricity access investment	2,000,000,000	0.48	0.03

The capacity utilisation scenario assumes that power plants generate at an optimal efficiency of 80%. This is grounded on an estimation of the mean efficiency of the different energy sources from which power is generated across Africa. The electricity access investment scenario looks at the effect an increase in investment rate poses on electricity access. The annual investment rate in this scenario is increased from one to three per cent of GDP.

3.5.1 The baseline scenario

This scenario considers how variables in the model will develop if nothing changes, or no policy intervention is implemented. This scenario assumes that all parameters will retain their base values and the future dynamics of the model is predetermined by such values. This is sometimes referred to as the 'business as usual case', suggesting that there is no change from the present initial conditions defined within the model. This scenario is important because it can help analysts decide whether the modelled problem requires intervention, or is destined to self-correct in the future.

3.5.2 Economies of scale scenario

This scenario considers the fact that average unit cost of production declines as an industry enjoys economies of scale. Through research and development, innovation, and the learning that occurs as a result of accumulated experience, the average real cost per GW unit of power is expected to decline over time. The scenario therefore assesses the implication of the learning effect on the unit cost of power over the simulation period. If there is high learning, the unit cost would decline, resulting in a rise in the number of people who gain access to electricity. On the other hand, a low learning effect indicates limited advantages accruing from the additions of capacity. This is especially common in cases where the technology has matured and therefore the potential for further innovation to improve it is very limited.

3.5.3 Capacity utilisation factor scenario

The utilisation factor scenario is based on the understanding that no power plant operates at 100% efficiency. The actual fraction of energy generated compared to the potential energy based on the capacity installed is termed as the capacity utilisation factor (CUF). The CUF is thus the ratio between total energy a power plant generates *vis-a-vis* the maximum energy that it can possibly generate within a given period of operation. It is important to consider this scenario, because it is necessary to ascertain whether the lack of electricity access is due to infrastructural inadequacy (limited installed capacity), operational inefficiency (low utilisation factor), or both.

3.5.4 Electricity access investment scenario

This is the key policy parameter in the model. The overall thesis of the chapter relies on the hypothesis that an increase in the investment rate will result in more people gaining access to electricity. Under this scenario, the investment rate is varied, to observe the dynamics of the population without access to electricity over time.

4 AFELA model results

The AFELA baseline results replicate how the variables changed over time (see Figure 2).

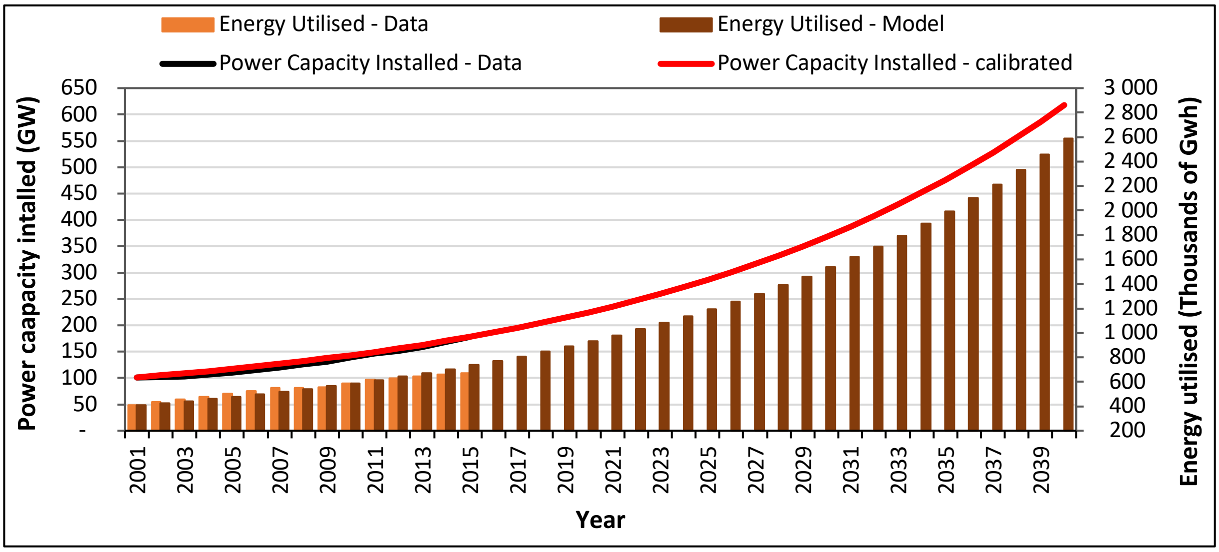


Figure 2: A comparison of data and baseline results of power installed and energy utilised

The baseline result of the simulation is juxtaposed with historical data, to establish confidence in the model as a form of validation before using it as a policy tool. Figure 2 shows both the historical data and the baseline simulation results of the power capacity installed in Africa, as well as the energy used by all consumers for the period 2001 to 2015 and 2001 to 2040 respectively. The results show a reasonable fit between historical data and model results.

The baseline results on the proportion of the African population with access to electricity in 2005 and 2010 was 39% and 43% respectively (see Figure 3), consistent with the findings of the IEA [44]. Figure 3 indicates that, under the baseline scenario, the number of people in Africa who would still live without electricity by 2030 will exceed half a billion people (approximately 597 million people), representing approximately 35% of the total population. This is also consistent with the forecasts of the AfricaProgressPanel [7] and IEA [3], that a total of 600 and 635 million people, respectively, would not have electricity access by 2030. This calls for a concerted effort from stakeholders (governments and international agents) in the African electricity sector across local, national, and international levels, to set in motion policies that accelerate access from 65% under the 'business as usual case' to 100% by the year 2030.

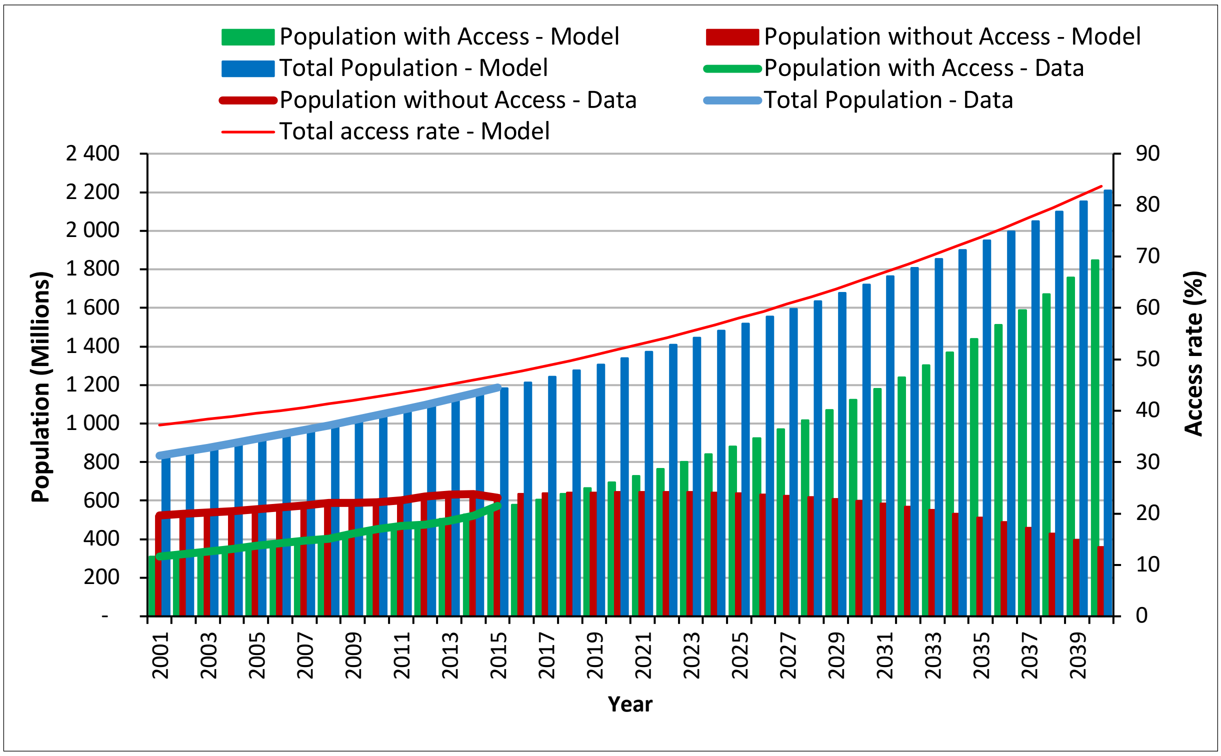


Figure 3: Africa's population with, and without, electricity access, and total population

4.1 Scenario analysis

All scenarios were simulated from 2019 to 2040. The scenarios are discussed in relation to their effect of key variables namely; power capacity installed, energy utilised, total electricity access, and the population without electricity access.

4.1.1 Power capacity installed

The Electricity access investment scenario, which increases the annual investment rate from one to three per cent of GDP, has the highest impact, where the total capacity installed reaches 871 GW in 2040 compared to 618 GW in the baseline scenario (see Figure 4). The Economies of scale, and Capacity Utilisation Factor scenarios reaches 783 GW and 618 GW respectively. The difference of 261 GW between the Baseline and Electricity access investment scenario by 2040 shows how much extra power capacity can be added if annual investment increased to three per cent. Figure 4 shows the total power capacity installed results from the four scenarios.

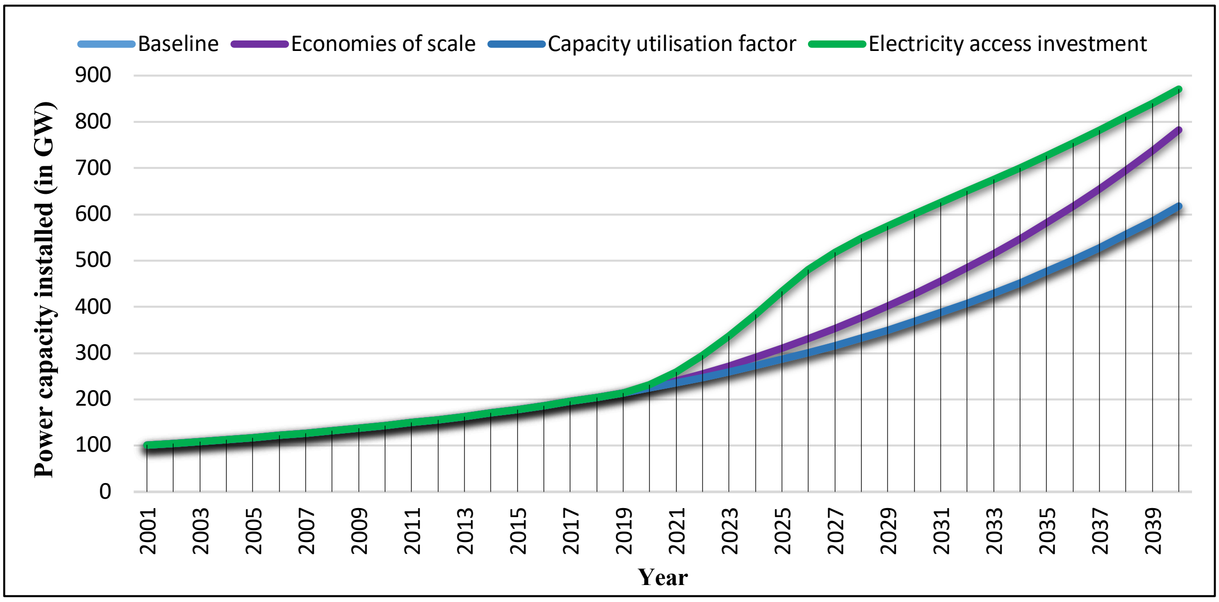


Figure 4: Power capacity installed under the different scenarios

A potential decline in the GW unit cost under the Economies of scale scenario will also lead to more capacity being installed because the baseline annual investment can procure more GW units. There is, however, no change in the power capacity installed under the Baseline scenario and the Capacity utilisation factor scenario. The latter only boosts the efficiency of already installed capacity without adding new power capacity units. In effect, it only impacts on the GWh and not the GW.

4.1.2 Energy utilised

In Figure 5 the total power installed is greater (428 GW) under the Economies of scale scenario than that of the Capacity utilisation factor scenario (368 GW) in 2030. However, the total energy utilised in the Capacity utilisation factor scenario is 3.9 million GWh, which is greater than what is observed in the Economies of scale scenario, 3.3 million GWh in 2030 (see Figure 5). This is because the two scenarios influence the power sub-sector at different stages. The Economies of scale scenario ensures that more power plants are installed, and the Capacity utilisation factor scenario focuses not on installation, but on improving the efficiency of the capacity already installed. In brief, the Economies of scale scenario means more power installed while the Capacity utilisation factor scenario means more energy utilised. While the power capacity installed influences electricity access rate, the energy that is utilised/consumed is more critical in determining the number of people who have access to electricity.

Even though the utilisation factor does not directly affect the power capacity installed, it can be conceptualised that the rise in energy available through a higher utilisation factor would eventually lead to a lower overall capacity requirement. Compared to the baseline scenario, the utilisation factor and electricity access investment scenarios leads to an extra one million GWh of energy available in the African electricity market by 2040.

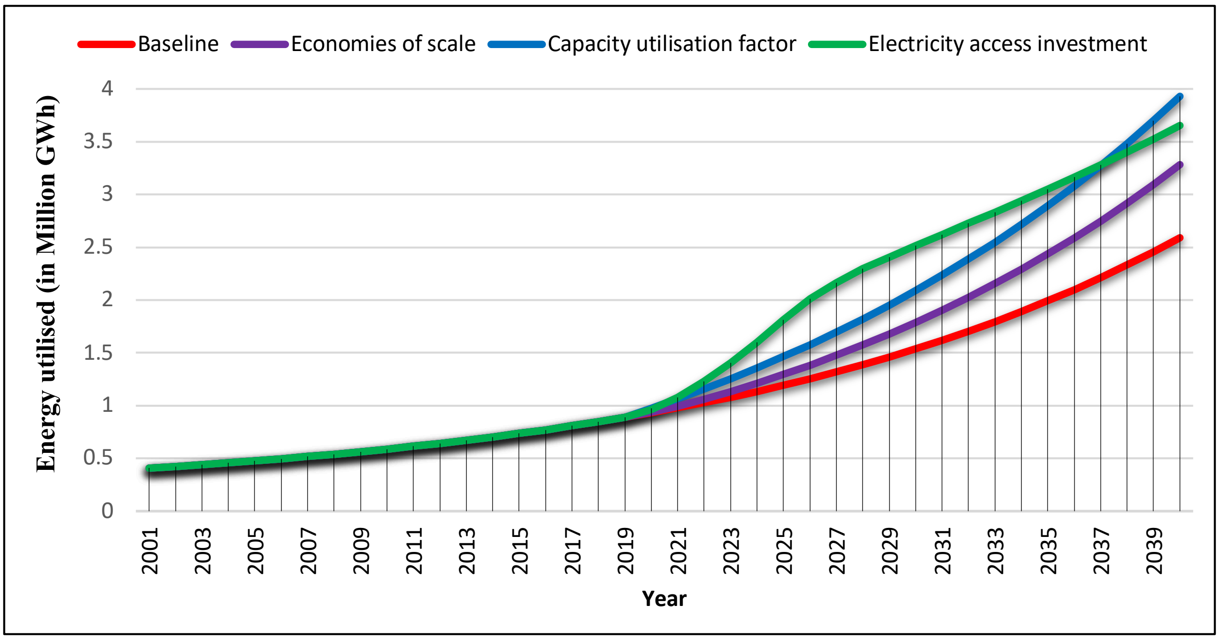


Figure 5: Energy utilised under the different scenarios

4.1.3 Total electricity access

The results (see Figure 6) reveal that, from the scenario start time of 2019, the access rate would be 51%. Under the Baseline scenario, approximately 65% of Africans will have access to electricity by 2030, while 35% remain without access. The access would increase to 84% access and 16% without access by 2040.

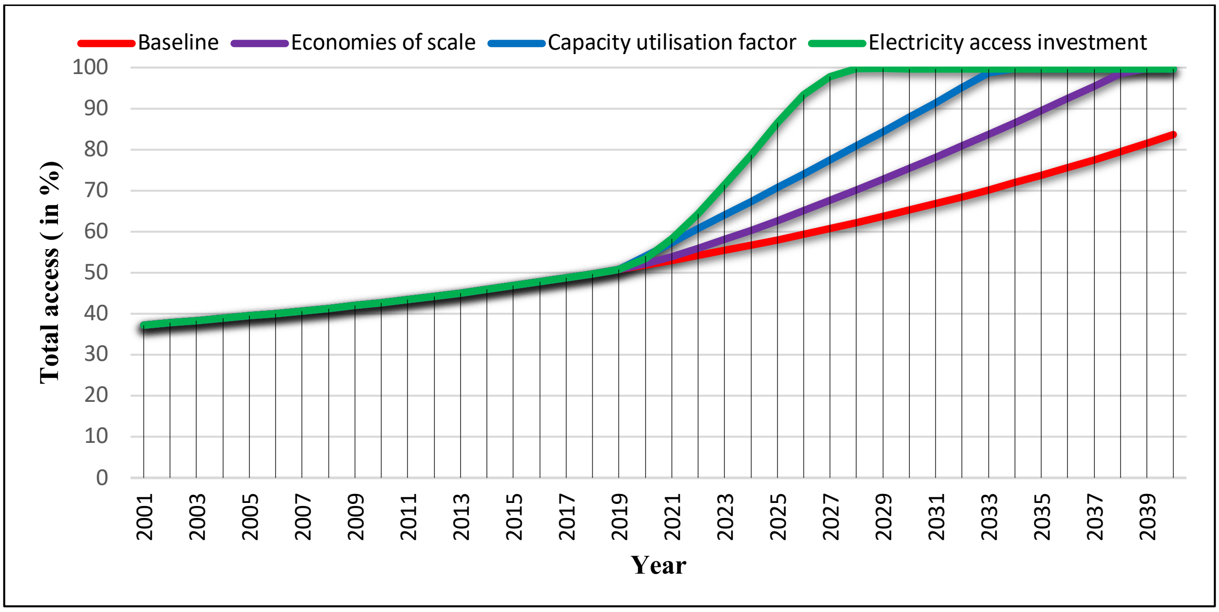


Figure 6: Total access under the different scenarios

Under the Economies of scale and Capacity utilisation factor scenarios, total electricity access rate would only reach 75% and 88% respectively by 2030. Universal electricity access in Africa, under these scenarios, would not be achieved until 2038 and 2033 respectively.

The Electricity access investment scenario, however, will ensure that universal access is attained across the continent by 2028, a feat that would mean a realisation of the SDG7 in relation to electricity.

4.1.4 Population without access

The goal relating to energy access in Africa is to get the stock of population without electricity access to zero. Under the Baseline scenario, about 600 million Africans would not have electricity access by 2030, and this would reduce to 360 million by 2040. This emphasises the need for stakeholders to act in a timely manner if the SDG7 is to be attained.

Similarly, as shown in Figure 7, Economies of Scale, and Capacity Utilisation Factor scenarios would not lead to universal electricity access by 2030. The number of people in Africa who would remain without access to electricity by 2030 would be 423 million and 208 million respectively. The objective of universal electricity access would have failed.

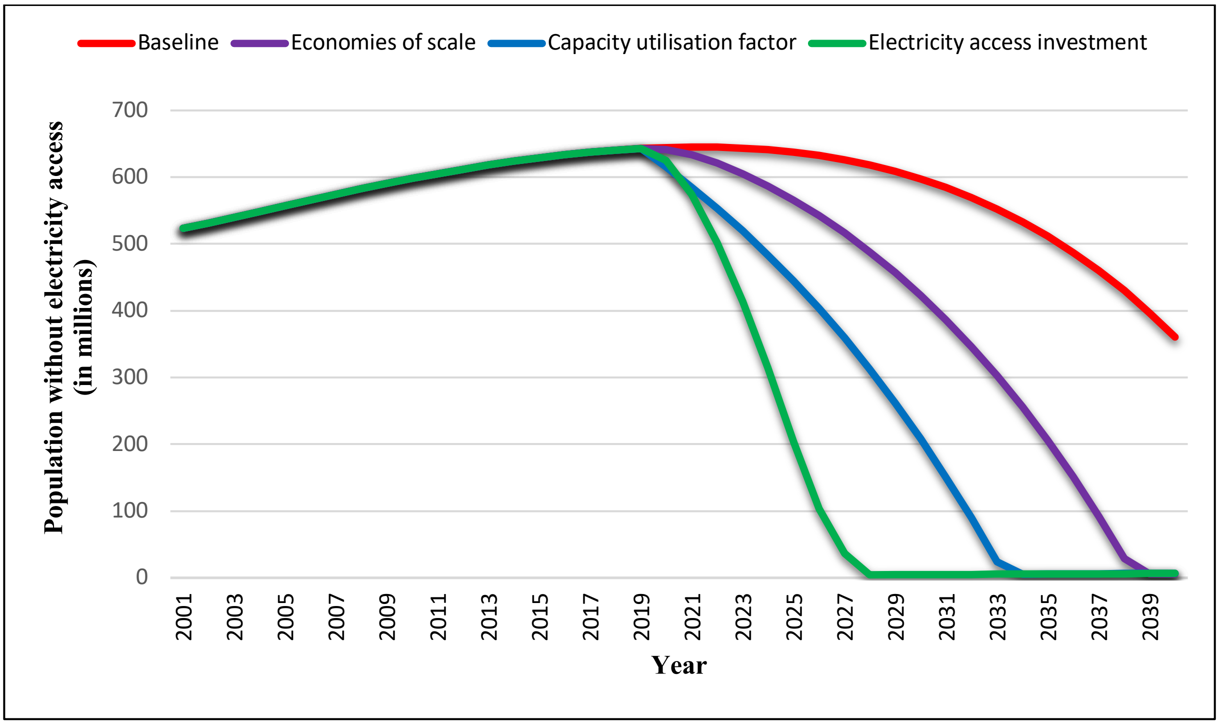


Figure 7: Population without electricity under the different scenarios

The Electricity Access Investment scenario is the only one among the four scenarios that would ensure universal access by 2030. Under this scenario, universal access to electricity will be attained by 2028. Therefore, any future policy decisions designed to deliver universal electricity access in Africa by 2030, should focus on new investment in the region's electricity infrastructure.

Governments themselves, with their severe financial limitations, would struggle to realise the investment needs under the Electricity access investment scenario. The annual investment would have to increase from US$26 billion in 2019 to US$114 in 2026 in order to achieve universal electricity access in 2028. Approximately US$ 500 billion dollars, equivalent to the investment backlog in 2019, would have to be cleared through the yearly investment during this period. The finding is similar to the latest IEA [44] report, which projects that an additional US$ 391 billion dollars would be needed to provide electricity to some 674 million people between the period 2017 to 2030. The enormous financial resources required to pursue universal electricity access in Africa by 2030 affirms the deduction of Eberhard, Gratwick, Morella and Antmann [45] that the present investment is less than what is required. It also supports the principal hypothesis of the study that private finance is essential to meet the investments required in Africa's unmet electricity markets.

Although the financial requirements appear out of reach, the incentive to incur lower capital expenditures in the future, in order to provide a service as critical as electricity, and the opportunity to utilise various funding sources within and beyond national and continental boundaries, makes this surmountable.

Having affirmed the need for private sector investment in the Africa electricity market, a change in market conditions, including liberalising markets that restrict private sector entry through regulatory reforms, and offering tax incentive to private firms is necessary. The success of the various power pools in the European electricity market, populated by private sector operators, is evidence that the involvement of private entities in the African power market could boost the region's power generation capacity. In fact, if other SDGs are also considered pertaining to, for example, climate change, such market policies could be a stimulus for expanding the renewable energy share in the total energy mix and increase power availability.

5 Conclusions

The perpetuating energy poverty in Africa challenges the attainment of universal electricity access by 2030. The study considered four scenarios, namely: the Baseline Scenario, Economies of scale Scenario, Capacity utilisation factor Scenario, and Electricity access investment Scenario; to determine which, under the constraints of the introduced AFELA model, offers the fastest means to universal electricity access in Africa. We found that neither the current learning effect on cost decline, nor the optimal utilisation of present capacity, is enough to achieve universal access. An increment of the annual investment in the power sector is the most viable option for that purpose.

National governments, and multilateral and bilateral aids, are crucial sources of funds for power infrastructure in Africa. These funding sources, however, appear inadequate, less reliable, and, in the long-term, not sustainable for addressing the financial challenges associated with the electricity access. Private finance is a viable alternative that can bridge the finance gap as it offers an opportunity to expand the financial robustness of the energy sector amid national budget constraints and inconsistent multilateral and bilateral fund flows. It is therefore imperative to induce investment from the private sector, given the limited funds from multilateral and bilateral aids, and constraint budgets of national governments tasked with the mandate of providing electricity.

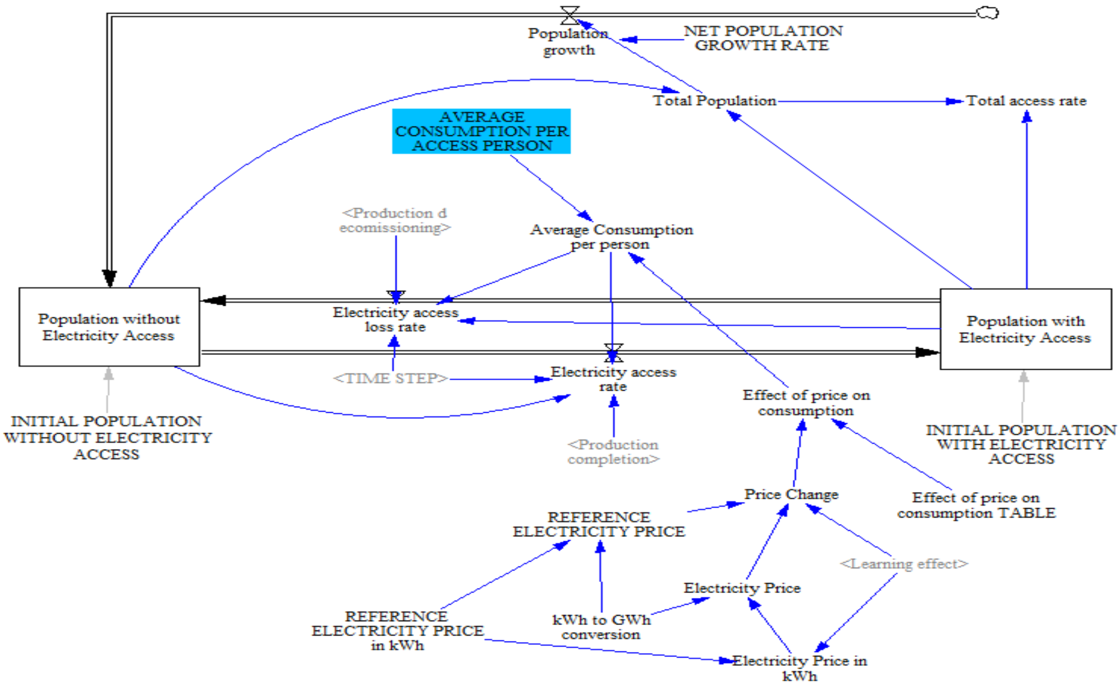
The path to universal electricity access in Africa is characterised by a litany of challenges. This paper affirms limited finance for power infrastructure as one of them. The market conditions and regulatory structures of Africa's electricity sector may explain why this challenge persists. In addition, given the abundance of renewable energy resources in relation to the challenges that pertain to conventional energy power plants in Africa, investing in renewable energy could accelerate the attainment of universal electricity access status. Indeed, there are limitations (e.g. lower utilisation factor) to pursuing renewable energy sources for electricity generation than conventional energy sources. The pursuit of renewables for electricity could avail funding opportunities including the Climate Investment Fund, the Global Environment Facility, and the Clean Technology Fund; to reduce the financing gap and consequently promote universal electricity access in Africa.

Going forward, policy reform should strengthen the institutions within the electricity sector, allow private investors to participate in the sector, and offer guarantees and safety nets to hedge risks of private investors. This would lay the foundation for improving innovation and performance, and increase the funding available to the electricity sector.

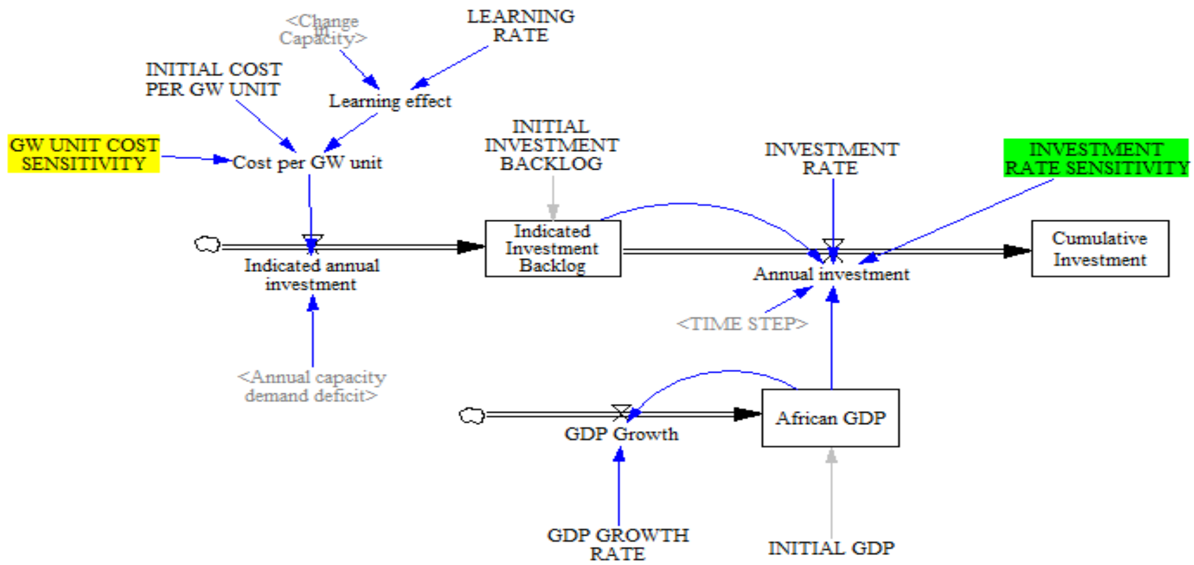
There are a number of limitations to this study. The broad nature of the scope of the study makes it harder to draw a specific case study that corresponds to the entire African market. The study does not also distinguish the key differences such as level of electricity access in the countries across Africa. It considers the African power sector as a homogenous market. The study does not also differentiate between electricity generation and distribution, or conduct a specific case study of private sector participation. The AFELA model is an aggregate model that does not disintegrate the different power sources that makes up the African power market. The different consumer groups, such as industry, commercial, and residential, are not distinguished. While the results of the study are not gravely compromised by these limitations because of its stated scope, focus, and overall objective, future research is encouraged, taking cognisance of these limitations.

APPENDICES

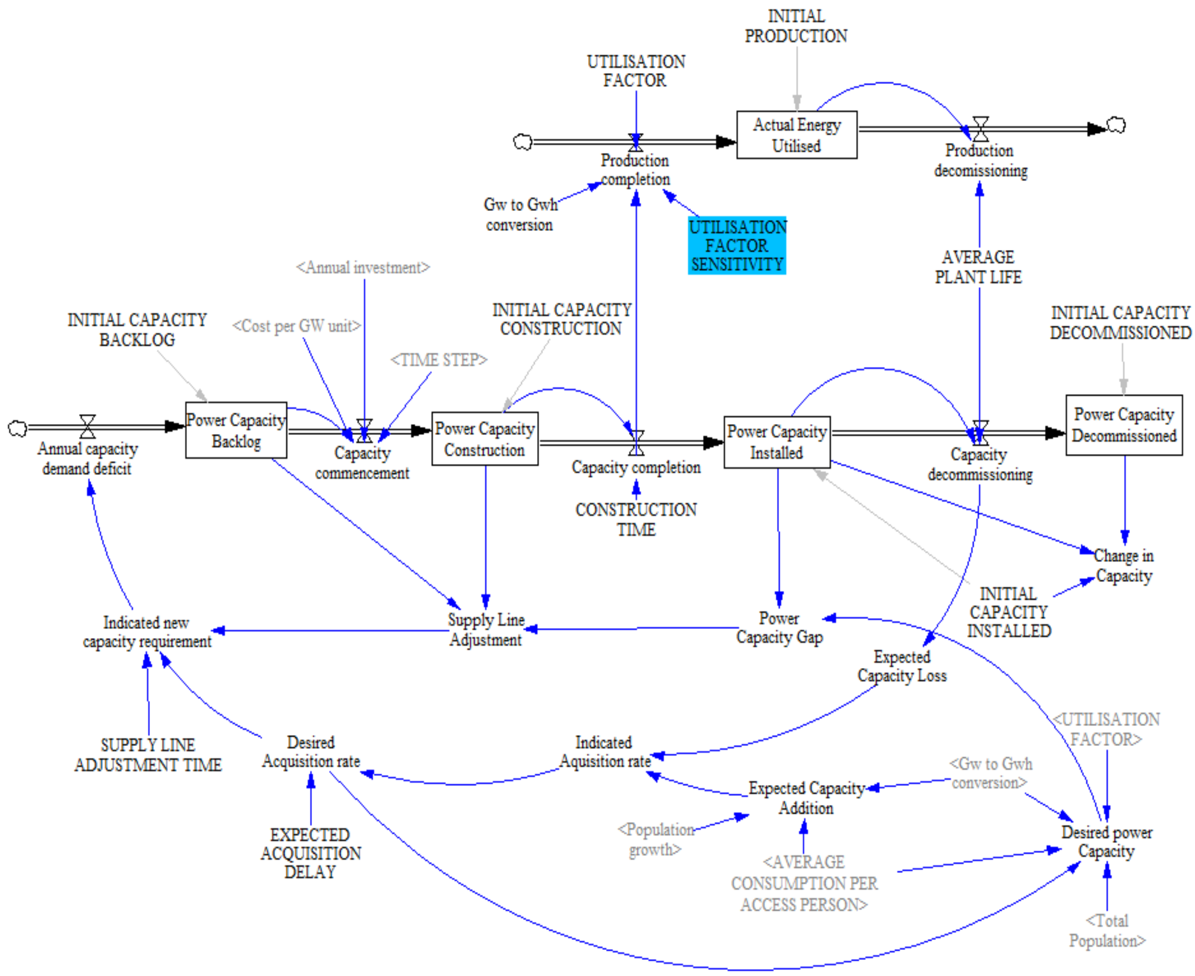
Appendix A: Electricity access sub-model



Appendix B:Electricity capital investment sub-model



Appendix C: Electricity supply capacity sub-model



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