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Scenarios for universal electricity access with spatial changes in urbanisation: The case of Kenya

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ABSTRACT

Kenya has one of the fastest electrification rates in Sub-Saharan Africa. Despite the increase in electrification rates, rural and underserved regions remain a critical challenge requiring a cost-effective strategy that maximises the use of stand-alone and off-grid solutions. This paper uses the Open-Source Spatial Electrification Tool coupled with a binomial logistic regression model of urbanisation to explore least-cost electrification scenarios for universal access in Kenya. The premise is that as more areas are electrified and the population increases, more regions will likely become urban, leading to changes in their electricity demand. The regression model reveals at least four regions where new urban settlements will likely be concentrated: central Kenya, the coastline, and the border regions to the west and north of Kenya. Electrification scenarios prioritising off-grid ($5.2 billion) and stand-alone solutions ($1.8 billion) significantly reduce the required investment compared to scenarios prioritising grid extension ($8.1 billion). Given the crucial role of stand-alone solutions in minimising costs associated with electricity access, this paper suggests a shift in policy to promote the uptake of stand-alone systems over the previous focus on grid extension and large-scale projects that have dominated Kenya's energy policy landscape.

1. Introduction

Electrification provides opportunities for local economic development in developing countries [1], yet roughly 50 % of the population in Sub-Saharan Africa (SSA) lacks access to electricity [2]. The degree to which developing countries can benefit from the economic gains derived from renewable electrification is an understudied issue. Many developing countries are striving to increase electrification through renewable energy sources. Considerable investments are required to support the structural change that will enhance opportunities to develop local capabilities in designing and constructing renewable electrification plants [1].

Kenya considers the energy sub-sector a key enabler in ensuring sustainable energy [3]. The country has one of the fastest electrification rates (76 %) in SSA, with targets to reach 100 % electrification by 2030 [2]. However, the pursuit of universal access to electricity is not one without challenges. Kenya's electrification efforts face obstacles due to weak implementation capacity, high connection costs, especially when supplying to rural areas, and a lack of incentives to attract private sector investments [4]. In addition, Kenya experiences high electricity system losses, roughly 23 %, compared to a global average of 8 % [5]. It therefore requires significant investments in efficient and resilient grid infrastructure while supporting its universal access goals. Despite those challenges, Kenya, through projects such as the Last Mile Connectivity project and the Kenya Off-Grid Solar Access Project (KOSAP) by the World Bank, has accelerated the pace of electrification. The former maximises the use of 35,000 existing distribution transformers to extend connection to 1.2 million people in the vicinity of the transformers. It entails the construction of 12,000 m of low-voltage distribution lines and installing equipment to connect a minimum of 30,000 commercial customers and 284,200 residential customers [6]. The latter, on the other hand, targets underserved counties in Kenya through the implementation of mini-grids and stand-alone technologies. The project identified 14 counties that represent about 70 % of Kenya's land area as underserved. These counties include Lamu, Mandera, Marsabit, Narok, Garissa, Isiolo, Kilifi, Kwale, Wajir, West Pokot, Samburu, Taita Taveta, Tana River, and Turkana [7].

Kenya's electricity mix is dominated by renewables, with geothermal, solar, wind, and hydro accounting for 90 % of generation [5]. Electricity imports account for approximately 6 % of the energy mix

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[8]. Kenya aims to rely on 100 % clean energy for its electricity by 2030. The current transmission network in Kenya is approximately 4127 km. The transmission infrastructure includes interconnection projects linking Kenya to Uganda, Ethiopia, and Tanzania to enhance power exchange among the countries. Between 2021 and 2040, Kenya plans to reach 12,782 MVA of substation capacity and 10,869 km in circuit length of transmission lines [9]. The existing and planned transmission infrastructure is illustrated in Fig. 1 [10].

The existing distribution network has more than 300,000 km of grid circuit. The network has experienced a network growth of approximately 160,000 km in the past 10 years [11]. Roughly 52 % of the total consumption is by large commercial and industrial customers, with the remaining 48 % by domestic consumers (31 %), small commercial enterprises (16 %), and street lighting (1 %) [8]. With the gains in expansion, the system experiences significant network and resource strain that affects the efficiency [12].

The Kenyan government's commitment to increasing access to electricity is evidenced by the regulatory frameworks implemented, such as the Kenya Vision 2030, Kenya Energy Transition and Investment Plan 2023–2050 (ETIP) and the Kenya National Electrification Strategy 2018 (KNES). Kenya's Vision 2030 is a blueprint for transforming Kenya into an industrialising middle-income country. The blueprint highlights increasing electricity access and developing renewable energy sources as some of the key areas of focus [3]. The ETIP focuses on decarbonisation technologies such as clean cooking, green hydrogen, renewable energy, e-mobility, and energy storage as the main technologies to anchor an orderly transition [13]. KNES was introduced as a roadmap to accelerate access to electricity. The strategy recognised the role of affordable and sustainable energy in achieving Vision 2030, and supporting food and nutrition, affordable housing, healthcare, and manufacturing. The electrification strategy identified the potential to add 269,000 connections through grid expansion within 15 km of the existing electricity distribution system, 1.96 million through solar home systems, 2.77 million connections through grid densification and intensification, and 35,000 connections through new mini-grids [4]. In 2024, Kenya introduced the Energy (Net Metering) Regulations that govern net metering arrangements with consumers; a consumer being a customer who is supplied electricity to and generates electricity for self-consumption and net metering using a renewable energy source with installed capacity less than 1 MW. The net metering regulations aim to promote further uptake of renewable energy among domestic and commercial consumers by providing the grid as a means of energy storage. It caps domestic installed capacity at 4 kW and 10 kW for single and three-phase supply, respectively [14]. With the new regulations, there is likely to be an increase in the use of distributed energy systems.

The total population living in urban areas in Kenya grew from 12 million to 14.8 million between 2009 and 2019. However, the urban population as a proportion of the total population decreased from

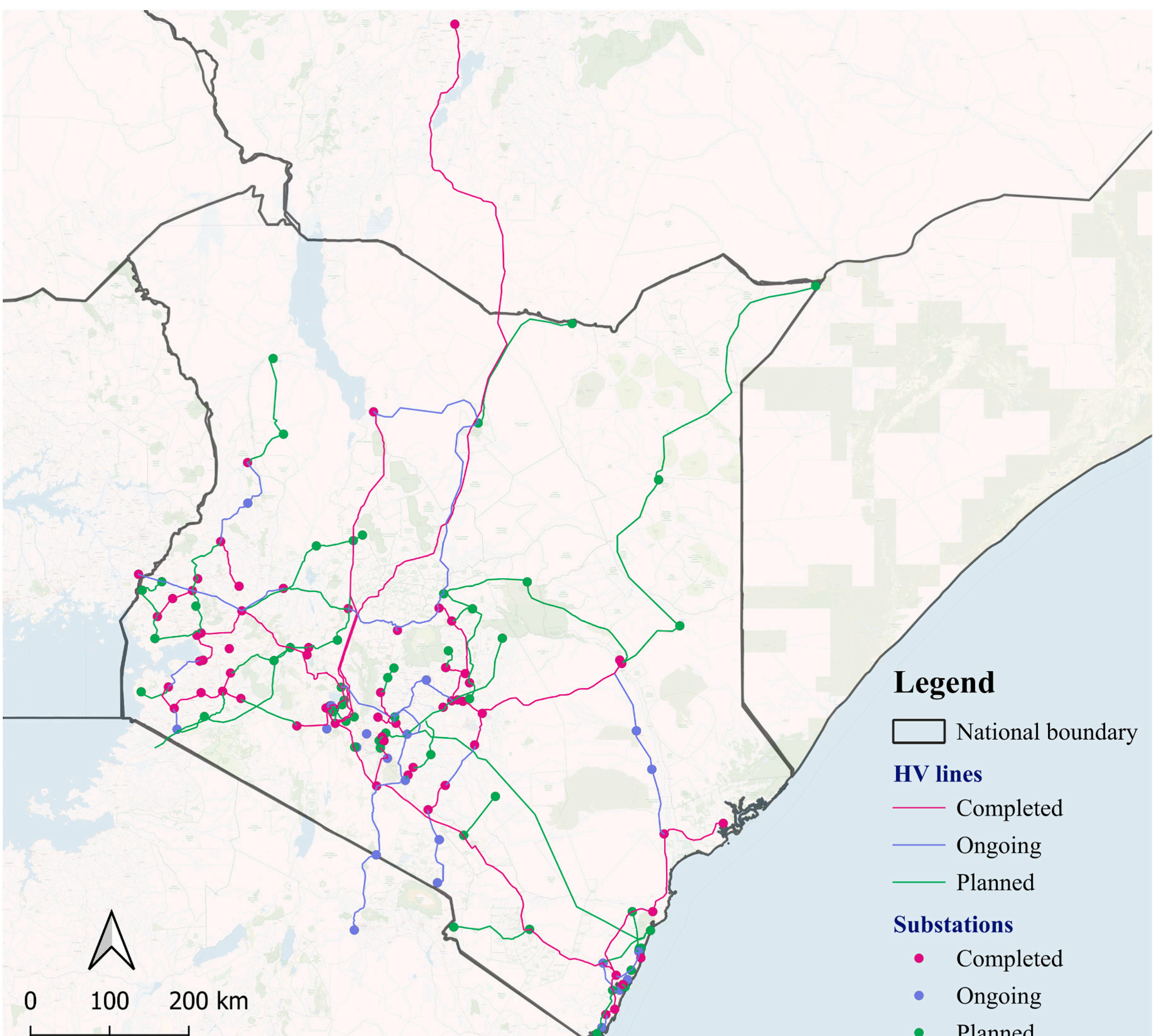

Fig. 1. Kenya's existing and planned electricity transmission infrastructure.

31.9 % to 31.2 % in the same period. Nairobi, Mombasa, and Kisumu are the major cities, while urban centres include Nairobi city, Nakuru, Ruiru, Mombasa, Kisumu, Eldoret, Thika, Kikuyu, Naivasha, Juja and Kitengela. The capital, Nairobi, has maintained a decreasing intercensal growth rate since 1969 (12.2 %), 1979 (4.9 %), 1989 (4.7 %), 1999 (4.5 %), 2009 (3.8 %), to 2019 (3.5 %). Mombasa shows a similar general trend of reduction in population growth rate from 1999 (3.7 %) to 2019 (2.7 %). This decrease in growth rate in major urban cities is partly explained by the emergence of satellite regions that attract higher net in-migration due to the strategic balance in proximity to major urban areas [15]. These satellite regions are close enough to major cities to benefit from access to jobs, services, and markets, but far enough to avoid the high costs and congestion associated with the major cities. Table 1 shows a comparison of the growth rates and migration patterns in major cities, satellite cities and rural areas in Kenya [15].

Several studies have been conducted to explore the social, economic, and political aspects of electrification in Sub-Saharan Africa (SSA) [16–26], and the use of stand-alone systems and mini-grids for rural electrification [27–34]. Studies exploring various technology options for electrification are shown in Table 2.

While various studies provide the least-cost strategies to target unelectrified regions, there is a need to better represent the conditions that often vary by country in SSA to enhance the relevance and effectiveness of the proposed solutions. Urbanisation and infrastructure systems evolve through complex, interdependent processes, where changes in land use, population distribution, and infrastructure access mutually reinforce each other. Such patterns are also shown to be particularly important in rapidly urbanising contexts [44]. Building on such an understanding, this study explicitly connects the interaction between urbanisation dynamics and electricity provision to capture the bidirectional feedback between settlement growth and infrastructure expansion. We contribute a new perspective on cost-optimal electrification planning that incorporates spatial analysis of urbanisation changes through a binomial logistic regression model to drive population growth and electricity demand in the OnSSET (Open-Source Spatial Electrification Tool) model. The paper addresses the inadequacy of existing spatial electrification models, such as OnSSET, in better representing evolving demographics and urbanisation patterns to improve the applicability of the findings. The scenario analysis includes assumptions from existing policies to better compare their effectiveness in supporting universal electrification. Fig. 2 shows the conceptual framework adopted in the study.

2. Research methods and data sources

2.1. Data collection and sources

Table 3 shows the data sources used in the electrification (OnSSET) and binomial logistic regression models.

2.2. Data processing

Data processing before fitting the regression model involved handling missing values, assessing predictors for correlation and multicollinearity, and handling class imbalances. Pearson's correlation coefficients were computed between all pairs of the predictor variables. Belsley collinearity diagnostics [58] were used to determine the strength of collinearity among the predictor variables.

The class distribution for the settlements raw dataset was rural (403,466) and urban (65), resulting in an imbalance ratio of 6207.1692. Synthetic Minority Over-sampling Technique (SMOTE) [59] with down-sampling of the majority sample (rural) was applied to handle the class imbalances in the dataset. For points in the minority sample, we find the nearest neighbours (k = 5), calculate the squared Euclidean distance, randomly pick one neighbour, and generate a synthetic data point along the line connecting the point and neighbour. The majority sample was down-sampled by randomly selecting indices in the majority sample. The target ratio was set to 1:5 (minority: majority). 80 % of the sample was used in training the regression model, with the remainder (20 %) used for validation.

2.3. Binomial logistic regression model for urbanisation prediction

A supervised machine learning approach was adopted to project future urbanisation trends. Specifically, a binomial logistic regression was used to create a relationship between the target binary variable (urban) and the input features; population density (P_D), electrified population (P_E), distance to major road (D_R), elevation (E), distance to water bodies (Rivers, Lakes) (D_W), distance to grid (D_G) and distance to urban areas (D_U). The natural logarithm form (logit) of the probability is given by the general equation (1) while the full logistic regression equation is given by equation (2).

$$logit(p) = log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7 \tag{1}$$

$$p = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 + \beta_7 x_7)}} \tag{2}$$

Where p is probability that the settlement is urban, β_0 is the intercept, x_1 to x_7 are predictor variables, and β_1 to β_7 are coefficients for the predictor variables. The model predictors were standardised using Z-score and the regression model was fit as a generalised linear model with a binomial distribution. Settlements were classified based on the order of highest probabilities of urbanisation. For the final year, settlement reclassification was capped at 50 %. The resulting regression model results were used in the OnSSET model (a Levelized Cost of Electricity Model) as illustrated in Fig. 3.

The changes to the OnSSET model [60] include urbanisation reclassification after each timestep. In addition, demand tiers and the

Table 1
Comparison of population growth rates and migration in satellite cities, major cities, and rural areas of Kenya.

	City	Distance from Nairobi (km)	County-level population growth rate		Net in-migration per 1000 population	
			1999–2009	2009–2019	2009	2019
Satellite cities	Ruiru	20	3	4	−1.13	72
	Kitengela	35	5.5	4.9	48.99	90.1
	Ngong	30	5.5	4.9	48.99	90.1
	Thika	40	3	4	−1.13	72
Major cities	Nairobi		4.1	3.4	30	52.3
	Kisumu		2.1	1.8	5.56	−9.58
	Mombasa		3.8	2.5	33.41	60.9
Predominantly rural (non-arid)	Bomet		0.5	1.9	−6.67	−34.09
	Kwale		2.8	2.9	−8.38	−10.47
	Tharaka Nithi		1.8	0.7	−27.16	−14.11

Table 2
Studies on electrification in Kenya and the greater Sub-Saharan Africa regions.

Region	Tool/Model	Limitations	Source
East Africa	OnSSET-LCOE	The model is uniformly applied across East Africa, overlooking regional differences in infrastructure, access, and socioeconomic conditions.	[35]
Kenya	Cost optimization model	Restricted to two technology options: Grid extension and SA PV systems.	[36]
Kenya	LCOE	Applies a 10 km buffer. It excludes the cost of connection borne by the electricity distributor.	[33]
SSA	OnSSET-LCOE using four financing scenarios	Generalises across SSA, assumes a 50 % electrification rate by 2025 for all countries.	[37]
Global	CGE, climate model, global transport model	Limited to the transport system, fails to address varying electrification needs in developing countries.	[38]
SSA	OnSSET-LCOE	Generalised assumptions on cost across SSA.	[39]
SSA	Financing business models	Generalises across SSA, overlooking regional differences in infrastructure, access, and socioeconomic conditions.	[40]
Kenya	OnSSET, OSeMOSYS	Uses coal and natural gas as technology options for the existing grid, which is not aligned with Kenya's existing energy mix (90 % renewable) or its commitment to achieve 100 % renewable energy use.	[41]
Kenya	LEAP, NEMO	It does not consider geography-specific electrification needs.	[42]
Kenya	OSeMOSYS, FlexTool	It does not consider geography-specific electrification needs.	[43]

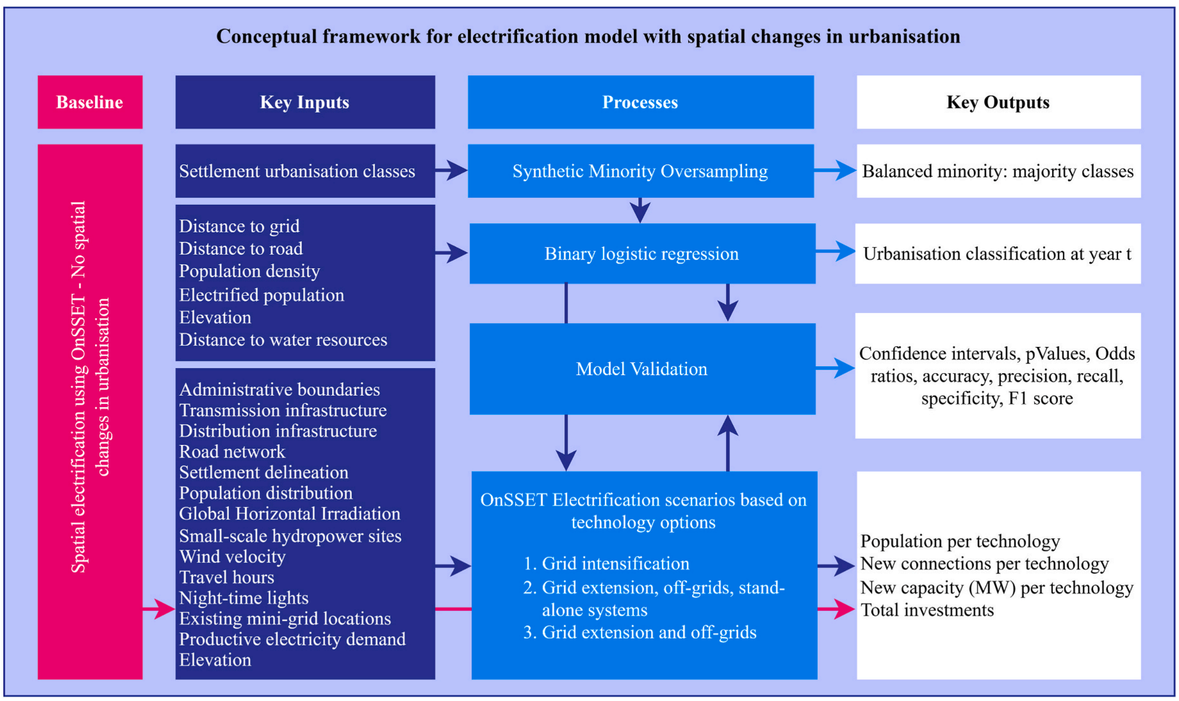

Fig. 2. Conceptual framework linking urbanisation and electrification planning. The framework combines a regression model of spatial urban growth with the OnSSET model to estimate the most cost-effective electrification pathways, capturing feedback between settlement expansion and electricity provision.

number of people per household for new urban settlements were adjusted at each timestep. The urban, satellite, and rural growth rates were set to 2.5 %, 4.5 %, and 1.8 %, respectively. For purposes of the analysis, a satellite region is defined as any region within 20–35 km of an existing urban area. The original OnSSET model retains the urban-rural classification of settlements, resulting in constant household demand and population growth rate for each settlement for the duration of the analysis. In contrast, the new model reclassifies settlements so that for new urban areas, household electricity demand increases, and the population growth rate reduces.

2.4. Electrification modelling with OnSSET

Three electrification scenarios are explored: a) grid intensification where new connections were through grid expansion, b) renewable energy potential where new connections were through the existing grid, stand-alone PV (SA PV), wind, hydro mini-grids, and PV mini-grids, and grid expansion, with priority going to the least cost option, and c) all technology options in scenario b excluding SA PV systems. In scenario a, SA PV and mini-grids were excluded from the model entirely. For each scenario, we compared the difference in including and excluding mini-grid interconnection to determine whether allowing mini-grids to be connected to the grid affects the total investments required in each scenario. A baseline scenario that excludes the spatial changes in urbanisation was also run for each scenario.

The scenarios for the research were selected based on the country's historically demonstrated focus on grid expansion to increase electricity access [4], Kenya's ambition to achieve a 100 % renewables target [9], and the increased recognition of the strategic role of stand-alone systems in reducing household electricity costs [7]. Table 4 shows the model parameters.

2.5. Sensitivity analysis

Taguchi main effect analysis was selected to efficiently minimise the runs required to establish the influence of key parameters on the model results. An orthogonal array of 128 runs was generated on Minitab using the parameters: grid connection cost (0.1–0.5 USD/kWh), hydropower

Table 3
Data inputs and their sources.

Layer	Model	GIS type	Source
Administrative boundaries	OnSSET	Polygon	[45]
Medium-voltage lines (existing)	OnSSET, Regression	Lines	[46]
Service transformers (existing)	OnSSET	Points	[46]
Substations	OnSSET	Points	[10]
High-voltage lines (existing)	OnSSET	Lines	[10]
High-voltage lines (planned)	OnSSET	Lines	[10]
Road network	OnSSET, Regression	Lines	[47]
Settlement delineation (clusters)	OnSSET, Regression	Polygons	[48]
Population distribution	OnSSET, Regression	Raster	[49]
Global Horizontal Irradiation (GHI) - Solar resource	OnSSET	Raster	[50]
Small-scale hydropower sites	OnSSET	Points	[51]
Wind velocity (m/s)	OnSSET	Raster	[52]
Travel hours (min or h)	OnSSET	Raster	[53]
Night-time lights	OnSSET	Raster	[54]
Existing mini-grid locations	OnSSET	Points	[46]
Productive electricity demand	OnSSET	Polygons	[55]
Water resources (rivers + lakes)	Regression	Lines	[56]
Elevation	OnSSET, Regression	Raster	[57]

capital cost (2000–6000 USD/kW), wind turbine capital cost (1000–5000 USD/kW), target urbanisation rate (40 %–60 %), urban growth rate (2 %–6 %), rural growth rate (4 %–8 %), and peri-urban (satellite) growth rate (1 %–5 %). The responses recorded in each run include the total capacity (MW) and total investments. The sensitivity analysis combined both regression model and OnSSET model.

3. Results and discussion

3.1. Regression model validation results

The class distribution after SMOTE and down-sampling was rural (32,175) and urban (6,500), with a ratio of 4.95. From a test sample of 7,735, the resulting classification matrix had 6248 true negatives (96.82 %), 205 false positives (3.177 %), 996 true positives (77.69 %), and 286 false negatives (22.31 %). The model had an overall accuracy of 93.65 %, with precision, recall, specificity, and F1 score of 83 %, 78 %, 97 %, and 80 % respectively. On the other hand, the unbalanced dataset resulted in a model with accuracy of 97.03 % with precision and F1 score of 0.54 % and 1.07 % respectively. This implies that the high accuracy in the unbalanced dataset is driven by the dominance of the majority class as the model is accurately predicting the majority class (Rural) and misclassifying the minority class (Urban). Thus, the balanced dataset model provided a better less biased distinction between classes.

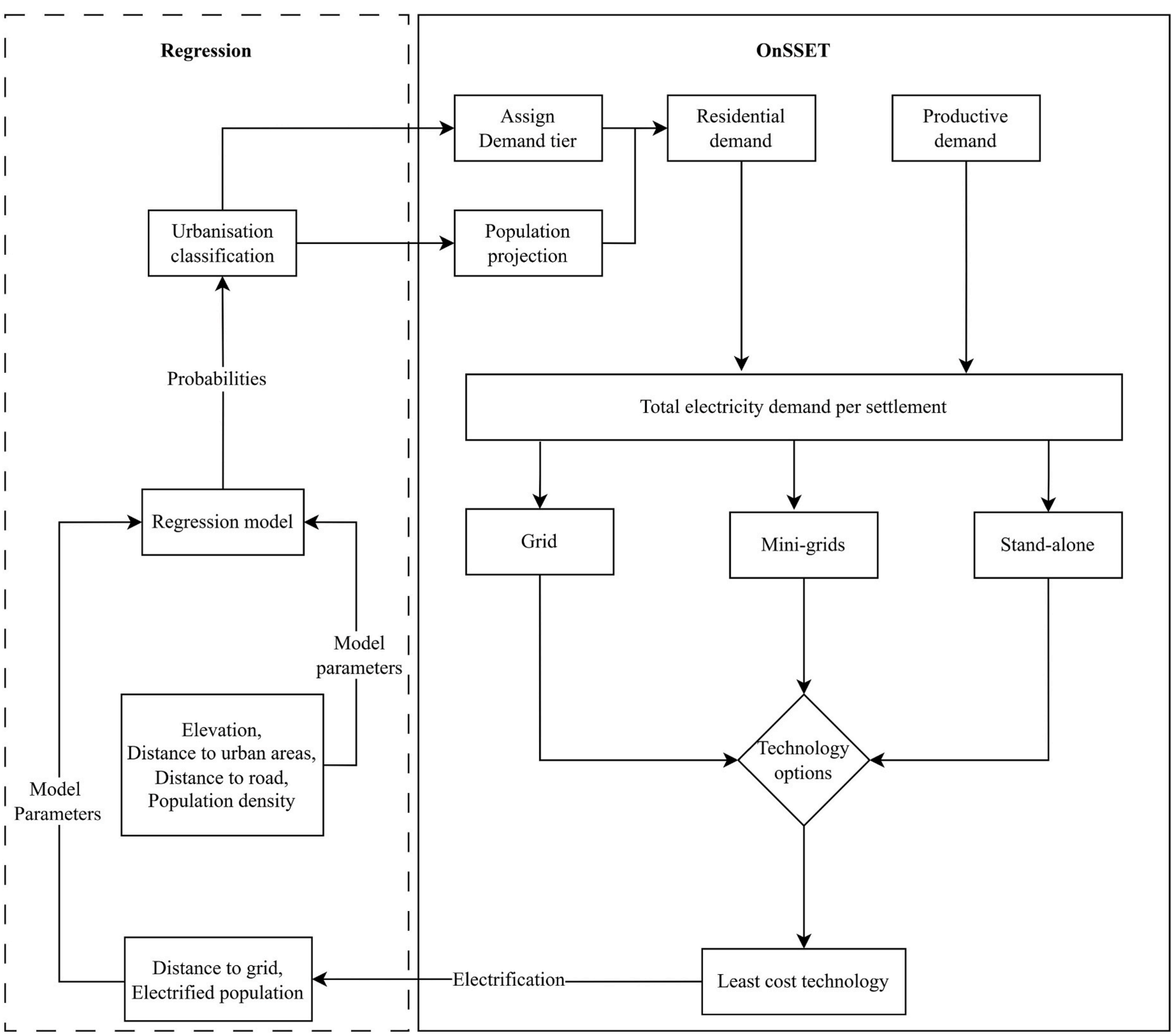

Fig. 3. OnSSET integration with Bayesian model for urbanisation projection.

Table 4
OnSSET Model parameters.

Variable	Value
Start year	2020
End year	2030
Intermediate year	2025
Urban target demand tier	4
Rural target demand tier	2
End year electrification rate target (%) [61]	100
Intermediate electrification rate target (%)	89.5
Buffer distance (km) for automatic intensification (scenarios b and c)	2.00
Discount rate	0.12
Start year population [15]	47,564,296
End year population [62]	57,811,161
Urban population at start year [63]	0.27
Urban population at end year [64]	0.50
Start year electrification rate [2]	0.715
Start year electrification rate (Urban) [2]	0.941
Number of people per household (Urban) [15]	3.00
Start year electrification rate (Rural) [2]	0.627
Number of people per household (Rural) [15]	4.00
Grid cost electricity USD/kWh [65]	0.12
Cost in USD/kW for capacity upgrades of the grid-connected power plants	1800.00
Transmission and distribution losses	0.16
Base-to-peak ratio	0.80
The additional cost per round of electrification (%)	0.10
Diesel price in USD/Litre	1.41
SA PV cost (USD/kW) under 20 W	1937.00
SA PV cost (USD/kW) 21–50 W	1860.00
SA PV cost (USD/kW) 51–100 W	1713.00
SA PV cost (USD/kW) 101–200 W	1372.00
SA PV cost (USD/kW) over 200 W	1162.00
Cost of MV lines in USD/km	25,000.00
Cost of LV lines in USD/km	15,000.00
Capacity of MV lines in kW/line	33.00
Capacity of LV lines in kW/line	0.24
Maximum length of LV lines (km)	0.50
Cost of HV lines in USD/km	120,000.00
Maximum distance that the grid may be extended using MV lines	50.00
Maximum new households that can be connected to the grid	No limit
Maximum generation capacity added to the grid in a year	No limit

3.2. Sensitivity analysis results

Table 5 and Fig. 4 summarise the effects on the model results for the factors: grid connection cost, hydropower capital cost, wind turbine capital cost, target urbanisation rate, urban growth rate, rural growth rate, and peri-urban (satellite) growth rate.

Effect size (Δ) column in Table 5 shows the difference between the two levels of each parameter when determining the capacity and total investments. Urban growth rate ranks first with the highest effect size, suggesting that it is the most sensitive factor with largest effect on the results. The grid connection cost, hydro capital cost, and wind capital cost have low effect size (close to zero), implying their effect is insignificant. As urbanisation rate and urban growth rate increased, the responses (capacity and total investments) increased as shown in Fig. 4. Conversely, as rural growth rate and peri urban growth rate increased, the total capacity and investments reduced.

Table 5
Summary of sensitivity analysis showing the relative influence of selected parameters on model results.

Factors	Effect size (Δ)		Sensitivity Rank	
	Capacity	Investments	Capacity	Investments
Grid connection cost	0	0	7	7
Hydro capital cost	0	0	6	6
Wind capital cost	1	0	5	5
Urbanisation rate	119	30	3	4
Urban growth rate	348	619	1	1
Rural growth rate	219	426	2	2
Peri-urban growth rate	84	137	4	3

3.3. Regression model results

Pearson's correlation results indicated minimal correlation between the predictor variables. There was weak positive correlation between; electrified population and population density, $r = 0.02$, $p < .01$; distance to major road and distance to water bodies, $r = 0.0386$, $p < .01$; and distance to grid and distance to urban areas, $r = 0.3691$, $p < .01$. The correlation statistics are shown in Table 6.

From Table 6, there was weak negative corelation between: electrified population and the distance to grid, $r = 0.0671$, $p < .01$; the distance to road and the electrified population, $r = 0.1376$, $p < .01$; and the population density and elevation, $r = 0.0687$, $p < .01$. Multicollinearity checks showed a condition index (condIdx) of less than 5, suggesting low multicollinearity. At condIdx 3.1188, the distance to urban areas and distance to major roads have moderately high variance proportions (0.7564 and 0.5606), suggesting moderate correlation. The respective variance proportions at different condition indices are shown in Table 7.

The logistic regression results revealed significant coefficients for population density ($t = 46.10$, $p < .01$), electrified population ($t = 51.443$, $p < .01$), distance to major road ($t = -3.32$, $p < .01$), elevation ($t = -7.8012$, $p < .01$), distance to water bodies ($t = -3.69$, $p < .01$), distance to grid ($t = -8.15$, $p < .01$) and distance to urban areas ($t = -21.533$, $p < .01$). The resulting regression model is illustrated in equations (3) and (4).

$$logit(p) = -0.20846D_G + 1.2218P_E - 0.45811D_U - 0.13544E - 0.07062D_R + 2.6344P_D - 0.06802D_W \tag{3}$$

$$p = \frac{1}{1 + e^{-(-0.20846D_G + 1.2218P_E - 0.45811D_U - 0.13544E - 0.07062D_R + 2.6344P_D - 0.06802D_W)}} \tag{4}$$

The distance to grid ($B = -0.21$), distance to urban areas ($B = -0.46$), elevation ($B = -0.14$), distance to major roads ($B = -0.07$) and distance from water bodies ($B = -0.07$) had a negative association with the dependent variable, suggesting an increase in these predictors reduced the likelihood that a settlement was urban. Conversely, the electrified population ($B = 1.22$) and population density ($B = 2.63$) had a positive association with the dependent variable, suggesting that an increase in the two variables increased the likelihood that a settlement was urban. The regression model was statistically significant ($p < .01$), indicating that the predictor variables sufficiently distinguished between urban and rural settlements. Table 8 shows the predictors' standard errors, test statistics, confidence intervals, and odds ratio.

3.4. Urbanisation reclassification results

Fig. 5(a) shows the urban settlements at the start year (2020), intermediate year (2025) and final year (2030), while Fig. 5(b) shows the distribution of key infrastructure, including mini-grids, major roads, substations, and development corridors [3].

The urbanisation trends in Fig. 5(a) reveal at least four distinct regions for discussion: the coastal region, central Kenya, western Kenya, and northern Kenya. In the central region, new urban settlements are concentrated along the major roads joining Nairobi (Point 1) to Meru County (Point 2). The favourable road infrastructure connecting trade towns such as Thika, Embu, Kerugoya, Muranga, Nyeri, and Meru may explain the pattern of urban settlements in central Kenya. The northern region (Marsabit, Isiolo, Mandera, Wajir and Samburu), despite being predominantly arid, had high probabilities of urbanisation. This is partly explained by several factors: cross-border trading activities, rapid population growth, new economic hubs, and infrastructure projects. In 2025, Kenya and Ethiopia (bordering Kenya to the north) signed a free trade agreement for up to 100 km in Kenyan territory and 50 km in

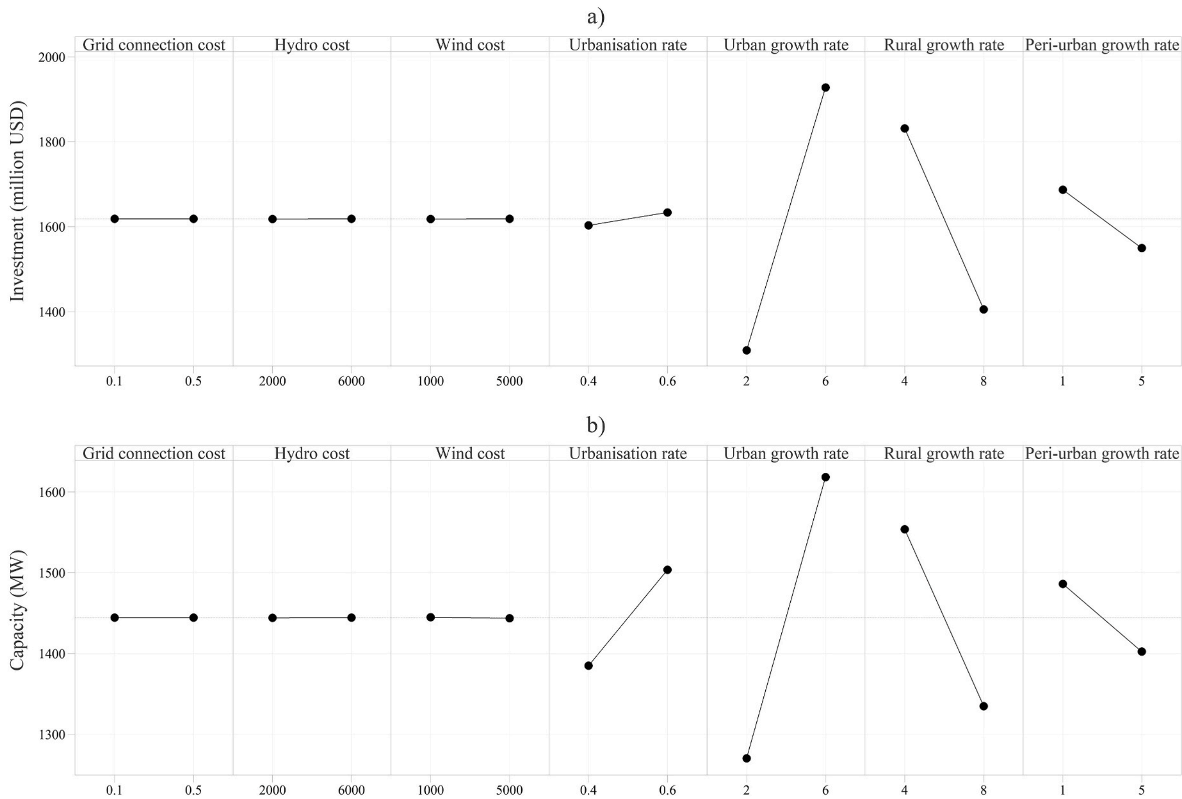

Fig. 4. Plot of average change in responses: 4a) change in total capacity (MW), 4b) change in total investments (million USD).

Table 6
Pearson's correlation statistics ($p < .01$).

	D_G	P_E	D_U	E	D_R	P_D	D_W
D_G	1*	−0.0671	0.3691	−0.1863	0.3605	0.1669	0.1104
P_E	−0.0671	1*	−0.0881	−0.015	−0.1376	0.02	0.0032**
D_U	0.3691	−0.0881	1*	−0.3266	0.307	0.0413	0.058
E	−0.1863	−0.015	−0.3266	1*	−0.1896	−0.0687	0.0339
D_R	0.3605	−0.1376	0.307	−0.1896	1*	0.1357	0.0386
P_D	0.1669	0.02	0.0413	−0.0687	0.1357	1*	0.0673
D_W	0.1104	0.0032**	0.058	0.0339	0.0386	0.0673	1*

**p = .0432, *p = 1.

Table 7
Collinearity test results.

sValue	condIdx	D_G	P_E	D_U	E	D_R	P_D	D_W
1.7946	1.0000	0.0236	0.0060	0.0297	0.0272	0.0302	0.0174	0.0306
1.0255	1.7499	0.1355	0.5777	0.0032	0.0259	0.0146	0.0095	0.0154
0.9343	1.9208	0.0204	0.0816	0.0162	0.0264	0.0051	0.7732	0.0237
0.8608	2.0848	0.3912	0.3017	0.0072	0.0537	0.0014	0.1799	0.0638
0.6932	2.5888	0.2118	0.0064	0.0695	0.0082	0.2631	0.0023	0.5599
0.5754	3.1188	0.0074	0.0077	0.7564	0.0000	0.5606	0.0176	0.0309
0.5496	3.2656	0.2100	0.0189	0.1177	0.8585	0.1250	0.0002	0.2757

Ethiopia [66]. The trade agreement, coupled with road and grid infrastructure projects, is likely to increase economic growth in the northern areas of Kenya. In addition to the increase in trading and economic opportunities, the northern region has maintained a rapid population growth that generally exceeds that of the capital, Nairobi. Between 2009 and 2019, Nairobi had a growth rate of 3.4 %, compared to Wajir (6.7 %), Marsabit (4.6 %), Isiolo (6.3 %), and Samburu (3.3 %) [15].

The coastal region's urbanisation trend showed an outward growth from the coastline, with settlements closer to the shoreline having higher probabilities of being urban. The counties in this region include Mombasa, Kwale, Kilifi, Tana River and Lamu. Regions closer to the shoreline benefit from economic opportunities due to the booming tourism industry, access to the port, and road infrastructure. The northern and coastal regions increased probability of urbanisation, are also supported by development corridor projects. Kenya, as shown in Fig. 5(b) has two key development corridors. The two corridors under Kenya's Vision 2030 have major infrastructure projects such as the "Lamu Port-Southern Sudan-Ethiopia Transport" (LAPSSET), Standard Gauge Railway (SGR), and the East Africa Railways Master Plan (2009) meant to connect Kenya to its neighbouring countries of Ethiopia, South

Table 8
Predictors' standard errors, test statistics, confidence intervals, and odds ratio.

	Estimate	SE	tstat	pValue	95 % CI		Odds ratio
					lower	upper	
D_G	−0.20846	0.02557	−8.1523	0	−0.2586	−0.1583	0.8118
P_E	1.2218	0.02375	51.443	0	1.1752	1.2683	3.3933
D_U	−0.45811	0.021275	−21.533	0	−0.4998	−0.4164	0.6325
E	−0.13544	0.017361	−7.8012	0	−0.1695	−0.1014	0.8733
D_R	−0.07062	0.021281	−3.3184	0.000905	−0.1123	−0.0289	0.9318
P_D	2.6344	0.057148	46.098	0	2.5224	2.7465	13.9355
D_W	−0.06802	0.01843	−3.6908	0.000224	−0.1041	−0.0319	0.9342

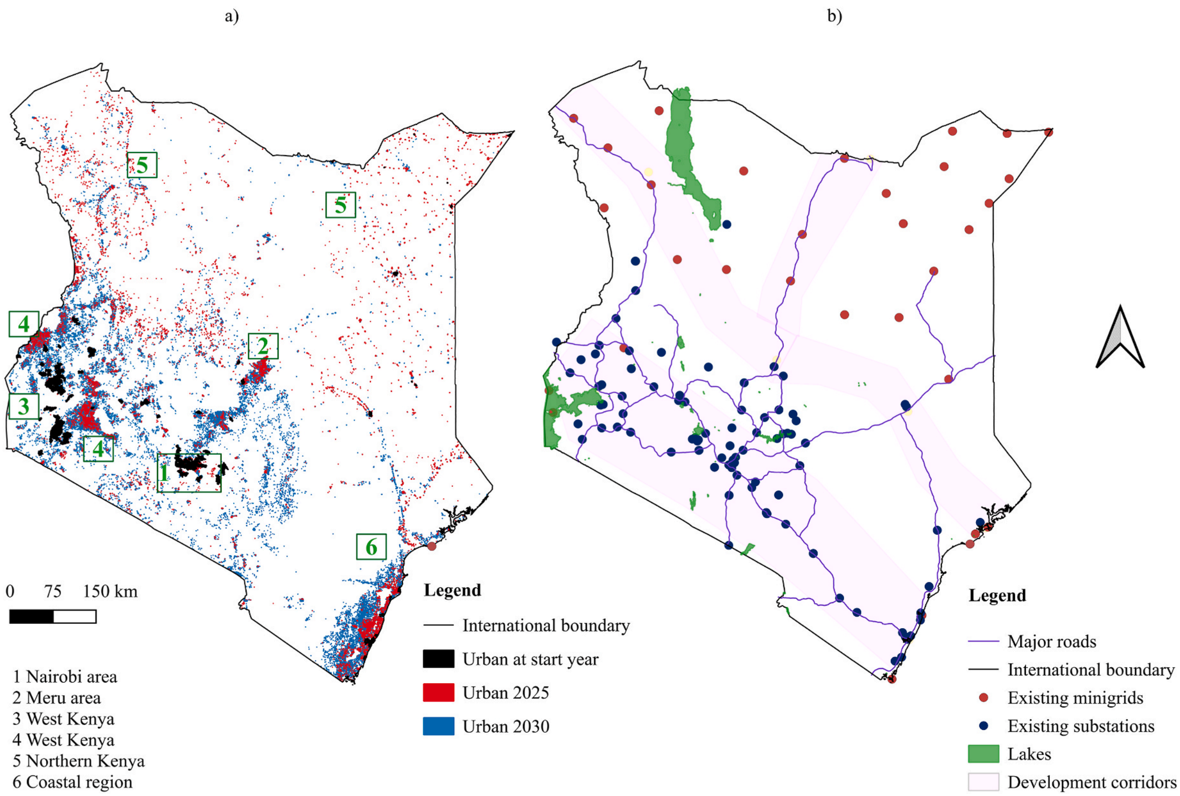

Fig. 5. Illustration of urban settlements and existing infrastructure: a) Urban settlements at start year, intermediate year and final year, b) location of mini-grids, substations, development corridors, and major roads.

Sudan, Uganda, and Tanzania to promote economic growth particularly in underserved regions [3].

To the west of Kenya, the settlements that had the highest probabilities (Point 4) were those near the border with Uganda (Busia town and part of Bungoma), and Kericho county and areas of Sotik and Konoin that border Kericho. The border town of Busia's high probability of urbanisation is partly explained by cross-border trade between Kenya and Uganda. Kericho, on the other hand, has in recent years experienced a rapid population increase following the adoption of devolved government. In addition, the county has had major road development linking Kipchimchim, Cherote, Ainamoi, and Muhoroni areas [67]. The existing urban settlements of Kisumu and Kisii are not likely to experience an increase in urban settlements in their vicinity as more of the population seeks areas with less urban congestion, land pressure, and lower costs of living.

3.5. Electrification scenarios

The three electrification scenarios were compared based on the total population per technology in the final year of analysis, the new connections for each technology, the capacity and total investments at the final year of analysis. Table 9 demonstrates this comparison against the change from the baseline (denoted by **Δ%)**.

As can be observed from Table 9, the grid intensification (scenario a) had the highest investment cost (8107.76 million USD), followed by renewable energy potential without SA PV (5191.07 million USD), with renewable energy potential (scenario b) having the least investment cost (1839.68 million USD). In terms of total capacity, grid intensification had the least capacity (692.01 MW), followed by renewable energy potential without SA PV (1327.65 MW), and renewable energy potential (scenario b) having the highest capacity requirements (1614.99 MW).

In scenario a, about 70 % (5,099,093) of total new connections (7,043,866) were through grid intensification. When all technologies, including grid intensification and SA PV, were included (scenario b), approximately 66 % (4,739,002) of the new connections were through SA PV. The remaining connections for scenario b were primarily through the existing grid (28 %) and MG PV (6 %). When SA PV was excluded as a technology option (scenario c), 72 % (5,076,431) of new connections were through MG PV.

When the model was allowed to connect mini-grids to the grid, this only affected scenario a's total investments. In scenarios b and c, grid extension is spatially limited as the model prioritised alternative

Table 9
Comparison of capacity, investment, new connections, and population per technology.

	Total population	Δ%	New Connections	Δ%	Capacity (MW)	Δ%	Investment (million USD)	Δ%
a) Grid intensification								
Existing grid	37,203,669	−21.65	1,944,773	−66.33	426.1	−79.25	994.82	−72.45
Grid extension	20,607,491	99.74	5,099,093	99.31	265.9	∞	7112.94	∞
SA PV	0	0.00	0	0.00	0	0.00	0	0.00
MG PV	0	0.00	0	0.00	0	0.00	0	0.00
MG Wind	0	0.00	0	0.00	0	0.00	0	0.00
Hydro mini-grid	0	0.00	0	0.00	0	0.00	0	0.00
Non-electrified	0	0.00	0	0.00	0	0.00	0	0.00
Total	**57,811,160**	**0.02**	**7,043,866**	**−15.48**	**692.011**[a]	**−66.30**	**8107.76**[a]	**124.55**
b) Renewable energy potential								
Existing grid	37,270,742	−21.51	1,966,450	−65.95	433.39	−78.89	1005.55	−72.15
Grid extension	3,571	151.66	964	146.55	0.04	∞	0.05	∞
SA PV	18,740,468	90.23	4,739,002	86.03	673.53	110.80	755.25	142.80
MG PV	1,793,741	280.31	405,085	2804.2	506.86	4197.4	77.4	3533.80
MG Wind	1799	234.39	477	258.65	1.11	138.51	1.21	132.69
Hydro mini-grid	837	−27.47	230	−20.14	0.06	−26.69	0.21	−40.00
Non-electrified	0	0.00	0	0.00	0	0.00	0	0.00
Total	**57,811,161**	**0.00**	**7,112,208**	**−14.70**	**1614.99**[b]	**−32.29**	**1839.68**[b]	**−53.13**
c) Renewable energy potential without SA PV								
Existing grid	37,231,987	−21.59	1,950,211	−66.23	424.17	−79.34	992.93	−72.50
Grid extension	3,167	−35.35	769	96.68	0.04	∞	0.05	∞
SA PV	0	0.00	0	0.00	0	0.00	0	0.00
MG PV	20,551,307	100.29	5,076,431	99.50	902	146.17	4160.09	58.45
MG Wind	1799	245.96	467	264.84	1.03	305.18	1.19	260.61
Hydro mini-grid	22,898	−61.65	5501	−60.32	0.42	−55.26	36.82	−54.95
Non-electrified	0	0.00	0	0.00	0	0.00	0	0.00
Total	**57,811,160**	**0.00**	**7,033,379**	**−15.61**	**1327.65**[b]	**−45.16**	**5191.07**[b]	**−17.84**

[a] Allowing mini-grids to be connected to the grid increased values to 8842.35 million USD for investments and 857.91 MW for capacity.
[b] Allowing mini-grids to be connected to the grid did not affect this value.

technologies for electrification. In contrast, scenario a has forced grid expansion, meaning the grid eventually extends to locations with mini-grids, leading to some mini-grids being interconnected to the grid.

The largest change from the baseline is observed in the grid intensification scenario, where capacity requirements were reduced by 66.30 % and investments increased by 124.55 %. The maximum population in an urban settlement in the baseline scenario was about 6.7 million, compared to alternative scenarios at a maximum of about 2 million. Suggesting that in the baseline scenario, as the population increases within the urban settlements (established earlier as being a minority class at start year), if the target population at the end year is high, then the few urban settlements will carry the bulk of the country's additional population. Since the existing urban areas are likely already calibrated as grid-connected at the start year, then the additional population is also added to the existing grid. In the alternative scenarios, the population is calibrated to increase and reclassify areas; hence, the population increase is not concentrated in the minority class settlements. Consequently, settlements that were initially calibrated to be grid-connected at the start year (likely also urban) have settlements around them also increase in population and urbanisation, leading to either the need for grid extension (grid intensification scenario) or the use of other least cost technologies (for scenarios b and c) for new connections.

Fig. 6 illustrates the spatial distribution of the least-cost technologies

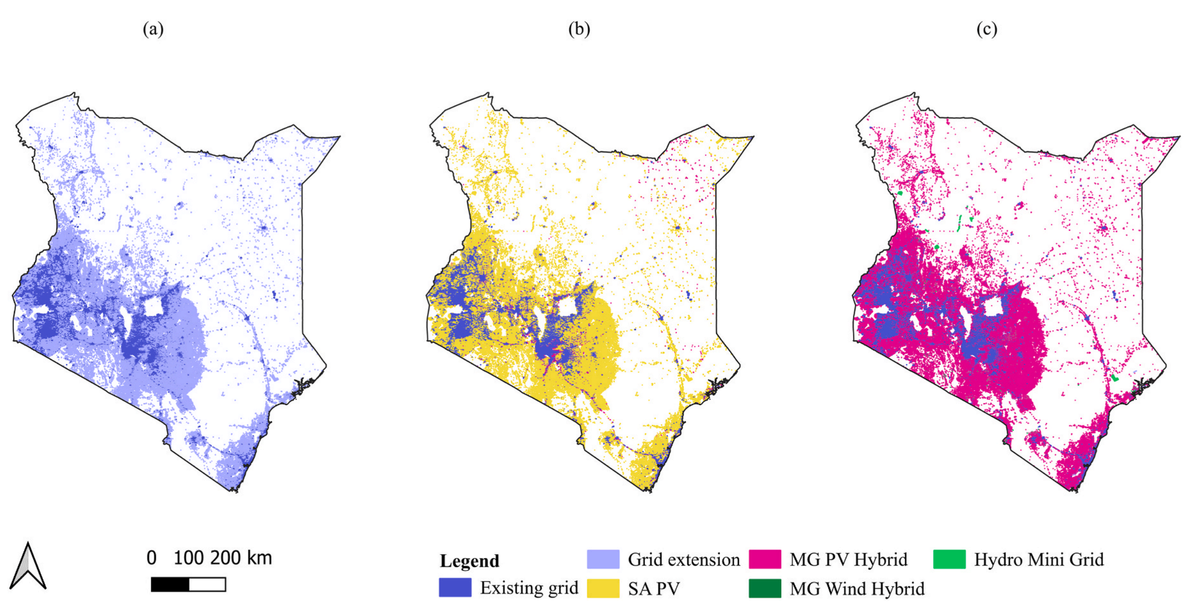

Fig. 6. Spatial distribution of least cost technologies by scenario: a) Grid intensification, b) Renewable energy potential, c) Renewable energy potential without SA PV.

in each scenario.

Prioritising grid extension (a) and excluding stand-alone PV systems (c) resulted in investment costs approximately five times and three times higher than scenario b, respectively. This is partly explained by falling technology costs, in particular batteries and solar panels.

The results of this study align with previous studies [33,36,37,39] that suggest stand-alone systems are crucial to minimising the cost of electrification. Kenya's policies and strategies, including the Kenya National Electrification Strategy, Vision 2030, last-mile connectivity and KOSAP show a strong commitment to achieving universal electrification by 2030. It is, however, imperative that the shortcomings of the policies are addressed to ensure better planning to target underserved regions. For instance, the Kenya National Electrification Strategy had the ambitious target of attaining 100 % electrification rates by 2022. Despite the strong focus on universal electrification, this strategy had a heavy dependency on grid connection with limited consideration of off-grid and stand-alone solutions. Similarly, the Vision 2030 and the last-mile connectivity program have a preference for grid extension. Moreover, Vision 2030 overemphasises large-scale projects, which may undermine the use of stand-alone systems. Despite the balanced focus between urban and rural settlements in the last-mile connectivity program, the project had minimal consideration of the affordability of electricity, resulting in grid expansion to rural areas but with minimal use of electricity. This pattern of non-consumption or low electricity consumption can be partly explained by rising electricity prices. Kenya has maintained an increase in its retail electricity prices [68] despite the assumption that renewable capacity would have lower costs than fossil fuel-fired electricity [69], which would translate into lower costs for the consumer. Between 2016-2020 and 2020–2024, for the 50 kWh consumption category, electricity prices per unit rose by 48 % and 68 %, respectively. Similarly, the prices rose by 34 % and 35 % in the 200 kWh consumption category [68,70]. This trend in electricity prices is counterproductive to the objectives of ensuring affordable and sustainable energy.

KOSAP, on the other hand, emphasises off-grid and stand-alone solutions in underserved regions [7], with the drawback being challenges in scalability due to limited grid integration. However, the new Energy (Net Metering) Regulations (2024) allow domestic, commercial, and industrial consumers to feed surplus power to the grid. With this regulation, the country will likely experience a further increase in the adoption of net-metering systems. Contrary to the previous national electrification strategy, the Net-Metering regulations empower domestic and commercial consumers and industrial entities to adopt stand-alone systems. As more domestic and commercial consumers opt to connect to the grid, grid management becomes more complex. In the absence of a grid management strategy, the existing grid is likely to face further instability from the increase in intermittent supply, challenges in balancing supply and demand, and voltage fluctuations. This may compound the pre-existing problems of grid reliability issues [5].

As part of the strategy for Vision 2030, Kenya also launched the Nuclear Strategic Plan 2023–2027 to guide the introduction of nuclear power into Kenya's energy mix. In Kenya's strategic plan, nuclear power is crucial to enhancing energy reliability, given its stable baseload power. However, nuclear requires high capital investment and has environmental, waste management, and safety concerns [71]. In the context of this paper, considering the proposed location for Kenya's nuclear plants is along the coastal region, the immediate benefits of the technology to the underserved areas, such as northern Kenya, are uncertain. Introducing nuclear to the energy mix suggests a further focus on the grid or centralised generation, which presently relies on aged grid infrastructure marred by high transmission and distribution losses [4].

While this study offers valuable insights into cost-optimal electrification, the robustness of the results is limited by the assumptions applied in approximating key parameters, the quality and uncertainties of input data, and assumptions about population growth rates and urbanisation. The OnSSET model does not explicitly account for future changes in infrastructure expansion, technology costs, or policy interventions, and its scope is limited to the technologies considered in this analysis. Similarly, the logistic regression model, while effective for capturing broad spatial trends, has limited ability to capture non-linear or dynamic feedback between urbanisation and infrastructure development. Although the proposed approach to projecting the spatial urbanisation trends for cost-optimal electrification planning may be generalised across Sub-Saharan Africa, the relevance of specific key predictors and their influence on the urbanisation dynamics may vary by country.

4. Conclusion and policy recommendations

This paper set out to identify the least cost strategy to attain universal electricity access in Kenya by 2030 while factoring in the changes in urbanisation and the corresponding effect on residential electricity demand. Four regions: the coastal region, central Kenya, western Kenya, and northern Kenya, have the highest probabilities of urbanisation, a trend explained by their proximity to existing urban settlements and infrastructure projects such as roads, railways, and electricity networks. Electrification scenarios prioritising off-grid ($5.2 billion) and stand-alone solutions ($1.8 billion) significantly reduce the required investment compared to scenarios prioritising grid extension ($8.1 billion).

This paper highlights that while Kenya's policies have maintained a strong commitment to universal electricity access, the implemented policies have, in most cases, been characterised by heavy dependence on grid expansion, or a strong focus on large-scale projects, as in Kenya's Vision 2030, which undermines the potential benefits from stand-alone systems.

This paper suggests a hybrid approach factoring in the trade-off associated with grid expansion and stand-alone systems. The existing policies and strategies fail to consider the impact of grid expansion on the affordability of electricity to households. Ultimately, the adoption of stand-alone systems may be cheaper for both the government and the consumer as these systems are immediate solutions that can reduce pressure on the existing grid, which is marred by reliability issues from ageing infrastructure. In addition, rising electricity costs have proven to be a barrier for low-income households. Policy changes related to financial and regulatory mechanisms such as subsidies and incentives can encourage the adoption of stand-alone systems, reducing the total investments required for universal electricity access.

There is also a need to adopt a robust grid management strategy for the existing grid and any planned expansion activities to reduce transmission and distribution losses. With fewer losses, the country will reduce the required total generation capacity and potentially minimise costs for connected households. Future research may build on how the balance between grid expansion and decentralisation impacts the investment requirements, efficiency, and the electricity market.

CRediT authorship contribution statement

Cynthia Omondi: Conceptualisation, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualisation, Project administration. Francis Njoka: Supervision, Resources, Writing – review & editing. Francesco Tonini: Supervision, Resources, Writing – review & editing. Edo Abraham: Supervision, Resources, Funding acquisition, Writing – review & editing.

Authors' declaration

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of competing interest

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2025.102015.

Abbreviations

CGE	Computable General Equilibrium
ETIP	Kenya Energy Transition and Investment Plan
KNES	Kenya National Electrification Strategy
KOSAP	Kenya Off-Grid Solar Access Project
LEAP	Long-range Energy Alternatives Planning
LCOE	Levelized Cost of Electricity
MG	Mini-grid
MVA	Megavolt-amperes
MW	Megawatt
NEMO	Next Energy Modelling system for Optimization
OnSSET	Open-Source Spatial Electrification Tool
OSeMOSYS	Open-Source energy Modelling System
SA PV	Stand Alone Photovoltaic
SMOTE	Synthetic Minority Over-sampling Technique
SSA	Sub-Saharan Africa

Data availability

All data supporting the findings of this paper that are not subject to third party terms and conditions have been cited at relevant sections of the paper and can be accessed from the cited sources.

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