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https://doi.org/10.1088/1748-9326/abc7de

PUBLISHER

IOP Publishing Ltd

VERSION

VoR (Version of Record)

ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

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To cite this article: Nandi Moksnes *et al* 2017 *Environ. Res. Lett.* **12** 095008

IOP Publishing Environ. Res. Lett. 15 (2020) 129501 https://doi.org/10.1088/1748-9326/abc7de

Environmental Research Letters

OPEN ACCESS

RECEIVED
30 October 2020

ACCEPTED FOR PUBLICATION
5 November 2020

PUBLISHED
11 December 2020

CORRIGENDUM

Corrigendum: Electrification pathways for Kenya–linking spatial electrification analysis and medium to long term energy planning (2017 *Environ. Res. Lett.* 12 095008)

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Abstract

We have identified input values that were not harmonized with the paper and have therefore submitted this corrigendum. *Qualitatively, there are no major differences between the two versions, and the insights generated are unchanged.* However, part of the results, figures and discussion needed to be updated based on the new findings. We present those in the form of a corrigendum. In the model runs there were input parameters that were not harmonized with the published paper as seen in annex in table 1. Therefore, to amend the incurred values, we have re-run the model and updated the following sections of the paper.

In the first paragraph of the Abstract (page 1), electrified population (%) were incorrectly reported. The corrected sentence is:

> However, in case of the low demand scenario high penetration of stand-alone systems is evident in the country, reaching out to approximately 51% of the electrified population.

In the fourth paragraph (page 3) the demand from the Ministry of Energy and Petroleum projection is industry demand. The corrected sentence is:

> For the industry grid demand modelled in OSeMOSYS the projected demand follows the Ministry of Energy and Petroleum Kenya projection from '*Development of a Power Generation and Transmission Master Plan, Kenya*'.

In the fourth paragraph (page 3) the demand deducted from the projection is the total domestic demand. The corrected sentence is:

> The total domestic demand was deducted from the projected demand to avoid double counting the capacity need as seen in figures 2 and 3.

Figures 2 and 3 has therefore been updated to these changes. The corrected figures are:

The current electrification status in figure 4 is updated due to the initial population start was incorrect, and therefore more settlements are connected. The corrected figure is:

On page 6 the grid cost in the first paragraph in 3.1. Low demand scenario should be 0.074 USD kWh^{-1}. The corrected sentence is:

> From the Low demand scenario, the optimization from OSeMOSYS gives a grid cost at 0.074 USD kWh^{-1} which is iterated to OnSSET.

Figures 7–9 are updated based on the new model runs. The corrected figures are:

On page 6 the second paragraph in section 3.1 is updated with stand-alone share to 51% and the range of LCOE is 0.074–0.28 USD kWh^{-1}. The corrected paragraph is:

> For the residential electrification optimization, the low demand of 43.8 kWh/capita for rural demand and 423.4 kWh/capita for urban displays a split by technologies with a high share of stand-alone solutions (51%) as seen in figure 8. The preferred stand-alone technology is solar PV in remote areas. As the demand is low in the rural areas the proximity to the grid will in most cases still not lead to a grid connection (only

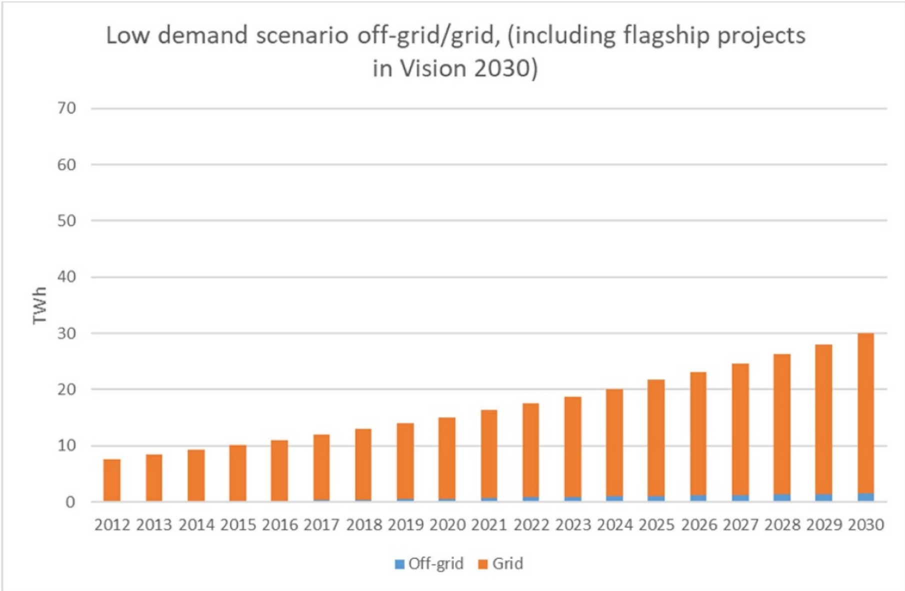

Figure 2. Low demand scenario off-grid/grid demand for Kenya.

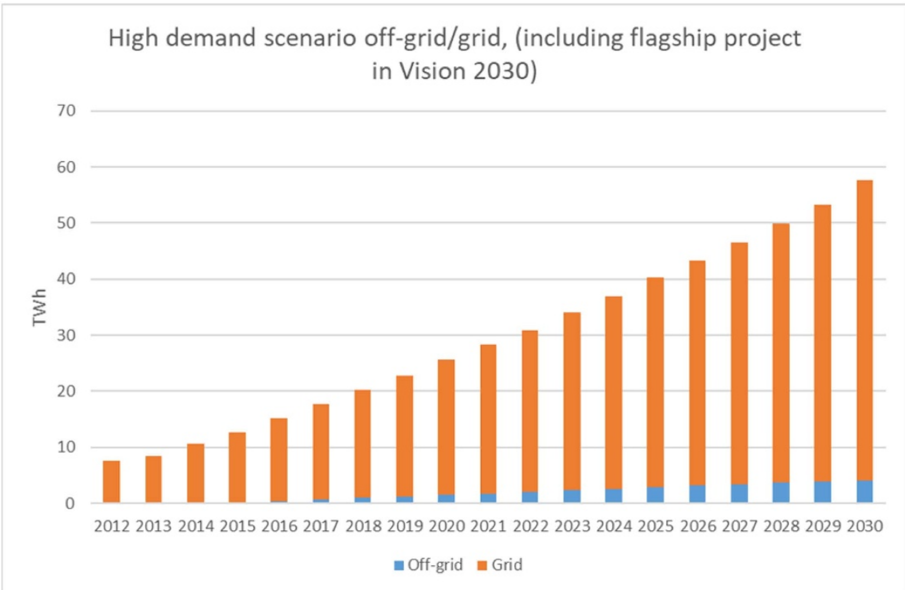

Figure 3. High demand scenario for Kenya.

49% will be grid connected in 2030). The LCOE for the OnSSET analysis ranges between 0.074 USD kWh^{-1} and 0.28 USD kWh^{-1} as seen in figure 9, where the existing grid have the lowest cost at 0.074 USD kWh^{-1} and the stand-alone in the rural areas have a higher LCOE.

On page 6 the fourth paragraph in section 3.1 the investment cost is updated to 22.1 billion and the transmission share is 33%. The corrected sentence is:

The investment costs related to the low electrification scenario amounts to 22.1 billion USD, as seen in table 4, where transmission cost represents 33% of the total discounted cost from 2012 to 2030 including the planned grid by KENTRACO of 5666 km and the Last Mile project connecting 1.2 million people.

Table 4 is updated based on the new model runs. The corrected table is:

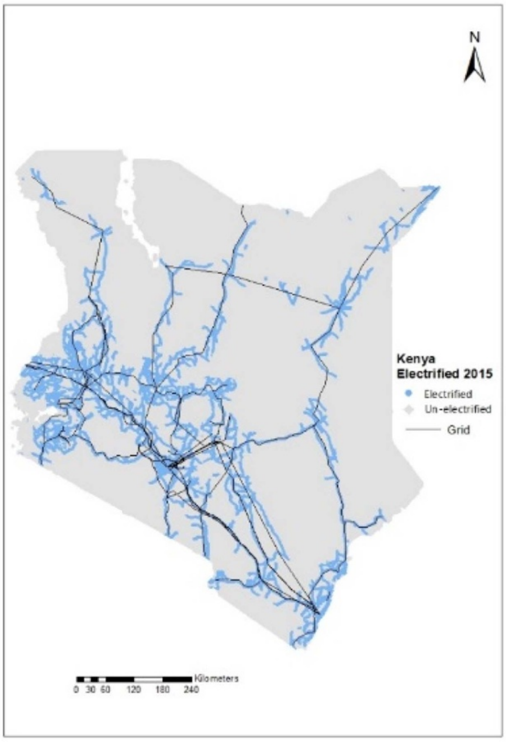

Figure 4. Electrification status and KETRACO existing transmission lines (GEOFABRIKK, 2016) (Kenya Electricity Transmission Company KETRACO, 2016).

Table 4. Total discounted investment cost for low scenario 2012–2030.

		MUSD
Transmission	3.4 GW HV transmission, and 10 045 914 new connections	7252
Mini grid		–
Stand alone	34 206 181 people	2618
Power plants (including fuel cost and O&M)	5 GW	12 279
SUM (MUSD)		22 149

On page 6 section 3.2 in the second paragraph the grid cost correct value should be 0.062 with the range 0.062–0.28 USD kWh^{-1}. The corrected paragraph is:

> For the high demand scenario, the optimization from OSeMOSYS gives slightly lower grid cost compared to the low demand scenario at 0.062 USD kWh^{-1}. The cost optimal solution for the residential electricity demand (423.4 kWh/capita for rural and 598.6 kWh/capita for urban) has a much higher share of grid connections and mini-grid solutions as compared to the low scenario as seen in figure 11. The LCOE for the geospatial cost optimal solution ranges between 0.062 USD kWh^{-1} and 0.28 USD kWh^{-1} as seen in figure 12 where lower range is where the demand is high per settlement and is situated close to the grid.

Table 5. Total discounted investment cost for high demand scenario 2012–2030.

		MUSD
Transmission	7.53 GW HV transmission and 36 880 916 new connections	16 331
Mini grid	653 191 people	540
Stand alone	6 717 988 people	5008
Power plants (including fuel cost and O&M)	9.5 GW	18 998
SUM (MUSD)		40 877

The model runs for the high demand scenario are updated and for figures 10–12 the corrected figures are:

On page 7 the first paragraph the transmission share and investment cost is updated to 40% resp. 40.9 billion USD.

> For the high energy demand scenario, the costs for both the OnSSET and OSeMOSYS model amounts to 40.9 billion USD where the transmission costs represent 40% of the costs as seen in table 5.

Table 5 is updated according to the results from the high demand model runs and the corrected table is:

In section 3.3 on page 7 the corrected paragraph is updated with an additional hydro technology in the low discount rate scenario. In addition coal was omitted in the high discount rate scenario. The corrected paragraph is:

> An increased discount rate will favour power production with a low capital cost such as natural gas. When decreasing the discount rate from 9.8% to 5.75% the electricity generation will favour technologies with a higher capital cost which in this case shifts to geothermal, hydro and solar utility but the shift is not as significant as seen for the 18% discount rate.

The corrected figure 13 is:

On page 7–8 in the last/first paragraph the LCOE is updated to 0.062 and 0.074. Furthermore the number of connections and technology shift is updated. The corrected paragraph should be:

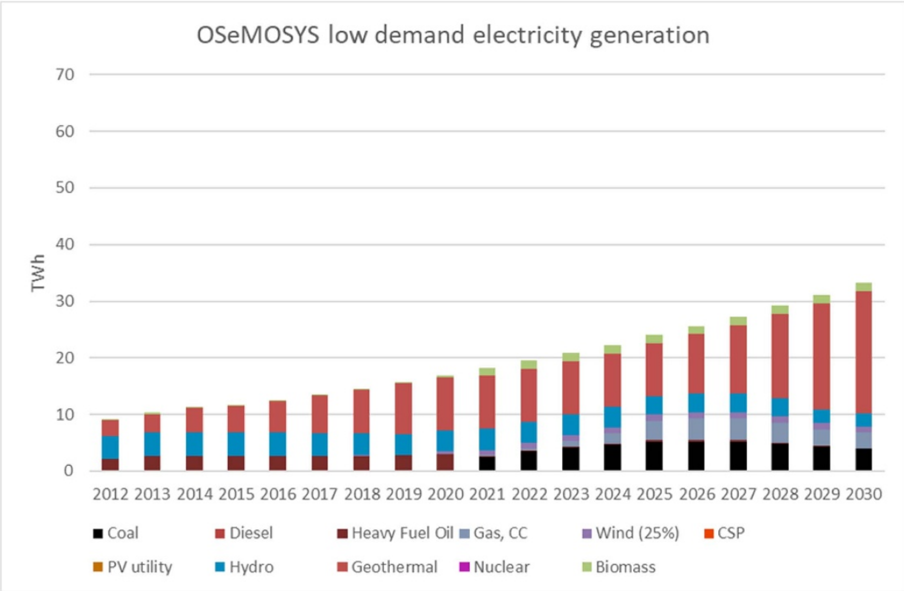

Figure 7. Electricity generation for grid demand, low scenario.

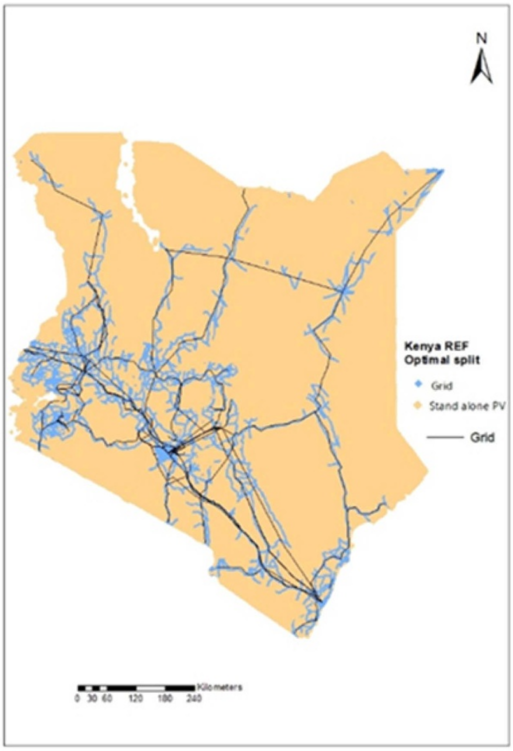

Figure 8. OnSSET technology split low demand.

Figure 9. LCOE for low demand.

The changes in technology mix for both scenarios is displayed in figure 14 where the grid cost changes from 0.125 USD kWh^{-1} to 0.074 USD kWh^{-1} and 0.062 USD kWh^{-1}. The total grid connections are increased by 2.3 million people in the high demand scenario in favour of Hydro and PV, whereas in the low demand there are only small shifts from hydro and PV to grid.

The corrected figure 14 is as follows:

On page 9 first paragraph the number of connections is updated as well as the LCOE. The corrected sentence should be:

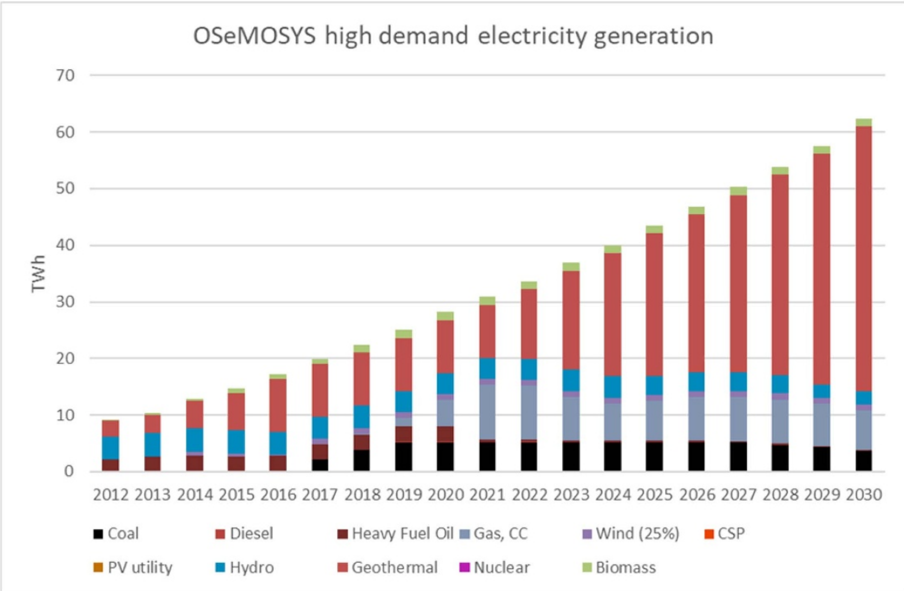

Figure 10. Electricity generation for grid demand, high scenario.

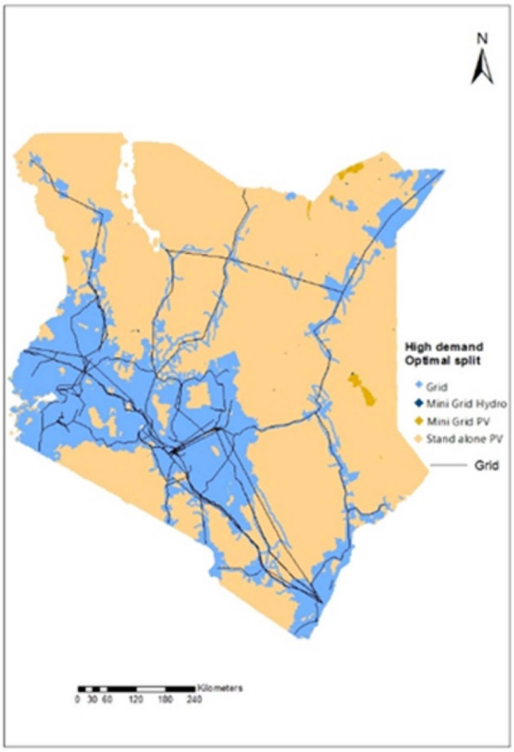

Figure 11. OnSSET technology split high demand.

Figure 12. LCOE for high demand.

Based on the sensitivity analysis a shift from 0.125 USD kWh^{-1} to 0.062 USD kWh^{-1} would imply 2.3 million more people connected to the grid for the high demand scenario but no major difference in the low demand scenario.

On page 9 in the second paragraph the grid LOCE and energy demand increase (TWh and %) is update based on the model runs. The corrected paragraph should be:

> The change of demand from a grid cost at 0.125 USD kWh^{-1}

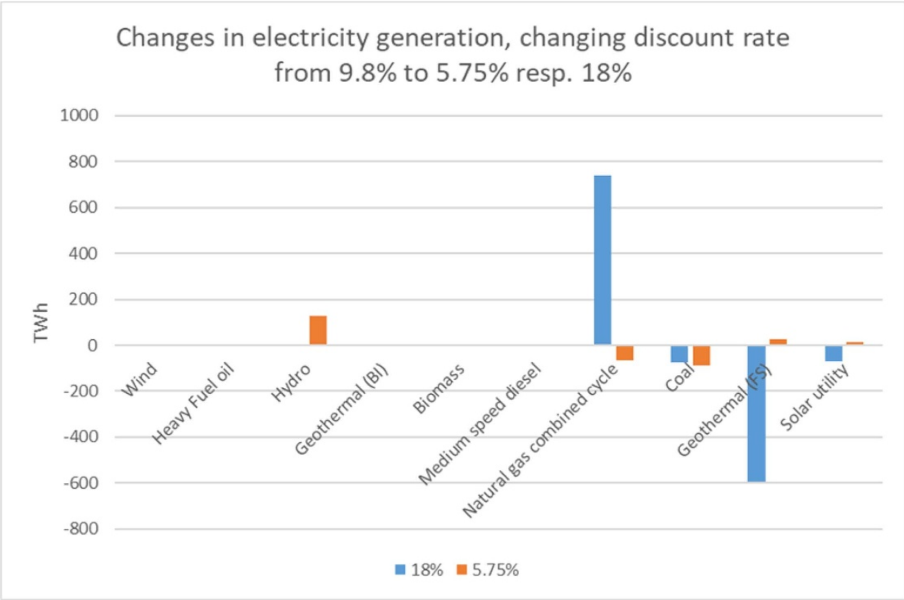

Figure 13. Changes in electricity generation when changing from 9.8% to 18% and 5.75% for high demand scenario.

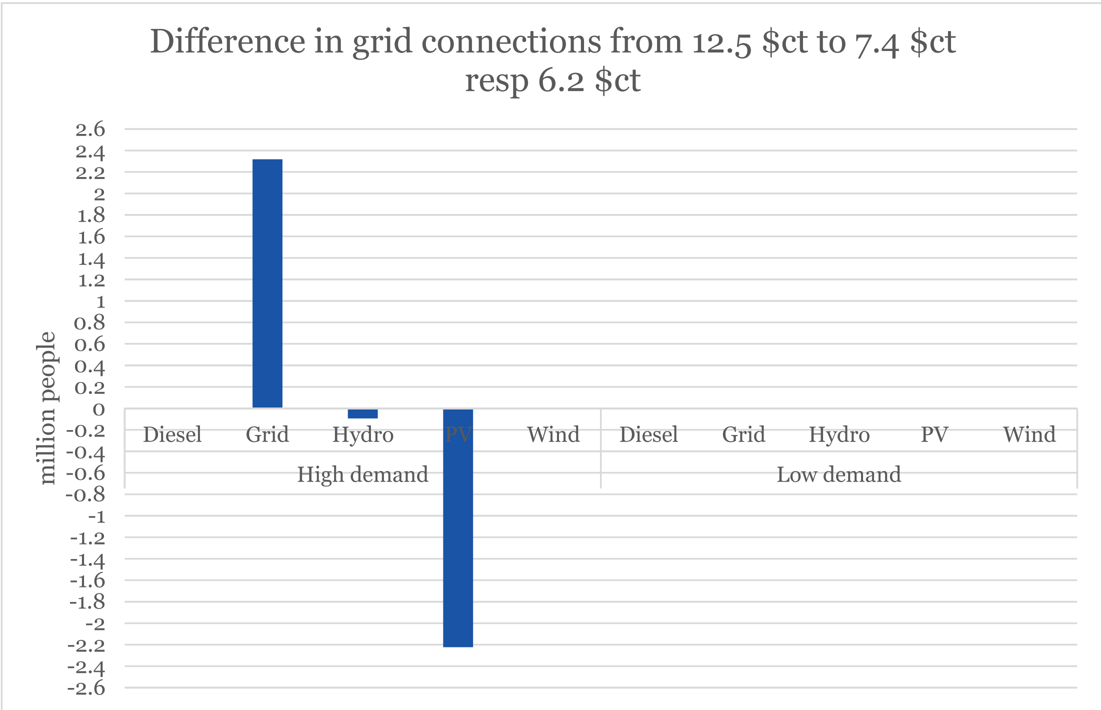

Figure 14. Changes in technology when decreasing the grid cost from 0.125 USD kWh^{-1} to 0.074 USD kWh^{-1} respectively 0.062 USD kWh^{-1} for high and low electricity demand.

to 0.074 USD kWh^{-1} and 0.062 USD kWh^{-1} would imply with no change in the low demand and an increase of 0.74 TWh for the high demand scenario in 2030. Looking at the total grid demand for the high scenario, 0.74 TWh represents a 1.3% increase of demand in 2030.

In appendix clarifications has been made to table A that the capacity factor is dynamic in the OnSSET model runs. Furthermore, the diesel price is harmonized with OSeMOSYS model runs. The corrected table A is:

In table C a duplicate Transmission and distribution line was removed. The updated table C is:

In table D a duplicate PV utility row was removed. The updated table D is:

Table A. Technical performance and cost for 2015, OnSSET.

Parameter	Capital cost (USD kW^{-1})	O&M ($ kW^{-1})	Fuel cost (USD MWh^{-1})	Capacity factor	Efficiency
PV stand-alone + Li-ion battery (1688 USD kW^{-1})	1633 + 1688 = 3321	10		Dynamic	–
Wind (capacity factor 20, 30, 40%) + Li-ion battery (1688 USD kW^{-1})	2214 + 1688 = 3902	49		Dynamic	–
Diesel generator, Stand alone	937.85	93.4 (assumed 10% of capital cost)	85	50%	28%
Diesel generator Micro grid	721.4	72.1 (assumed 10% of capital cost)	85	70%	33%
Mini grid PV + Li-ion battery (1688 USD kW^{-1})	1363 + 1688 = 3051	8		Dynamic	–
Mini hydro	2902	58 (assumed 2% of capital cost)		50%	–
Transmission distribution HV/MV/LV	92 823/9000/5000 per km				81.8%

Table C. Technologies efficiencies modelled.

Technology	Efficiency
Coal steam cycle	35%
Medium speed diesel/Heavy fuel oil combined cycle	45%
Geothermal	10%
CSP	15%
PV	16%
Nuclear light water	36%
Biomass, bagasse	33%
Natural gas combined cycle	55%
Transmission and distribution	81.8% increase to 85%

Table D. Technologies investment cost, fixed cost, variable cost and total max capacity.

Technology	Investment cost (USD kW^{-1})	Fixed cost (USD kW^{-1})	Variable cost (MUSD TWh^{-1})	Total max capacity (GW)
Geothermal	Binary: 5049 Flash steam: 3787	Binary: 63 Flash Steam plant: 63	Binary: 24.84 Flash Steam plant: 9	Binary: 3.285 Flash steam: 6.715
Wind	2044 (2015)/2214 (2030)	50	19.98	See section 3.4.4 in (Moksnes, 2016)
Heavy fuel oil combined cycle/Medium speed diesel	1678	62.5	9	–
Hydro river run off <10 MW	2902	2.05	4.464	0.5
Hydro dam <30 MW	3409	1.39	4.104	0.55
Hydro dam >30 MW	3078	1.39	4.104	1.49
PV utility	2133 (2015)/1143 (2030)	4.2	0 (included in fixed cost)	See section 3.4.4 in (Moksnes, 2016)
Biomass CHP (Bagasse)	2181	27.7	9.252	0.192
Natural gas Combined cycle	770	31	1.8	Max 0.54 annually earliest 2018
Coal single cycle	2903	69	4.608	Max 0.9 annually earliest 2016
Nuclear light water	6164	0 (Included in variable cost)	15.984	Earliest date 2023 1.2 GW
Concentrated solar power, solar tower with storage	7381 (2015)/3508 (2030)	0 (Included in variable cost)	40	See section 3.4.4 in (Moksnes, 2016)
Transmission	112	0	0	–
Distribution	16	0	0	–

Annex

Table 1. Difference in key input/output between initial submission and corrigendum.

Corrected values	Published paper	Corrigendum (harmonized with paper)	Difference	Unit
Population start (OnSSET)	32 527 000	46 050 302	13 523 302	People
Diesel price (OnSSET)	0.577	0.850	0.273	USD l^{-1}
Wind MG (OnSSET)	3732	3902	170	USD kW^{-1}
PV MG (OnSSET)	4101	3051	−1050	USD kW^{-1}
PV SA (OnSSET)	5088	3321	−1767	USD kW^{-1}
SA diesel (OnSSET)	70%	50%	−0.2	Capacity factor
Demand in OSeMOSYS for high demand	Without flagship	With flagship demand		
Demand for residential was not adjusted in OSeMOSYS for grid from OnSSET (high demand)	13 041	31 459	18 418	GWh
Demand for residential was not adjusted in OSeMOSYS for grid from OnSSET (low demand)	6797	9467	2670	GWh
Updated capacity factors for wind harmonized with NREL learning curves (OSeMOSYS)	Constant	Learning curve		
Capital cost wind (OSeMOSYS)	1991	2044	53	USD kW^{-1}
Capital cost CSP (OSeMOSYS)	6254	7381	1127	USD kW^{-1}
Capital cost large hydro (OSeMOSYS)	3665	3078	−587	USD kW^{-1}

Environmental Research Letters

OPEN ACCESS

RECEIVED
22 February 2017

REVISED
15 June 2017

ACCEPTED FOR PUBLICATION
6 July 2017

PUBLISHED
11 September 2017

LETTER

Electrification pathways for Kenya–linking spatial electrification analysis and medium to long term energy planning

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Keywords: Kenya, OSeMOSYS, optimization, OnSSET, off-grid, SDG

Abstract

In September 2015 UN announced 17 Sustainable Development goals (SDG) from which goal number 7 envisions universal access to modern energy services for all by 2030. In Kenya only about 46% of the population currently has access to electricity. This paper analyses hypothetical scenarios, and selected implications, investigating pathways that would allow the country to reach its electrification targets by 2030. Two modelling tools were used for the purposes of this study, namely OnSSET and OSeMOSYS. The tools were soft-linked in order to capture both the spatial and temporal dynamics of their nature. Two electricity demand scenarios were developed representing low and high end user consumption goals respectively. Indicatively, results show that geothermal, coal, hydro and natural gas would consist the optimal energy mix for the centralized national grid. However, in the case of the low demand scenario a high penetration of stand-alone systems is evident in the country, reaching out to approximately 47% of the electrified population. Increasing end user consumption leads to a shift in the optimal technology mix, with higher penetration of mini-grid technologies and grid extension.

1. Introduction

In 2012 1.1 billion people still lived without access to electricity, the majority of which are Sub-Saharan Africa[3] (World Bank 2015). Energy access is one of the most critical parameters from an economic, environmental and developmental perspective that the world is facing today. Energy access is a way out of poverty, increasing the productivity and improved health from a population perspective. Almost 3 billion people rely on biomass for heating and cooking in buildings which often are not well ventilated and with incomplete combustion. This can have harmful effects on health. The use of biomass also often requires long hours of collecting wood which can lead to down prioritizing education, especially for women in the developing world (AGECC 2010). In 2015 the sustainable development goals (SDG) were announced by the UN where one of the goals was *Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all*, which should be achieved by 2030 (UN General assembly 2015).

In Kenya only 46% of the population has access to electricity (2015) (Power Africa USAID 2016) which leads the majority of the population to rely on traditional fuels for energy (such as firewood, charcoal, kerosene) (World Bank 2016). The average electricity consumption in 2012 was estimated at 300 kWh/household (International Energy Agency 2013) (World Bank 2013). In reality most households situated in urban areas would have access to more than 300 kWh/household, whereas in the rural areas electrified households would be low, reaching only 32% (Power Africa USAID 2016).

Tackling energy poverty in the country is a major challenge and electrification has been the focus of extensive research of the past few years (Parshall *et al* 2009) (Zeyringer *et al* 2015). Zeyringer *et al* (2015) analyses grid/off-grid connection for households in Kenya considering PV panels for off-grid solutions. The supply optimization is based on a Geographical Information System (GIS) approach where the cost of extending the transmission network is compared to PV stand-alone systems. The study found that in 2020 17% of the population could cost effectively install PV panels.

[3] Excluding South Africa.

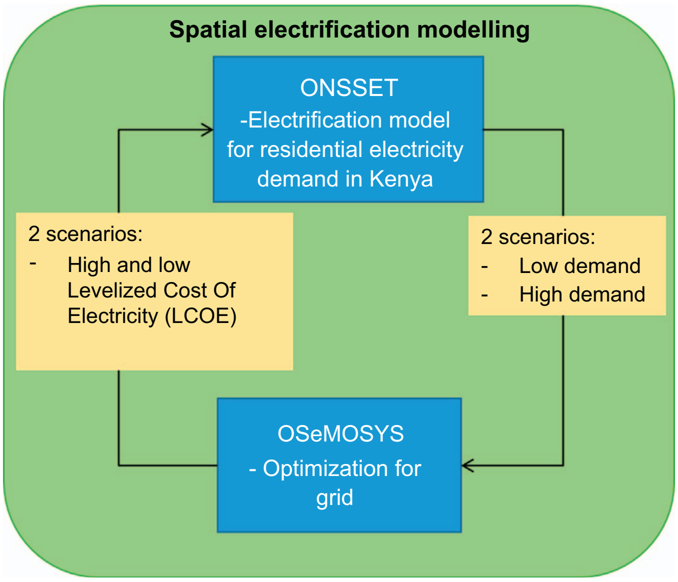

Figure 1. Modelling approach.

Achieving universal electricity access in Kenya by 2030 would require considering both off-grid and centralized grid supply due to the short time horizon and the large part of population lacking access today. Combining a geospatial electrification analysis that optimizes the off-grid supply with a long term energy model that optimizes the grid connected bulk power supply has not been previously developed for Kenya. This will enable a more holistic analysis of possible electrification pathways for Kenya to reach SDG 7 by 2030.

The main objectives of this paper are to:

- Optimize the residential electricity demand for two levels of demand, based on geospatial conditions for off-grid and grid supply.
- Optimize the grid supply for Kenya's total electricity demand for two levels of demand.
- Soft linking the two models to find the cost optimal solution for the overall system.

2. Method

OpeN Source Spatial Electrification Toolkit (OnSSET) provides the optimal electrification mix for household electrification (grid vs. off-grid technologies)[4]. OnSSET uses a GIS-based approach to estimate, analyze and visualize the most cost effective electrification option for residential demand. The tool selects between:

- National grid
- Mini-grid (PV, Wind, Hydro, Diesel)
- Stand-alone (PV, Diesel).

The tool is developed to enable the access to affordable, reliable, sustainable and modern energy for all by 2030 (SDG 7) (UN General assembly 2015). OnSSET assumes an 'overnight electrification'. i.e. techno-economically optimal electrification with no time, finance, supply-chain, economic or political constraints. The choice and cost of electrification option is techno-economically optimal. It is a function of location specific discounted costs. Those include location specific Renewable Energy Technologies (RET) (wind, solar and mini/small hydro), diesel (including transportation cost), and grid (connection, extension and strengthening) specifics.

We choose this approach (and limit our scope) to provide quantitative insight to the policy process. OnSSET indicate how those populations (remote or close to the grid) would most economically be served to reach different tiers of access.

Open Source Energy MOdelling SYStem[5] (OSeMOSYS) is a fully-fledged, open source, systems optimization model for applications to medium and/or long term energy planning. It determines the minimum cost energy technology mix required to satisfy an exogenously defined energy demand.

The demand identified in the spatial electrification model (OnSSET output), was used in the long term energy planning model (OSeMOSYS input), as seen in figure 1. From the OSeMOSYS optimization the grid cost[6] was an input parameter to OnSSET. The grid cost from OSeMOSYS enables analysis on

[4] For the full description on OnSSET please see (Mentis *et al* 2015).

[5] For the full description on OSeMOSYS please see (Howells *et al* 2011).

[6] The grid cost, referred to as LCOE/grid cost, is the average annualized cost of electricity, see appendix equation (1) for details.

Table 1. Low and high residential demand (rural/urban).

Scenarios	Residential electricity consumption (2030)	Rural electricity consumption	Urban electricity consumption
Low electricity consumption	140.9 kWh/capita	43.8 kWh/capita	423.4 kWh/capita
High electricity consumption	468.2 kWh/capita	423.4 kWh/capita	598.6 kWh/capita

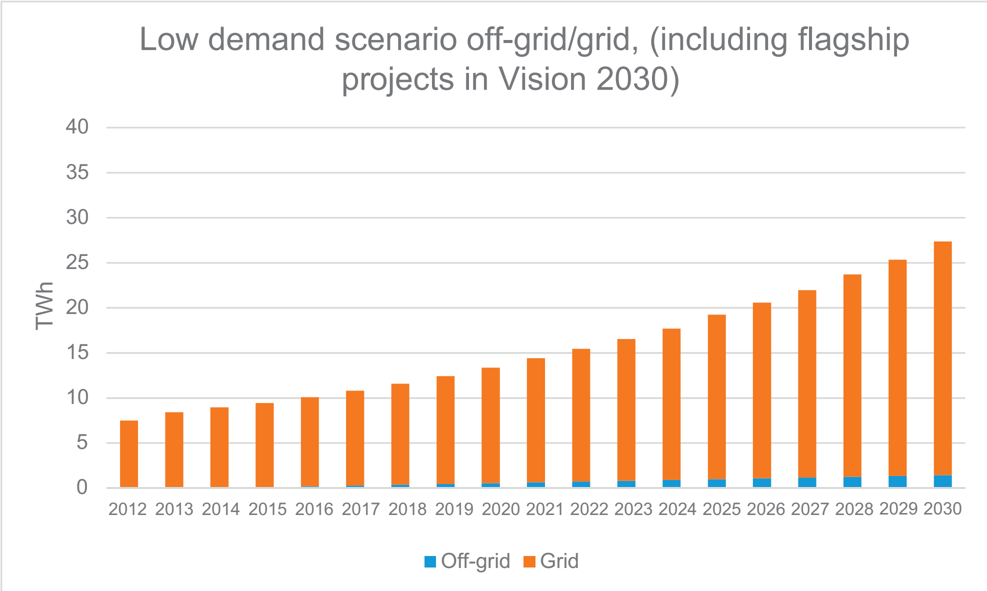

Figure 2. Low demand scenario off-grid/grid demand for Kenya (Ministry of Energy and Petroleum 2016).

what impact the changes in the technology mix in the grid has on the technology mix for the off-grid/grid spatial electrification modelling.

The electrification pathways modelled in this analysis were based on two different demands which would entail different realities in terms of living standards and economic growth. The *residential electricity demand* modelled in both OSeMOSYS and OnSSET follows the World Bank Electrification Tiers framework as seen in table 1.

Tier 2 has an electricity consumption of 43.8 kWh/capita per year which would be equivalent to electric lighting, TV and air circulation. Tier 4 has a consumption of 423.4 kWh/capita per year, enough electricity to supply most appliances such as washing machine, refrigerator, microwave. The highest modelled level (Tier 5) is 598.6 kWh/capita per year which would except for all appliances in Tier 4 also include air conditioning (Nerini *et al* 2016) (Angelou *et al* 2013).

As OnSSET is not a multiyear modelling tool, but instead is only modelled for 2015 and 2030, the linear growth rate for residential off-grid demand from 2015 to 2030 is applied for a continuous demand as input to OSeMOSYS.

The grid demand modelled in OSeMOSYS follows the projected demand from the Ministry of Energy and Petroleum Kenya projections from '*Development of a Power Generation and Transmission Master Plan, Kenya*'. The demand projections are based on a Model for Analysis of Energy Demand which considers socioeconomic, technological and demographic development in Kenya. As a part of the governments development plans for their Vision 2030 several flagship projects are planned to be implemented until 2030. All demand projections include the implementation of energy demand from all flagship projects. For the low demand scenario, the reference scenario was chosen. For the high demand scenario, the Vision 2030 scenario was chosen (Ministry of Energy and Petroleum 2016). The off-grid demand was deducted from the grid demand to avoid double counting the capacity need as seen in figure 2 and figure 3.

Common modelling settings

- The discount rate applied is 9.8% for all models based on the average interest rate from the Central bank of Kenya (Central Bank of Kenya 2017).
- Populations growth is assumed to follow the UN population prospects projections (United Nations–Population Division 2014).
- Residential demand is divided into urban and rural households.

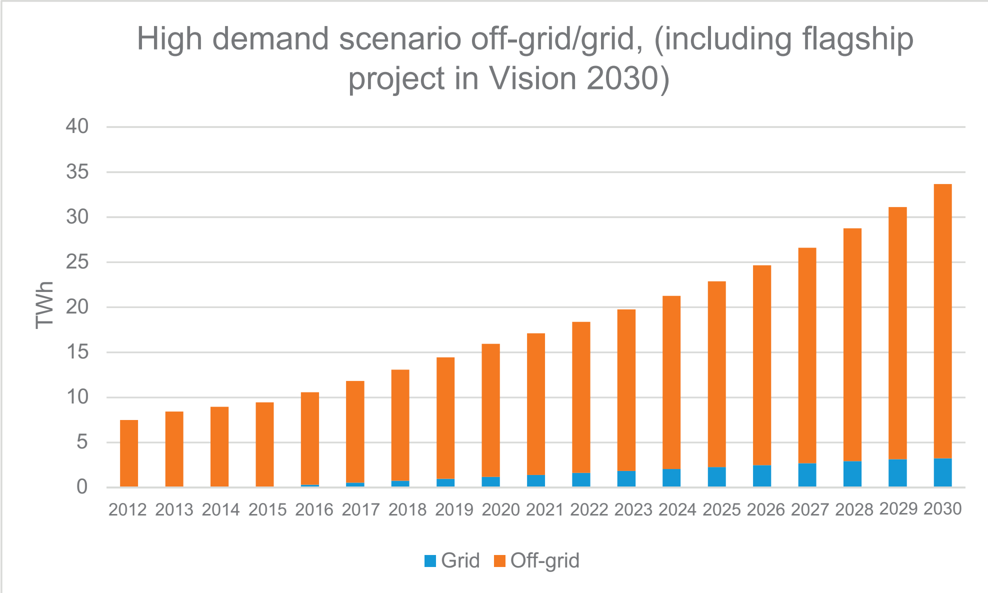

Figure 3. High demand scenario off-grid/grid demand for Kenya (Ministry of Energy and Petroleum 2016).

- OSeMOSYS and OnSSET only consider electricity demand (transport and heat are excluded).

2.1. OnSSET modelling

The following parameters and assumptions are considered in OnSSET.

- For the residential electrification analysis, the base year is 2015 with an electrification rate of 46% (Power Africa USAID 2016). To represent the last mile project of additional 1.2 million connections (African Development Bank 2017) the model considers a 49.6% electrification rate. The model was projected until 2030 where the objective is 100% electrification in Kenya, in line with SDG Goal 7, universal electricity access.
- For system costs related to the grid, mini grid and stand-alone see appendix table A.
- The 'settlement' size which all GIS layers are related to is approx. 1 km × 1 km. For the GIS layers used please see appendix table B.

For the first iteration the grid cost for grid is 0.125 USD/kWh based on 2013 electricity production as seen in table 2.

Table 2. Grid cost for GRID in Kenya for first OnSSET model.

Power supply source	LCOE USD/kWh (8% discount rate) (Ondraczek 2014)	Production (TWh) 2013 (International Energy Agency 2013)	Weighted cost
Geothermal	0.069	2.007	0.016
Wind	0.091	0.018	0.00018
Medium speed diesel	0.217	2.726	0.065
Medium hydro	0.093	3.945	0.041
Biofuels	0.001	0.179	0.002
LCOE GRID		**8.875**	**0.125**

The existing and planned transmission network is central input in OnSSET methodology as the distance from the transmission lines combined with the electricity demand per settlement will impact the penetration of grid to the electrification mix. To identify the current electrification status across the settlements (electrified vs un-electrified) four spatially explicit parameters were considered; population density, distribution and proximity to the transmission network distance to road as well as night light. To achieve 49.6% electrification rate it was assumed that the distance from the current grid is 19 km and 2 km from the road with a minimum population of 800 people per settlement. The electrified settlements, as seen in figure 4, are concentrated around the south–south-western areas where the population density is high.

2.2. OSeMOSYS

- The time domain is from 2012–2040 to avoid any unwanted edge effect around 2030.
- 36 time slices per year, based on a 12-hour day interval, 4-hour peak hour evening and 8-hour night (as Kenya is situated on the equator) and actual days per month (excluding leap year for February).
- The load curve for 2015, as seen in figure 5, shows that the variation between night, evening and day varies between 800 MW night time, and 1200 MW daytime with a peak load between 7–10 pm reaching 1400 MW (KPLC 2015). The

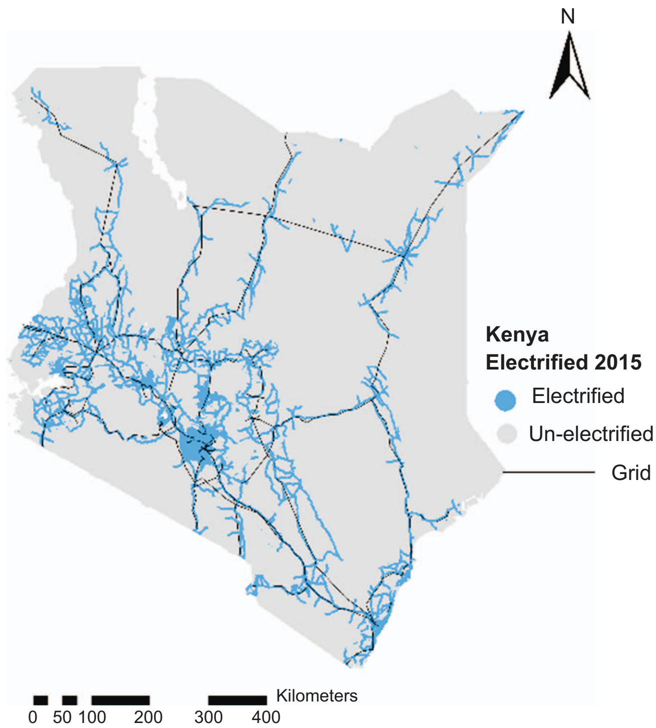

Figure 4. Electrification status and KETRACO Existing transmission lines (GEOFABRIKK 2016) (Kenya Electricity Transmission Company KETRACO 2016).

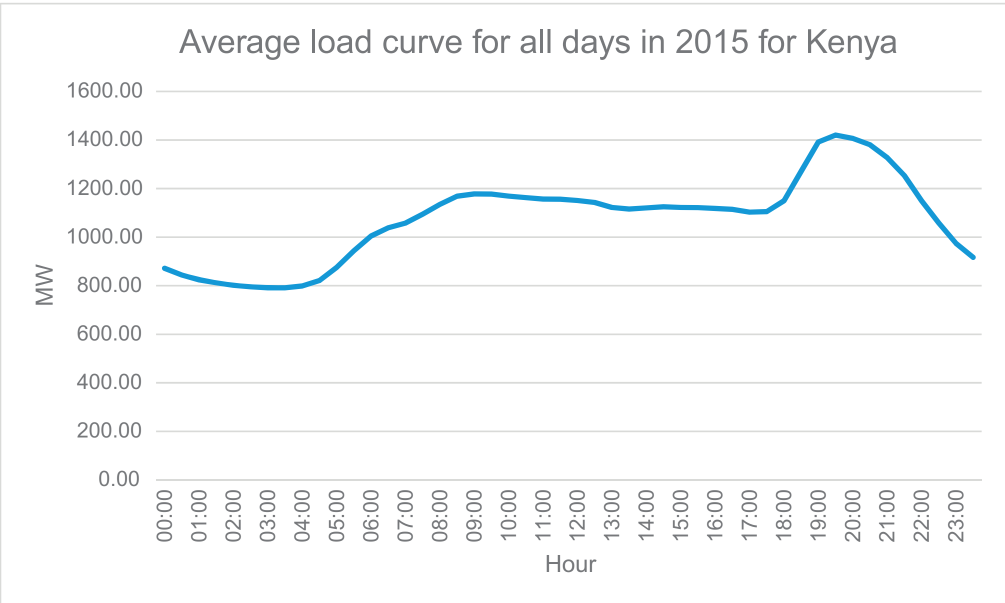

Figure 5. Average load curve for 2015 (KPLC 2015).

demand profile was therefore adjusted to three daily time slices to represent the peak hours in the evening.

The fuel cost (figure 6) follow the World Bank commodities price forecast for 2012–2025 (World Bank 2016, July) and after 2025 follow the New Policies scenario from World Energy Outlook 2016 (IEA 2016) for heavy fuel oil, natural gas and coal. The cheapest fuel is uranium at 0.23 USD/GJ and Bagasse which is bio waste from the sugar industry is assumed to have no cost as the fuel would be waste otherwise. For details on technology performance and cost see appendix tables C and D.

The renewable potential for PV and CSP was developed from GIS maps which are outlined in (Moksnes 2016). A summary of the potential in Kenya can be seen in table 3.

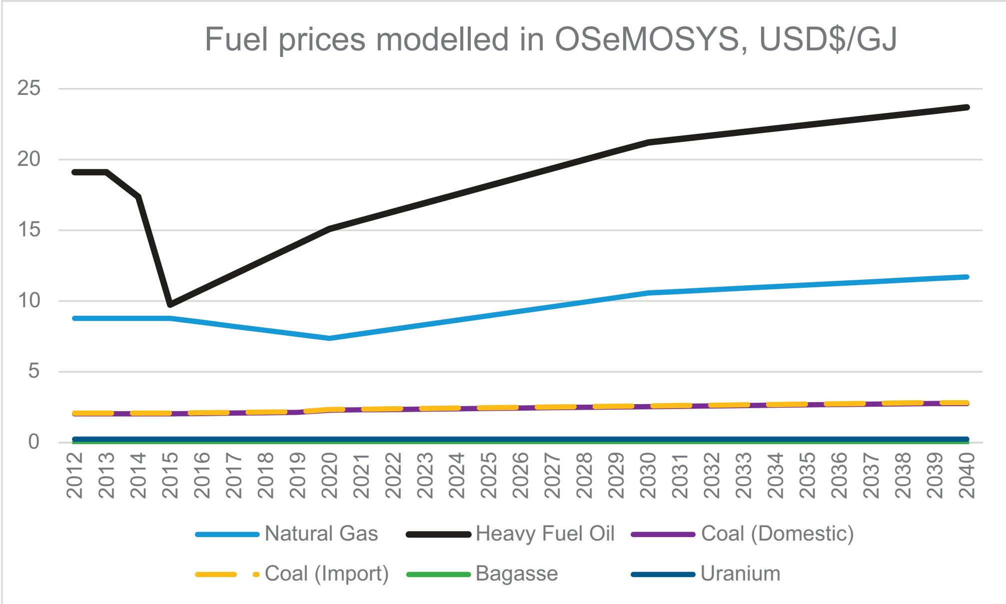

Figure 6. Fuel prices modelled in OSeMOSYS.

Table 3. Solar and wind energy potential in Kenya.

Renewable source	Annual energy available (TWh/year)
CSP—Direct Normal Radiation	183 (Moksnes 2016)
PV—Global Horizon Irradiation	1105 (Moksnes 2016)
Wind energy potential	647 (Mentis *et al* 2015)

The hydropower availability was modelled using a Water Evaluation And Planning (WEAP) model to account for the capacity factors for the largest hydropower plants in Kenya. However, the detailed description of the WEAP model is not in the scope of this paper and can be found in (Moksnes 2016).

3. Results

3.1. Low demand scenario

For the grid electricity generation, the major technologies which are the least cost for Kenya are geothermal, coal, hydro and natural gas combined cycle as seen in figure 7. From the low demand scenario, the optimization from OSeMOSYS gives a grid cost at 0.08 USD/kWh which is iterated to OnSSET.

For the residential electrification optimization, the low demand of 43.8 kWh/capita for rural demand and 423.4 kWh/capita for urban displays a split by technologies with a high share of stand-alone solutions (47%) as seen in figure 8. The preferred stand-alone technology is diesel where the travel time from the city is close, whereas in remote areas PV is preferred. As the demand is low in the rural areas the proximity to the grid will in most cases still not lead to a grid connection (only 53% will be grid connected in 2030). The LCOE for the OnSSET analysis ranges between 0.08 USD/kWh to 0.42 USD/kWh as seen in figure 9, where the existing grid has the lowest cost at 0.08 USD/kWh and the stand-alone in the rural areas have a higher LCOE.

The investment costs related to the low electrification scenario amounts to 21.4 billion USD, as seen in table 4, where transmission cost represents 35% of the total discounted cost from 2012–2030 including the planned grid by KETRACO of 5666 km and the Last Mile project connecting 1.2 million people (African Development Bank 2017).

3.2. High demand scenario

For the OSeMOSYS grid optimization similar results as seen for the low demand with a high share of geothermal, coal, hydro and natural gas where geothermal reaches 6.75 GW installed capacity by 2040.

For the high demand scenario, the optimization from OSeMOSYS gives the same grid cost as the low demand scenario, 0.08 USD/kWh. The cost optimal solution for the residential electricity demand (423.4 kWh/capita for rural and 598.6 kWh/capita for urban) has a much higher share of grid connections and mini-grid solutions as compared to the low scenario as seen in figure 11. As can be seen in the north-west area the wind capacity is very high in the Lake Turkana eastern area where mini-grid wind is the optimal solution. The LCOE for the geospatial cost optimal solution ranges between 0.08 USD/kWh to 0.42 USD/kWh as seen in figure 12 where lower range is where the demand is high per settlement and is situated close to the grid.

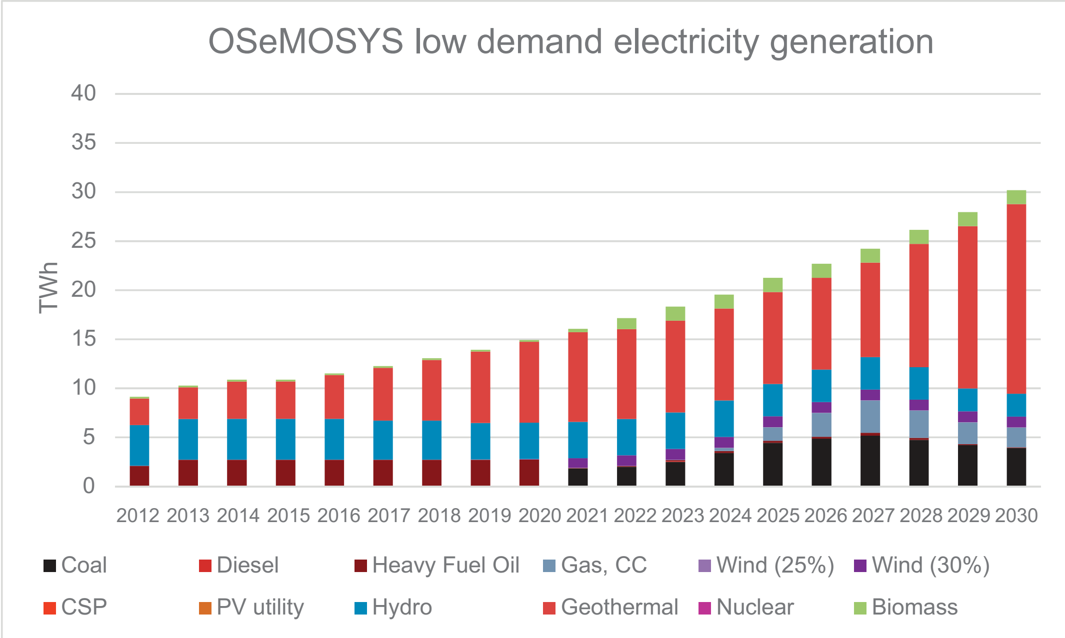

Figure 7. Electricity generation for grid demand, low scenario.[7]

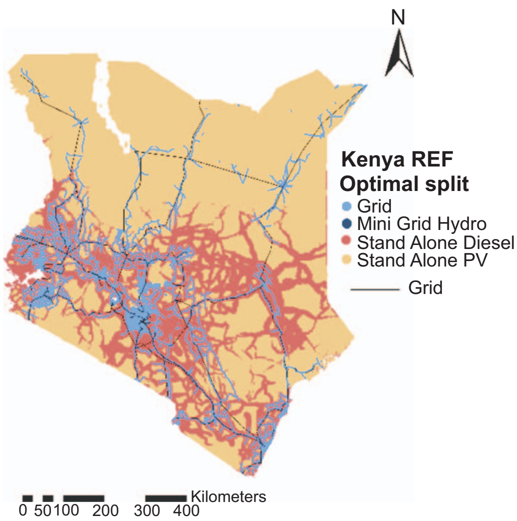

Figure 8. OnSSET technology split Low demand.

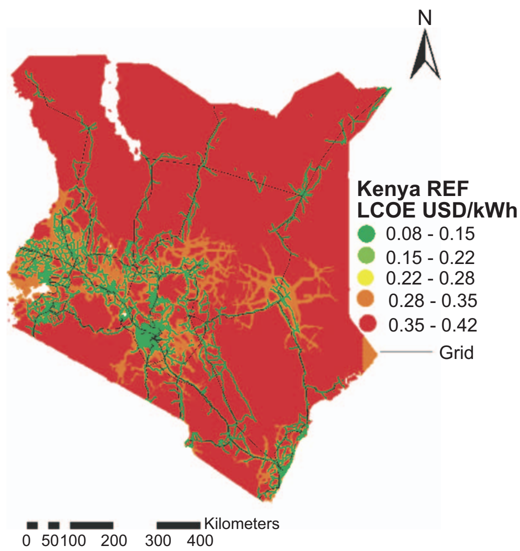

Figure 9. LCOE for Low demand.

For the high energy demand scenario, the costs for both the OnSSET and OSeMOSYS model amounts to 33.1 billion USD where the transmission costs represent 51% of the costs as seen in table 5.

3.3. Sensitivity analysis of discount rate for OSeMOSYS and LCOE in OnSSET

The discount rate for the OSeMOSYS modelling was set to 9.8%, but the discount rate affects the technology mix as seen in figure 13. An increased discount rate will favour power production with a low capital cost such as natural gas and coal. When decreasing the discount rate from 9.8% to 5.75% the electricity generation will favour technologies with a higher capital cost which in this case shifts to geothermal and solar utility, but the shift is not as significant as seen for the 18% discount rate.

Furthermore, the grid cost affects the share of settlements that will get connected to the grid in the optimization. The changes in technology mix for both scenarios is displayed in figure 14 where the grid cost changes from 0.125 USD/kWh to

[7] The technology Wind (25%) represents a capacity factor of 25% and Wind (30%) a capacity factor of 30%.

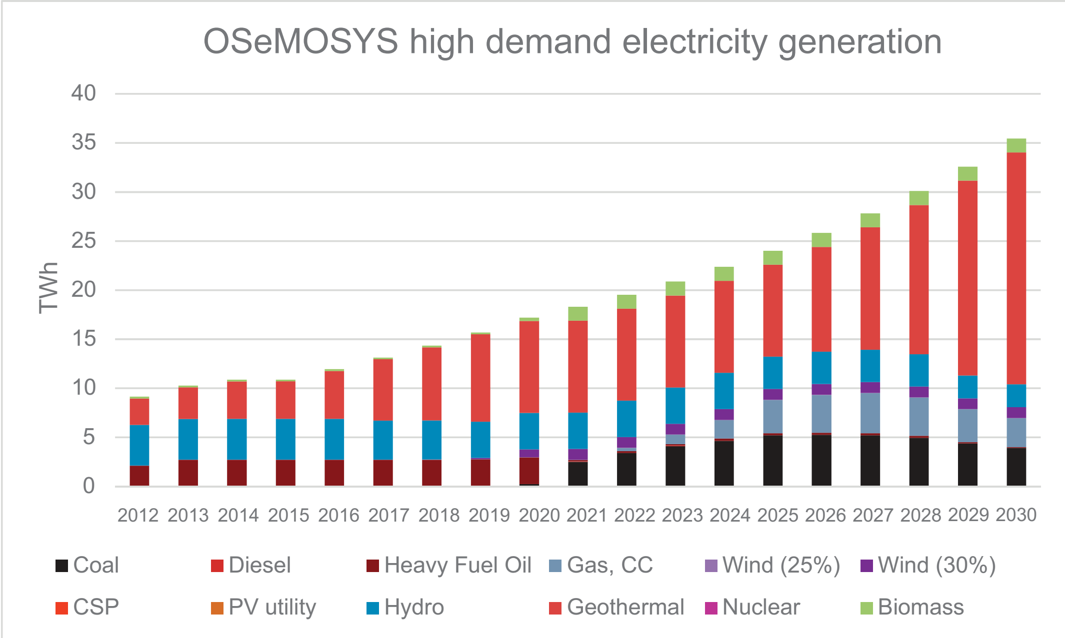

Figure 10. Electricity generation for grid demand, high scenario.

Table 4. Total discounted investment cost for low scenario 2012–2030.

		MUSD
Transmission[8]	3.13 GW HV transmission, and 19704810 new connections	7546
Mini grid	962 people	0.11
Stand alone	31 305 619 people	1859
Power plants (including fuel cost and O&M)	4.58 GW	11 980
SUM (MUSD)		**21 385**

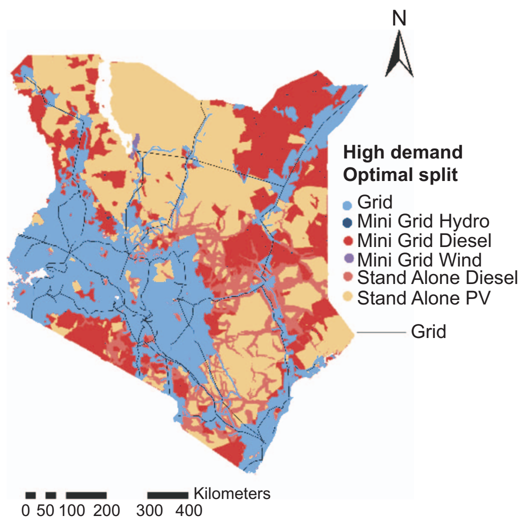

Figure 11. OnSSET technology split high demand.

0.08 USD/kWh. The total grid connections are increased by 1.22 million people in the high demand scenario in favour of Hydro and Diesel, whereas in the low demand scenario the additional grid connections increase by 1.62 million people in favour of PV and Diesel.

4. Discussion

This paper quantified selected implications of meetings two levels of demand for 2030 for all of the country's un-electrified. These would represent two different realities for the majority of the population in Kenya. The low demand at a Tier 2 level for the rural population would in 2030 imply that they still would not have access to refrigerators or electric cooking stoves. Whereas higher demand would imply electricity levels similar to a middle-income country.

A number of important results have emerged from the study. First, stand-alone technologies such as PV can play a major role for Kenya in ensuring electricity access to all by 2030. Second, the demand plays a key role to which extent the grid will be economically feasible to expand in the OnSSET analysis. Areas which are located in remote areas will not have the economy

[8] The sum of discounted costs from the OSeMOSYS and OnSSET analysis plus the planned transmission lines from KENTRACO which amounts to 2100 MUSD and Last mile project connecting 1.2 million people at a cost of 686 MUSD (African Development bank 2017).

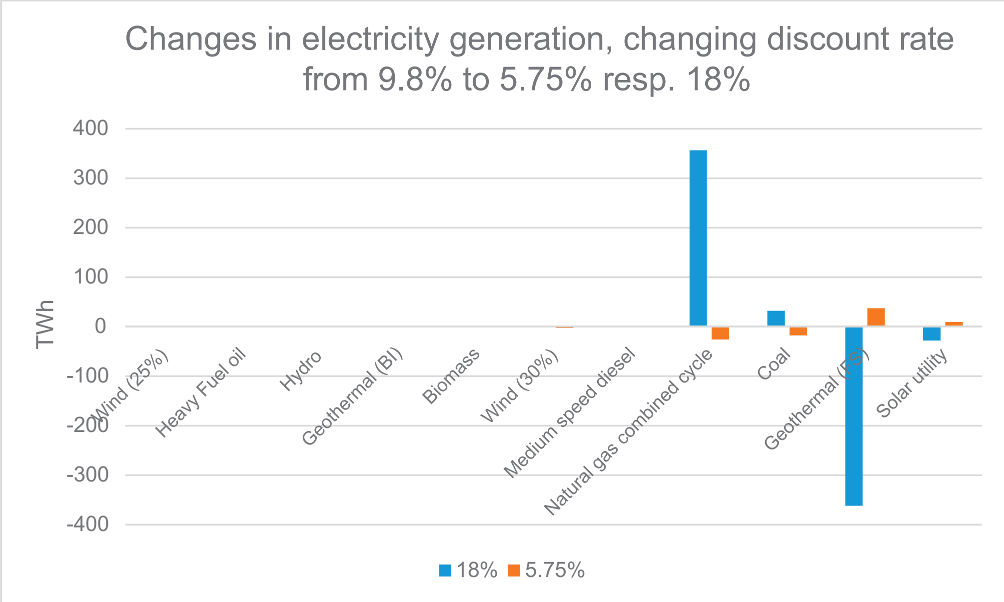

Figure 13. Changes in electricity generation when changing from 9.8% to 18% and 5.75% for high demand scenario.

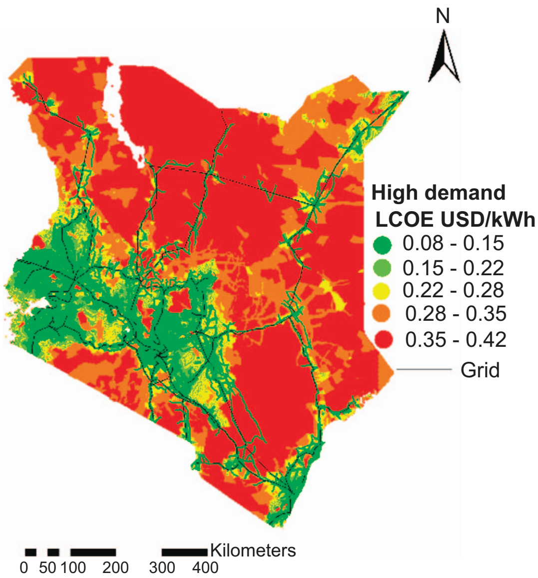

Figure 12. LCOE for high demand.

of scale to decrease the costs which leads to a higher cost per kWh than a household located in a more urban area. Third, the cost of grid generated electricity can be reduced based on the OSeMOSYS optimization from Kenya's current higher grid cost at 0.125 USD/kWh. Based on the sensitivity analysis a shift from 0.125 USD/kWh to 0.08 USD/kWh would imply 1.22 million more people connected to the grid for the high demand scenario and 1.62 million people for the low demand scenario.

However, there are limitations to the work which if addressed would improve the analysis. The first iteration from OnSSET considers a 0.125 USD/kWh grid cost, which affects the number of new grid connections, and thus the OSeMOSYS grid demand is underestimated. As the analysis only considers one iteration (between OnSSET and OSeMOSYS) this could have an impact on the overall results. The change of demand from a grid cost at 0.125 USD/kWh to 0.08 USD/kWh would imply a change in the low demand with and increased of 0.228 TWh and an increase of 0.571 TWh for the high demand scenario in 2030. Looking at the total grid demand for the low scenario, 0.228 TWh represents an 0.8% increase of demand in 2030.

One important limitation is the time resolution in OnSSET which assumes overnight electrification. Linking OnSSET with OSeMOSYS, which is a multiyear tool, can be misleading. To be able to add a multiyear analysis to OnSSET however it would

Table 5. Total discounted investment cost for high demand scenario 2012–2030.

		MUSD
Transmission[9]	3.87 GW HV transmission and 44 558 182 new connections	17 094
Mini grid	4 952 851 people	1718
Stand alone	1 500 357 people	1317
Power plants (including fuel cost and O&M)	5.4 GW	12 969
SUM (MUSD)		**33 098**

[9] The sum of discounted costs from the OSeMOSYS and OnSSET analysis plus the planned transmission lines from KENTRACO which amounts to 2100 MUSD and Last mile project connecting 1.2 million people at a cost of 686 MUSD (African Development Bank 2017).

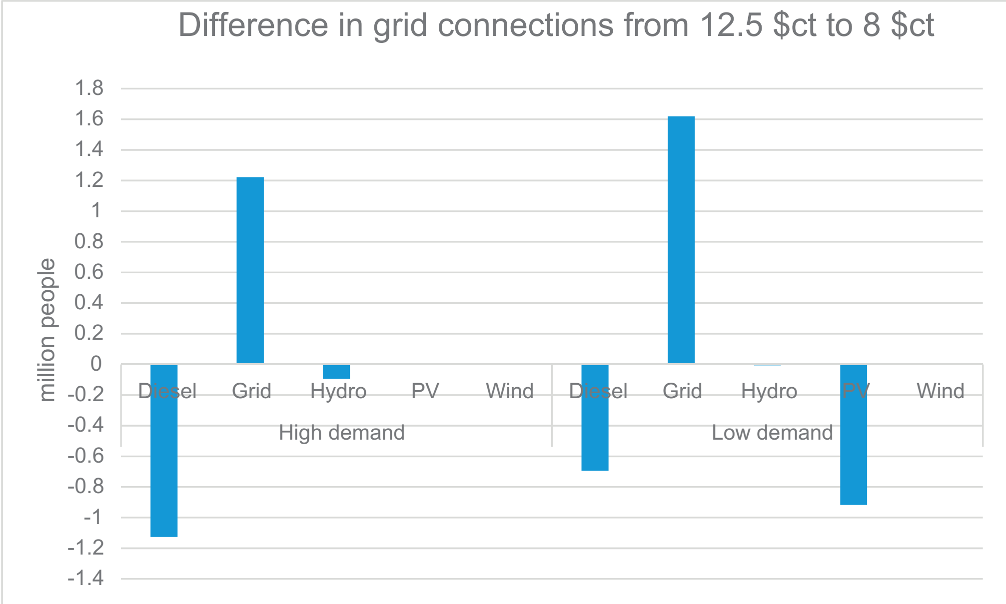

Figure 14. Changes in technology when decreasing the grid cost from 0.125 USD/kWh to 0.08 USD/kWh for high and low electricity demand.

require information about the priority areas for electrification. This can differ from country to country depending on policies and national plans. It would also help better reflect logistical realities.

Feed-in tariffs are not included in the analysis. Kenya has feed-in-tariffs for wind, biomass, small hydro, geothermal, biogas and solar energy which range between 0.06–0.2USD/kWh (Ministry of Energy Kenya 2010). As the least cost optimization for both scenarios did not install CSP and did not utilize the full wind potential, the feed-in tariffs could shift the investments towards these technologies. However, the feed-in-tariffs is a system cost (re-distributed) and as the analysis for this paper is based on costs, feed-in-tariffs would not be applicable for the current analysis.

5. Conclusion

This paper has demonstrated how a soft-link between OnSSET and OSeMOSYS could provide selected insights for the analysis of complete electrification for a country. The novelty of the analysis is the utilization of the strengths of both tools which, by soft-linking, can give an optimal split between off-grid and grid electricity system.

The geospatial analysis shows that PV panels will play a key role in the rural areas to achieve universal access to all by 2030.

The modelled demand levels play a key role in which service the household will be able to expect. When the demand increases the grid connections increases which in turn allows for those connected households to have a more stable and flexible supply compared to off-grid solutions.

Acknowledgments

I would like to thank Oliver Broad for the review of OSeMOSYS results, Youssef Almulla for all help with MOMANI and Christopher Arderne for the GIS-advice and Python scripts. This paper is the result of a masters thesis in Sustainable Energy Engineering carried out at the division of Energy System Analysis at KTH Royal Institute of Technology.

Appendix

Annualized cost of grid electricity

$$GRID\,cost = \frac{\sum_{t=1}^{n}\left\{\frac{\text{Annualised Investment Cost}_t}{(1+r)^t} + \text{Discounted Operating Cost}_t\right\}}{\sum_{t=1}^{n}\frac{(\text{Annual production}_{EL1})}{(1+r)^t}}$$

Annual Investment Cost[10] = CapitalInvestment ∗ CRF

$$\text{Capital Recovery Factor} = \frac{r(1+r)^N}{(1+r)^N - 1}:$$

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[10] The residual capacity's capital cost was included in the analysis using a straight line depreciation method for all power plants for 2012 to include the current cost of grid.

Table A. Technical performance and cost for 2015, OnSSET (NREL (National Renewable Energy Laboratory) 2016) (ESMAP–World Bank 2015) (US Energy Information Administration 2016) (Ministry of Energy Kenya 2010) (Energy Regulatory Commission 2013).

Parameter	Capital cost USD/kW	O&M $/kW	Fuel cost USD/MWh	Capacity factor	Efficiency
PV stand-alone + Li-ion battery (1688 USD/kW)	1633 + 1688 = 3321	10		20%	—
Wind (capacity factor 20, 30, 40%) + Li-ion battery (1688 USD/kW)	2214 + 1688 = 3902	49		20%, 30%, 40%	—
Diesel generator, stand alone	937.85	93.4 (assumed 10% of capital cost)	172	50%	28%
Diesel generator micro grid	721.4	72.1 (assumed 10% of capital cost)	172	70%	33%
Mini grid PV + Li-ion battery (1688 USD/kW)	1363 + 1688 = 3051	8		20%	—
Mini hydro	2902	58 (assumed 2% of capital cost)		50%	—
Transmission distribution HV/MV/LV	92 823/9000/5000 per km				81.8%

Table B. GIS-layers for OnSSET analysis.

GIS-layer	Description	Source
Administrative boundary	Administrative boundary for Kenya, shape file	(DIVA-GIS 2016)
Population data	Population data for Kenya, Raster file 1 km grid cells	(WorldPop 2016)
Transmission lines data	Transmission lines 2015, shape file	(GEOFABRIKK 2016)
Travel time to major cities	Travel time to major cities in Kenya, shape file	(Joint Research Center EU 2016), further developed by team at dESA.
Solar global horizon Radiation	1 degree resolution based on monthly averages of 22 years data (July 1983–June 2005).	(NASA 2008)
Night lights	Nightlights, raster file	(NASA Earth Observatory 2016)
Roads	Road network, raster file	(CIESIN, Columbia University, ITOS, University of Georgia 2013)
Land cover	Classified land cover, raster file	(NASA-MODIS 2012)
Solar restrictions	Layer developed at dESA KTH, raster file	
Wind data	0.5 × 0.667 degrees spatial resolution	(EarthData–NASA 2016)
Hydropower points	Layer developed at dESA KTH, shape file	

Table C. Technologies efficiencies modelled (International Energy Agency 2010) (Burmeister and Wain Scandinavian Contractor A/S 2016) (International Energy Agency 2013) (Energy Regulatory Commission 2011) (International Energy Agency 2010) (International Energy Agency 2014) (International Energy Agency, ETSAP 2016) (International Energy Agency 2007) (International Energy Agency 2010).

Technology	Efficiency
Coal Steam cycle	35%
Medium speed diesel/Heavy fuel oil combined cycle	45%
Geothermal	10%
Transmission and distribution	94% and 87%
CSP	15%
PV	16%
Nuclear light water	36%
Biomass, bagasse	33%
Natural gas combined cycle	55%
Transmission and distribution	18.2% decrease to 15% 2015

Table D. Technologies investment cost, fixed cost, variable cost and total max capacity (Energy Regulatory Commission 2011) (Energy Regulatory Comission 2014) (International Energy Agency 2010) (International Energy Agency ETSAP, 2016) (World Bank, International Finance Corporation 2015) (International Energy Agency 2014) (International Energy Agency ETSAP 2016, p. Technology Brief E03) (International Energy Agency ETSAP 2016, p. Technology Policy Brief E10) (Energy Regulatory Commission 2012) (NREL (National Renewable Energy Laboratory) 2016).

Technology	Investment cost USD/kW	Fixed cost USD/kW	Variable cost USD/MWh	Total max capacity GW
Geothermal	Binary: 5049 Flash steam: 3787	Binary: 63 Flash steam plant: 63	Binary: 24.84 Flash steam plant: 9	Binary: 3.285 Flash steam: 6.715
Wind	2044 (2015)/ 2214 (2030)	50	19.98	See section 3.4.4 in (Moksnes 2016)
Heavy fuel oil combined cycle/ Medium speed diesel	1678	62.5	9	—
Hydro river run off < 10 MW	2902	2.05	4.464	0.5
Hydro dam < 30 MW	3409	1.39	4.104	0.55
Hydro dam > 30 MW	3078	1.39	4.104	1.49
PV Utility	2120	4.2	0 (included in fixed cost)	See section 3.4.4 in (Moksnes 2016)
Biomass CHP (Bagasse)	2181	27.7	9.252	0.192
Natural gas Combined Cycle	770	31	1.8	Max 0.54 annually earliest 2018
Coal single cycle	2903	69	4.608	Max 0.9 annually Earliest 2016
Nuclear light water	6164	0 (Included in variable cost)	15.984	Earliest date 2023 1.2 GW
PV-Utility	2133 (2015)/ 1143 (2030)			
Concentrated solar power, Solar tower with storage	7381 (2015)/ 3508 (2030)	0 (Included in variable cost)	40	See section 3.4.4 in (Moksnes 2016)
Transmission	112	0	0	—
Distribution	16	0	0	—

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