CORRIGENDUM

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

Nandi Moksnes®, Alexandros Korkovelos®, Dimitrios Mentis and Mark Howells
KTH Royal Institute of Technology, Brinellvägen 68, 100 44 Stockholm, Sweden
E-mail: nandi@kth.se

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 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.

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

| Component                  | MUSD  |
|----------------------------|-------|
| Transmission               | 7252  |
| Mini grid                  | –     |
| Stand alone                | 2618  |
| Power plants (including fuel cost and O&M) | 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.

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:

| Component                  | MUSD  |
|----------------------------|-------|
| Transmission               | 16 331|
| Mini grid                  | 540   |
| Stand alone                | 5008  |
| Power plants (including fuel cost and O&M) | 18 998 |
| SUM (MUSD)                 | 40 877|

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:

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 the first paragraph the transmission share and investment cost is updated to 40% resp. 40.9 billion USD.
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 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:
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 LCOE 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.

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  | Fixed cost  | Variable cost | Total max capacity |
|-----------------------------------|------------------|-------------|---------------|--------------------|
| Geothermal                        | Binary: 5049     | Binary: 63  | Binary: 24.84 | Binary: 3.285      |
|                                   | Flash steam: 3787| Flash Steam plant: 63 | Flash Steam plant: 9 | Flash steam: 6.715 |
| Wind                              | 2044 (2015)/2214 | 50          | 19.98         | See section 3.4.4 in (Moksnes, 2016) |
| Wind                              | 1678             | 62.5        | 9             | –                  |
| Heavy fuel oil combined cycle/Medium speed diesel | 2902 | 2.05 | 4.464 | 0.5 |
| Hydro river run off <10 MW       | 3409             | 1.39        | 4.104         | 0.55               |
| Hydro dam <30 MW                 | 3078             | 1.39        | 4.104         | 1.49               |
| Hydro dam >30 MW                 | 2133 (2015)/1143 | 4.2 | 0 (included in fixed cost) | See section 3.4.4 in (Moksnes, 2016) |
| PV utility                        | 2181             | 27.7        | 9.252         | 0.192              |
| 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 | 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 $^{-1}$       |
| 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 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$^{-1}$     |
Electrification pathways for Kenya–linking spatial electrification analysis and medium to long term energy planning

Nandi Moksnes1,2, Alexandros Korkovelos1, Dimitrios Mentis1 and Mark Howells1

1 KTH Royal Institute of Technology, Brinellvägen 68, 100 44 Stockholm, Sweden
2 Author to whom any correspondence should be addressed. E-mail: nandi@kth.se

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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 Africa3 (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.
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). 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 (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 was an input parameter to OnSSET. The grid cost from OSeMOSYS enables analysis on

\[ \text{LCOE/grid cost} = \text{average annualized cost of electricity} \]

For the full description on OSeMOSYS please see (Howells et al 2011).

For the full description on OnSSET please see (Mentis et al 2015).
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.
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.

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

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

| Power supply source | LCOE USD/kWh (8% discount rate) (Ondracek 2014) |
|---------------------|-----------------------------------------------|
| Production (TWh)    | Weighted cost (2013 International Energy Agency 2013) |
| 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 |
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.
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 (Moksnes2016).

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.

| 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) |

Figure 6. Fuel prices modelled in OSeMOSYS.
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

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

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

| Description                              | Cost (MUSD) |
|------------------------------------------|-------------|
| Transmission $^8$                        | 7546        |
| and 19704810 new connections             |             |
| Mini grid                                | 962 people  |
| Stand alone                              | 31 305 619 people |
| Power plants (including fuel cost and O&M) | 4.58 GW  |
| SUM (MUSD)                               | 21 385      |

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

Figure 11. OnSSET technology split high demand.

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$^8$ 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).
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 an 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 require 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).
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 0.06–0.2 USD/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.

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Appendix

Annualized cost of grid electricity

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

Annual Investment Cost\(^{10}\) = CapitalInvestment * CRF

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

ORCID iDs

Nandi Moksnes \(\text{https://orcid.org/0000-0002-8641-564X}\)

\(^{10}\) 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%       | —          |
| 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 = 3031  | 8        | 172              | 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           |                             |
| 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                                                | 13%                                             |
| 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 Commission 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 | Fixed cost | Variable cost | Total max capacity GW |
|--------------------------------|-----------------|------------|---------------|-----------------------|
|                                | USD/kW          | USD/kW     | USD/MWh       |                       |
| Geothermal                     | Binary: 5049    | Binary: 63 | Binary: 24.84 | 3.285                 |
| Flash steam:                   | 3787            | 63         | 19.98         |                       |
| Wind                           | 2044 (2015)/    | 50         | 19.98         | See section 3.4.4 in  |
|                               | 2214 (2030)     |            |               | (Moksnes 2016)        |
| Heavy fuel oil combined cycle/ | 1678            | 62.5       | 9             |                       |
| Medium speed diesel            |                 |            |               |                       |
| Hydro river run off < 10 MW    | 2902            | 2.05       | 4.464         | 0.192                 |
| 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             | 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      |
|                               |                 |            |               | Earlier 2016          |
| Nuclear light water            | 6164            | 0          | 15.984        | Earliest date 2023 1.2|
| PV–Utility                     | 2133 (2015)/    | 0          | 40            | See section 3.4.4 in  |
|                               | 1143 (2030)     |            |               | (Moksnes 2016)        |
| Concentrated solar power,      | 7381 (2015)/    | 0          | 40            |                       |
| Solar tower with storage       | 3508 (2030)     |            |               |                       |
| Transmission                   | 112             | 0          | 0             |                       |
| Distribution                   | 16              | 0          | 0             |                       |

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