POLITECNICO DI TORINO

CORSO LAUREA IN INGEGNERIA ENERGETICA E NUCLEARE

SPATIAL ENERGY PLANNING FOR THE ENERGY-WATER NEXUS IN MOZAMBIQUE

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ABSTRACT

Energy, water and food are the basic perquisites to ensure human well-being and sustainable development. It is projected that in the near future growth of population, urbanization, changes in life-style, as well as climate changes, will lead to an increase of the competiveness between food, water and energy rosources.
For instance, today agriculture accounts for 70% of global water withdrawal and food chain is responsible for 30% of global energy consumption. By 2050, water demand is projected to increase by 55%, energy by 80% and food by 60%, mostly driven by developing countries.
In this contest, it is crucial to correctly manage natural resources, being aware of the indissoluble link between them.

The aim of this analysis is to provide a geo-spatial assessment to discuss how the electricity requered to pump groundwater for irrigation can effect the electrification process in *Mozambique*. The study is performed by means of OnSSET, an open source optimization tool based on GIS data (Geographic Information System) that has been developed by the division of Energy Systems Analysis of the KTH Royal Institute of Technology in Stockholm.

They reason why Mozambique has been chosen as study country are:

1. It has one of the lowest electrification rate (27%) in the World.
2. It is reach in energy resources (both conventional and renewable).
3. It has a very high population growth rate (2%/year), that will lead to an increasing food demand.
4. It has considerable amount of cultivated land that is still farmed without modern techniques (such as irrigation) and that can be exploited both for internal demand and export.
5. It has one of the largest groundwater potential in Africa.

The irrigation groundwater demand is evaluated in a particular scenario called “closure-gap scenario”, in which the gap between current and potential cropland yield (produced food per cultivated land) is minimized, avoiding, at the same, time the groundwater deplention.

The OnSSET outputs consist of the optimum technology distribution, chosen between grid extension, PV stand-alone, PV mini-grid, wind mini-grid, hydro mini-grid, that minimize the local LCoE’s. The only-residential results will be compared to the case in which the pumping energy is added considering different scenarios with different household energy tiers.

It comes out that solar stand-alone systems are a valid solution for a considerable portion of the unelectrified rural population, where grid exension would not be affordable. As the rural consumption grows, the national grid exension becomes more suitable, replacing part of the stand-alone solutions.

The electricity required by the groundwater pumping is relatively low with respect to the only residential demand (1-4%), but its distribution is sufficient to change the OnSSET outputs. The great majority of the pumping energy is required in rural areas, with low population density and far away

from the national grid. In this sites, PV and hydro mini-grids turn out to be the best solutions, replacing the too expensive solar home systems.

INTRODUCTION

In 2016 the number of people without access to electricity was estimated at 940 milion (WorldBank), with a global electrification rate that have steadily increased from 1990 (71 %) to 2016 (87 %). Like so much else, this is not uniformely widespread. High-income countries, in fact, are assumed to have 100% electrification rate, while in most of sub-saharian countries it is still unacceptably low and it struggles to rise up, even because of the high population growth.
This is the case of sub-Saharan Africa, which counts more than 620 million people without access to electricity services, and nearly 730 million people that rely on traditional fuels (firewood and charcoal).
The largest part of the unelectrified population is located in rural areas, far away from the existing, usually poorly developed grid network. Electrifying these areas is a challenging process and usually requires significant investments, as well as technological and structural changes in energy systems. In order to maximize impact, not only public and private investments need to increase, but they need to be deployed in a cost-effective way.

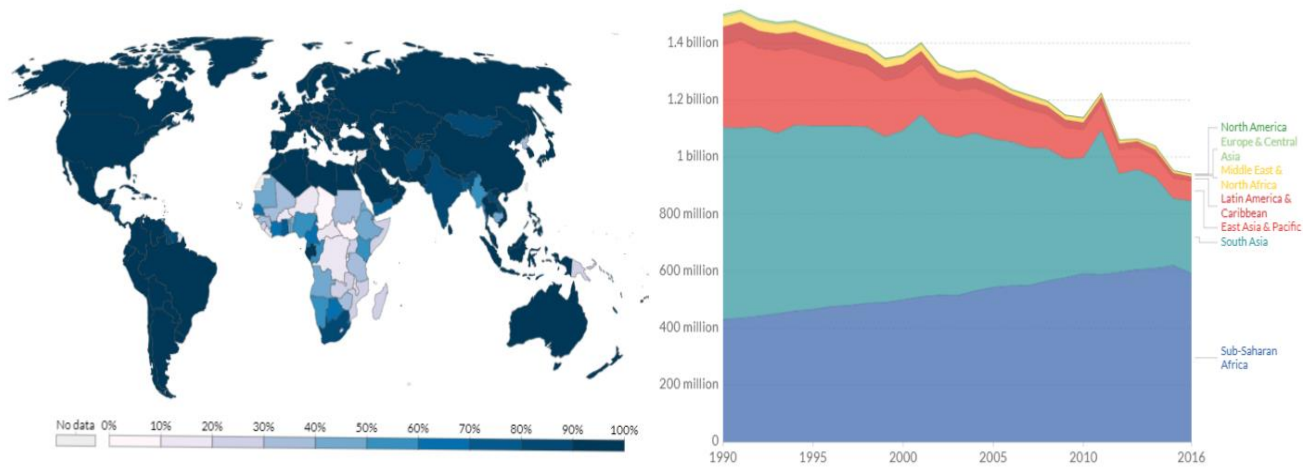


Figure 1-electrification in the World (WorldBank)

The goal 7 (“affordable and clean enery”) of the “Agenda for Sustainable Development” envisions universal access to modern, sustainable, cost effective and reliable energy services by 2030. There is evidence that quality of life is strongly correlated to electrification. For instance, basic service like illumination, can involve people to read in night time, leading to increased education. The use of TV, radio, smartphones or other information channels result in reduction of isolation, as well as in disaster risk mitigation. Refrigeration can improve health condition by means of food, medicine and vaccines storing.
However, providing access in such services will not automatically result in economical growth. Several studies show that electrification can produce economical benefits if a productive use of electricity is inserted in a context in which economical develpment has already taken place.

A possible productive use of electricity is rapresented by the groudwater pumping and irrigation, that can lead to more effective exploitation of agricultural and labor resources and, then, to a structured economical growth.

The Water-Food-Energy nexus

Electricity, water and food, lie at the hearth of the so-called "Water-Food-Energy Nexus" (WFE nexus). These three aspects are indissolubly linked and predicted to significantly increase in the next few decades. For instance, today agriculture accounts for 70% of water global withdrawal and food chain is responsible for 30% of gloabl energy consumption. In Europe aproximately 43% of the fresh water withdrawal is involved in power plant cooling and, more in general, 90% of the global generated power is water-intensive. By 2050, global water demand is projected to increase by 55%, energy by 80% and food by 60%, mostly driven by developing countries.
As demands grow, the competiveness between resources rises up. For instance, a large-scale hydropower plant can provide electricity and can store water for irrigation purposes, but it might happend at expense of down stream agro-ecological systems. In countries like India, China and Pakistan the introduction of irrigation schemes based on groundwater has allowed these economies to grow up fast, but, at the same time, it promote the deplention of aquifer and groundwater storage.The food started to be vulnerable to the electricity prices, resulting in improving of the pumps electrical efficiency.
These examples are useful to understand the strong link between different resources and why large-scale planning should never ignore possible implications in other sectors.

The WFE nexus is a promising multi-sectorial methodology consisting in the assessment of current and future pressure on natural and human resources, as well as interaction between different sectors. The context analysis allows researchers to identify main issues and goals and try to figure out how to handle them. In this way, it is possible to provide information in order to plan investments, policies, reforms and infrastructures at large-scale level, without occurring in unwanted second effects.

The WFE approach can be divided in three main working areas:

- *evidence*: it is the starting point of the assessment, in which the current status of the natural resources, as well as the human pressure on them, are evaluated.
- *scenario development*: it can help to understand the effect of different policies and strategies. Different scenarios can be compared and it is possible to extrapolate key and irrelevant fators.
- *response options:* it refers to planning investments, policies, incentives, legislation, business models etc. Specific indicators have to be monitored to assess the effects of interventions in the variuos sectors.

The main drawback of the nexus methodology is the complexity, that is typical of multi-sectorial approaches.

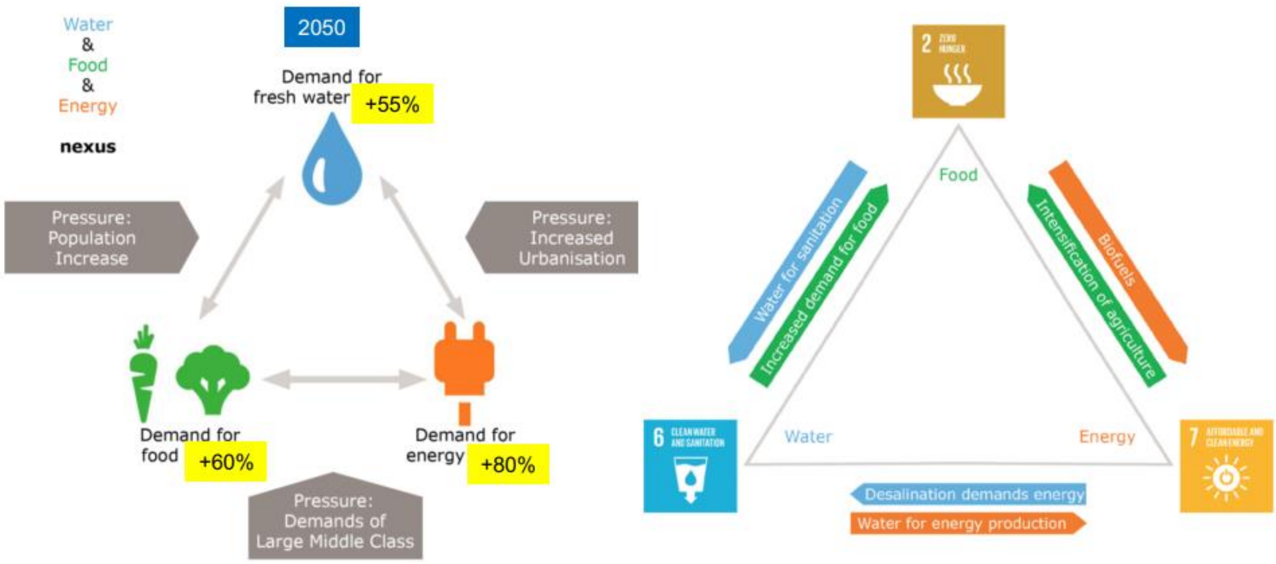


Figure 2-WFE nexus and related sustainable goals (IRENA)

In this study the *evidence* consists in the fact that Mozambique has one of the highest groundwater potential in the south-eastern Africa, as well as a great amount of cultivated land that are still rainfed and that could strongly benefit of irrigation schemes. An efficient groundwater lifting could be easily provided by electric pumps, but in Mozambique the great majority of rural smallholder farmers has not electricity access.

The *scenarios* involved in this study will consider first the 100% electricity access for only residential demand and, then, the addiction of the lifting energy. The irrigation groundwater demand is evaluated in a particular scenario called "closure-gap scenario", in which the gap between current and potential cropland yield (produced food per cultivated land) is minimized and the groundwater withdrawal occurs without the resource deplention.

For each scenario it will be discussed investmets cost, installed capacity and distribution of the most cost effective technologies.

1. BACKGROUND

Mozambique is a low-income country in Southeast Africa with a population of 31.2 million (35 inhabitans per km^2), 61.7 % of which located in rural areas (WorldPop).
Poverty is widely spread in the country, effecting 55% of the population, and only 51% of Mozambicans can benefit of improved drinking water sources. The Human Development and Gender Equality Index are one of the lowest in the World.
The public spent on health is about 3% of the GDP and only 21% of the Mozambicans has access to adequate sanitation facilities. Malaria and AIDS, in fact, are concerning problem, as well as regular outbreaks of colera.

Mozambique population and youth dependency ratio (0-14 aged people rapresent 45% of the population in 2015) are rapidly growing (2%/year) and they are continuing to pose pressure on public service and infrastructure. Like in many other developing countries, Mozambique urban rate is increasing, but it is primarily due to natural urban population growth instead of migration from rural areas (it accounts for only 12 % of the overall urban population growth).

There is a great difference in quality of life index within Mozambique. The south, which includes the capital Maputo, is far richer and more developed than the north. Maputo attracts almost all of the foreign investment, while the northern regions still rely entirely on rural activities. As a conseguence, in the south infrastructure, agriculture and health care services are progressing but in the north this is not happening. There is also a remarkable difference between rural and urban realities.

Figure 3-Mozambique

Mozambican society and economy still bears the sign of the civil war fought between 1977 and 1992, started 2 years later the independence from Portugal and ended with the fall of Sovietic Union (thanks to the mediation of S. Egidio Community). In reality, fights have continued untill 2019, when the will of undertake a peace path was formalized.

In march of the same year, Mozambique has suffered the effects of one of the deadliest tropical cyclone recorded in the South-West Indian Ocean basin. The nothern and central part sustained the worst damages, including severe flooding, landslides, power cuts and hundreds of thousands of dispaced people, resulting in aproximately 800 milion $ damage.

Despite the difficulties, Mozambique has one of the African highest potential in terms of arable land, water (as explained before), renewable energy, gas, coal and mineral resources. It is also located in a strategical position, with strong markets in five neighbouring countries, that give it the opportunity to become a leading African economy. Ensuring that all Mozambicans enjoy a share of that potential may be the country's greatest challenge.

1.2 Energy sector and electrification status

The country is rich in fossil and renewable energy sources and has emerged as a regional energy hub. It can boast 12 GW of hydropower potential (the highest among sub-Saharian countries), high solar potential (GHI can reach 2200 kWh/y in Nothern Mozambique), as well as important gas reserves in the Rovuma Basin and offshore in the Northern region of the country (700 bilion m^3). Mozambique also has world class reserves of coal, part of wich have sufficient quality to be exported.
The country’s vast energy resources are far in excess to satisfy domestic demand and the country is also well positioned to engage in significant regional trade with South Africa, the country’s largest purchaser of electricity. Despite that, the pro-capita primary energy consumption is among the lowest in the World, estimated at 0.44 TEP in 2014 (World Bank), more than 5 times lower than the italian value (2.48 TEP).

In the 2017 the overall electricity demand was 15,000 GWh, the majority of which was largely generated hydropower (56%) and thermal power plants (42%).
Cahora Bassa Hydropower is the largest power generation company, in charge of operating the 2,075 MW Cahora Bassa Hydropower plant and the associated transmission system. The generation sector is complemented by independent power producers, that has played an important role in Mozambique’s generation capacity expansion since 2014.

Access to grid electricity has expanded more than three times in past 10 years through grid extension and, among the 20 countries in the world with largest access deficit, Mozambique increased electricity access at a rate faster than the average.

On the other hand, the transmission infrastructures limit to further development. In fact, there is no internal connnection between the north, where electricity from Cahora Bassa comes from, and the

south, where most of demand is. Power from Cahora Bassa, is then routed to the southern system through the South Africa's grid.
Besides, Mozambique transmission network lacks resilience and very high energy losses (29%), in addiction to fragile economical condition of the national power company (Electricidade de Moçambique).
As a conseguence, about two-thirds of Mozambicans do not have access to electricity, which is below the average for Sub-Saharan Africa and with a remarkable disparity between urban and rural.

Along with technical transmission network issue, many other barriers to rural electrification have been identified:

- Scattered population.
- Lack of generation capacity.
- High investment cost and relatively low involvment of the private sector.
- Poverty and low household affordability.
- Inadeguate planning strategies, as well as policy support and monitoring.
- Lack of awereness of human and economical benefit of electrification.
- Unwillingness to change lifestyle.

There is also a declared intention to make a better use of renewable resources by means of off-grid systems, displacing off-grid diesel generators that are condidered problematic under a tecnical, ecnomical and enviromental point of view. Today the main options are pico/mini hydropower and solar photovoiltaic systems.

Recently new players have started promoting the solar market develpment, providing high-quality certified solar products with more flexible payment schemes.
Nevertheless, the price of these products is still not affordable for most of the population, except for few consumers located in urban and peri-urban areas of large cities. The conseguence is that the market is dominated by low-quality products, which are traded in informal (untaxed) markets, and which has negatively affected the consumer confidence in solar solutions.

1.3 Agriculture

The 22 percent of Mozambique's GDP is rapresented by the agricultural sector, which employs about 71 percent of the population and almost the totality of the poor and rural people.
Today this sector is dominated by smallholder farmers using family labour (97%), cultivating small plots of land ranging between 0.5 to 1.5 hectare (average of 1.8 hectare). For this farmers agricultural production is entirely rainfed and only a small group of them uses to sell their harvest in the local markets.
The remaining part is mainly located in the Southern region, consisting of small/medium private companies which can have access to credit and irrigation.

Mozambique has the largest, most accessible and fertile lands in the southern Africa. Natural vegetation covers about 78% of the territory and 45% of the whole surface is suitable for agriculture.

Moreover, its strategical position, between five neighboring countries and the Ocean, give the Mozambique the opportunity to become a large food exporter.
For these reasons, improving agricultural productivity is now a top priority for the country's leaders. Groundwater exploitation could help to achieve this goal but today, like in many other sub-Saharian countries, groundwater remains the ultimate source of irrigation water when surface water have been depleted. In Mozambique, in fact, only 0.54 % of the total area equipped for irrigation makes use of groundwater (AQUASTAT, 2017).
The internal renewable groundwater resource is estimated at 17.0 billion m³/year, which is largely higher than global Mozambique water demand (1.47 billion m³/year in 2015 ,70-80 % for agricultural purpose).
In conlusion, the groundwater recharge is more than enough to sustain the current and future agriculture demand (at country level) but its usage is still limitated to provide drinking water in large urban and rural areas. Ensuring Mozambique to benefit of this huge potential will be challenging and will require complementary infrastuctures, such as electrification services.

2.THE SPATIAL ELECTRIFICATION TOOL (OnSSET)

OnSSET (Open Source Spatial Electrification Tool) is an open source optimization tool based on GIS data (Geographic Information System) that has been developed by the division of Energy Systems Analysis of the KTH Royal Institute of Technology in Stockholm. Its source code, documentation, and example data can be found on the KTH-dESA GitHub (Python implementation), provided under an Open Source Initiative MIT License.
To the current state, OnSSET has supported electrification efforts in many countries around the World including Afghanistan, Nigeria, Ethiopia, Kenya, Tanzania, Madagascar and Benin as part of joint collaboration with the World Bank and the United Nations. In addition, OnSSET has featured in several publications including the World Energy Outlook in 2014, 2015 and 2017.

It is a high-level analysis tool for the assessment of the most cost effective way to electrifeid the population of the study region, basing on the minimization of the ***levelized cost of electricity (LCoE)***, defined as the ratio between the lifetime costs (investment and O & M) and the electricity generated. For the off-grid technologies it evaluated with the formual below:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where:

I_t = investment cost.
M_t = O & M cost.
F_t = the cost of the fuel, that in this analysis it is not taken into account because non-renewable off-grid technologieds (diesel generators) are not considered, for the reasons explained in section 1.2.2.
E_t = electricity demand.
n = project lifetime.
r = discount rate, set to 7% in this study, which is the result of a short to long term analysis made by TredingEconomics.

The grid LCoE is evaluated as the sum of the average LCoE of the national generation mix plus the marginal LCoE related to the grid extention.
The country is divided into uniformly-sized grid cells (commonly ranging from 1x1 km to 10x10 km depending on the input data resolution), each with unique characteristics that influence electrification costs, such as energy renewable potential, population density, distance from the existing and planned transmission network, etc.

OnSSET outputs could help answer questions like:

• What is the most cost effective way to electrify the country population?

• What would it cost to provide universal electricity access and how does this cost change according to different residential consumption?

•How much new installed power would that imply?

OnSSET code basis is flexible and modular and resolution of analysis, GIS input data, technology types and costs can all be customized as needed. It is written in Python language and it takes advantages of GIS deckstop applications, such as QGIS or ArcGIS.

In this analysis OnSSET has been implemented to identify the least-cost electrification options between five different tecnologies:

- Grid intensification/extension.
- Mini grid systems powered by renewable sources (solar PV, wind turbines, small-scale hydropower)
- Stand-alone systems (Solar home systems or solar kit)

The results consist in a spatial distribution of the most cost effective technologies with their relative LCoE's, as well as overall values like overall investment cost, overall new installed capacity, population split in different tecnologies.

2.1 METHODOLOGY

The Onsset modeling process can be diveded into six steps:

1. The GiS inputs are combined in the settlement table. Each row of the table corresponds to a cell, whose various informaton (coordinates, population, elevation, GHI, etc.) are stored in the table colums.

2. The calibration of the table is implemented. It consists in the determination of the current electrification status and in the distinction between rural and urban cells, taking into account the projected country's overall population. This process is needed to couple national statistics with the model's geospatial data.
   A cell's electrification status is calculated by evaluating its population density, night-lights in satellite images, distance from the nearest road and from the existing transmission network. If a cell has bright night time lights, it only needs to have a high population or be close to the grid or a road. If a cell has low night-time lights, it can only be considered electrified if it has very high population, and is close to the grid or a road. The parameters that determine the cutoffs for night-time lights, road and grid distances are iteratively adjusted until the final population that is considered as electrified approximates the 2020 national statistic.
   A similar iterative process is implemented to couple the future urban and rural cells status with the national parameter wich accounts for the projected 2030 population and urban rate.

3. Once the imput settlement table is calibrated, OnSSET can run starting from the residential energy consumption tiers. An electricity demand is assigned to each unelectrified cell and it is possible to set different energy tiers for urban and rural cells.

4. The off-grid LCoE is evaluated in each cell for the different technology options. This process is relatively straightforward, using technology-specific parameters and geospatial data for solar, wind, and hydro power potential. The mini-grid LCoE is not evaluated by means of the grid exention algorithm, but considering a fixed distrution lines cost, which depends on the number of household per cell, the cell size and the cell peak power demand.

5. Grid LCoE's calculation is the most complicated part and takes place in two steps. The first step consists in assuming that all the cell already electrified are grid-tied and they are provided with the national grid LCoE. In the second step, all cells that remain unelectrified are evaluated for grid-extension with the condition that the addictional MV lines lenght required to connect the unlectrified cell has to be lower than 50 km. This process is iterative and implements optimal extension paths to minimize extension costs for all feasible cells. Each time a new cell is identified for grid-extension, the grid effectively "reaches" that cell, making further expansion cheaper for other nearby cells.
   A penality function is used to consider the increase of grid extention cost based on particular territorial features. It accounts for the added cost considering five categories with scores from 1 (least) to 5 (most). The following list contains these five categories and their weights: proximity to the nearest road (5%) and substation (9%), category of land cover (39%),

elevation (15%), and slope (32%). The Grid Penalty is capped at 1.25 for the least suitable cells, increasing the costs of MV power lines stretching from the HV line to the cell by 25%.

6. The off-grid and grid LCoE's are compared and the most cost effective tecnology is assigned to each row (cell) of the settlement table. Then the non-GIS output are evaluated (overall investment and capacity requirements, population spilt in different tecnologies).

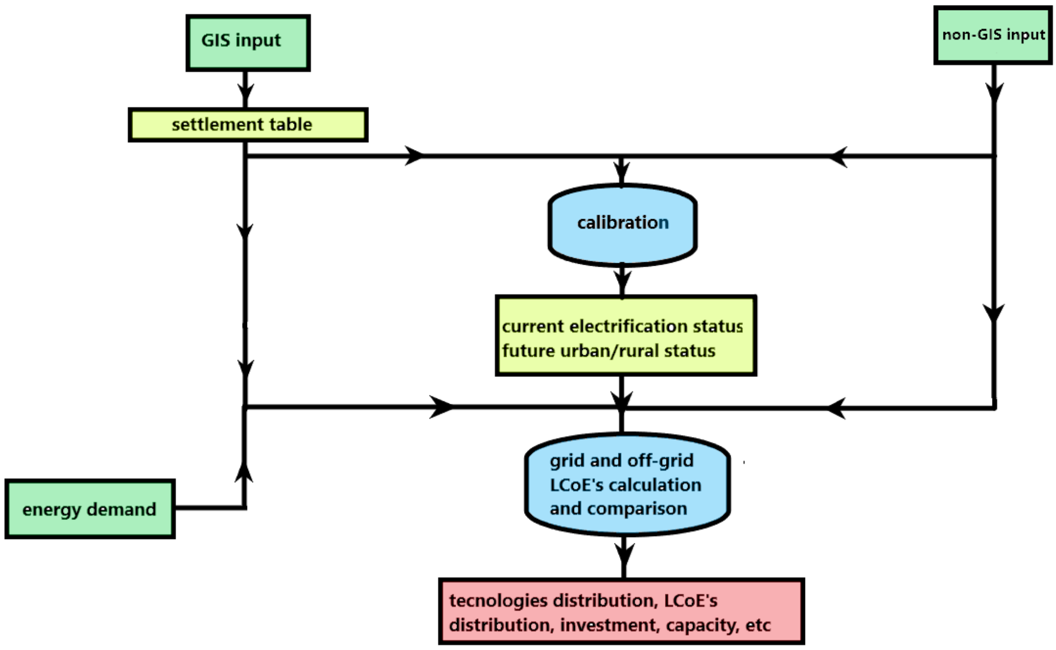


Figure 4-Conceptual Onsset scheme

The additional puping electricity is added at a cell level, assuming that is equally distribuited in each cell household and, hence, added to the residential demand. This could not rapresent a limitation since, at the time, the great mojority of farmers are smallholders that make use of family labour. By the way, the agricultural intensification assumed in the closure-gap scenario may change this asset, resulting in a more commercial schemes.

2.2 LIMITATIONS

Onsset is a large-scale modelling tool and, naturally, it has to consider a relatively simplistic evaluation of many aspects. The major limitations are:

- Iterative process based on night-time lights, population, distance from grid and roads is recognized to be not a very good tool to find electrification area with low consumption, especially if they lack street lighting (rural areas).
- There is no power-flow study to complete the grid extention simulation.
- The model do not provide temporal considerations about the electrification process.
- Planned HV lines are considered as equal as existing transmission network, taking for granted that they will be built.
- The quality of grid electricity is considered as good as the off-grid can offer. In many parts of the developing world, where bulk power systems have been shown to be very unreliable, this could not be true, to the point of negating the benefits of grid-connection.
- Onsset consider the only residential demand, which could not rapresent a limitation since, as explained before, the agriculture is mostly practised at household level.
- Chossing between only two consumption tiers could be limitating.

2.3 GIS INPUT DATA

Geographic Information Systems (GIS) are becoming more and more accesible and can provide a range of location-specific information in a wide range of study field.
They are very useful to assest analysis for large-scale projects and allows the researchers to quickly have a first idea of how and where tecnical, economical and computational efforts have to be spent.
The GIS based imput data involved in this analisys are raster and vector datasets. The first consists of digital aerial photographs, imagery from satellites and digital pictures, each pixel of them stores information about a specific feature. Vector data are points, lines and polygons that rapresents data in a dimensionless form.
A spatial resolution of 0.05 degrees (approximately 6 km) is used, making the number of cells equal to 27504, that is a good compromise between accuracy and computational effort.

2.3.1 Population distribution

Population density map is used in order to understand where population resides and where there is potential residential demand.
Gridded population is a raster type dataset, whose grid values indicate the number of people in each cell in 2020. Worldpop has developed gridded population layers for many countries around the World at 100 m spatial resolution.The layer has been resampled to the selected resolution and then calibrated to obtain the original overall population. Interpolation error is avoided, setting the cell population to zero where there are less then six people.

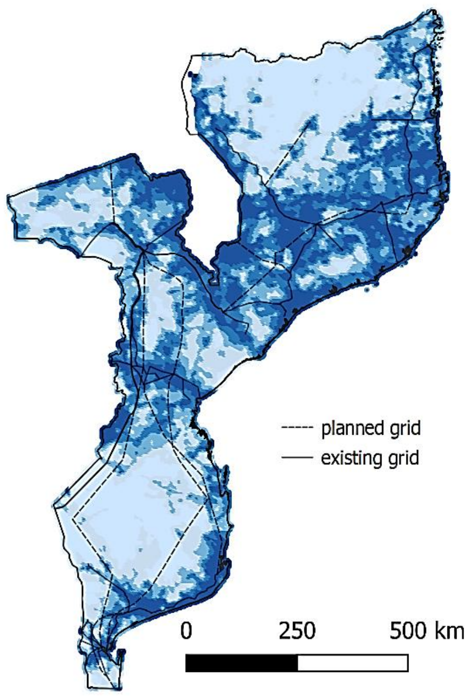


Figure 5-Population distribution, from 0 to 250,000 people per cell (6900 people/km^2)

As figure 5 shows, the majority of the population is not uniformely widespread but mostly concentrated in southern coast, in the central corridor and in the rural regions of the north.

23.46 milion of Mozambicans live within 50 km from the existing transmission network and this value rise up to 26.29 if we consider also the grid that is planned to be built in the near future.

2.3.2 Night-Time Lights

Night-time light raster layer indicates light sources on the surface of the study region using satellite imagery. Light pollution is one the most immediate and effective information to indentify electrified regions, but, of course, it is not immune to mistakes, as explained in the next lines.
The Visible Infrared Imaging Radiometer Suite (VIIRS) dataset is available at 250 m spatial resolution and provides a luminosity indicator (from 0 to 63) for each pixel.

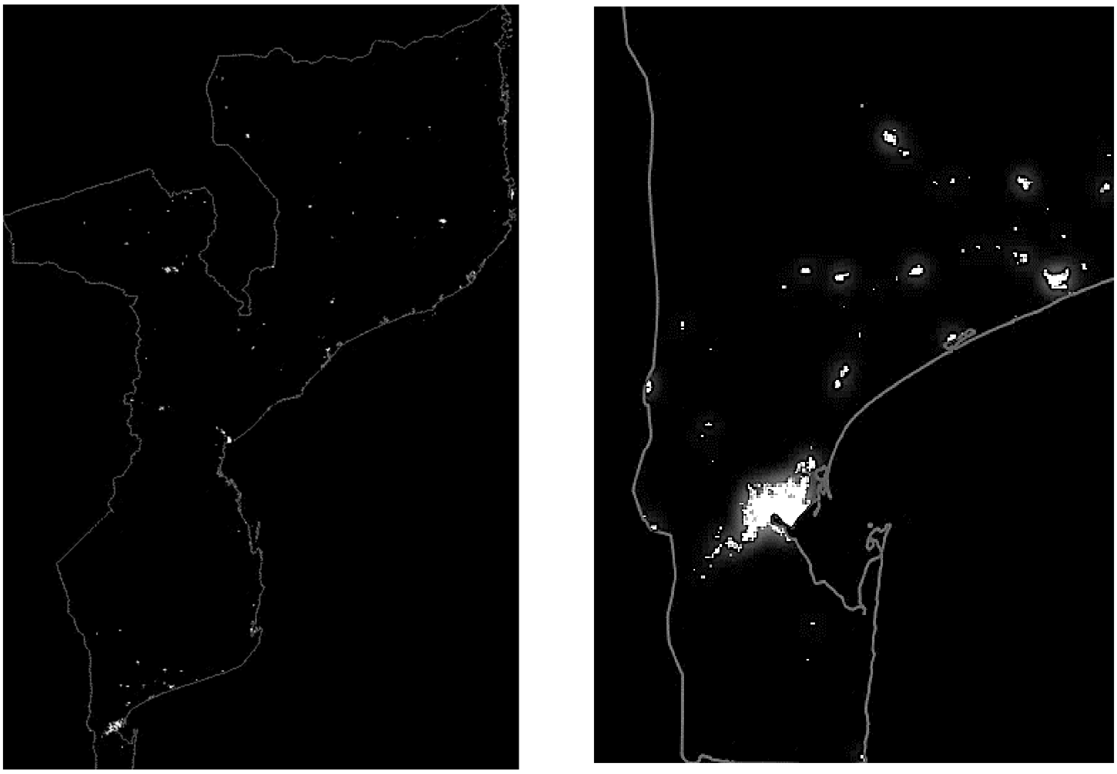


Figure 6-Night-time lights over the coutry (left) and over Maputo (right)

As it can be seen from the figures, Mozambique is a quite low illuminated country if compared with OECD nations. It is possible to locate the main cities: Maputo in the south, Beira and Tete in the middle region and Nampula in the north.
Satellite images are taken at regular times at night and compared to isolate transient light sources.
As explained in the section 2.2, they can lead to inaccuraties. In fact, in rural areas, where there is access but the consuption is low and street lighting lacks, it could under-represent electricity access. This is called “bottom censoring” and occurs when light levels are low enough resulting in light to be treated as transient.

2.3.3 Renewable resources

In order to estimate le LCoE's of stand-alone and minigrid solutions OnSSET makes use of three raster layer rappresenting the local energy potential.

"Energydata.info" provides global horizzontal irradiance maps for a several countries with a 100m spatial resolution. The dataset (expressed in KWh/m^2/y) is used to estimate the validity of solar based solutions, such as stand alone PV and PV minigrid. In the same way mean wind velocity at 10 m height map allows OnSSET to evalutate the wind capacity factor and the generation potential of wind turbines.

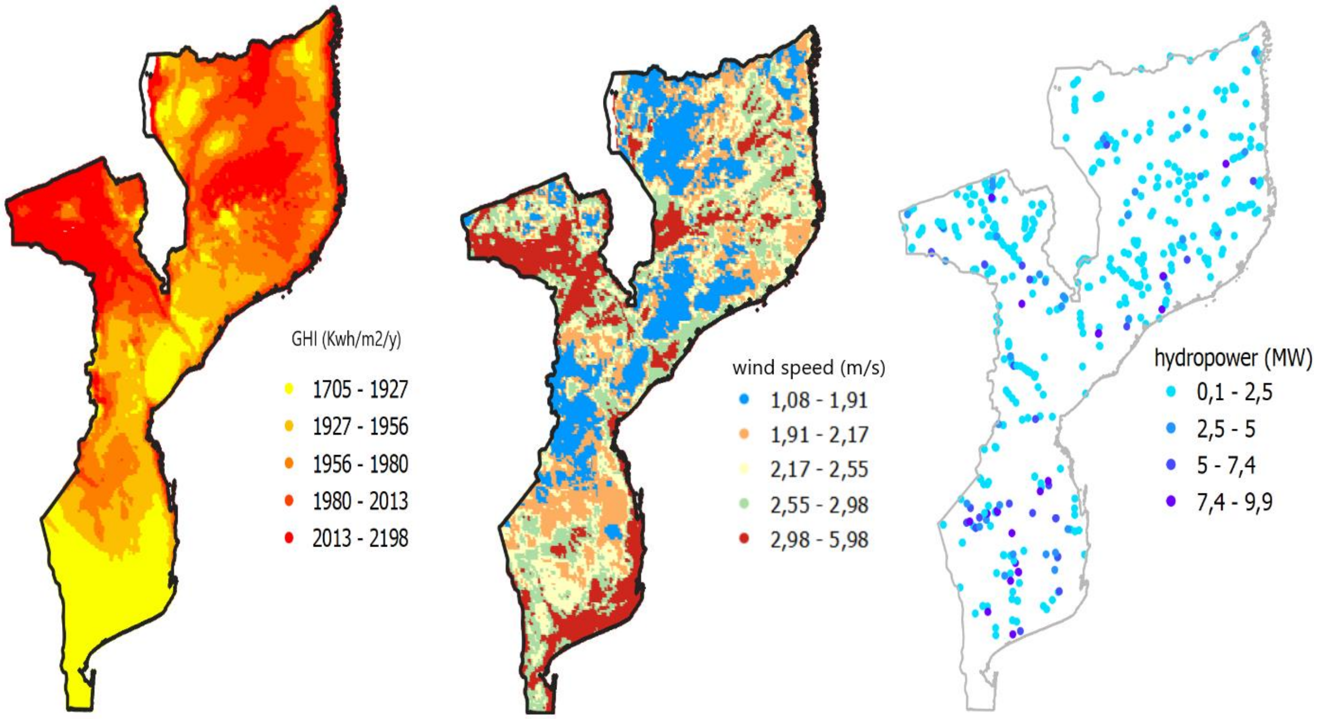


Figure 7-GHI, 10m height wind mean velocity, hydro-power potential

The hydropower minigrid are evaluated according to a point vector layer rappresenting the sites where there are the condition to exploit hydropower potential. This estimation is based on digital terrain analysis and hydrological modelling that provide data about head, discharge and potential power in each site. The cells are considered suitable for hydropower exploitation if they are located whitin 10 km from the hydro-power point.

According to the hydro-point vector layer, in Mozambique the average head of the hydropewer sites is 13 m and the average hydropower potential is aproximately 1.4 MW.

2.3.4 Territorial characteristics

A specif raster layer (figure 9) provides information about the Mozambique land cover. It distinguishes 17 different land covers, such as water bodies, grasslands, savannas, build-up zones, cropelands etc.

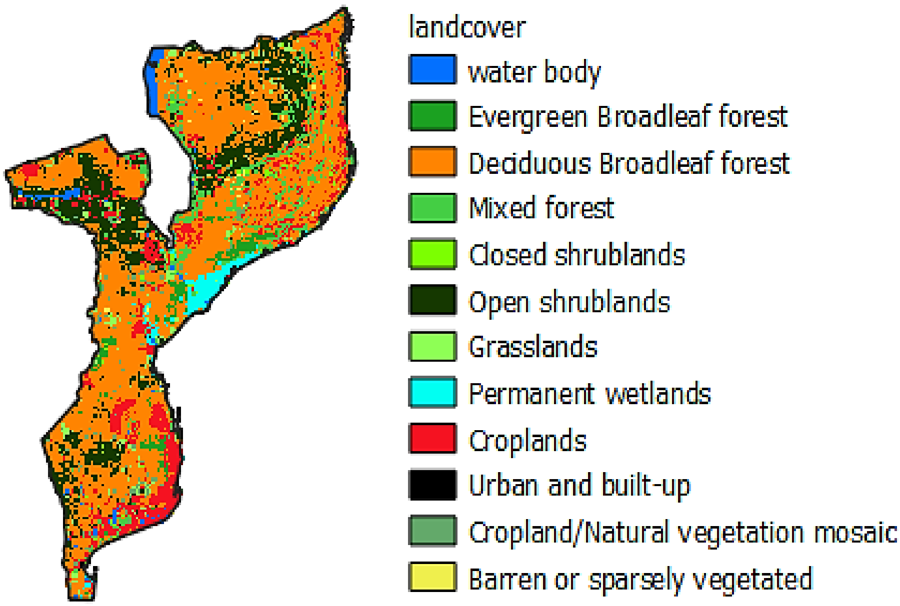


Figure 8-Landcover raster

78% of the territory is covedered with natural vegetations (in particular decidous broadleaf forest) and 45% are rapresented by arable land. The main croplands are located in the southern part of the country and, in the north, the small family farmlands merge with the natural vegetation. There is also a considerable expanse of open shrublands in the inland of the country.

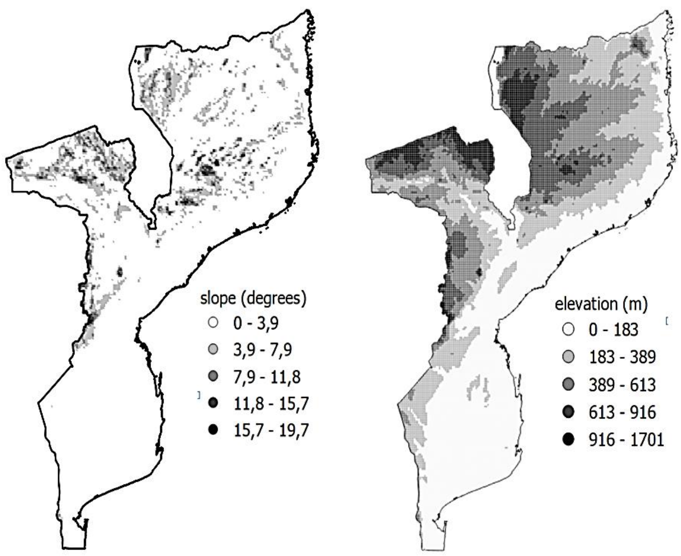


Figure 9-elevation and slope rasters

Two other raster layers (figure 10) aim to provide information about the elevation and the slope of the Mozambique territory and are used, together with the land cover vector, to quantify the grid extention cost increase due to inconvenient land condition, according to the penalty factor for the grid extention, as explained in section 2.1

2.3.5 Infrastructures

Main roads, planned and existing electric transmission network and electrical substations are involved by means of four different vector layers. These information, concurrently with the night-time lights layer, are used in order to estabilish if the cell is already alectrified and to distinct urban from rural areas. In the grid extention algorithm the planned transmission network is considered as equal as existing grid.

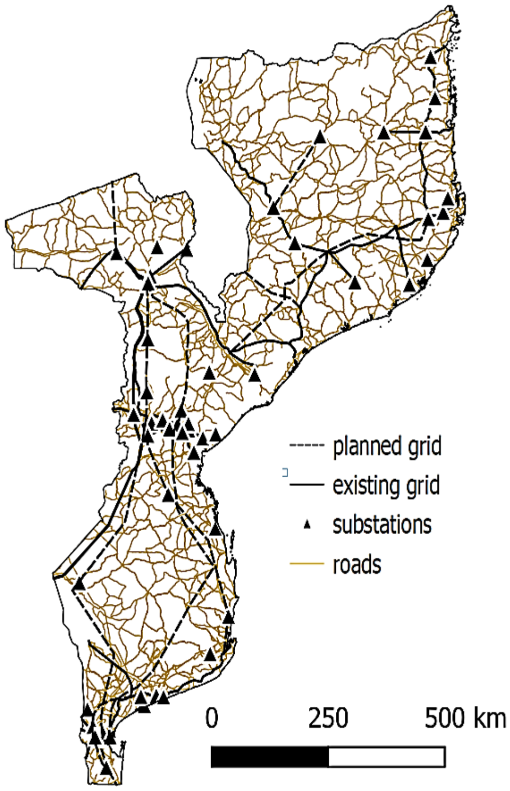


Figure 10-Infrastructures

2.4 NON-GIS INPUT DATA

In order to run the OnSSET, techno-econimic and demographic input parameters are used to estimated LCoE's and to calibrate the starting settlement table.

2.4.1 Demographic parameters

The current population of Mozambique counts 31.2 milion people and it is forecasted to reach 41.2 milion in 10 years (WorldPop). OnSSET estimates the electrical demand on the base of future population and of the average household size, which in Mozambique is 4.4 people for rural areas and 3.7 for urban areas. In the table below Mozambican demographic inputs are listed:

	population 2020	population 2030	rural HH size	urban HH size	urban ratio 2020	urban ratio 2030	electrification rate 2020
unit	people	people	people	people	%	%	%
value	31.2 M	41.2 M	4.4	3.7	38.3	44.2	27

table 1-demographic parameter

As said in the introduction, Mozambique urban rate is increasing at a lower pace with respect to other sub-Saharian countries and it is mainly effected by natural urban popultion growth rather than migration from rural areas.

2.4.2 Technological parameters

Technological parameters rapresent the most challenging non-gis inputs, because they are referred to the short-medium period and they reflect a fluid and a uncertain setting that is typical of developing countries. For this reason, similar project in simalar backgrounds are considered, making assumptions as likely as possible.

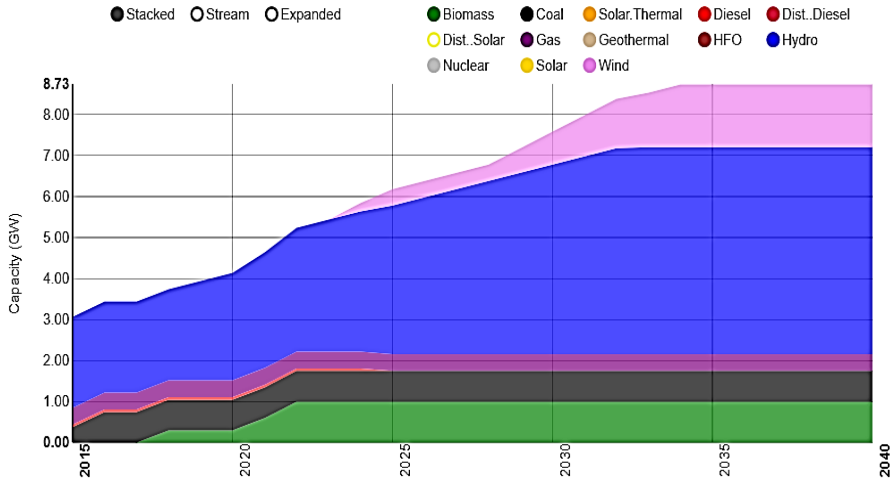
2.4.2.1 Grid

As explained in section 1.2.2, the national power network is supplied by Electricidade de Moçambique (EdM) and by Cahora Bassa hydropower company which are in charge of generation, transmission and distribution. Power transmission is rapresenting a critical issue for the country for several factors:

- not prospereous macroeconomical and power market situation.
- retail tariffs do not recover the cost of power generation and distribution.
- capital expenditures for rehabilitation of the grid are not adequately funded.
- weak link between the northern of the country, where Cahora Bassa hydropower plant is located, and the southern region, where most the electricity demand is.
- Cahora Bassa hydropower first sells electricity to Eskom (the South Africa electricity public utility), which in turn sells the power back to southern Mozambique at an increased price.
- high electricity losses, estimated at 29.8%.

In this study the grid weakness is ignored, considering the willingness of the Mozambique government to enhance this issue by way of the costruction of the planned transmission line (figure 10). It is also declared that the energy losses will be reduced from 29% to 19% by 2023 and, in the same way, this value is used in the model.

The capacity investment is the cost per unit power needed to increase the grid generation capacity and the grid price is the LCOE of the grid-generated kWh. Both parameters are estimated according to the projected generation mix, coming from TEMBA (The Electricity Model Base for Africa), an open source model initially developed for the World Energy Outlook 2014.



	capital investment ($/Kw)			
	2020	2023	2030	2035
BIOMASS	4447	4412.5	4332	4105
COAL	2080	2080	2080	2080
GAS	1021	1021	1021	1021
HYDRO	1777	1788.4	1815	1929
WIND	1940	1906.7	1829	1743

Figure 11-Projected generation mix and capacity investments (TEMBA)

Mozambique has one of the highest african hydropower potential and in the next future it will further increase its exploitation. Installed power fed by biomass and coal is expected to be constant, reducing their share.
As a result, the new grid installed power investment is set to 2250 $/Kw, which is the averge of the mix generation over the next 10 years.
A similar methodology is applied to evaluate the LCoE of the grid-generating KWh and the result is 0.10 $/kwh.

		SHARE	SHARE	SHARE
	LCOE ($/kwh)	2018	2023	2030
BIOMASS	0.08	0.00	0.13	0.10
COAL	0.12	0.11	0.14	0.10
GAS	0.08	0.15	0.09	0.07
HYDRO	0.10	0.74	0.64	0.69
WIND	0.03	0.00	0.00	0.05

Table 2-World average LCoE's and their share in Mozambique generated electricity (TEMBA)

The high large-scale hydropower share makes the grid LCoE slighty higher with respect to other similar countries, in which it can be lower than 0.05 $/KWh. As explained in section 2.1, this value is the starting point to evaluate the exented grid LCoE, adding the marginal deriving from transmission and distribution network.

The base to peak ratio parameter rapresents the ratio between the average consumption over the 8760 hours of the year and power pick. Onsset is implemented to model only the residential consumption and a typical tier 3 household consumption, able to support 4 led lights, 2 phone charger, 1 radio and 1 medium-size TV, has a base to peak ratio of 0.5.

	losses	Grid capacty investment	grid price	Base to peak ratio	max grid extention
unit	%	$/kW	$/kWh	%	km
value	19	2250	0.10	50	50

Table 3- Grid parameters

The cost of the grid extention depends on several parameters that are as important as hard to assess. In this study they are based on previous studies in others rural areas of Africa. The imput used in this analysis are presented in the following table:

	HV line	MV line	LV line	Transformer
unit	$/km	$/km	$/km	$/unit
value	53000	7000	4250	4250

Table 4- grid specific cost

Since there are not specific studies refering to the cost of HV/MV/LV lines in Mozambiqure, the only way is to compare the OnSSET results to existing papers that deal with the cost of electrification in a more general form. According to “The cost of providing electricity to Africa” (Orvika Rosnes, Haakon Vennemo), this cost is estimated at about 500 $ per urban household. Concernig the rural households, the connection cost ranges between 550 and 4300 $ in Tanzania and it is aproximately 2000 $ in Mozambique and Zambia.

2.4.2.2 Off-grid

Off-grid technologies are a valid solutions where it is not possible or not convenient to grid-connect an household. In this analysis stand-alone PV and solar/wind/hydropower minigrid are considered.

Stand-Alone PV

Solar home systems in Africa are small systems, with typical capacities of 20 W to 100 W, that provide off-grid electricity services.
There is a substantial difference in scale and configuration with respect to OECD countries, where small-scale solar rooftop systems are almost always grid-connected and range between 1 kW and 5 kW (10-250 higher than the typical African systems).
They usally provide only DC power, with no need for an inverter but requiring an expensive battery for nighttime use. This DC system directly powers the system's electrical load, generally highly efficient LED lights and/or other small DC-powered appliances, such as radios, televisions, mobile phone charging ports and USB chargers.

In the recent years the off-grid solar market has been developing thanks to the support of 25 small/medium business that are active or have an interest to enter in the market in the near future.
They typically purchase basic solar products that meet the Lighting Global Quality Standard at an average price of 126 $.
At the same time, the market is dominated by the so-called informal traders, which sell low quality products mostly coming from China, Tanzania and South Africa, avoiding to pay taxes. It is common that people living in rural areas buy basic solar kits at half of the "formal" price without receving warranty nor assistance.

OnSSET estimates the cost of the stand-alone PV starting from the specific capacity investment (expressed in $/KW); than it evaluates the required capacity considering the electricity peak demand and the capacity factor, which reflects the solar potential of each cell.
This methodology is typical of OECD PV rooftop systems that, as said before, are very different in terms of size and configuration and it is hardly implemeted when the size of the systems is not customable and of the order of few tens of Watts.
For these reasons i chose to assess and compare two cases:

1. The stand-alone PV systems are solar kits, like those purchased in informal traders. In this case the solar potential is not considered and the installed capacity is fixed with respect to the specific solar kit. The available solar kits are based on the local informal market but their price are doubled in order to ideally provide quality certification, warranty and payment of taxes.

the figures 12 shows a typical solar market in Maputo with its typical products and prices.

Figure 12-informal markets in Maputo, 1MZN = 0.013 $ (ECA, GREENLIGHT, "Off-Grid Solar Market Assessment in Mozambique")

The device 2, for example, can provide electricity to run 3 LED lights, 1 phone charger and 1 radio.

device	informal price ($)	formal price ($)
2	51	102
4	739	1478

Table 5- Solar kit price

2. The PV installed capacity is estimated according to the conventional OnSSET method, considering first the electricity peak demand and then the capacity factor. In this case the stand-alone price is expressed in terms of USD per installed kW.
   In this analysis i will refer to the typical african PV system price, that can vary in a very wide range (6000-14000 $/kW), according to the IRENA 2016 dataset.

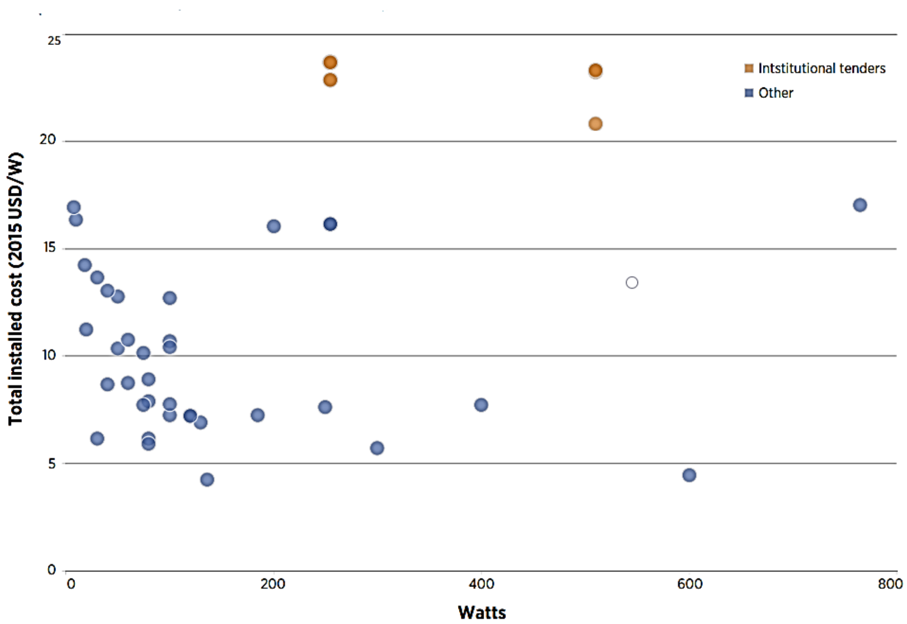


Figure 13-Per Watt investment cost of small SHS in africa, IRENA renewable cost database (2016)

First, i will consider the average price for pico-solar and sub-1kW systems (**11250 $/kW** and **9975 $/kW**) and then i will make the price vary in the whole range.

PV mini-grid

According to 6 existing african mini-grids with a 100% solar fraction, objects of ESMAP's study, the average capacity investment cost is 8362 $/KW and the distribution accounts for the 24% of the total cost.

country	PV size (KW)	CAPEX ($)	distribution cost (% of CAPEX)	investment cost ($/KW)
Chad	40	296529	26	7413
Tanzania	16	265312	12	16582
Nigeria	100	639212	40	6392
Liberia	23	151969	24	6607
Zambia	60	602757	29	10046
Sierra Leone	128	400703	15	3130

Table 6- Solar mini-grid projects in Africa (ESMAP)

The capital investment parameter should not include the compenents used for distribuiting electricity, because they are already taken into account by OnSSET.

Looking at the recent past, the costs of key mini grid components fell 62–85 percent between 2010 and 2018, due to the diffusion of utility-scale solar PV parks and of the deployment of rooftop solar home systems. In the same way, the cost of lithium-ion batteries fell by 85 percent, driven by the increased use of batteries in electric vehicles and utility-scale storage projects. The reduction in the cost of energy management systems, the ever-increasing computing power of power electronics and chips, and the decline in their cost, have contributed to the decrising of the capital investment as well.

If the prices of mini grid components will decline by the same proportion by 2030, the upfront capital cost of a solar mini grid would fall by almost 22 percent.

Under these considerations the capital investment cost of PV mini-grid is set to **4957 $/KW.**

Hydropower mini-grid

Small-scale hydro is a very suitable option for rural electrification in Mozambique, which can boast one of the gratest hydropower potential (12 GW) in sub-Saharian Africa.

Its investment cost can vary significantly depending on the site, size, and the cost of local labour and materials.

The total installed cost for large-scale hydropower projects typically range from 1000$/kW to USD 3,500$/kW, but it is not unusual to find projects with costs outside this range.

For instance, exploiting an existing dam that was built for other purposes may have costs as low as 500$/kW, but projects at remote sites, without local infrastructure and located far from existing transmission networks, can cost much more than 3,500 $/kW.

Small projects have investment costs in higher range due to economy of scale.

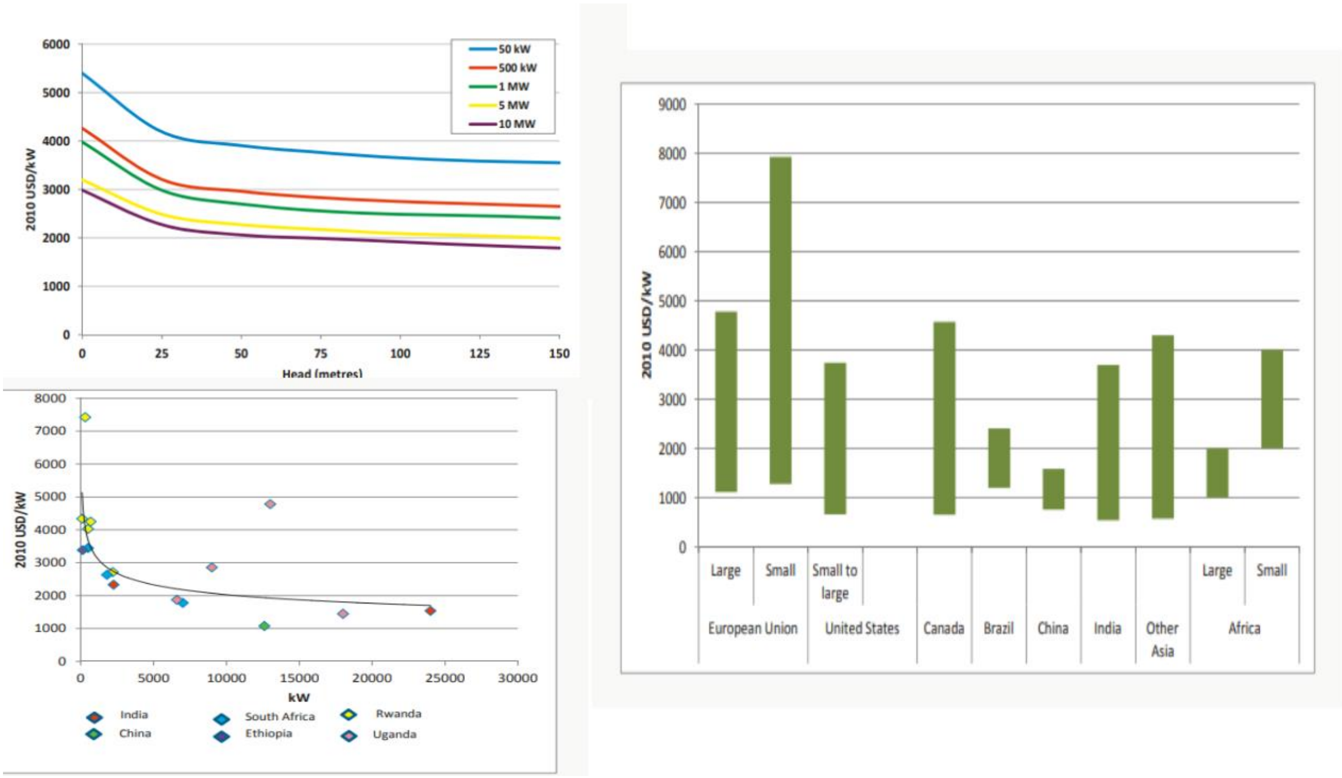


Figure 14-Hydropower capacity investment (IRENA)

According to the hydro-point vector layer, in Mozambique the average head of the hydropewer sites is 13 m and the average hydropower potential is aproximately 1.4 MW.
On the base of that, and using the hydropower IRENA database, the capacity investment cost has been set to 3500 $/kW.

On-shore wind mini-grid

Today the installed cost of wind power projects is currently in the range of 1 700 $/kW to 2150 $/kW for onshore wind farms in developed countries. There are considerable economies of scale in wind power developments, as projects under 5 MW have significantly higher total installed costs than larger systems. For example, In Mozambique the 0.3 MW pilot Inhambane project cost the equivalent of about 5000 $/Kw. Moreover, it has been observed that in many countries the costs per unit of planned project are higher then the unit cost of completed pilots.

In this analysis the capital investment cost is set to 5000 $/kW on the base of the only small-scale project in Mozambique.

2.5 RESULTS OF THE CALIBRATION

The first part of the analysis consists in the assesment of the already electrified cells and the distinction between rural and urban cells, as explained in section 2.1:

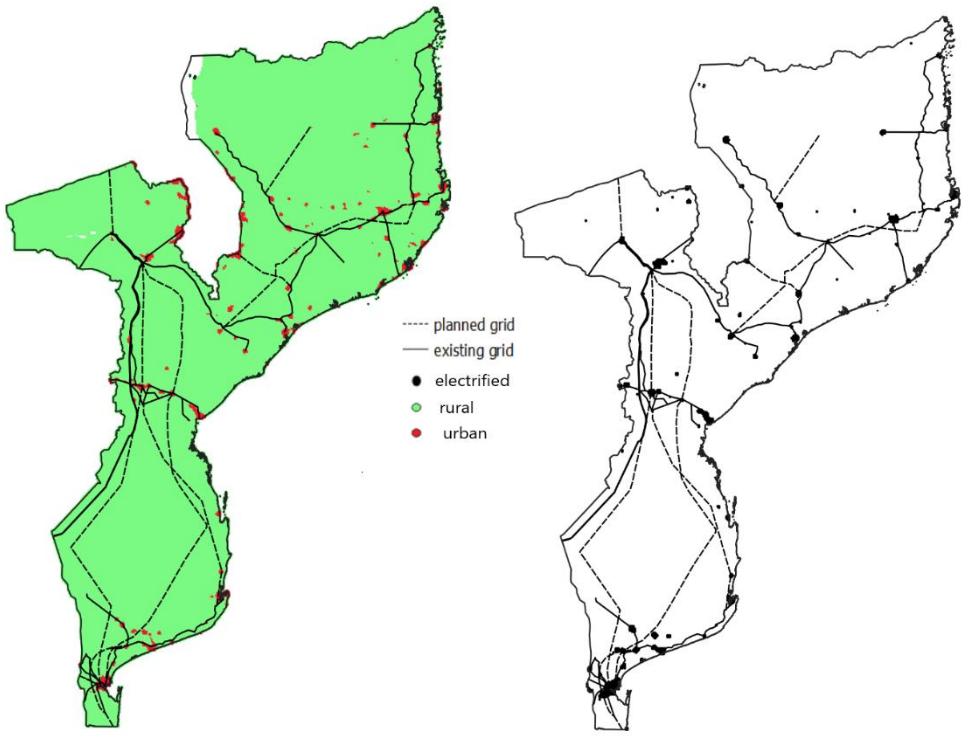


Figure 15-results of calibration

As figure 15 shows, urban population is concentrated in a few provinces: Maputo Province and Maputo City (in the south), Sofala and Manica (in Mozambique's central corridor) Nampula and Ligonha (in the north). The urban cells cover 2.8% of the whole territory and host 44.2 % of the 2030 population.

The electrified population is mostly concentrated in urban areas, near the existing trasmission network. In particular, the electrification rate results to be 68.3% for urban population and 1.2 % in rural areas. The rural electrification seems to be slightly lower than the national statistic (4-6%). This is due to the "botton censoring" effect concerning the nigh-time lights raster layer (setcion 2.3.2), that tends to classify low rural lights as transient light sources, especially where street lighting lacks.

As expected, a key factor is rapresented by the distance from the existing transmission network:

Distance from existing grid (km)	<5	5-10	10-20	20-50	>50
Electrification rate (%)	62.9	40.0	7.0	5.5	4.7
Unelectrified population (milion)	3.25	2.48	3.58	5.99	7.39

Table 7- electrification status as a function of grid distance

Starting from 10 km from the existing transmission network, there is a significant drop in the electrification rate, that continues to decrease with the distance from the grid with a lower pace.

3. ELECTRIFICATION FOR THE RESIDENTIAL DEMAND

In this chapter the results of the analysis are presented considering only the residential demand.

3.1 ENERGY DEMAND

The result of the analysis is presented for two residential electricity demand options:

-*Tier 1 consumption*: the household can support basic electrical devices (3 LED lights, 1 phone charger, and 1 radio) with a resulting **30 kWh/y**.

-*Tier 3 consumption*: the household can support a more advanced alectrification (5 LED lights, 3 phone-charger, 1 radio, 1 medium size LCD television and one 100 lt fridge) with a resulting **410 kWh/y**.

Onsset allows one to set different electricity demand for urban and rural households. In this analysis two scenarios will be considered:

-*Tier 1-3 scenario*, in which urban population are supported to make use of Tier 3 consumption, while rural are provided with Tier 1 consumpion.

-*Tier 3-3 scenario*, in which more effert are involved in order to provide Tier 3 consumption option also to rural households.

In the figure 17 the geographical distributions of electrical demand are presented:

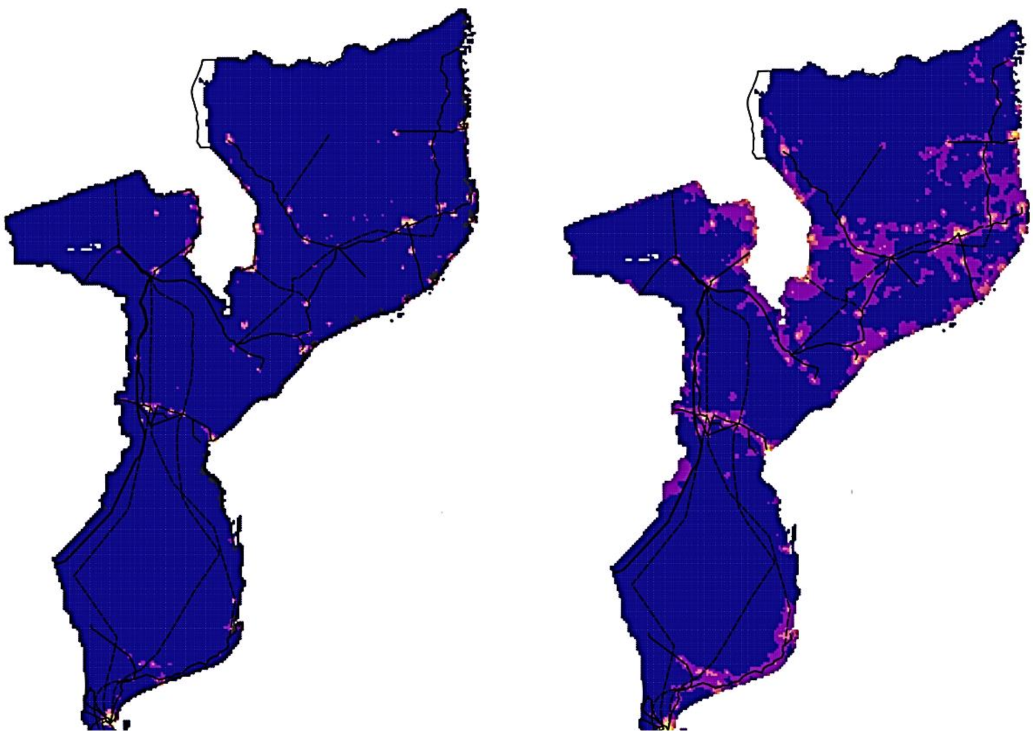


Figure 16-addictional residential demand distribution in tier 3-1 scenario (left) and tier 3-3 scenario (right), ranging from 0 to 14.5 GWh/y/cell

The overall electricity demand are respectively 1275.0 GWh/y and 3228.5 GWh/y. In the first scenario the majority of new electricity requirement (88.3 %) comes from urban areas. This values decreases to 34.8 % in the second scenario, where the large unelectrified rural population in the northern Mozambique makes the demand more widespreaded. In the soutern region, far away from Maputo and from the coast, the very low population density involves almost zero demand in both cases.

3.2 RESULTS

Onsset provides information about the optimum spatial tecnology distribution that minimize the LCoE, with its related installed capacity and investment requirement.
The stand-alone PV system appears to be a valid solution but, at the same time, it has a very wide installed cost range (section 2.4.2.2). For this reason, different specific cost are tested, based on local markets and on african market databese.

Besides, Onsset methodology consists in evaluating the installed capacity starting from the per-household electricity demand using the capacity factor, which reflects the solar energy potential. This could appear misleading when we immagine to buy solar devices from local markets, in where, at the contrary, the electricity demand, as well as the installed capacity, depends on the choosen solar kit and the PV potential is not taken into account. As a conseguence, two different case are considered, as explained in section 2.4.2.2.

3.3.1 First case

The stand alone solar solution price is based on Mozambique local solar products, whose price has been increased to take into accout duties, assistance and quality certification, as illustated in the section 2.4.2.2. The cost of PV system are set to 102 $ per household for tier 1 consumption and to 1478 $ per household for tier 3 option. The most cost effective technology distribution is presented below:

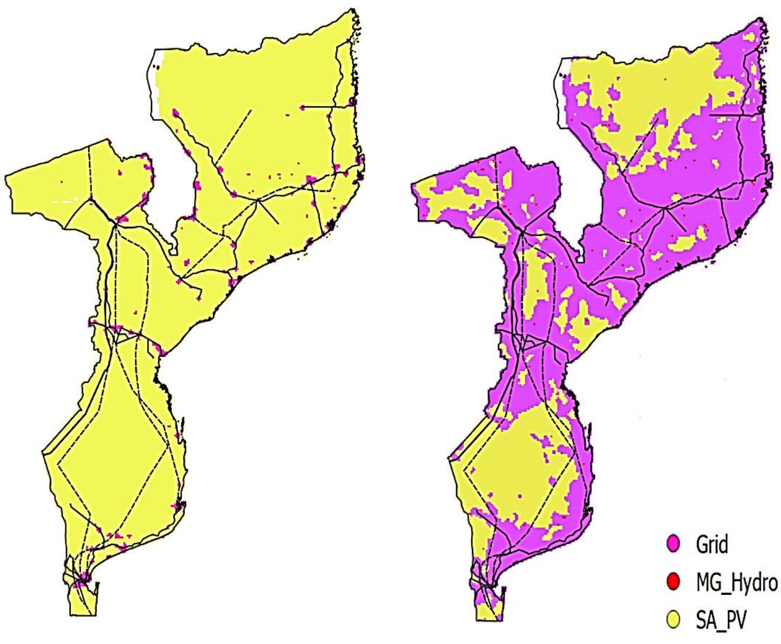


Figure 17-Optimal technology distribution in Tier 3-1 (left) and Tier 3-3 (right) scenario

In the Tier 3-1 scenario the stand alone PV device is the most cost effective solution for 22.56 milion of Mozambicans and 10.00 milion people can benefit of the connection to the national grid. The grid extention seems to be the best solution for only urban household, that require an higher electricity demand and that are relatively closed to the existing or planned transmission network.

On the other hand, in the Tier 3-3 scenario the higher electricity demand leads to a wider grid extension. In this case only 1.03 milion people benefit of electricity by means of stand alone solar devices and the 68.1% of new grid connections are located in rural areas.
In both cases the hydropower mini-grid seems to be the best solution for aproxinately 150,000 Mozambicans, with a different dispersion in the two scenarios. In the first case 15 cells are classified as MG hydro connected (2.42 MW of average installed capacity) and they are all located in urban areas.
Differently, in the Tier 3-3 scenario hydropower mini-grids seem to be more widespread and smaller sized (79 cells with 62 kW of average installed capacity), the majority of which (88.6 %) are located in rural regions.
The 25% of the stand alone solar solutions is located within 20 Km from the existing or planned transmission network and it regards low density population area, in which extend the grid would not be convenient.
In fact, low demand decreases the competitiveness of Mini-Grid and Grid investments, as higher LCOE's are required to recover fixed costs of distribution infrastructure. As a conseguence, more Stand-Alone technology solutions are required to reach 100% access in areas rural areas with low population density.

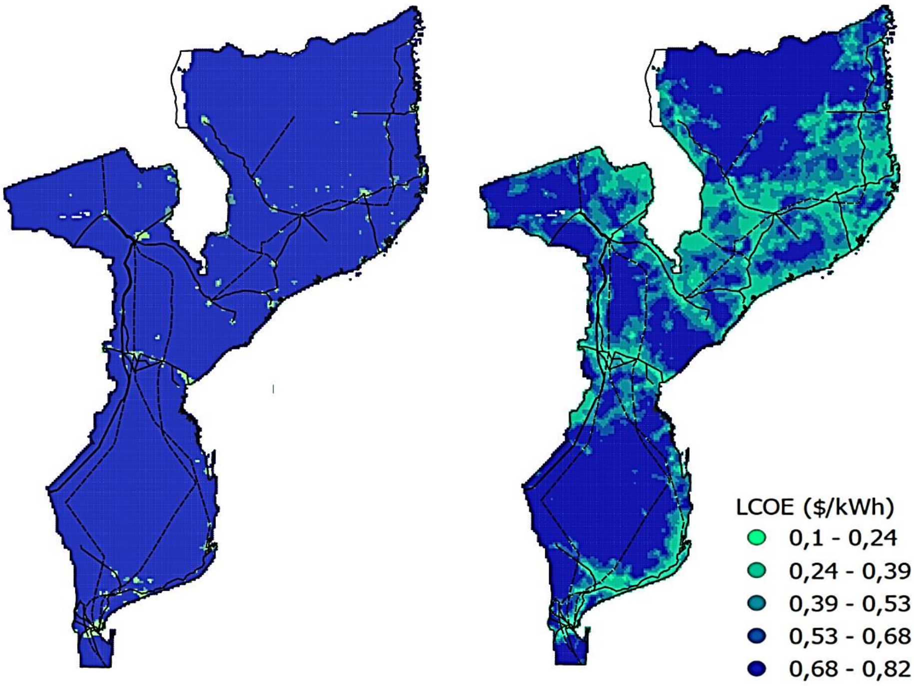


Figure 18-LCoE distribution in tier 3-1 (left) and tier 3-3 (right) scenario

The maximum LCoE are 0.773 $/kWh and 0.819 $/kWh and they are both dictated by the stand-alone solar solution. In the Tier 3-1 scenario the maximum grid LCoE is estimated to 0.402 $/Kwh and the its marginal cost is not enough to outpace the solar device solution.

In the Tier 3-3 scenario the maximum LCoE is higher but less scattered all over the country and it contributes to lower the average LCoE from 0.755 $/kWh of the Tier 1-3 scenario to 0.609 $/kWh.
It sould be noted that solar stand-alone LCoE's are fixed in the two scenarios, unlike the next case in which it depends on the capacity factor. On the other hand, grid LCoE's incresing with the distance from the existing or planned transmission network.

With a discount rate of 7% the investmets required to reach the 100% electrification goal are 2.14 B$ and 9.58 B$ respectively for Tier 3-1 and Tier 3-3 scenarios. The majority of these is intended for the grid extention (74.8 % and 95.9%), which recording an average of 1045 and 1429 $ per new grid-connected household in the two scenarios. The hydro mini-grid per connection investment is estimates at 946 $ in the first scenario and 1195 $ in the second one.

3.3.2 Second case

In this case the stand alone solar system cost is set to the african average of PV sub-1kW installations, as illustrated in the section 2.4.2.2.

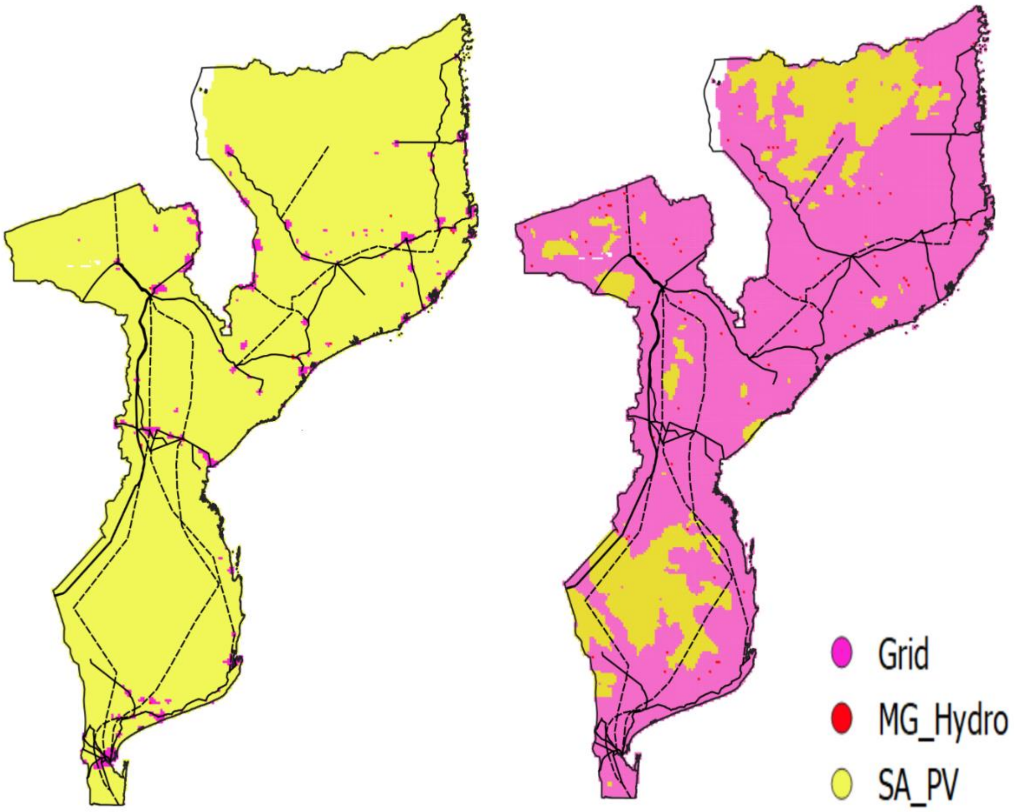


Figure 19-Optimum technology distribution in Tier 3-1 (left) and Tier 3-3 (right)

In the Tier 3-1 scenario the tecnology distribution seems to remain unchanged with respect the previous case. Still 22.56 milion people is electrified by means of solar home systems, the vast majority of which is located in rural areas.

In the Tier 3-3 scenario aproximately 231,000 Mozambicans make use of stand alone solar systems, about one-fifth compared the the previous case. Due to higher solar solution cost, the grid extention turns out to be the most suitable choice even for sites futher away from the transmission network. As a result, only 16% of stand alone solution is located within 20 km from the existing or planned grid, concentrated for the majority in the southern and northern low-populated regions.

The hydropower mini-grid seems not to be affected by the different PV specific cost and still about 150,000 mozambicans make use of this connection approach.

Even in this case the maximum LCoEs (1.654 $/kWh and 1,446 $/kWh) are dictated by the solar systems and they appear to be much higher, due to the specif PV cost. Unlike the first case, the stand alone LCoE is not fixed but depends also on the cell solar potential and particular high prices are observed in the south region, where the irradiance is lower (figure 8).

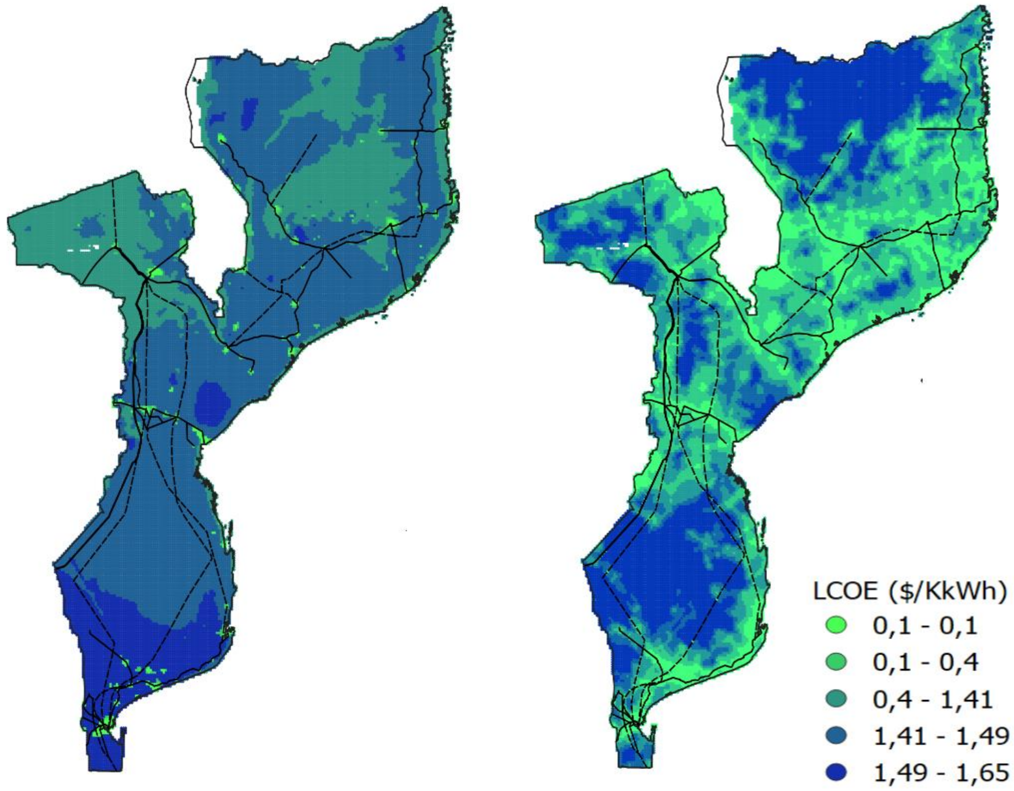


Figure 20-LCoE distribution in tier 3-1 (left) and tier 3-3 (right) scenario

In the Tier 3-1 scenario the maximum LCoE of the grid-connected solution (0.402 $/kWh) presents a gap with respect to the minimun stand alone PV LCoE (1.283 $/kWh), while there is not discontinuity in the Tier 3-3 scenario. As expected, the average LCoE is strongly influenced by the diffusion of stand alone solution and it is estimated at 1.398 $/kWh for the Tier 3-1 scenario and at 0.732 $/kWh for the Tier 3-3 scenario.

With a discount rate of 7% the investmets required to reach the 100% electrification goal are 2.58 B$ and 10.09 B$ respectively for Tier 3-1 and Tier 3-3 scenarios. Like the previous case, the majority of these is intended for the grid extention (62.0 % and 98.3 %). The average grid-connection cost is 1045 $ per household in the first sceanrio (like the first case) and 1501 $ per household in the tier 3-3 scenario (slighly higher due to a more extended grid diffision).
The average investment in solar stand-alone systems is estimated to 184 $ and 2272 $ per household, which are much higher than the local markets based price. For the hydro mini-grid, instead, it is practically the same as the previous case.

As exposed in section 2.4.2.2, the african solar home system cost vary in a very wide range and it would be intresting to figure out how the PV specific cost impacts on the final major outputs.

In the Tier 3-1 scenario even the lowest stand alone specific cost (4000 $/kW) is not enough to differently allocate the population, that is still dived in 22.56 milion with the solar PV tecnology, 18.52 milion grid connected and 0.15 milion with the hydropower mini-grid solution.
The figure 18 shows that the grid LCoE range is fixed with respect to the PV specific cost and it does not overlap the stand alone LCoE range. The reason behind this is that the rural consumption is anyway too low to promote the grid extention, even if the household is very close the transmission network. With specific cost lower than 4000 $/kW the stand alone PV system would replace the grid technology, starting from the grid connected cell that are more distant from the transmission network.

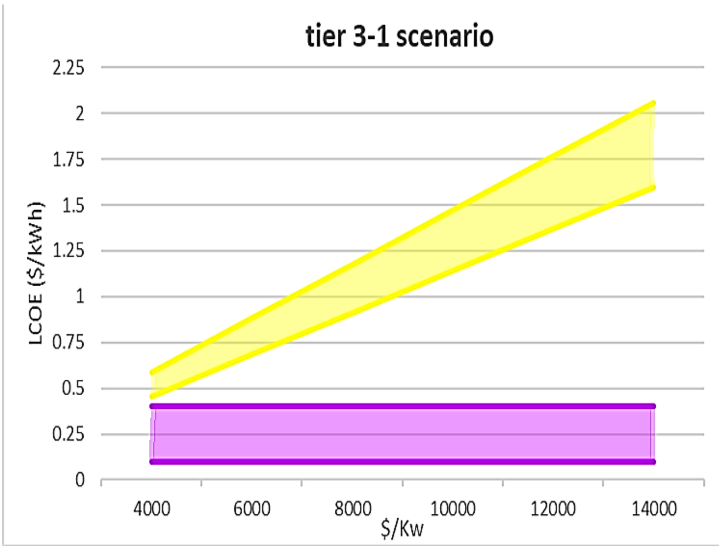


Figure 21-grid LCoE range (purple) and SA PV LCoE range (yellow)

The behaivor is different in the tier 3-3 scenario, in which the higher rural demand makes more feasible the grid extention solution. The stand alone cost, in fact, affects the number of Mozambican that can benifit of electrification by means of such solution.

As expected, the population electrified with stand alone solar devices decreases with the specific cost of the solar installations. In particular, there are about 4 milion people located near the transmission network, which can be easily grid connected when the stand alone specific cost increase from 4000 $/kW to 6000 $/kW.

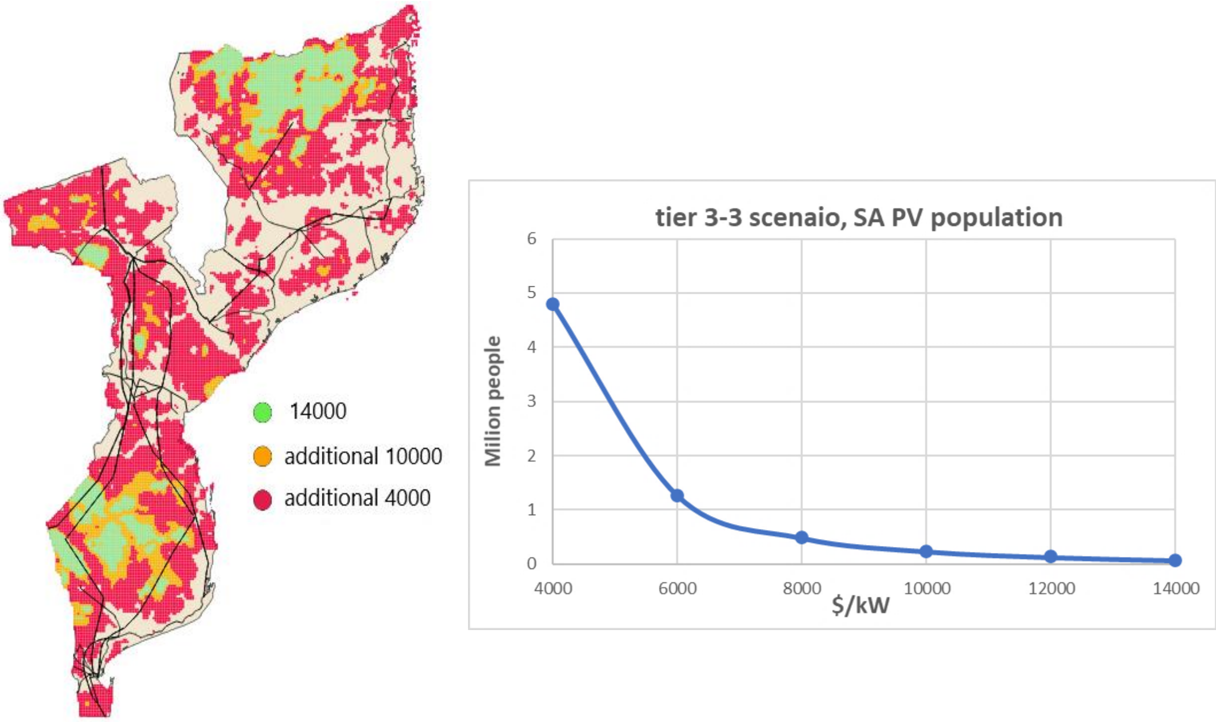


Figure 22-Changes in SA PV distribution, when SA PV cost is 14 $/W, 10 $/W and 4 $/W

In the Tier 3-1 scenario the average LCoE increase linearly with the stand alone PV specific cost, while in the second scenario the diffusion of the grid solution and the higher demand make the increase less pronounced.

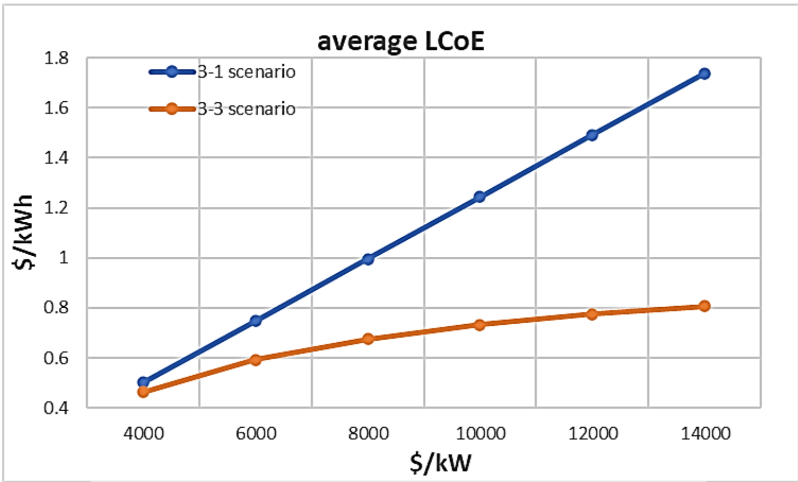


Figure 23-Average LCoE as a function of SA PV cost

As happened earlier, the investment cost is dominated by the grid exention. In the high demand scenario it has higher incidence and it helps to mitigate the incresing stand-alone specific cost, stabilizing the total investment at aproximtely 14 bilion $. In the tier 3-1 scenario, at the contrary, expenditure in grid exention remains constant and the overall investment increases with specific PV cost

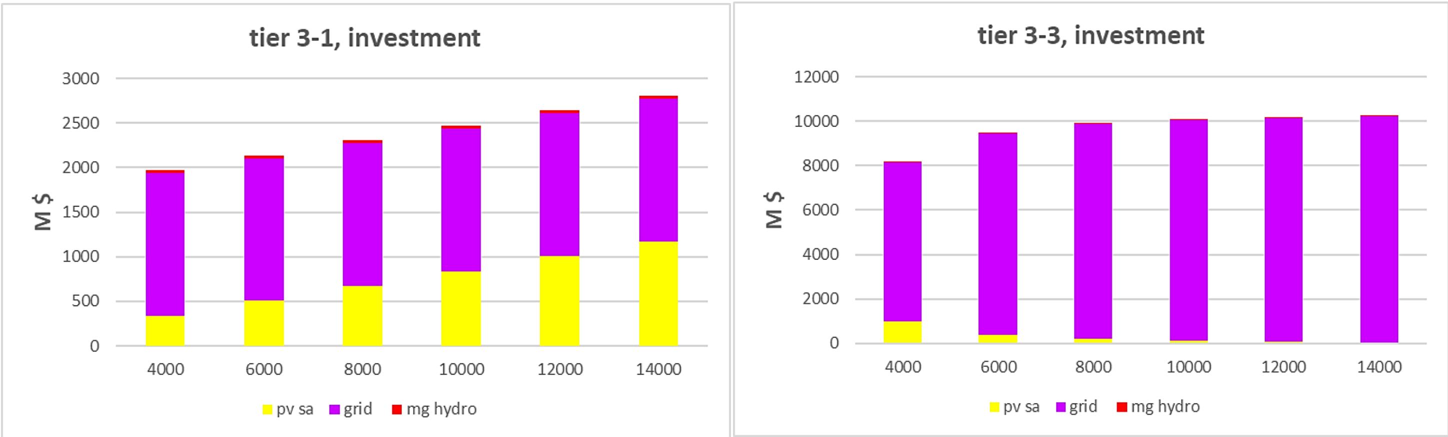


Figure 24-investment cost

The figure 25 shows the trends of the per-household connection cost for the two scenarios and for the two main tecnologies. It can be said that the stand alone connection cost used in the first case (on the base of solar market pre-set kits and without considering the capacity factor) corresponds to an equivalent cost of 6000-8000 $/KW, using the conventional OnSSET methodology.

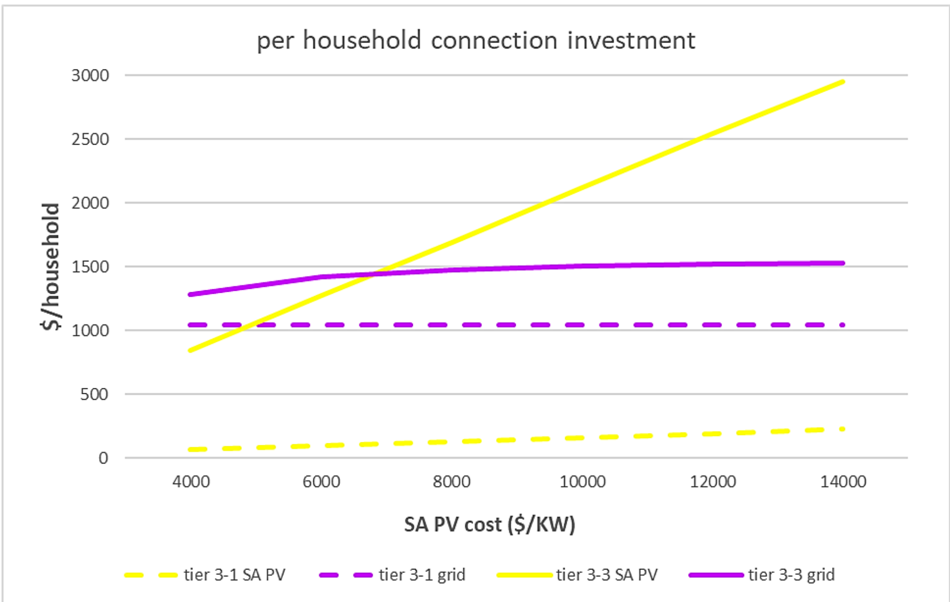


Figura 25-per household investment

4. ADDING THE PUMPING ENERGY FOR GROUNDWATER IRRIGATION

In this chapter it is evaluated the electricity demand required to lift the irrigation groundwater in a particular scenario in which agricultural intensification is praticed without occuring in deplention of water resources (yield-gap closure scenario).

4.1 Groundwater for irrigation

From 1950 to 2000 the global demand for irrigation groundwater has increased from 100-150 km^3 to 950-1000 km^3, but, as figure 26 shows, Africa still make a little use of it.
It is widely recognised that economical growth starts from the agricultural sector, and in the near past so it was for many developing countries, such as India, China and Pakistan.
These economies have drawn support from the exploitation of groundwater resources to increase the croplands yield and reduce the cost of irrigation. The same process is desiderable in sub-Saharian african countries, in which agriculture is the driving sector but the scarse use of modern irrigation techniques results in a very low productivity.
Most of these countries are experiencing ‘economic water scarcity’ due to lack of infrastructure investment, rather than ‘water resource scarcity’, as reflected by the recognised high groundwater potential. This means that the main issue related to the groundwater development in Sub-Saharan Africa is the high cost of water-well construction, mainly due to inappropriate well design and construction.
As a result, in Africa only about 1% (14 % in Asia) of the cultivated land makes use of groudwater.

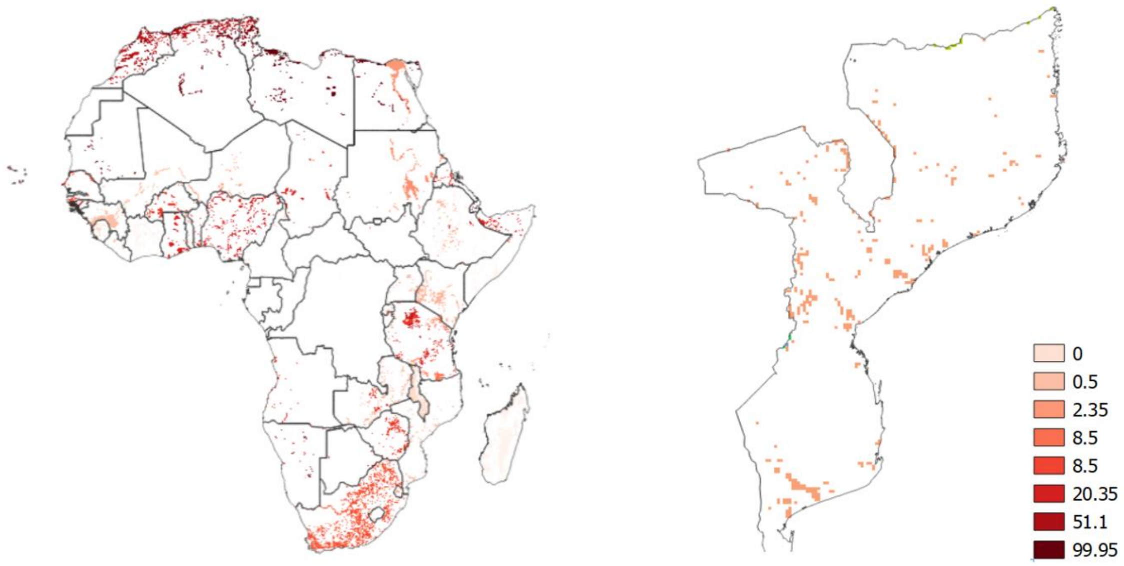


Figura 26-areas equipped for groundwater irrigation as percentage of the area equipped for irrigation (AQUASTAT)

4.2 The yield-gap closure scenario

In the near future african agriculture have to face four important challanges:

-enhance the production to feed the increasing population.

-generate job in order to contribute to reduce poverty, especially in developing countries.

-manage the water resources in a sustainable way.

-face climate changes

African population is quickly growing (projected 2.6%/year in the next 30 years) and it is becoming even more important to find a way to ensure food security without causing irreperable environmental impacts. Food production is one the most water-intensive human activities (it takes about 1 litre of water to produce 1 Cal of food energy, 3000-5000 litres per 1 Kg of rise), resultifng in the fact that water use grows at almost twice (1.7) the rate of population increase.
Climate changes will rapresent a further issue, altering rainfall patterns and affecting the availability and quality of both surface and groundwater. Warmer temperatures could benefit some areas, but negatively effect others, resulting in an overall negative impacts. Climate changes, moreover, could particulary bear down on smallholders, which are the backbone of the african agricultural sector.

In this context, increasing the productivity of croplands by means of *agricultural intesification* is not an option.
Agricultural intensification is a practice whose goal is to achieve the so called "yield-gap closure". This term refers to the difference between a crop's maximum potential yield and real yield, expressed as the amount of produced food per cultivated hectare. The maximun potential yield is defined as the maximum yield of a crop grown in an environment in which is perfectly adapted, with non-limiting water and nutrients supplies and without occurences of diseases. On average, the World's most significant crops (soybean and wheat) produce less than 50% of their maximum potential yield.

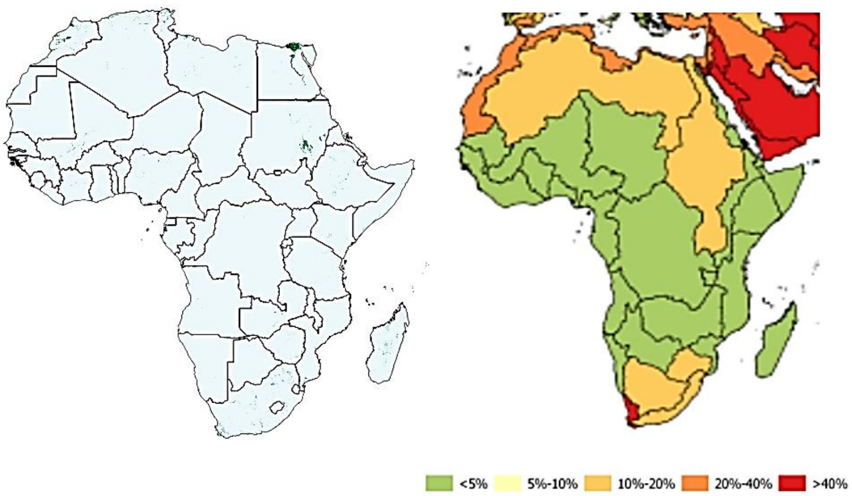


Figure 27-current irrigated areas (left) and water scarsity (right), expressed as the excess of water demand over availabe supply (AQUASTATS, Food and agriculture Organization of the United Nations)

These conditions cannot be obtained unless modern agricultural techniques are practiced. One of them is the irrigation, which is well-consolidated in developed countries, but it is still at an early stage in most of the sub-Saharian Africa. As figure 27 shows, in fact, irrigation is quite diffused in Egypt, Sudan, Morocco and South-Africa, countries that are all experiencing water scarsity.

The Polito's Hydrology Department has developed a GIS dataset that shows the amount of irrigation groundwater demand needed in the yield-gap closure scenario, in such a way that in each cell the withdrawal is lower than the water renewal. The required water for irrigation is calculated as the product of the fresh water requirement of a certain cropland and its respective irrigated area. The first value is the amount of water needed to satisfy the crop evaporative demand, substracting the contribution of precipitations and considering the change in soil water storage. It is then coupled with the local recharge groundwater potential, obtained by hydrological models.

The closure gap scenario accounts for both agricultural intensification in already cultivated lands and for exent of irrigation in raindfed croplands. In areas in which precipitaion are enough to support agricultural intensification the irrigation is not needed.

Accoriding to the figure 28, the African groundwater for irrigation would increase from 27.4 km^3/y to 99.3 km^3/y, with the major contribution from the sub-Saharian countries.

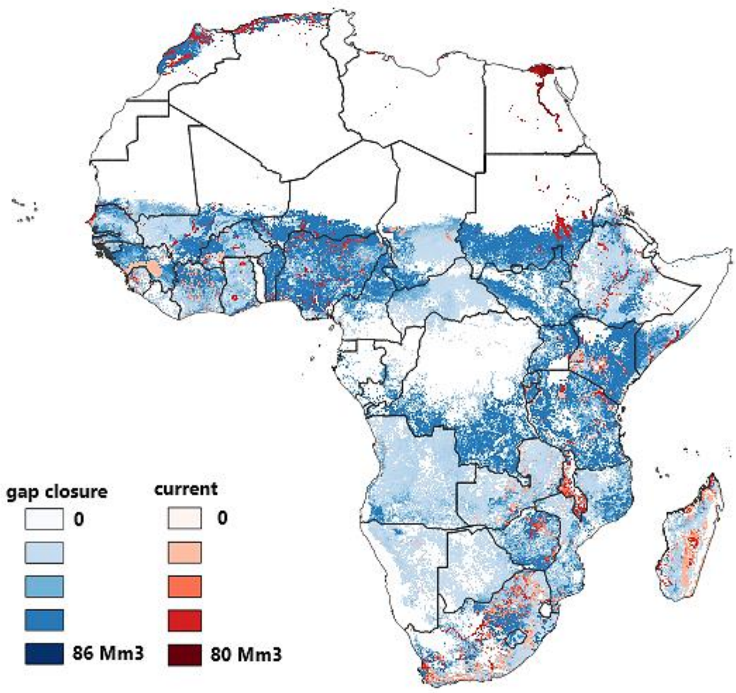


Figure 28 groundwater demand in current (red) and yield-gap clousre scenario (blue), POLITO Hydrology Department

As is clear from the figure 28, there is an impressive exension of irrigation in the great majority of sub-Saharian countries. The current groundwater withdrawal is higher in Morocco, South-Africa and Nigeria, as also figure 29 shows. The agricultural intensification will promote a great development of grounwater irrigation in country that makes a little of use of it. For instance, Congo irrigation demand will increase more than 6000 times, while Egypt, which makes already a large use of irrigation, cannot furher increase it without occuring in water resource deplention.

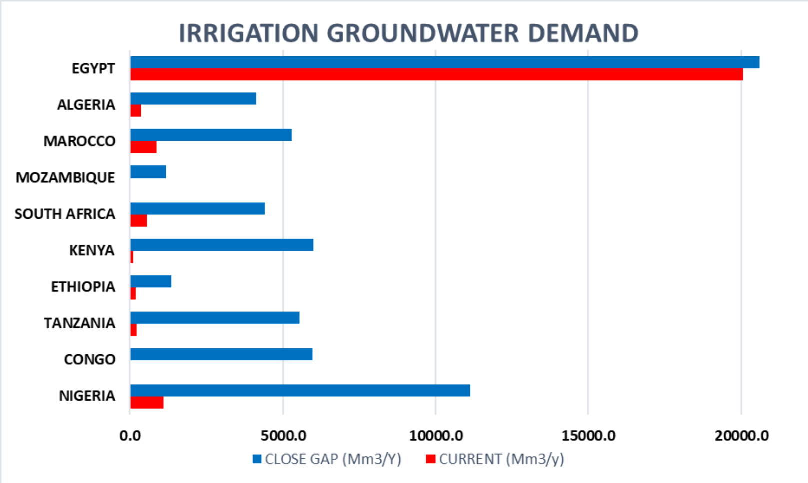


Figure 29-Current and yield-gap closure groundwater withdrawal (POLITO Hydrology Department)

The Mozambique groudwater demand will increase from 19.6 Mm^3/y to 1165 Mm^3/y (very close to the current overall irrigation demand), with a particular demand extension in the northern areas of the country. There is a region, in the south, where croplands are adeguately fed by precipitations and the increase of the irrigation water demand would not be rewarding.

As expected, the majority of the demand is requered in rural areas and aproximately 30% of the overall irrigation water requirement is located more than 50 Km away from the existing or planned transmission network.

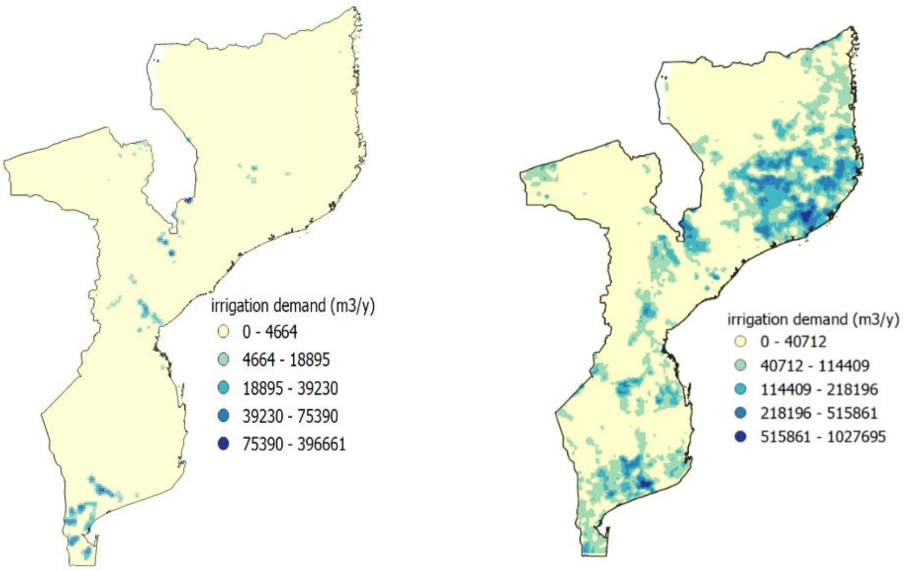


Figure 30-Mozambique current (left) and yield-gap closure (right) groundwater demand for irrigation

4.3 Energy demand

Electricity demand required to pump up the groundwater is evaluated according to the formula:

$$\boldsymbol{E} = \frac{\Upsilon * \boldsymbol{GW} * \boldsymbol{GWD}}{\boldsymbol{\eta}}$$

Where:

η= electrical efficiency, set to 0.75

ϒ=water specific gravity (9810 N/m^3)

GW = per cell groundwater demand (m^3/y)

GWD = per cell average groundwater storage depth (m)

The depth of the groundwater depends on the cell location and it is modelled using an empirical rules-based approach, according to rainfall and aquifer type, as well as proximity to rivers:

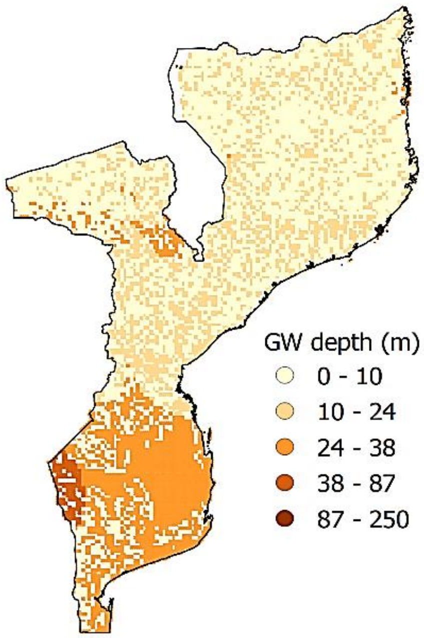


Figure 31-Average per cell groundwater depth (POLITO Hydrology Depertment)

With this assumptions the addictional energy demands due to ground water lifting results is shown in figure 32:

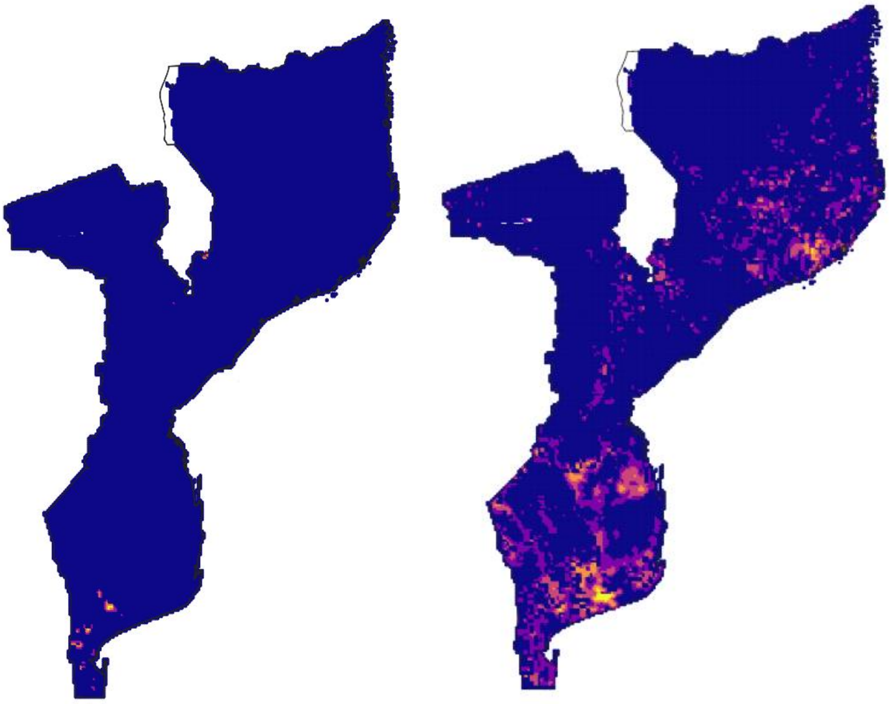


Figure 32-electricity required to lift groundwater in the yield-gap closure scenario (right) and current scenario (left)

The electricity demand results to be 1.029 GWh/y for the 20% scenario and 53.84 GWh/y for the 100% scenario. The demand distribution is vet different between the two scenarios, as well as the peask demand (11 MWh/cell and 127 MWh/cell).

As shown in figure 32, the relatively shallow depth of the northern region compensates for the high groundwater demand, resulting in a not extreme energy requirement. On the other hand, the combination of high water demand with high aquifer depth leads to remarkable electricity demand in several sites of the southern areas.

The electricity demand seems to be far away from urban areas, in low-populated areas, far away from the existing or planned transmission network. In particular:

	rural	<5 km	5-10 Km	10-20 km	20-50 km	>50 km
Closure yield-gap (GWh/y)	52.11	6.48	5.94	10.36	18.00	13.06
Current (GWh/y)	0.87	0.49	0.28	0.16	0.07	0.02

Table 8-additional electricity demand as a function of distance from the grid

In the yield-gap closure scenario 96.7 % of the pumping energy demand comes from rural areas, 55.8 % from sites more than 20 km away from the existing or planned transimission network. Including the fact the most of the southern demand is located in very low-populated areas, it could cause a significant change in the most cost effective techology distribution. This is surprending if we consider that the addictional electricity corresponds to to 4.1% of residential demand in the Tier 3-1 scenario and to the 1.6% in the Tier 3-3 scenario. This demonstates that even a very low demand increase can lead to a radical change in best solution choice and investment.

4.4 Results

In this section the results of OnSSET are discussed, assuming that the electricity to pump-up the groundwater is equally distributed in cell households, which reflects the small-scale agricultural structure of Mozambique. As said before, the introduction of groundwater irrigation schemes could lead to the diffusion of more-commercial activities, but in this study such possibility will not be considered. Since the electricity demand in the current scenario does not cause any relevant changes in the OnSSET outputs, only the yield-gap closure scenario is considered.

In accordance with the chapter 3, two cases will be considered in each scenario: the Tier 3-1 scenario and the Tier 3-3 scenario. They differ in the rural consumption, which is higher in the second one. In this case only the conventional OnSSET methodology will be proposed, because the addictional electricity demand is not uniformely distributed in rural population and it is not possible to assign a specific solar kit for each energy consumption level. By the way, the entire PV specific cost range will be explored and one can keep in mind that, as resulted from the previous chapter, solat kit price can be identified in the 6000-8000 $/kW cost range.

All the addictional irragation water is lifted from underground, resulting in sgnificant diffusion of mini-grids (both solar and hydro), where peak of electricity demand occur. In the figure below the technology distribution which minimize the LCoE's is presented:

In the same way as the previous results, the stand-alone PV solution is visibly more widespread when rural houesolds electrical consumption is set to 30 kWh/y and it is widely replaced by the grid extension when the rural consumption is brought to the urban level (410 kWh/y). In this case, however, one can notice the precence of a forth technology: the solar based mini-grid.

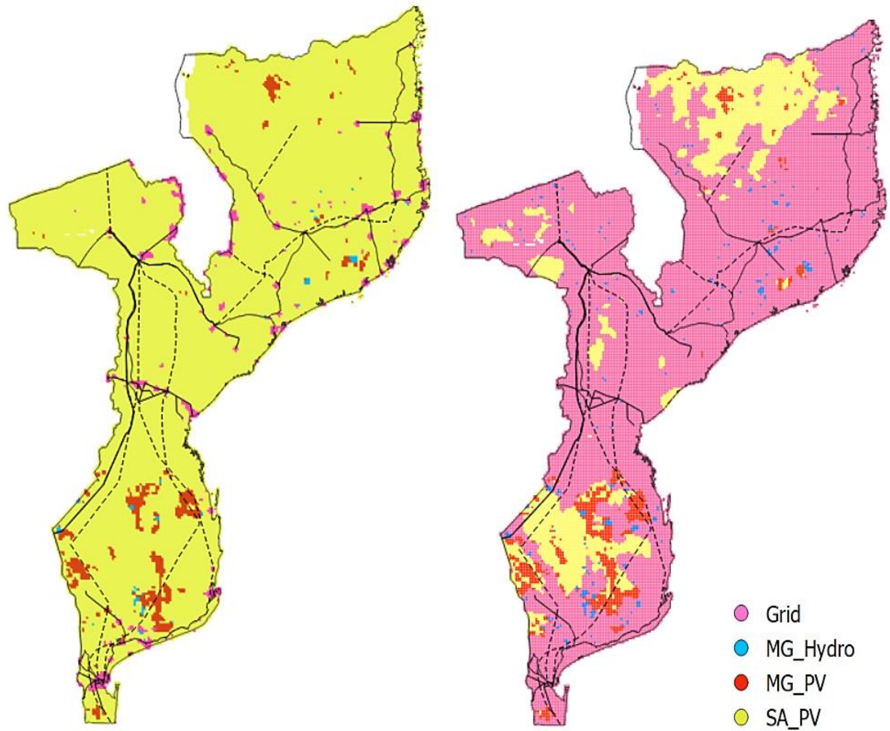


Figure 33-most cost effective technology distribution

This solution seems to be the best choice in cells with low population density and especially where high groundwater irrigation is needed. In fact, in the Tier 3-1 scenario, depiste only 159,000 mozambicans are electrified by means of PV mini-grid, it provide aproximately 26.5 % of the overall pumping electricity demand. This values decrese to 74,300 and 22.1 % in the Tier 3-3 scenario.

And 77.6 % (Tier 3-1) and 87.7 % (Tier 3-3) of new PV mini-grid connections are located in the rural southern areas. The table below shows the distribution with distance from the existing or planned network:

PV mini-grid new connections (thousands of households)				
	<5 Km	5-10 Km	10-20 km	>20 km
Tier 3-1	7.8	3.0	4.8	24.5
Tier 3-3	1.8	1.7	3.0	10.3

Table 9-Pv mini-grid new household connections

It is interesting to notice that also hydropower mini-grids benefit from the new electricity demand distribution, recording 43,800 (Tier 3-1) and 99,600 (Tier 3-3) extra connections with respect to the chapter 2 analysis. The grid connected population remain unchanged in the Tier 3-1 scenario (18.52 milion) and counts for 40.71 milions in the other scenario (150,000 people less with respect the only-residential demand case). This means that in few cells mini-grids are prefereble to the connection to the national grid, but in most of the cases they replace stand-alone solutions.

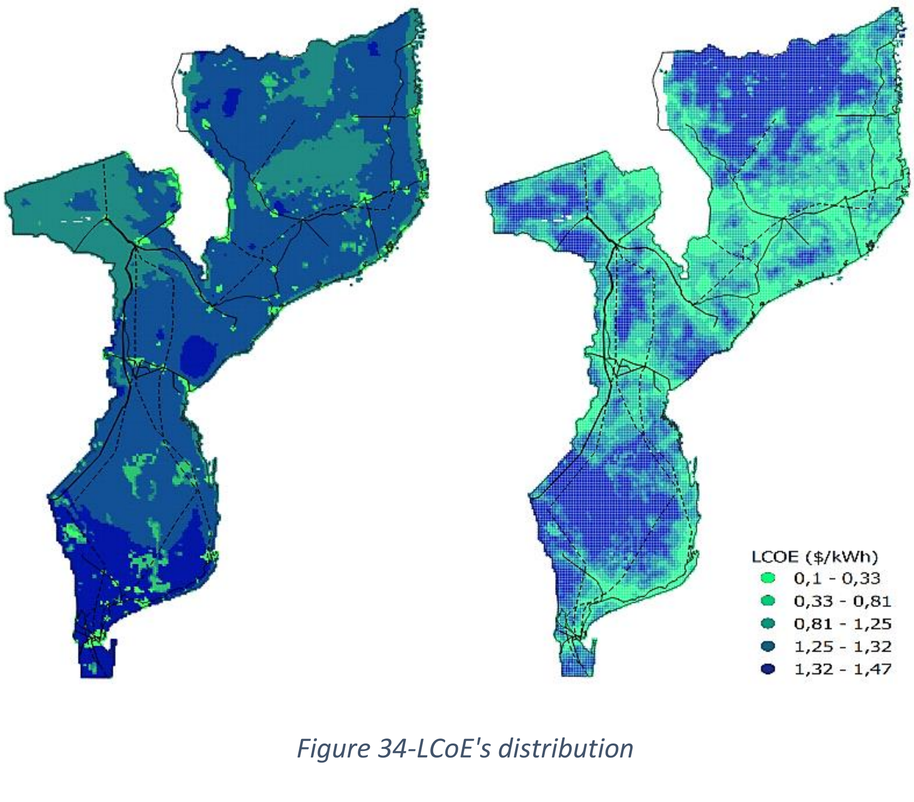
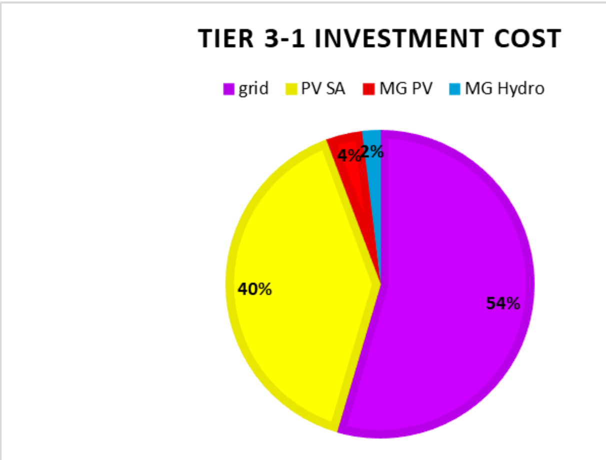


Figure 34-LCoE's distribution

The pumping electricity demand and the conseguent mini-grid solution contribute to lower the local LCoE, especially in the south region where low irradiance tends to make it higher. In the Tier 3-1 the average LCoE is 1.384 $/KWh (without irrigation it is 1.398 $/KWh).

In the high rural residential demand scenario the average LCoE results to be 0.720 $/KWh (0.732 $/KWh without irrigation).

For the Tier 3-1 scenario the overall investment required results to be 2.93 B$, higher whith respect to only residential demand case (due to the higher stand-alone PV installed capacity). In the other scenario, instead, it is almost unchanged (10.19 B$).



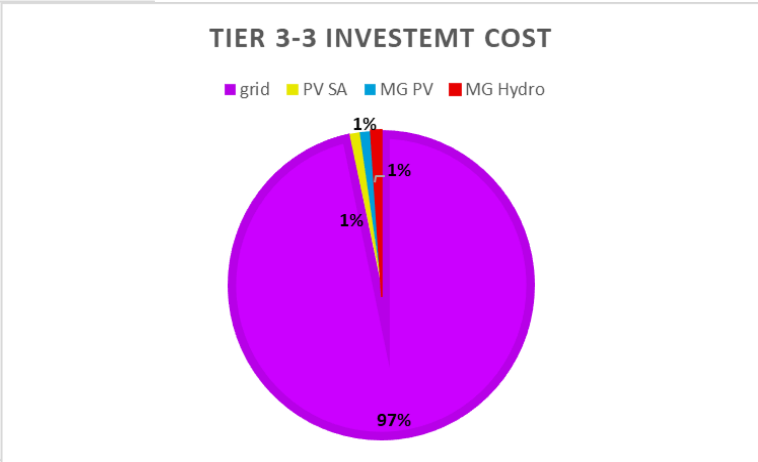


Table 10-investment share for the various technologies

In the 117 M$ and 102 M$ are intended to solar mini-grid respectively in Tier 3-1 scenario and Tier 3-3 scenario. The investment cost per household result are summarized in the table below:

per household connection cost ($)				
	grid	PV SA	MG PV	MG Hydro
Tier 3-1	1046	229	3094	1052
Tier 3-3	1498	2590	7086	1649

Table 11-per household average investment cost

The cost of PV stand-alone and grid connection remains almost unchanged with respect to the case in which only residential demand is considered. The high solar mini-grid cost is due to the higher installed capacity which, in turn, reflects the addictional power required for the groundwater lifting.

By the way the minigrid investment cost result to be 12680 $/kW (Tier 3-1) and 11037 $/kW (Tier 3-3), that are considerable higher that the reference price of 8362 $/kW assumed in sectiom 2.4.2.2. This means that distribution cost turn out to higher than the African average for this kind of techology.

per household average installed power (W)				
	grid	PV SA	MG PV	MG Hydro
Tier 3-1	93	20	244	121
Tier 3-3	95	259	642	146

Table 12-per household average installed capacity

The higher per-household installed capacities of PV mini-grid are due to their remarkable electrity demands, that are on average 420 kWh/y in the Tier 3-1 scenario (with respect to the residential 30 kWh/y) and 1106 kWh/y (410 of which for residential purpose). Besides, the majority of PV mini-grid new connections are located in the southern Mozambique, in which the solar potential is lower.

It should be noted that a uniform increase of the demand leads to the grid exention. In this case, instaed, there are few demand peaks in sites with a very low population density. The results is that in such cases mini-grid seems to be a better choice because the building of HV/MV lines, transformers, as well as network upstream renforcement, would not be rewarded by the low number of new connection, even if the household demand is relatively high. If the peak is more marked with respect to the uniform residential load, the solar PV mini-grid diffusion is wider. That is the case of the Tier 3-1 scenario.

As explained before, the specific cost of the stand-alone PV system is a very uncertain value, due to the particular sub-Saharian changeble and varied situation. For this reason, different PV cost are tested and the outputs are compared.

it can be said that in both the scenarios the increasing PV specifc price makes room for mini-grids solutions, which did not happend in the absence of the addictional pumping electricity demand. In fact, in the previous case the number of new connections by means of hydropower mini-grid is constant (150,000) and independent from the stand-alone specific cost. In this case, instead, it is possible to note a displancement of the solar stand-alone systems, which are substituted by solar and hydropower mini-grids.

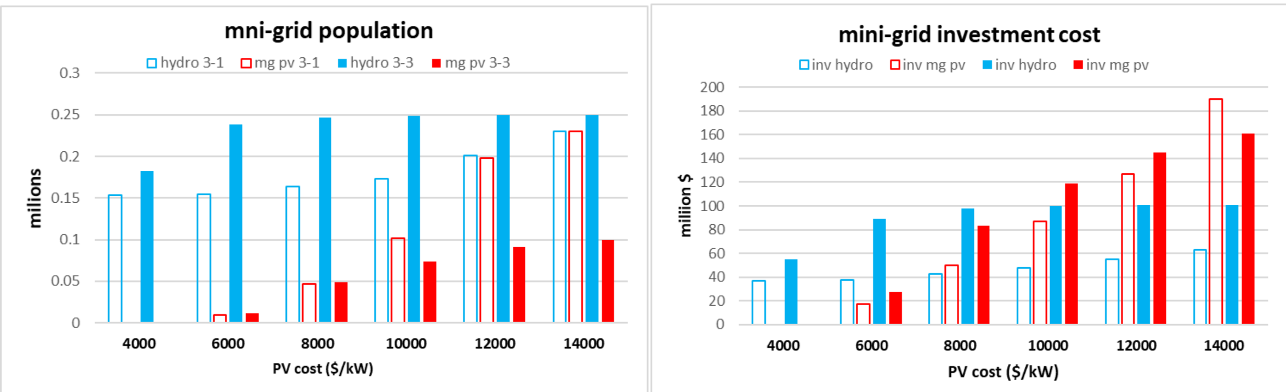


Figure 35-mini-grid population and investments cost as a function of stand-alone cost

In figure 36 the diffusion of mini-grid for two different stand-alone cost (6000 $/kW and 14000 $/kW) is illustred. The number of people connected by means of hydropower seems to be much higher in the 3-3 scenario than what it is. This is due the fact that in tier 3-3 scenario the hydropower mini-grid are suitable in very low populated area.

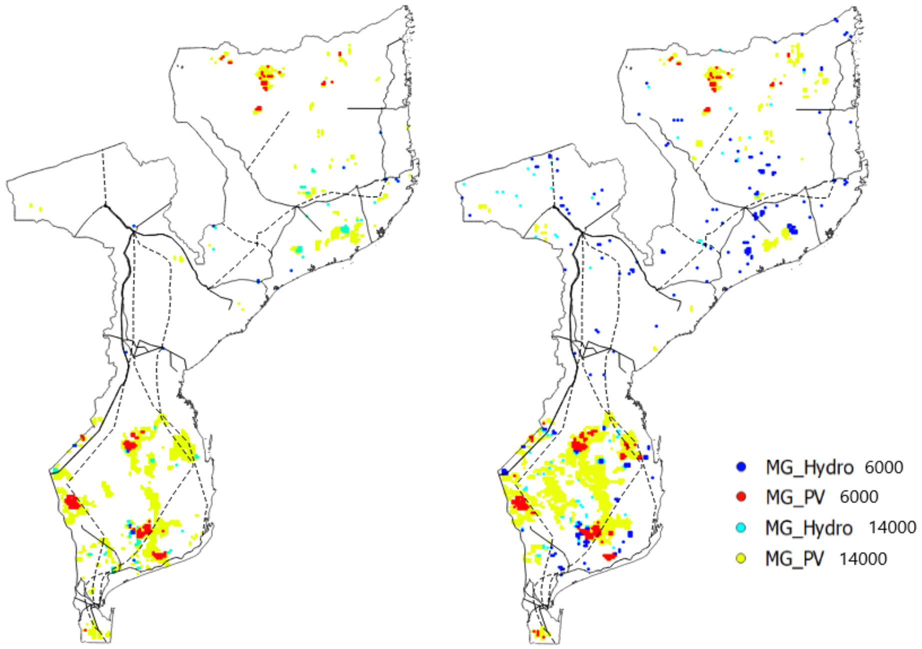


Figure 36-mini-grid distribution for PV cost of 6000 $/KW and 14000 $/KW, in Tier 3-1 (left) and Tier 3-3 (rigth) scenario

In the high rural demand scenario the grid-connection takes on part of the solar stand-alone displacement, while in the Tier 3-1 scenario the grid exension remains unchanged and whole PV stand alone reduction is covered by mini-grids, resulting in a considerable diffusion of them.

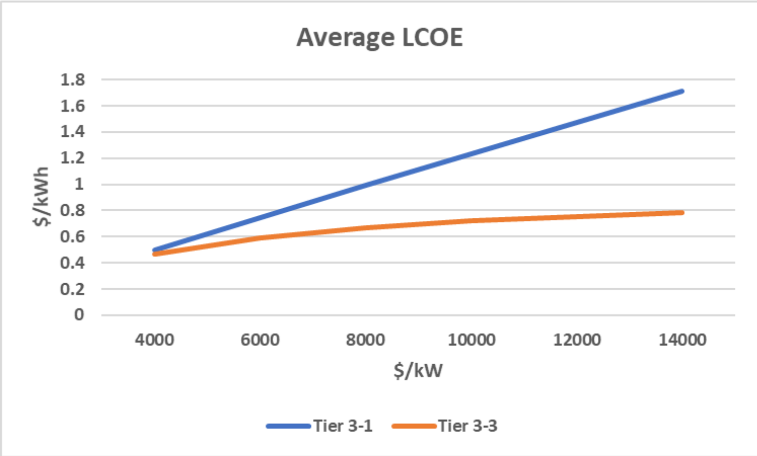


Figure 37-average LCoE as a function of PV stand-alone cost

Like the case of only residential demand, higher consuptions lead to lower LCoE's and grid exension contributes to offset the LCoE increase in the Tier 3-3 scenario.

The investment cost trend for household connection in show in the figure below:

Figure 38-per household investment cost and installed capacity, as a function of PV stand alone cost

With higher stand-alone specific cost the solar-PV solution become more suitable also for household with a lower electricity demand, resulting in smaller-sized systems. That is the reason behind the decreasing of the per-household investment cost, that is accompanied with an increasing of per-kW specific cost (from 8000 to 15000 $/kW).

5. CONCLUSIONS

GIS analysis is crucial in order to make a first assesment and to figure out how and where resources have to be channeled. Of course its functionality is limited by several factors:

- Inaccuraties of the input data. As shown in the study, a big number of GIS and non-GIS information have to be provided to the model. These data are often extrapolated from a varied and not stabilized context. Moreover they refer to the short/medium period, which increases the possibility that the model departs from reality. In this study the issue of the solar home systems price has been treated and it has been shown how different specific prices can effect the analysis outputs. For sure, due to the important role of the grid exension, cost of LV/MV/HV, transformers and other devices should be further analysed but, at the moment, the only way seems refering to similar studies in similar regions.

- Inaccuraties of the model. OnSSET is large-scale simulation tool and its aim is to provide a first idea of how and how much it would cost to electrify an entire country, assigning a certain consumption level to rural and urban population. The most crucial aspects are the calibration of the settlement table and the grid exension algorithm, as explained in the section 2.2. It do not consider the non-residential electricity demand, which could deeply effect the simulation output. Other limitations are listed in section 2.2.

Nevertheless, it is still possible to arrive at important conlcusions:

- The grid exension plays a very important role in the electrification process, especially when the electricity demand from rural households is significant. In fact, it is easy to understand that for cunsumption of the order of 30 kWh/y (the amount of energy consumed by an italian 4 people household in a few days) the grid connection is not an option and smaller-scale stand-alone or mini grid sysems are preferable, even if their specific cost is extraordinarily high. On the other hand, when consumptions are higher (but still not comparable with OECD levels) the grid connection become competive with the other technologies, whose cost can strongly effect the exension of the national grid. It has to be said that grid exension electricity is considered as good as the other systems can offer but this is not the case in many devolping countries, in which power generation and distribution is very unreliable.
  It is likely that, even for higher consumption levels, stand-alone systems or mini-grids based on renewable sources would remain the best choice in remote and low populated rural areas.

- Mozambique's groundwater recharge potential is more than ten times higher than the country overall 2017 water demand. It also has one of the largest amount of arable lands in south-eastern Africa and great commercial potential, thanks to the proximity to ocean and to five strong neighbouring markets. Groundwater irrigation could rapresent a key factor in order to ensure food security to its increasing population and, at the same time, to promote economical growth.
  The focus has been on the electricity required to lift the groundwater for irrigation in a particular scenario in which 100% energy access is achieved and agricultural intensification is practised. It has been shown that pumping electricity is a small fraction of the residential consumption (from 1.6% to 4.1%, depending on the scenario).

Nevertheless, its distribution (mostly located in rural areas with very low population density and far away from the national grid) promote the diffusion of hydro and solar mini-grids.
The majority of new mini-grid connections raplace the too expensive solar home systems in sites where there is a peak demand due to goundwater withdrawal.
As said before, the addictional electricity is relatively low and it is just a portion of the electricity required for the whole irrigation process. Despite this, it is sufficient, to strongly alter the technology distribution, promoting mini-grids and the intensification of rural and isolated peak demand would likely reinforce the validity of such solution.

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