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Hybrid microgrids for electricity production: techno-economic analysis of a system located in Meknassy, Tunisia

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Abstract

Hybrid micro-grid systems are a novel technology which is spreading worldwide and can represent a possible solution to the electrification issue, as deployment of these hybrid plants can be an optimum way to fully exploit renewable resources and meet local energy demands. In Tunisia, although access to electricity is guarantee, clean energy is not widespread at national level; however, RESs are abundantly available, hence the project developed wants to investigate the feasibility of a biomass and photovoltaic energy system located in a rural town in the central-western region of Tunisia, called Meknassy.

This work gives, firstly, a worldwide overview on technical aspects and favourable environment of micro-grids. Then, the Tunisian context is analysed: this is crucial for the delineation of a clear and predictable regulatory framework for the micro-grid feasibility.

The design of the plant is based on solar radiation and biomass availability in the community of Meknassy, which is composed of municipal organic waste, wastewater and agriculture and livestock wastes. Furthermore, the forecasting of the daily load profile of the electric demand is performed. Finally, the analysis of technical and economic aspects is implemented on HOMER Pro software which identifies the most viable solution.

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Introduction

Nowadays, electrification is not a good guaranteed at a global level. Too many people have any access to electricity and a great number can not rely on affordable electricity. Most of them live in rural areas in developing countries in Africa and Asia. The most important countries, such as India and China, make great progresses in this direction, but, frequently, the poorest states can not afford it. The most critical scenario is represented by rural towns and villages, since here it is often unfeasible to extend the national grid.

New solutions to this issue have been developed: solar home systems can be a first approach to electrification, but it is not enough to assure to families an appropriate way of living. Mini-grids are filling this void. Even if these systems can find applications in developed countries too, for example in order to manage fluctuations of renewable energies, their characteristics well suit this issue. Hybrid micro-grids are characterized by relatively low costs, generally, and the generation of electricity has low prices. Furthermore, they are scalable solutions and, according to the technology installed, have an easy maintenance. All these features make micro-grid economically and socially feasible in developing countries. In addition, in case of success of a project in a specific area, it is easy to replicate it in other neighbouring areas with same characteristics.

This work aims to model a mini-grid for a rural town in Tunisia, Meknassy. Here the electrification ratio is 100%, however the energetic mixture is composed quite exclusively by natural gas, hence it is important to vary this energy composition. Furthermore, the installation of a new hybrid plant can lead to properly manage local resources. In fact, the mini-grid is a hybrid mini-grid and utilises as resources the biomass available in the municipality and in the rural area of Meknassy and the solar irradiance. This energy mix is able to partially meet the load required by the town.

In the first chapter, an overview on micro-grid is presented. Then the Tunisia scenario is explained, with a particular focus on the energetic issues.

In the second chapter, it is explained how the system is modelled. The software used to simulate and optimize the mini-grid is HOMER Pro, which is a software developed by NREL. The resources available are analysed and the most suitable ones are chosen. Here it is also defined the load profile of the town, which is a crucial aspect for the simulation phase.

The third chapter is fundamental: the technical characteristics and economic aspects are illustrated. The components considered are: biogas genset, photovoltaic modules, inverter, battery and the national grid.

The fourth chapter describes and analyses the optimizations performed by HOMER for the chosen configurations. Finally, a sensitivity analysis is developed to investigate how the system configuration changes, modifying some key variables.

This work ends with the conclusions, where the results are discussed and some observations about future development are illustrated.

Chapter 1

Energy for sustainable development

1.1 Access to electricity

Energy has always played a central role in human activities, from economic sphere to everyday life. UN has recently outlined seventeen Sustainable Development Goals (SDGs) and universal access to electricity, coming from reliable, affordable and modern sources, is one of the targets of the 2030 Agenda [1]. Furthermore, the ability of relying on an accountable electric connection underlies most of the SDGs, such as the eradication of extreme poverty and the achievement of equality in all regions. Moreover it can boost a sustainable growth, especially in developing countries [2].

It is estimated that 1.1 billion people worldwide have no access to modern energy services, which represents 14% of world population. This number of people is decreasing through the years, it was 1.7 billion in 2000, and most of them, 84% of the total, live in rural areas [3]. Nevertheless other 2 billion people have access to unreliable electricity for their everyday duties [4].

According to IEA [3], the countries that lack an adequate electrification rate are mainly located in South East Asia and sub-Saharan Africa, but the pace at which these areas are facing the problem is different, as shown in Figure 1. Projections reveal that in 2030, 90%

of people who do not gain access live in sub-Saharan Africa: this is the greatest barrier to fulfil the SDGs.

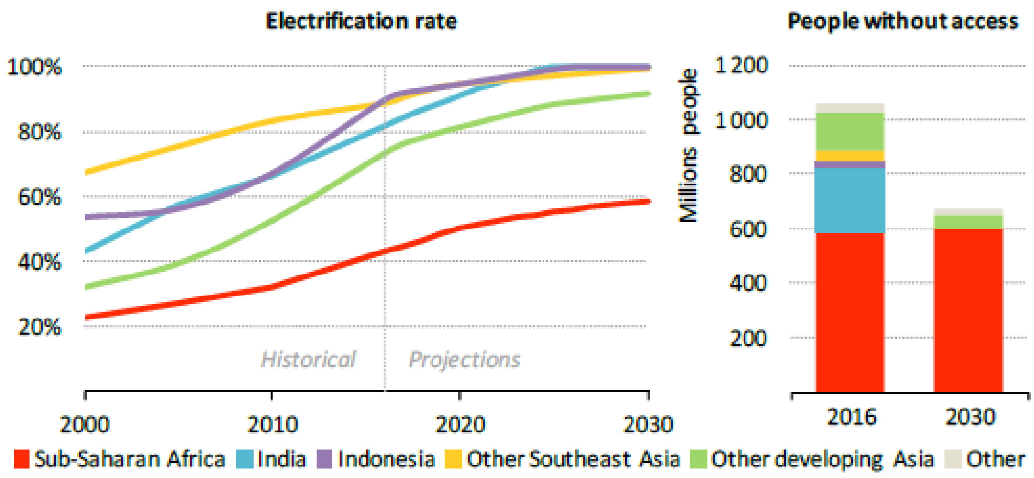


Figure 1- Electricity access rate and population without electricity [2]

Developing Asia has significantly reduced the population without access to energy, particularly China, where they achieved global electrification, and India, where an extraordinary effort have been made taking the country from 43% to 82% of people who gained access in 16 years; while other nations show an improvement and generally the electrification rate reaches values higher than 90%.

Sub-Saharan Africa presents a slightly different situation: the improvements made in this field must face a population growth that only in last few years the pace of electrification overcame.

Anyway, it can be assumed by studies and graph above that the general trend is toward an increasing in electricity access and the rate of this improvement is accelerating. Another aspect should be underlined, that is the way this goal has been and will be reached. Great part of the progress has to date been obtained thanks to fossil fuels (mainly coal, followed by natural gas), but the evidence reveals that renewable energy sources are slowly gaining ground, this is true especially in sub-Saharan Africa [3].

As said before, most of the areas where there is no electric connection are rural areas, far away from centralised plant for energy production, and this fact is something to contemplate carefully when dealing with the solutions and challenges to face the electrification process. According to [4] there are three main ways: extension of the national grid or off-grid solutions, that are solar-home systems or micro-grids. The former solution is the most economically affordable [5] and has been widely used until now. It could be the most suitable solution for 30% of rural areas [4] and according to the previsions described before the expansion of national grid is the main responsible of new progresses, 50% of new access [3]. Anyway, the advantage of extending the grid is reduced when dealing with villages far from the main power generation plants, regions where the population density is low and consequently the energy demand. In addition, the roads to reach these areas are usually challenging, because of their remoteness. These aspects lead to increase the connection costs, causing isolation of rural communities and limiting their economic prospects [4].

Taking into account that it does not exist a universally suitable solution, when speaking about rural areas it is preferable to consider decentralised plants. It is a profitable way and includes two different modalities: solar-homes are small systems powered by diesel gen-set or photovoltaic panels (pico solar) that provide energy for a limited amount of household services (basically lighting and mobile phone charging). On one hand, they allow initial access to electricity and provide to satisfy basic needs, on the other hand it is not an appropriate solution if the aim is to foster development and creation of new business activities [4]. These installations generally "provide a level of access to electricity that is lower than the IEA's minimum threshold definition", but to their advantage are economically viable, scalable and permit to reduce the pollution inside a household generated by other sources of lighting , such as kerosene lamps [3].

The other approach regarding the decentralised solutions is represented by micro-grid systems. Generally, the capacity of a micro-grid is bigger, it can vary from 10 kW to 10 MW, therefore it is a more structural solution and, according to the size, a plant can supply electricity for one or a cluster of villages in the same area, leading to a net positive impact in the communities, where new businesses can grow. These plants, generally, exploit diesel generators or, increasingly, renewable energy sources which permit to use local sources guaranteeing a major suppling security and reducing environmental pollution. Increasing in local economy and electricity demand may make grid extension economically feasible in the future [4].

These lasts solutions are essential to comply with the always increasing energy demand coming from developing countries in Asia and Africa. And considering that the regions, where this basic good lacks, are more and more remote, thus difficult to reach from the network, it will be important to rely on these typologies of plant too.

1.2 Micro-grid

1.2.1 Definition and typologies

A micro-grid is an on-grid or off-grid system for electricity and heat generation designed for a particular load. This system may be renewable or diesel based and, generally, is made up of different distributed energy resources and storage devices [6]: in this regard the electric grid may be defined as a system of systems (SoS). SoSs are "large-scale integrated systems that are diverse and autonomous, but are working together to achieve a common goal", similarly a micro-grid comprises various power generation technologies and control strategies, which can communicate between each other but, at the same time, are self-sufficient [7].

The innovative characteristic of micro-grids is their capacity of disconnection from the main load: this possibility to work independently, called island mode operation, leads to do not depend on grid fluctuations or failures and ensure a constant energy supplying. Consequently, this feature guarantees continuity and a high quality of the service which is of crucial importance also in regions with unreliable provision of electricity.

Micro-grids can be classified according to different factors [8].

1. *Type of source of generation*

   The system can be powered by renewable energy sources, fossil fuels or both (hybrid systems). The major goal is to make advantage of local renewable resources anyhow, hence hybrid solutions are generally preferable. But frequently the design of a micro-grid includes diesel generators in order to ensure a constant service. The main drawback of this plant design is the cost of diesel and especially its transportation cost, which can reach an excessively high price and in turn operational costs rise; alternatively, it may be possible to exploit local biomass, which is a widely utilized solution, since it is a widespread source in rural areas and has low or null cost.

2. *Connection to the grid*

   The micro-grid can be connected to the national grid through a point of common coupling or it can work in islanded mode.

3. *Type of load supplied and electric characterization*

   The network structure can be based on alternate current or direct current. The former structure is more mature, especially the control and protection systems. However, converters for DC sources, such as photovoltaic panels, are required. Direct current micro-grids are a comparably new solution, which developed thanks to DC generators and loads deployment, in fact they can be easily connected to the load, allowing a reduction in losses and costs. Thirdly, AC/DC hybrid micro-grid is a practicable alternative: it includes two sub-grids (AC grid and DC grid) connected with a bidirectional converter. This last type could have wide application in the future, considering that AC loads are predominant in the power market and simultaneously direct current sources, loads and batteries are more and more exploited [9].

Thanks to its flexible structure, the concept of micro-grid may be applied to many contexts, from residential and campus applications in developed countries to rural areas. An always increasing trend shows that investments are growing towards smaller power plants for electricity generation at the expense of traditional ones. In well-developed power markets, the factors that drive the deployment of such systems are mainly related to economic reasons and energy affordability, an example is represented by the United States, since they are subject to extreme natural calamities and microgrids can have a backup function in the periods of inactivity of the national network, limiting inconveniences associated with power failures. In addition, the intent of integration of distributed renewable technologies plays a crucial role, as it is preferable to coordinate few mini-grids, which appear as sources or consumers to the main load, instead of a great number of distributed energy resources [10].

The advantages of such systems are evident also in remote areas, where the access to electricity is limited or does not exist. Particularly, hybrid micro-grids are revealing a great prospect thanks to their features of sources diversification and low operating costs [10].

Micro-grids represent a significant opportunity for this communities, both in social and economic terms, however there are a multitude of barriers and challenges to face.

1.2.2 Micro-grid in rural areas

As indicated previously, micro-grids represent a cost-effective solution to bring energy in remote areas in developing countries. With the view to achieving the goals fixed by international organizations, it is necessary to rely on alternative forms for electricity access other than grid extension: micro-grids are a viable alternative and they can foster sustainable development and energy affordability [11].

An alternative was needed since in these regions grid extension is unprofitable and where diesel generators are installed, the fuel cost is extremely high due to the transport in such remote places. Hybrid micro-grids are particularly suitable: diversification in power generation allow to fully benefit of local resources [12] and consequently the design phase of a mini-grid is crucial, considering that each system must be modelled according to a specific load and place. This is the reason why during the project phase, it is essential to consider all facets concerning the community: beyond the economic dimension, social and environmental considerations are of great relevance.

Access to electricity should be eco-sustainable too, avoiding negative consequences and pollution caused by fossil fuels. Nowadays, great part of micro-grids is diesel based, however they can be converted in hybrid systems adding a renewable source for energy production. The estimated capacity available is in the range 50 MW and 250 MW and, if the price of diesel remains constant, this conversion leads to a reduction in operation costs [4], [13].

Researches underline that success of decentralised solutions is linked to the attachment of the community and creation of new business may be a decisive aspect. Measurement of social impact is challenging, since it is required to "draw causal links between the observed changes and the intervention" [13]. Depending on this study access to electricity alone is insufficient to boost a sustainable development, indeed the integration of the micro-grid in the community and the definition of the real necessities of the population should underlie the project phase. This approach may lead to a lot of advantages: empowerment of marginalised people and increasing economic activities, which is connected to employment rate growth. Finally, successful results achieved in a community can inspire neighbourhood to replicate the project, as well as have a wider impact at a policy making level.

As underlined in Figure 2, one of the main issues whether decide if the construction of a mini-grid is affordable or not is the initial energy demand, which must be high enough to support an investment from private entities or by the state. This fact is related to the number of people living in the community, their density and the presence of commercial activities. Another important aspect is to foresee a connection to the national grid, otherwise, if the grid is extended (for example thanks to a growth in energy consumption), the investment cost would be hardly returned [3].

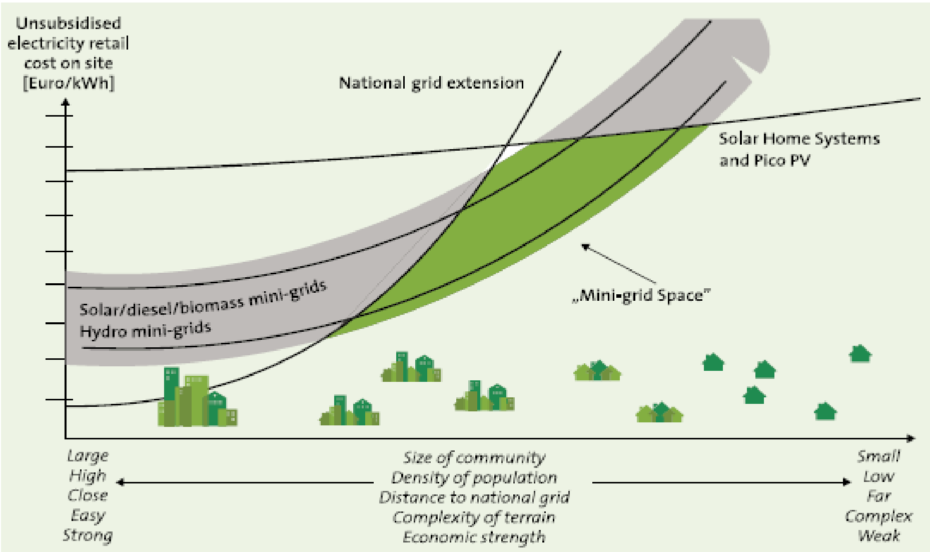


Figure 2-Mini-grid space [14]

According to World Bank, 19000 mini-grids are installed worldwide, the great majority powered by diesel and hydro. South Asia, followed by Africa and East Asia, are the places where most of the systems are located, while the planned ones are in most part in Africa. It is estimated that the cost of electricity from hybrid mini-grids is still higher compared with utilities, but it is expected that this cost will decrease by 2030, ensuring lower prices. The prospect of this scenario is made possible if a supportive regulatory framework is developed in the countries [15]. From this standpoint, Tanzania, Kenya and Senegal are an example since they have established a favourable environment for micro-grid deployment [14].

Installed	Planned
9300 South Asia	4000 Africa
6900 East Asia and Pacific	2200 South Asia
1500 Africa	900 East Asia and Pacific
1100 OECD and Central Asia	200 OECD and Central Asia

Table 1- Micro-grid: worldwide trend [15]

Governments should play a crucial role by defining a clear legislation framework and developing policies aimed to determine tariffs and future grid expansion [3].

In conclusion, employment of micro-grids in remote areas can be promising thanks to their environmental advantages, scalability and low investment cost. Nevertheless, highlighting some issues is essential: minimum energy threshold is required and, usually, it is complicated to estimate this electricity demand; technical skills are limited in rural areas, which in turn makes hard to find people able to manage and maintain the plant; finally, difficulties in providing components, lack of business models and a supportive and defined regulatory framework are crucial points and they may be obstacles to micro-grid deployment [5].

Micro-grids cost

An investigation conducted by ESMAP [15], regarding solar-hybrid micro-grids deployed in several countries around the world with different scenarios, assessed the cost of micro-grid systems. The Levelized cost of electricity (LCOE) expresses the plant investment, operation and maintenance costs per kWh produced. This value corresponds to the minimum electricity tariff which allow a return of the initial investment cost. The average cost estimated is $0,66 per kWh, furthermore the study performed some forecasts varying the load factor, as shown in Table 2. Small values of load factor correspond to low income-generation electricity use and high tariffs, while an increase in local business and enterprises makes the load factor grow, from which derives a significant reduction of

LCOE. In 2030 these costs will be further reduced, considering economic development and decline of cost components.

	Levelized cost of electricity [$/kWh]	
Load factor	**2018**	**2030**
22%	0,55	0,33
40%	0,42	0,22
80 %	0,35	0,23

Table 2- Levelized cost of electricity

1.2.3 Load profile and forecasting

Load profile evaluation is one the most challenging problem to face during the design phase of the project. This issue results mainly from a lack of data regarding electricity utilization at household level. Nevertheless, load forecasting, both over long and short term, is crucial in order to have a successful investment. On one hand in terms of long-term forecasting, the general trend shows an increase in electric consumption, behaviour which should be taken into consideration with the aim to avoid insufficient energy supply in the future; on the other hand, fluctuation of daily demand is also of central importance, particularly when dealing with off-grid renewable energy plants. It has been demonstrated that the return of the investment cost is related to the capacity factor, from which it originates the importance of short term load profile forecasting [16].

Over-prediction of electric consumption leads to an over dimension of the plant and affects the financial performance. If energy demand doesn't increase, oversizing may provoke an electricity price rise that would reduce the payment capacity of customers. While under-prediction causes a reduction of the plant reliability, compromising technical operation which damages the operator and eventually the components lifetime. In the second case, customers experience a quality reduction of the service with possible financial losses caused by the lack of electricity and consequently it may negatively influence the possible construction of other micro-grids [5].

Methodologies to formulate daily load profiles

The best approach would be to have access or measured consumption data, but, if this information is not disposable, other methods are needed: one of the most common is to refer to appliance power rating and usage. These data, usually, derive from interviews among local population or from assumptions based on practical experience.

A formalized approach has been elaborated by [17]: daily load profile is constructed on the basis of hypothesis and data from rural customers. The minima inputs required are:

- Classification of specific user classes, j, such as shop, hospital, household, and definition of number and type of electric appliances, i.
- Appliances are modelled on their nominal power.
- Functioning time: period of usage of an appliance.
- Functioning window: when, during the daytime, the appliance is used.

The last two parameters, defined respect to a minimum time step of 1 hour, are of crucial importance as their values define the daily electric consumption and, particularly, the peak demand. The daily electric consumption E_c [Wh/day] depends on the number of users in each class, N_j, number, n_{ij}, and nominal power rate, P_{ij}, of appliances within a class and functioning time, h_{ij}:

$$E_c = \sum_{j}^{user\ class} N_j * \left(\sum_{i}^{appliance} n_{ij} * P_{ij} * h_{ij} \right) \tag{1.1}$$

Then, the windows, $w_{F,ij}$, allow to determine how the consumption is distributed through the day. They are defined into two manners: in the first approach the functioning time equals the sum of functioning window duration (left side); while, in the second method the sum is higher (right side):

$$\sum duration(w_{F,ij}) = h_{ij} \quad \forall ij \qquad \sum duration(w_{F,ij}) > h_{ij} \quad \forall ij \tag{1.2}$$

In the first case, the power peak is over-estimated, since any coincidence behavior is considered and the load presents great variations, instead the other approach generates under-predicted flat loads as consequence of the fact that the average power of appliances is distributed in the time windows. Finally, the load profile is built considering the electricity consumption, $E_{L,ij}$, and the average power, $P_{av,ij}$, of each appliance:

$$E_{L,ij} = P_{ij} * h_{ij} \tag{1.3}$$

$$P_{av,ij} = \frac{E_{L,ij}}{\sum duration(w_{F,ij})} \tag{1.4}$$

The first approach has been used in [16], here the authors compare the load curve based on interview-based data (and generated according the method above) and on measurements, with the aim to assess the reliability of the method. The profile built on surveys was constructed on the basis of questionnaires distributed between a set of representative costumers chosen among the population of the town. The questions sought to determine all the input parameters described above. According to the data obtained a load at a certain time is calculated and consequently the daily load profile is constructed. The comparison with the measured load points out that the electric profile is not much precise, most notably in some hours of the day, such as during the night, where the discrepancies are too large. These variations cause an underestimation of load factor and capacity factor, with heavy consequences on definition of plant dimension and operation.

An alternative model, proposed in [5], which is called data-driven proxy method, supposes that the energy demand of one mini-grid can be derived from another mini-grid, which exhibits similar characteristics. This approach is more accurate, as shown in the research, and the error with respect to the real load is considerably reduced. This method is extremely useful if it is not possible to survey or estimate the set of data mentioned before.

Other structured methods applied in a rural context include as first step an interview or an assumption of the appliances and their time of usage, but then this initial amount of data is further processed in a view of formulation of the load profile.

The review [17] formulates the load profile assessing the functioning window, while the times when an appliance is switched on within the time span is defined in a stochastic way. This procedure is utilized for each device and the daily load is constructed by aggregation of single appliances profile. The implementation is carried on Matlab, where the algorithm has been developed, it is called LoadProGen (Load Profile Generator). The resulting load is well formulated, especially during daytime, and the power peak is representative of the real profile; the discrepancies are present only in night hours and they are probably due to the survey through which the initial data are gathered and this is the same issue observed in the other researches. Anyway, thanks to the stochastic nature of this method, the daily demand profile can be considered a good approximation of on-field data.

Finally, software tools can be also useful in the design step of the mini-grid. ESCoBox is a software that can produce an average daily energy demand and need as input data the typology and the number of appliances and the relative duty cycle [18]. This is a stochastic approach too, and it is another suitable tool in electric load prediction.

The last research presented is a bottom-up method, as the ones previously described, that means that the load is evaluated from basic blocks which are represented by appliances, but it is not applied to a rural area. The load profile constructed in this method [19] refers to a city in the East Midlands, UK. The main peculiarity of this approach is that is time-correlated: the output is a one-minute step dwelling load and is based on how many people live in the household and, in particular, how much time they stay in the house. Thus an "active-occupancy" is defined: the usage of an appliance is correlated with the number of people living in the dwelling and on their behaviour. Typical habits of English people were determined thanks to a statistical research carried out in UK. The share of possession of different appliances was a statistical investigation too.

A stochastic simulation was elaborated in order to vary the "activity profile" of appliances, that is their likelihood of usage changes through the day and is different for each dwelling.

The validation of the results obtained was possible thanks to the measured data of the power demand of 22 household: 22 simulations was performed and the resulted profile was quite similar to the real one, with a very good approximation of base load and peak load.

1.2.4 Business models and regulatory framework

A supportive environment for micro-grid development should be promoted by governments, whose contribution is critical for the establishment of clear and favourable regulatory conditions. Nowadays, public authorities aim to attract investments from private sector by supporting them through an adequate policy. The most advantageous ones, as indicated by [4], are:

- Laws and clear future plans: licencing arrangements are essential for obtaining authorizations, which enable the investor to build power plants and distribute electricity. The cost should not be excessively high, lower than 10% of capital cost. Undefined bureaucratic procedures hinder new investments as well as non-specified plans regarding rural electrification, resulting in higher risks and time consumption.
- Recovery of cost and tariff: it is a complicated issue since on one hand governments should guarantee that all costumers serviced by the load can afford electricity tariffs, on the other hand tariffs must economically sustain micro-grid viability. A possible solution for low capacity systems is a meeting between investors and community, where tariffs are fixed by common consent, otherwise institutional mechanisms are needed, guaranteeing a more transparent process.
- Enabling access to finance: key point for attracting investments in which governments must play a central role. Figure 3 illustrates the phases of financing requirements: project development, proof of concept and project rollout. Generally, the former phase does not receive funding, even if it can happen that environmental impact researches or other reviews concerning the community are funded by banks or national developing plans. The second phase foresee a split according to the micro-grid size. The mini-grids with lower capacity are, usually, financed by public entities, while larger capacity plants require for more substantial grants. The project rollout phase is a "capital-intensive phase", thus grants are needed from a multitude of sources.

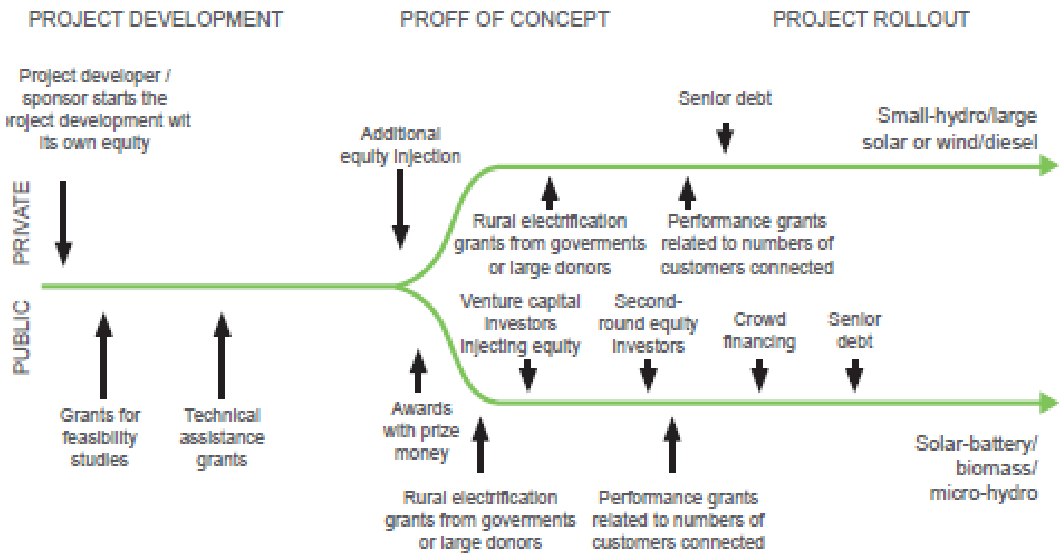


Figure 3 - Phases of financing requirements [4]

Even though governments seek a private sector commitment, several business models may be applied. They foresee different levels of participation of local institutions and investors. The main models are four, as explained in [4]:

1) Utility model

In this approach the national utility builds and manages the mini-grid, hence every aspect regarding the plant management, from installation, operation and maintenance to tariff collection, are of its responsibility. As usual for these systems, tariffs would be higher respect to those applied to customers connected to the main grid, however with the aim of introducing social benefits, governments may require to fix the same tariff used at national level. Consequently, the electricity bills collected at state level would subside the mini-grid project.

The major advantage associated to this operation model is that the utility, namely the unique administrator for the micro-grid, has great experience and technical background in the energy sector. This expertise enables the utility to proper manage the project. But by contrast, the wider energy market penetration from private sector forces public entities to pursue different market rules, that, generally, do not include policies with social purposes, such as inclusive rural energy access.

2) Private sector model

Private investor is the responsible for construction, management and operation of the project. They can take advantage of funding derived from governments or other donors, as well as commercial loans. At the present state, amount of systems developed by privates is limited and their capacity is smaller than the general trend. Crucial points that can increase the diffusion of this approach are: technological advancement, new forms of funding and an always greater public support.

3) Community model

Operation of micro-grid is assigned to end-users: local population is organised in cooperatives subjected to public laws. This model is supported by evidences that show how much significant community involvement is for successfully develop the project. These plants are funded thanks to subsidies, while local people may contribute in different ways, for example providing lands.

This scenario highlights the major advantages and drawbacks regarding mini-grid in rural areas: on one side it has a positive feedback, allowing empowerment and responsibilization derived from creation and management of new businesses and a possible income from feed-in tariffs. Then, in case of national grid extension follows also the connection to a more resilient load. In contrast, the group dedicated to micro-grid management, generally, doesn't have specific capabilities for grid administration, so that such operations are delegated to third parties. Thus, it is required that a part of the income must be dedicated to cover these costs. Moreover, lack of technical skills forces to train some people of the community; if it is not possible, the entire project proves to be unsustainable.

4) Hybrid models

These models mix various aspects of the precedent models. Conditions vary from approach to approach: the assignment of roles and responsibilities is determined through specific contracts. Electricity generation and distribution may be separated between the parts (local communities, state and private investors), but clear rules and regulatory framework are needed, in order to successfully implement this model. Some examples of contractual agreements are:

- Power Purchase agreements (PPA): distribution and generation are owned and managed by different organisms. The subscription of a PPA guarantees electricity supplying. The period of time of this agreement should be sufficiently long (generally 20 years), otherwise the risk for the private power generator is unreasonable.
- Concessions: the entity that supply electricity in rural areas obtains profitable terms, such as geographic monopolies or favoured tariffs.
- Partnership between public and private sector: privates are only responsible for maintenance, while all other aspects from construction to operation are provided by public authorities.

One of the major challenges, other than a supportive legal framework, is the creation of suitable business models for private developers. The focus is centred on issues related with low profits, with which operation and maintenance costs must be faced.

Each project should be accurately examined in its unique aspects and requirements according to local context. The micro-grid system durability is preserved if the definition of roles and cost recovery are clear.

Business models for private micro-grids [4], [20] are summarized in the table below.

Model	Main characteristics
Franchise	- Management costs are sustained by the franchise. - With increasing number of franchisees, marginal cost of operating a further one decreases. - Several examples of this model successfully implemented exist, especially in India.
Anchor, business and consumer	- An anchor customer is essential for this model application: it represents a stable load, thus can produce a secure and predictable cash flow, protracted over time. - Main drawback: households are considered as additional customers. They receive the remaining

	power, the one not utilized by anchor consumer, so that it is very likely to unmet local load requirements. - Another issue is the risk that areas where anchor clients lack would not be considered from potential investors. - Example of anchor customers: telecom towers, factories, gas stations and in addition local businesses. Particularly, telecom towers are widespread in rural sub-Saharan Africa, constituting a great potential for micro-grid operators. - It is of great interest the example of an Italian company that, instead of relying on a pre-existent customer, investigates on local needs and addresses the gaps found. In this way, micro-grid project is developed considering this new anchor client and allow creation of new business with positive implications for the community [21].
Clustering	- A group of micro-grids (from 5 to 10 typically) are bundled together, creating one operational unit with lower costs. - Reduction of transaction costs - Management of this system requires high level technical expertise. This can be a problem in some areas, where this kind of skills lacks.

Table 3 - Business models for private developers

1.2.5 Risk management

A risk management approach universally approved is not available nowadays. The major risks identified in literature [22], [23] are the following.

Political and institutional risk: energy market is strongly regulated from institutions and authorizations are essential for any project development, thus political instability or changing in legislations represents a great risk for an investor. Besides, the arrival of the main load falls within this type of risk, since it depends on government decision and plans. The probability of occurrence of political risk is relatively high and may have heavy implications.

Payment risk: customers in rural areas may not be able to economically sustain electricity bills. Sometimes, initial connection cost is too high, higher than monthly salary of families, so that they cannot afford this charge. This situation affects and limits the number of costumers of the mini-grid too. Another issue can be the unwillingness to pay caused by increases in tariffs cost or discontent for the service provided. The probability of occurrence is medium.

Resource price variability and availability: it regards diesel-based or biomass-based systems. Their price severely affects operational costs. Regarding biomass, the price grows when a gasifier is built since the demand increases, furthermore its availability can be critical. In fact, biomass from agricultural residues is not characterized by a uniform calorific value and this fact affects plant performances. Environmental risks could also be associated to biomass, because adverse weather influences harvests, reducing feedstock availability.

Technology risk: technical faults, defects or breakdown of the mini-grid. These problems can be caused by inappropriate maintenance or by poor quality of components. The impacts may be very high, but the frequency is low.

Risk of unpredictable electricity demand: a parameter very difficult to assess is the electric load, as explained previously. Beyond that, the demand can significantly vary over time, generating negative implications: income reduction if the demand results to be lower, reduction of service and component damaging if higher.

Social acceptance risk: a micro-grid project must consider the scenario and social context of application. If the population of rural community is not adequately involved, the possibility of failure is high.

Foreign exchange risk: nations where rural mini-grid are developed has generally weak currency. This aspect impacts on potential investments.

Methodology for improving risk profile

The need for a complete risk assessment is essential in order to determine specific risks and mitigate the risk profile. Management tools available are not suited for micro-grids and, usually, are too expensive, hence new methods has been developed which are explained below, according to [22].

Standardised Risk Management Procedure (SRMP), which has been approved by the main actors in electrification field, provide adequate information about risks and how mitigate them to companies. Moreover, this procedure creates a bridge between developers and investors through: evaluating risk profile, providing a program aimed at managing risk and performing a scheme through which report the level of risk and if it is possible how minimize it. It is of great importance to understand the real scenario of rural electrification market, thus allowing funding from financial institutions.

A second option is represented by the modification of business models by adding actions suited for dealing with sources of risk: productive use of electricity (PUE) is a demonstrated approach to mitigate risks. In fact, PUE allows to utilize as well as possible power produced. It is difficult to promote at local level but lead to manifold benefits.

Finally, public institutions can help operators to face technical and management issues: governments involved in rural micro-grid deployment can provide technical assistance thanks to specialized units. These actions may increase effectiveness on access to electricity in rural areas.

1.2.6 Future prospects and challenges

Micro-grids still have to demonstrate their full potential, since there are great possibilities that these systems will gain ground in electrification advancement and beyond. Data projections provided by IEA shows that mini-grids role in developing countries will increase and 34% people who gain energy access by 2030 do so via mini-grids [3].

Technology improvements are essential, but besides technical issues, the main challenges regard economic, market and regulatory spheres, as illustrated in previous section. In the following table these aspects are summarized [24].

Challenges for micro-grid implementation	
Economic	- Investment cost reduction. Initial investment is still high without some financing (such as incentives), in particular for renewable systems. Nevertheless, the trend is towards a decrease of such cost, thanks to technological advancement. - Development of funding mechanisms through detailed benefit and cost analysis.
Market	Active participation of micro-grid in market regulations. - An initial useful strategy could be to support business models. - Then the leading factors should be of technical type. Furthermore, financial and institutional assistance are crucial to help micro-grid deployment.
Regulatory	- Micro-grid must be incorporated in the regulatory framework. Nowadays, some progress has been made, however new laws, allowing to all society to benefit of micro-grid advantages, must be implemented.

Table 4 - Challenges for micro-grid implementation

1.3 Tunisian scenario

As explained in previous paragraphs, the legal framework characterizing a micro-grid installation varies considerably from one country to another. The micro-grid system in question is situated in Meknassy, a rural town in Tunisia, and this section, therefore, aims to fully investigate the Tunisian energy sector, starting from the current scenario to the recent solutions, implemented by the government, to integrate innovative technologies in Tunisia.

In recent years, Tunisian government has enacted new authorization schemes design to promote renewable energy with the aim to vary the national energy mix, now based on natural gas.

1.3.1 Tunisian energy sector

Tunisia is a North Africa country with about 164.000 km^2 surface and with a population of almost 11.500.000 inhabitants in 2018 [25]. The country is the smallest state in the region and it is divided in 24 governorates, which are further subdivided in delegations. Tunis, the capital and largest city, is in the north and its governorate represents the most populous of Tunisia, while great part of the territory, 40% of the national surface, is semi-arid and merges into the Sahara Desert [26].

Economic sphere in Tunisia is diversifies, but the leading sector is considered the agricultural one, the typical product production consists of dates and olives. Then another important sector is the energy and mines sector and, finally, tourism plays a key role too [27].

Political-economy environment reveals some contrasts: significant progress regarding democratic system are evident, but the same is not totally true about the economic sphere [25], and the energy sector is part of this scenario. The energy sector is strongly dependent on importations from neighbouring countries, especially Algeria, and based on fossil fuels. This situation does not benefit the economic growth; indeed, the Tunisian government is not able to meet the growing domestic energy demand and since 2001 Tunisia faces an electricity deficit.

This situation can be graphically visualised in Figure 4. However, new measures put in place by national institutions aim to restore the crisis. New investments from private sector are foreseen, in particular in renewable energy sector [28].

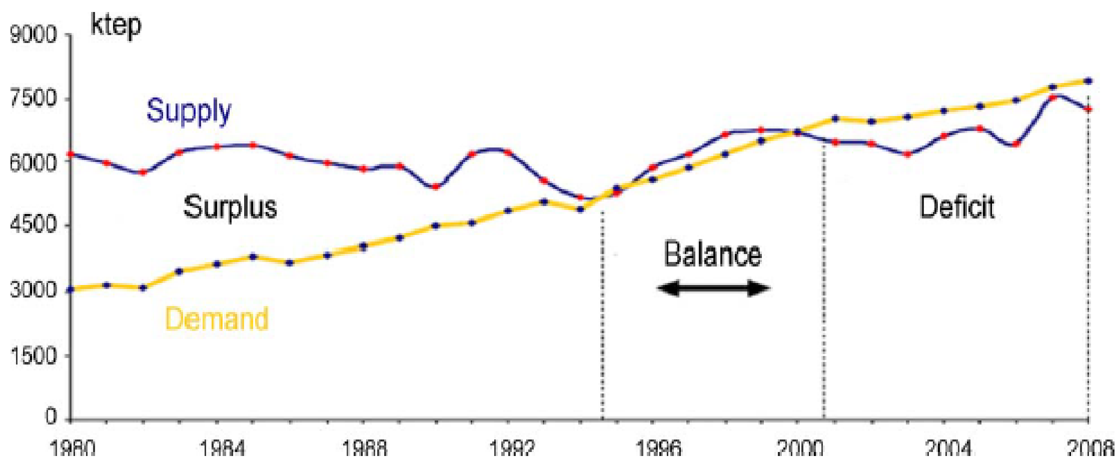


Figure 4 - Evolution of energy demand and supply in Tunisia [29]

In fact, new policies are required since the actual energy mixture is based on fossil fuels and in particular on natural gas. As evident from Figure 5, the share of renewables is very low and reaches a penetration of 3%. It is mainly based on hydro power plants, while newest technologies, from photovoltaic to wind, have not been developed in this country and they are at their first stage.

Government is taking small steps forward a more sustainable energy mix.

First of all, during the last 54 years, STEG (Société Tunisienne de l'Electricité et du Gaz) succeeded in increasing the electrification ratio from 21% to 99,8%, thus reaching a complete electrification in the whole country. Furthermore, if we focus on the rural electrification rate, this effort seems greater: from 6% population connected to national grid in 1962 to 99,5% in 2016 [28].

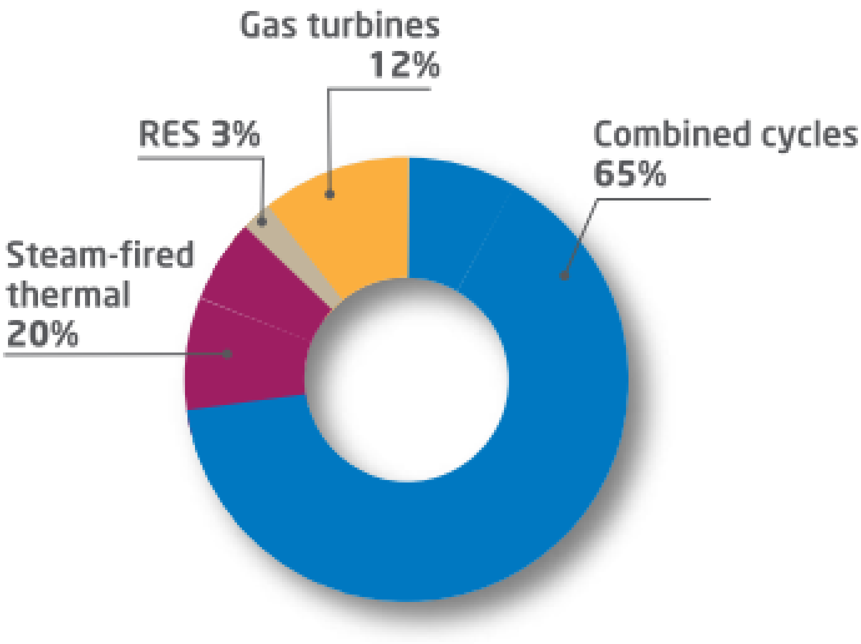


Figure 5 - Tunisian energy mix [28]

1.3.2 Policy and regulatory framework

It is very important to understand if a suited regulatory framework to allow the implementation of a micro-grid project exists. This paragraph aims to investigate the

Tunisian scenario and to find the most suitable solution which better suits the micro-grid system under study.

Until a few years ago the Tunisian energy market was closed and the only authority responsible for the production and distribution of energy was the STEG. Today Tunisia is starting to give space to private investors, but only in the field of energy production. This is partly due to the fact that since 2001 the country faced an energy deficit and, besides that, there is a need to give a boost to renewable resources. Thus, the government has put in place new tools to allow individuals to invest in this field [28].

Law n°2015-12 in May 2015 provides the first instruments for renewable energy deployment and outlines the regulation for the energy production. Then a second law, n°2016-1123 in August 2016, delineated in a better way this scenario and the New Action Plan was announced and it must be fulfilled by 2030. The goal is to produce 30% of energy from renewable sources and new power plants to be installed are planned. It is foreseen a starter period (2017-2020) for the construction of 1000 MW of capacity and a subsequent period until 2030. During this latter period the capacity to be installed is 1250 MW [30].

In 2017 private investors can install power plants and sell electricity to STEG: the Ministry of Energy, Mines and renewables is the authority which decides and communicates the possibility to invest in new projects. When new call is communicated, for each technology a maximum capacity threshold is fixed, for example for wind turbines the total capacity in November 2017 was 60 MW [30]. If the investor complies with this limit value, the project is under an authorization scheme, otherwise, if it is higher, the regulation is a concession scheme [28].

In the private sector three different schemes are outlined for the development of RE projects [28]:

- Concession scheme → export projects and large-scale projects
- Authorization scheme → small-scale projects
- Auto-production scheme → self-generation projects

The former regime is not relevant to the plant under consideration in Tunisia. While the authorization scheme seems to be a suitable framework, since the maximum installation power allowed for a project is set at 1 MW or 10 MW, according to the technology considered. The prices at which the electricity is sold to the grid are not specified, but they are decided on the basis of the offer from the private investor. This scheme includes two cases: connection to LV grid (no threshold to the electricity that can be sell to STEG) and connection to HV/MV grid (amount of electricity to sell to STEG limited to 30% of production).

1.3.3 Structure of the market

The energy production is mainly based on natural gas exploitation, so that the energy mix is not such diversified. This situation represents a heavy issue and can compromise the energy stability and security of the country. The main part of the energy production is delegated to STEG, as shown in the figure below [27], [30].

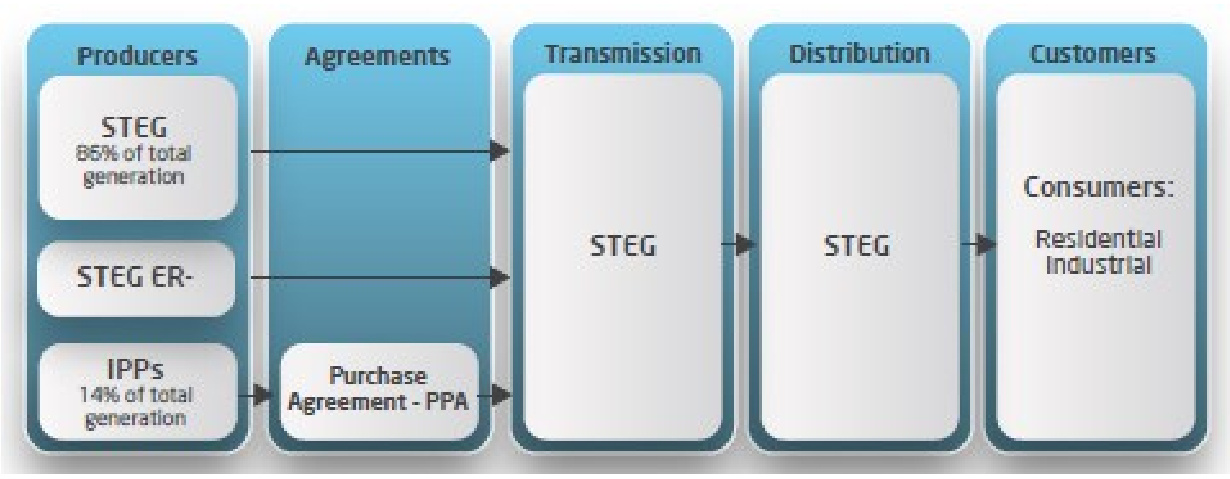


Figure 6- Energy market in Tunisia [28]

1.3.4 Future development

The primary targets of Tunisia regard energy efficiency and domestic energy sources exploitation. The former objective aspires to reduce 30% of the actual energy demand while the second target involves renewable energies, mainly wind and solar [27]. Figure 7 shows it graphically.

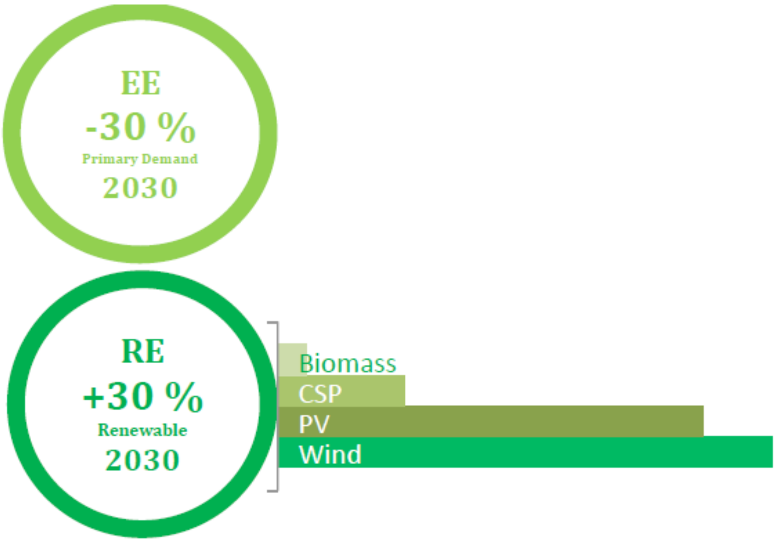


Figure 7 – Future targets [27]

In recent years, Tunisia shown an always growing interest in the sustainable growth, thanks to the new actions exposed in this section. However, it is very difficult that this country will reach all the targets fixed for 2030, since the progress of renewable is still low [32].

Chapter 2

Methodology and materials

In this chapter the methodology used to define the system and the characteristic resources of the location under study are presented. In the first part there is an overview on HOMER, the software potential in micro-grid design is explained, then, the scenario in which the system is developed is illustrated.
The hybrid micro-grid consists of a biogas genset, which must meet the base load, integrated with photovoltaic panels, thus the system is based only on local renewable resources. After a global view of the town of Meknassy, data about the resources exploited in the plant and the methods applied to measure them are described.

2.1 Simulation and optimization with HOMER Pro

HOMER Pro (Hybrid Optimization Model for Multiple Energy Resources) is a software developed by NREL, the US National Energy Laboratory. The purpose was to create a software which could be able to support the design of a microgrid by ranking different configurations and finding the optimal one according to an economic evaluation. Therefore, the user can compare the solutions found by HOMER. The following information is based on [6].

The software allows to model both on grid and off grid mini-grids.

The most challenging feature of modelling a micro-grid is the fact that some parameters have a high degree of uncertainty. This parameter can be essential for the system design, such as load profile or variation and volatility of fuel prices. In addition, the resources modelled on HOMER are totally renewable, except for diesel fuel, and this fact leads to other instabilities concerning availability and load supplying. However, the software is designed to face these issues.

HOMER main objectives are:

- Simulation: HOMER simulates a specific system in order to verify if its power output is able to supply the load. The most critical parameters are the economic inputs and the load. The hourly profile is a key point, since all the simulations are based on a chronological dispatch.
- Optimization: different configurations are compared. The aim of this step is to find the optimal configuration which has the lowest life cycle cost, fulfilling all the constrains imposed.
- Sensitivity analysis: it is possible to upload more than one value for quite every input. Starting from this data HOMER executes multiple simulation and optimize them. This analysis allows the user to verify the feasibility of the system for different values of uncertain parameters whose variation does not depend on the user.

Figure 8 illustrates how the different analysis are interconnected: the optimization analysis includes several simulations and the same for the sensitivity analysis, which comprises various optimizations.

In the following of this chapter and in chapter 3, input data required by HOMER are illustrated both for resources (chapter 2) and components (chapter 3).

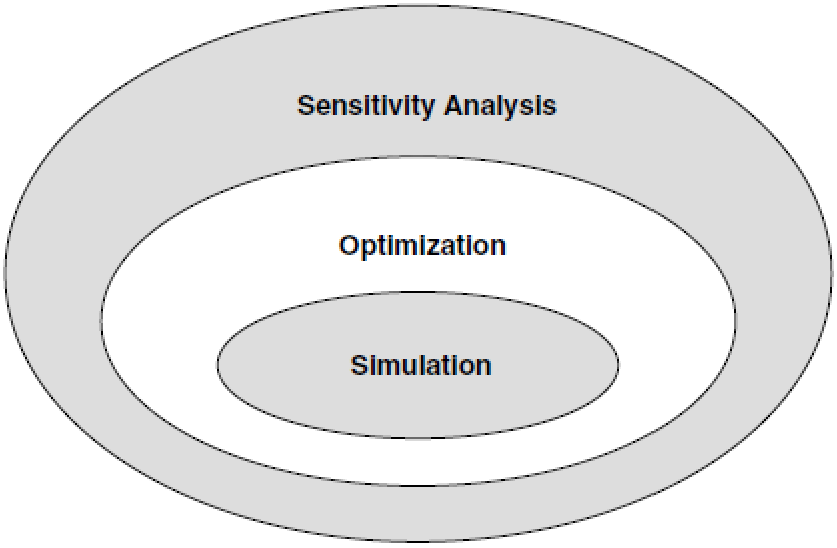


Figure 8 - Conceptual scheme of HOMER performance

2.2 The studied area

2.2.1 Overview of biomass situation and biogas plants in Tunisia

Renewable energies play a minor role in the Tunisian energy mix and the same is true for biomass and biogas resources. A recent study [33] analysed the waste situation in seven regions of Tunisia and estimated their energy potential, since waste exploitation for electricity production can be an effective solution to face the deficit issue in the country. The aim of the study was to estimate the potential of different typology of waste, from green and food industry discards to manure, and their possible energy recovery. It results that the potential of biogas in Tunisia is enormous, only in the Midwest region, where Meknassy in located, it is possible to produce 32,76 10^6 m^3 of biogas, equivalent to 196,6 GWh. Furthermore, investments in this field can help to solve the municipal waste issue that concerns most of the cities in the country and Meknassy too, as exposed in the following.

This potential has not been fully exploited, in fact limited number of biogas plants are situated in Tunisia, as reported in [34]: few anaerobic digestor plants of small/medium size (lower than 100 m^3) are reported and the technological level is considered low. In contrast, other North African countries present a diverse situation with several plants and a higher advancement of the technology.

Hence, great part of biogas plants is represented by small scale and, generally, rural systems. In fact, at the beginning of the eighties an institutional program, called “Programme spécial de l’énergie”, started the construction of 50 small size biogas activities, with the aim to avoid deforestation in rural areas and reduce kerosene consumption. Anyway, this plan ended in 1992 and did not manage in extending biogas deployment throughout the country [29], [35].

In rural context, the most popular technology for biogas production is the fixed-dome digester [36], while newest projects concern electricity generation plants at a higher scale. Some examples are Jebel Chakir landfill, which uses biogas from leachate in an internal combustion engine of 10 MW [37], Chotrana plant, the largest wastewater treatment plant, it treats 86000 m^3/day of substrate and through the electricity produced partially contributes in energy requirement of wastewater plant [38], and, finally, a 130 kW cogeneration plant utilises organic waste from Sotumag market. This plant was built in 2010 and obtained subsidies from government since the project was centred on energy recovery [39].

Such incentives could help biogas deployment and encourage private investors too. According to FAO [40], revise subsidy schemes and simplify the regulations represent essential steps to support this technology both at low and high levels.

2.2.2 Case study: Meknassy

Meknassy is a rural town in the Sidi Bouzid governorate, in the central-western part of Tunisia, located on latitude 34°64’N and longitude 9°66’E and at an elevation of 242 meters above sea level, the position is shown in the map below [41]. In 2016, the population amounted to 17000 inhabitants who live in the municipal area and 7000 inhabitants in rural area, that means a total population of 24000 people [42]. The town is internationally recognized for purebred Arabian breeding and, in fact, every year a thoroughbred horse festival takes place in July.

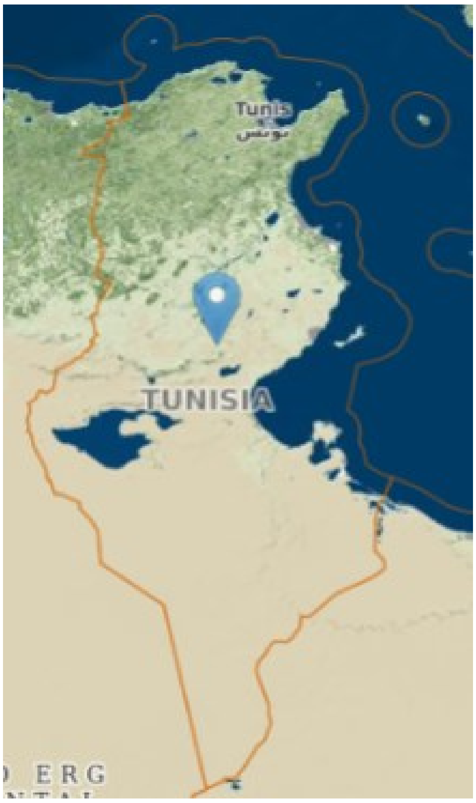


Figure 9 - Geographic position of the site of Meknassy

The governorate is semi-arid area, neighbouring Sahara Desert, however, after a national plan enacted to irrigate lands in the region, Sidi Bouzid become a rich agricultural territory. The most developed sectors of the area are based on processing of agricultural products. Grazing and breeding are developed sectors too [43].

The livestock population of the area is mainly composed of sheeps, 582000 heads. While the total number of goats and cattle livestock is 90000 and 53800 heads respectively. Figure 9 shows the percentage for each species. Comparing this data at a national level, it can be observed that the stock farming in Sidi Bouzid region fulfills an important economic role: sheep population is the grater of the country, and cattle and goat, even in lower proportion, represent a crucial contribution in livestock sector [44].

In the agricultural sector, the main production at a regional level include durum wheat, with a production of about 170000 tons, and barley, 88000 tons circa in 2017 [44].

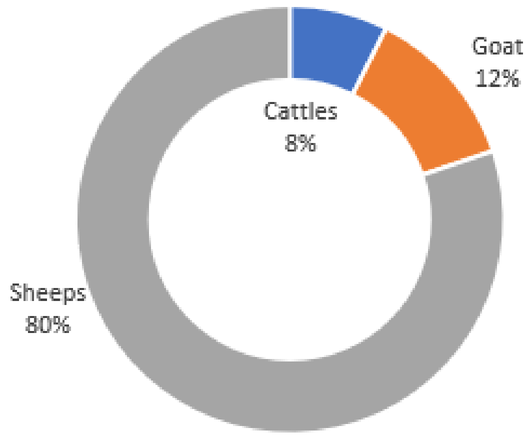


Figure 10 - Livestock population in Sidi Bouzid governorate

2.3 Data collection

2.3.1 Town load assessment

The method utilized to estimate the load demand profile, described in Load profile and forecasting section, is a bottom-up method [19], that means that the total load is built up from basic blocks, corresponding to appliances, and the final profile produced is based on when and how many times devices are utilized. The paper refers to a town in UK and founds that the resulting profile has good correspondence with the typical daily load in the country.

As explained in the previous chapter, load forecasting is an important step in the micro-grid design, therefore the method has been modelled on the community under study, so as to ensure that the demand profile estimated matches as much as possible the real one. In the following the assumptions adopted are explained.

Firstly, the average number of persons per household is supposed to be 4, which is the average family composition in Tunisia according to Institut national de la Statistique (INS) [45]. This data is useful since the electric load consumption estimation is based on number of people in a dwelling. Other important parameters, when considering energy consumption, are the solar source and typical temperatures in the area object of study: Meknassy solar radiation [41] is uploaded in the model, while in the view of reflecting the weather of the town and, consequently, people habits a cooling system is added to the total number of appliances of the original model. The appliances contemplated in both models are reported in Appendix A: a comparison between Great Britain and Tunisia was possible thanks to data available on INS website. The site lists the devices, from cooking to ICT sphere, owned by dwellings and the percentage of possession in the Delegation of Meknassy. Hence, the appliances which were not in Meknassy database were deleted, while for the other ones the real share of possession was assumed. Regarding the cooling, a system rated 1780 W was added to the total load during spring and summer only: if the temperature exceeds 29°C the cooling system is supposed to be on, otherwise it is off.

The graph below illustrates a typical meteorological year in Meknassy, it is defined as "a set of meteorological data with data values for every hour in a year for a given geographical location. The data are selected from hourly data in a longer time period (normally 10 years or more)" [41], the selected period is 2007/2016. The black line at 29°C underlines the days when the temperature is higher than the limit, which are concentrated in the period from June to the end of September.

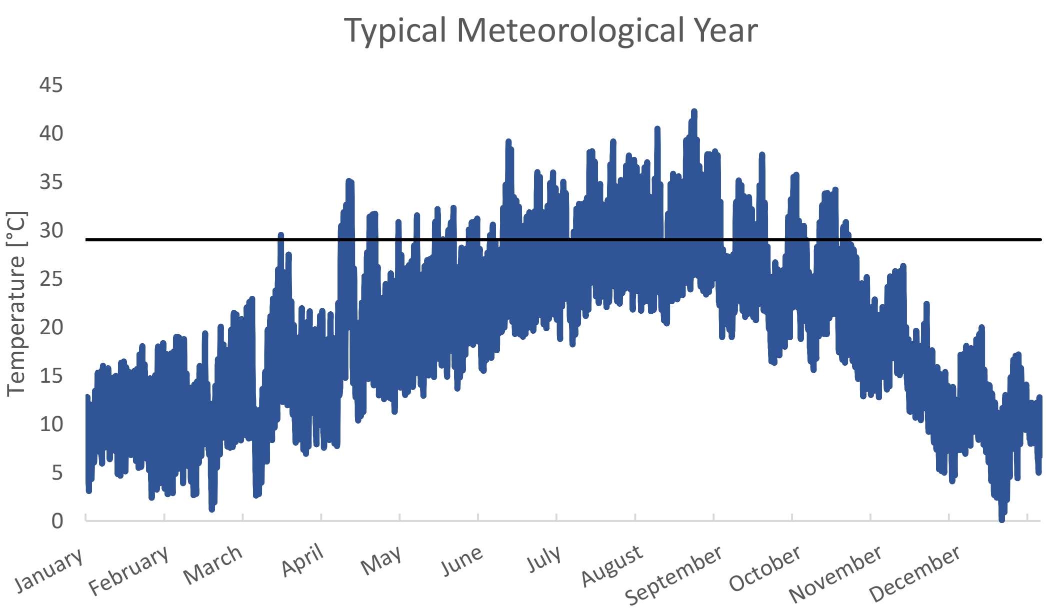


Figure 11 - Typical meteorological year in Meknassy [41]

Limited data access to energy demand in Meknassy was available, therefore the adopted electricity consumption per capita is evaluated on the basis of INS database [45], where information about electricity consumption for each region are reported. The calculated value is 753 kWh/pers in 2017 for the Center region, but it is adopted as a realistic value for Meknassy too. However, a little discrepancy was found by comparing the average electricity consumption in Tunisia provided by two different sources: on one side the consumption per capita at national level provided by IEA [46] and on the other side the value found estimating the mean value over every region in Tunisia from INS database [45]. Considering this inconsistency, a sensitivity analysis is carried on the electric consumption of the town.

Another reason why considering a lower consumption, respect to the national level one, is that analysing the appliances owned per household, the share of Sidi Bouzid governorate is lower compared to national level (particularly respect to northernmost areas and cities near the cost) and, within the governorate, Meknassy share is modest. Since electricity usage is mainly due to residential consumption or at most to little commercial activities running, it is reasonable assume that the energy demand is lower than the national value.

The weekday electric profile obtained, with one-minute resolution, is shown in the figure below, the weekend profile has a similar shape. HOMER requires an electric load profile for each day of the year, and it distinguishes between weekdays and weekends. The simulation is based on the hourly profile uploaded by the user: it must be ensured appropriate energy supply to the load, so it is a critical parameter to model and optimize the system.

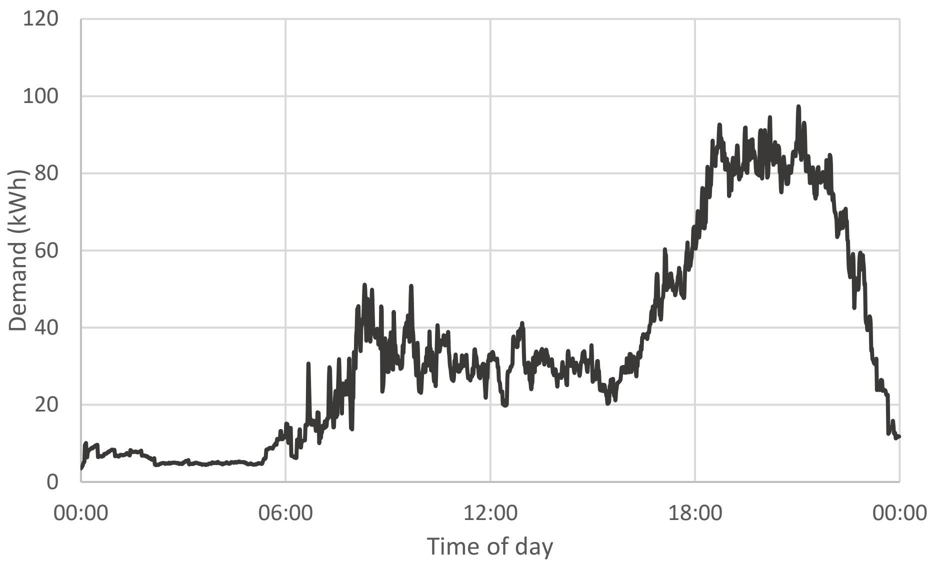


Figure 12 - Mean weekday demand profile

In figure 12 the seasonal profile of the town, elaborated by HOMER, is reported. It is evident a higher demand from June to September, which are the months when temperatures are higher and thus a cooling system was added.

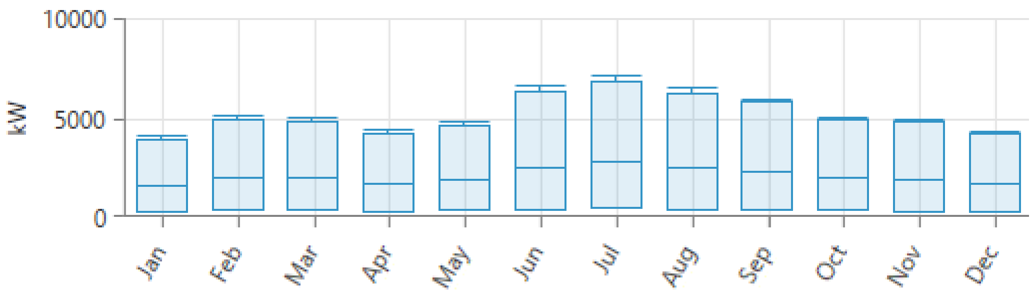


Figure 13 - Seasonal profile

And, finally, HOMER provides some information about the load uploaded. The average daily consumption of Meknassy results 49512 kWh/day, while the average load throughout the year is 2063 kW with a peak load of 7143,3 kW.

Information load profile	
Average daily consumption	49512 kWh/day
Average load	2063 kW
Peak load	7143,3 kW
Load factor	0,29

Table 5 - Information load profile provided by HOMER

2.3.2 Biomass resource assessment

Biomass consists of organic and vegetable matter located in a determined place. The construction of a biomass or biogas plant is, generally, economically feasible in rural areas, since this resource is present in various forms, from dung to vegetable waste from crops.

The municipality and rural area of Meknassy has a huge potential in terms of biomass resources: a fraction is currently used in agriculture by farmers as fertilizer, however it can be further exploited as energy source. The waste situation of Meknassy is illustrated in the following and is based on [42], unless other references are provided.

- **Household waste**

Organic fraction of municipal solid waste (OFMSW)

The collection rate is 70% circa with a frequency of collection of 3 days per week and is organized by the municipality. The total amount of production is different for municipal and rural area, data are shown in the following table.

	Municipal area	Rural area
Population (2016)	17000	7000
Waste production rate [kg/inhab/day]	0,815	0,15
Waste production [Tons/year]	5057,1	383,3
Total [Tons/year]	**5440**	
Total organic fraction [Tons/year]	**3300**	

Table 6 – Organic fraction of municipal solid waste

The percentage of organic matter is 60,6% of the total, so it is equal to 3300 Tons/year.

Beyond the energy potential of this waste matter, the waste management situation should be properly handled, since there isn't a controlled landfill in the area, so that free access to the dump is allowed to anyone. The landfill is near the town of Meknassy (3 to 4 km distance) and this proximity could cause problems to the population: for example, waste is frequently burned, generating unhealth conditions to inhabitants, as they are constantly exposed to chemicals from the fires. The pollution issue concerns the environment too, from soil to atmosphere.

The situation explained regards the municipality only, while conditions in rural areas is even worse, as they do not provide any waste management and, consequently, in the absence of infrastructures, garbage is dumped in natural environment with no control.

Therefore, the organic waste exploitation as energy resource can help to conscious manage waste matter and avoid further environment pollution.

Figure 14 - Waste management situation in rural area

Wastewater

The waste treatment plant of the municipal area is operated by ONAS, National Office of Sanitation, and produces 2530 Tons/year of wet sludge, which corresponds to 160 Tons/year of dried biological sludge. The plant treats wastes coming exclusively from the municipality and does not contain industrial wastes, while in the rural area wastewater is managed through septic tanks.

The biological sludge is currently used as soil fertilizer in local agriculture.

- **Agriculture and livestock sectors**

Green waste

This is one of the sectors with the higher potential: the biomass derives from annual fruit tree pruning and green waste from weekly markets. A survey conducted by municipality services estimated the quantity of tons available. The data are illustrated in the table below.

	Quantity	Specific rate production	Availability	Quantity of waste [Tons/year]
Fruit trees	1.413.030 trees	35 kg/tree	20%	9891
Vegetable crops (tomatoes, potatoes, peas, etc.)	800 ha	0,85 kg /m^2/year	50%	3400
Vegetable sellers	---	0,5 kg/inhab/week	100%	221
Total green waste				**13512**

Table 7 - Green waste

The quantity of green waste resource available can be assumed to be 13512 Tons/year.

Manure and droppings from livestock

The quantity of biomass derives from cattle, sheep and goat livestock and horse breeding, for which Meknassy is internationally known. According to a research about the estimation of the quantity of biomass that can be exploited for energy production conducted in Tunisia [33], the availability of this typology of biomass can vary from 40% to 70 %. The more the storage conditions are properly managed, the lower quantity of biomass is lost. In reference [42], no information about storage is provided, thus, since usually the conditions are not the best ones, the assumed availability is 40%.

	Quantity	Specific manure production by livestock [kg/day]	Total production [kg/day]	Total production [Tons/year]	Availability	Available total production [Tons/year]
Cattle	216	25	5400	1971	40%	788
Sheep	20000	4	80000	29200	40%	11680
Goat	3800	3	11400	4161	40%	1664
Horses	200	30	6000	2190	40%	876
Total	24216		102800	37522	40%	**15009**

Table 8 - Manure from livestock

The available tons per year are 14133 from cattle, goat and sheep breeding and 876 Tons/year from horse breeding, then the total quantity is 15009 Tons/year.

- **Total biomass available**

Finally, the available potential of organic waste can be summarized.

In this final part, it is essential to consider how HOMER manages the biomass resources: it is assumed that the biomass feedstock is converted into biogas [47], which represents the fuel entering the genset. Biogas is produced through anaerobic digestion, a biological process that transforms the organic fraction of biomass in biogas, whose composition is variable according to the substrate from which originates. The main elements of the gas mixture are methane, from 50% to 80%, and carbon dioxide, from 50% to 20%, plus traces of other compounds, such as hydrogen, nitrogen [48].

Each type of biomass is characterized by specific parameters, the variables are listed in Table 9.

Typology of biomass	Potential [Ton/year]	Gasification ratio [kg biogas/kg biomass]	LHV of biogas [MJ/kg]	Carbon content [%]
OFMSW	3300	0,260	20,9	51%
Wet biological sludge	2530	0,050	20,9	28%
Green waste	13512	0,099	20,9	50%
Manure from breeding	15009	0,165	20,9	53%

Table 9 - Total available biomass

Lower heating value of biogas depends on the amount of methane in the biogas mixture. For each of the typologies, the content of methane is about 65% and so LHV, according to [48], is 23 MJ/m^3. Considering a biogas density equal to 1,1 kg/m^3 [49], this variable is equal to 20,9 MJ/kg.

Gasification ratio strongly depends on the substrate, as can be noted in Table 9. The values are calculated according to the equation below [50] and the biogas yields assumed are summarized in Appendix B. The equation represents the actual biogas production from the available biomass feedstock: the biogas yield is, generally, provided as cubic meters of biogas in function of tons of volatile solids (VS), consequently it is crucial to refer this value according to the tons of biomass entering the digestor in order to estimate the effective biogas potential. The parameter t_{TS} corresponds to tons of total solids.

$$\frac{Nm^3{}_{biogas}}{t_{biomass}} = \frac{Nm^3{}_{biogas}}{t_{VS}} \frac{t_{VS}}{t_{TS}} \frac{t_{TS}}{t_{biomass}} \tag{2.1}$$

In Table 10, the different typologies of biomass are sorted according to the obtainable energy from biogas, estimated multiplying their potential and calorific value. As evident from this graph, wet biological sludge occupies the lowest position. Its quantity and biogas yield are minor compared to other typologies, then, in this study, this type is not exploited for biogas production. Another effective reason to not consider it in this plant, is that the construction of a new anaerobic digestor dedicated to sewage sludges is planned by local authorities.

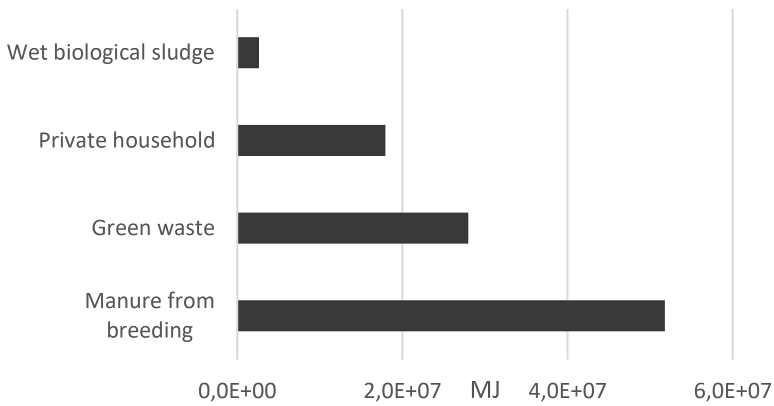


Table 10 - Obtainable energy from biogas according to different substrates

Therefore, the potential substrates that can be involved in the co-digestion process are organic fraction of municipal solid waste, 10%, manure from breeding, 47%, and green waste, 43%.

A search about the existing biogas plants and experimental digestors was carried on and none of the plants analyzed had the same proportion of co-substrates as the one available in Meknassy. In the experimental digestor assumed as reference [51], the biomass entering the reactor is composed of 54% manure and 46% agricultural waste and the biogas production yield results higher respect to the production from the single substrates. Thus, only the two typologies of biomass with the higher energy potential are considered, see Figure 14: green waste and manure for a total amount of resources of 28521 Ton/year. The biogas production in a co-digester is higher respect to a mono-digestor since the degradation of the organic fraction is intensified and the co-substrates, which are generally characterized by different elementary compounds, balance each other's acting synergistically [52]. These observations are true if the digestion process is managed accurately and if the process is constantly monitored [50].

It is assumed that the bio-wastes can be stored and, consequently, the total quantity is considered uniformly distributed through every month of the year (daily availability 78,1 Ton/day).

For conservative reasons, here the gasification ratio is evaluated as the weighted biogas yield, according to the equation below [52] and it is equal to 0,143 $kg_{biogas} / kg_{biomass}$.

$$\text{Weigthed biogas yield} = \sum_{i}^{N} biogas\ yield_i * P_i \tag{2.2}$$

Where P_i is the percentage of the i-th co-substrate referred to a volatile basis and biogas $yield_i$ is the gasification ratio.

The price of this resource refers only to collection and transport, this cost per ton is in the range between 60 TND and 80 TND, so that an average of 70 TND/Ton, i.e. 22,4 €/Ton, is a reasonable assumption [42].

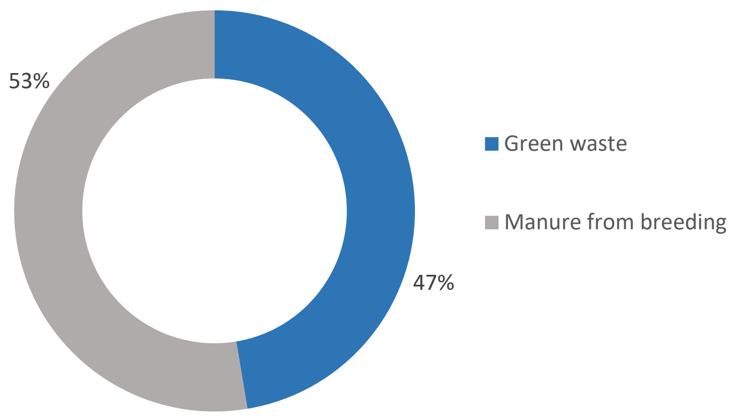


Figure 15 - Percentage of co-substrates in co-digestion process

Input data required by HOMER are summarized in the table below.

Price (€/ton)	Carbon content (%)	Gasification ratio of co-substrate (kg/kg)	LHV biogas (MJ/kg)	Quantity (ton/day)
22.4	51	0,143	20.9	78,1

Table 11 - Biomass input parameters

2.3.3 Solar resource assessment

Energy from solar radiation is a renewable, clean and eco-sustainable resource: properties which allowed a worldwide exploitation of this kind of energy. On one side the need to meet international concerns about pollution and the willingness to reduce greenhouse emissions lead to invest increasingly on alternative sources, on the other side the decline in photovoltaic panel cost and increasing of expertise in this technology permit photovoltaic to spread widely. Hence, the modest maintenance costs and the reduction of capital cost allow the deployment of PV in developing countries, where, generally, the solar potential is good, as it happens in Meknassy.

Data about solar radiation profile of the town derives directly from HOMER and are illustrated in the graphs below. Table 5, illustrates the average daily radiation for each month and the clearness index, which is a parameter between 0 and 1 that describes the portion of radiation reaching the Earth through the atmosphere [47].

Month	Clearness index	Daily radiation [kWh/m2/day]
Jan	0,481	2480
Feb	0,542	3510
Mar	0,554	4580
Apr	0,583	5820
May	0,607	6740
Jun	0,643	7410
Jul	0,665	7510
Aug	0,638	6610
Sep	0,575	5080
Oct	0,498	3480
Nov	0,473	2570
Dec	0,472	2240

Table 12 - Clearness index and monthly averaged Daily radiation

While Figure 10 gives a visual impression of the trend throughout the year. Meknassy presents good values for solar radiation exploitation, with 4,84 kW/m^2/day as average yearly datum and 7,51 kW/m^2/day the maximum and 2,24 kW/m^2/day minimum value, indicating a quite large difference of the irradiation between summer and winter. Clearness index is, also, quite high in central months of the year.

HOMER pro derives the data from NASA Surface meteorology and Solar Energy Database and are based on a 22 years period.

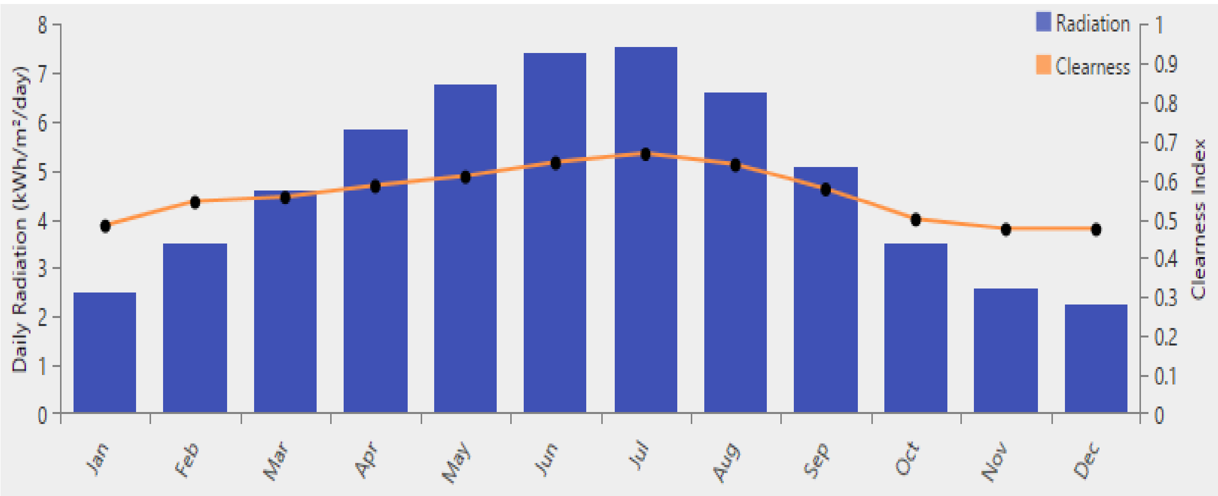


Figure 16 - Monthly horizontal radiation in Meknassy

Chapter 3

System design and analysis

3.1 Components modelling

The system delineated in this work is a hybrid system, so it involves various energy sources which can be renewable, such as hydro, photovoltaic, wind or biomass, or non-renewable, the traditional sources. The advantages of a hybrid plant may be significant: reduction of energy production cost, reliable supplying of electricity and a possible local technological development, as well as an economical one [53].

In this plant the components, whose characteristics are illustrated in this section, are all powered by renewable sources of energy, except for the grid. As described in previous chapters, energy mix in Tunisia is composed quite entirely by natural gas, therefore the introduction of a new hybrid plant can lead to a substantial emission reduction, in addition to the lowering of costs.

The components considered are: biogas genset, photovoltaic panels, inverters and batteries. The selected configuration must meet, totally or partially, the load delineated in Chapter 2. If the system is not able to fully supply the demand of Mekanssy, the national grid can intervene and provide the required electricity, allowing a successful operation of the system.

3.1.1 Biogas generator

HOMER Pro assumes that the biomass resource is converted into biogas: biogas genset JGS 320 GS-B.L [54] is assumed as the reference for technical parameters. Inputs required by HOMER are the fuel curve, which represents the fuel consumption as a function of a specific load (kg/h/kW), its slope is illustrated in the figure below together with the genset efficiency. These parameters are based on the technical catalogue of the genset previously mentioned, where consumption at partial loads 25%, 50%, 75% and 100% was provided and through these values the fuel curve is drawn. Then a minimum load ratio of 30% [55] and a lifetime of 80000 hours are specified [56].

Capital and replacement costs are 782 €/kW [57] referred to 2016, so it is actualized and results 890,7 €/kW. Different generator capacities are uploaded in HOMER: 900 kW, 1000 kW, 1100 kW and 1200 kW, to which corresponds an investment cost of cost of 712.563 €. This cost is assumed the same, since the specific cost as a function of maximum power remains constant for capacities greater than 800 kW [55]. The capacity is determined in the simulation section, according to the electric load and the biomass availability.

Operation and maintenance costs are here referred to scheduled maintenance, when oil is changed and little repairs are performed. The input data uploaded is 0,99 €/op. h (cost of oil plus labor): this cost is based on [58], actualising the cost and value according to the capacity considered.

Table and graphs below show the genset input parameters.

Lifetime		80000 h
Minimum load ratio		30%
Costs	Capital cost	712573 €
	Replacement cost	712573 €
	O&M cost	0,99 €/op h

Table 13 - Biogas genset input parameters

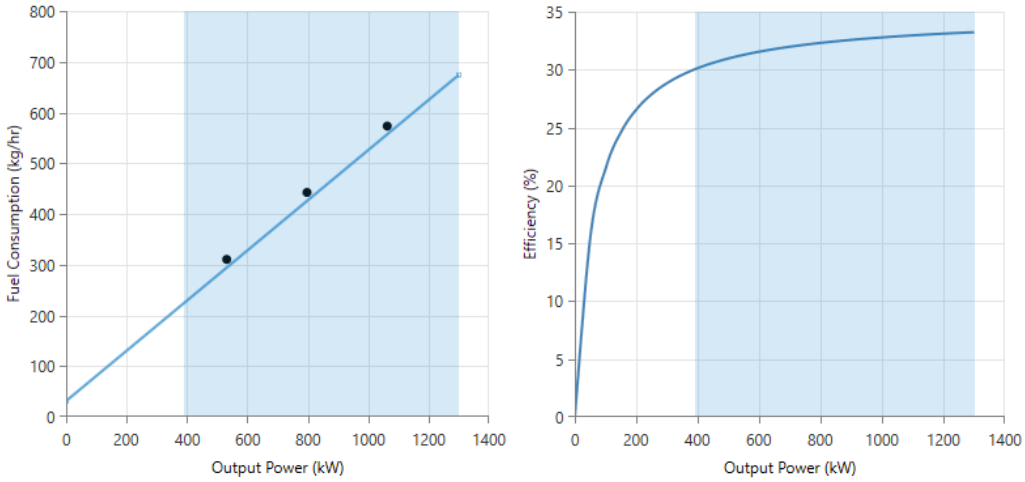


Figure 17 - Biogas genset properties

3.1.2 Solar photovoltaic

The selected solar modules are produced by a national manufacturer, IFRI-sol [59]: technical specifications are summarized in Table 13, which are the inputs required by HOMER.

PV panels cost drastically reduces in last years, particularly for local producers, as they are tax-exempted [60]. Costs typical of Tunisian context are also illustrated and are based on [53], capital and replacement costs correspond to 1382,58 €/kW. Since the system lifespan is 25 years, which is the lifetime of the selected PV modules, the replacement cost can be set to zero too.

Operation and maintenance cost is assumed equal to 1,5% of capital cost [62], that is 20,74 €/y, they account for panels cleaning, general check of components and other administration costs. The enter input value about size is set to 1 kW and then, during the simulation, HOMER optimizes the entire system and determines the best configuration and photovoltaic size.

Lifetime		25 years
Derating factor		80%
Efficiency at standard condition		16%
NOCT		45°C
Temperature effect on power		-0,41%/°C
Costs	Capital cost	1382,58 €/kW
	Replacement cost	1382,58 €/kW
	O&M cost	20,74 €/y

Table 14 - Photovoltaic data input for HOMER

HOMER models the photovoltaic system based on inputs parameters and calculating the output power according to the following equation:

$$P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_S} \tag{3.1}$$

PV array is modelled as a system producing dc current in proportion to the irradiance on the PV array; the parameters in the equation correspond to the derating factor, f_{PV}, rated capacity of PV modules, Y_{PV} (kW), the global solar radiation incident on modules surface, I_T (kW/m2) and the standard radiation equal to kW/m^2, I_S.

3.1.3 Converter

The inverter system is necessary to convert the DC power output from photovoltaic modules to AC power. The converter chosen is manufactured by Steca [63]. Table 7 summarizes the technical specifications of the inverter, characterized by 15 years lifetime and an efficiency of 95%. Initial investment cost is 1621 € and the operation and maintenance cost is 43,2 € per year.

Lifetime		15 years
Efficiency		95%
Costs	Capital cost	1621 euro
	Replacement cost	1621 euro
	O&M cost	43,2 euro/y

Table 15 - Inverter data input for HOMER

3.1.4 Storage batteries

Battery banks function is to store surplus energy from photovoltaic system, allowing exploitation of solar energy at night, otherwise it can have a back-up function.

The battery chosen for the system is a generic 6 V Lithium-Ion battery with 1 kWh energy storage, the optimization is performed by HOMER. Initially, Lead-Acid batteries were considered too, as they are characterized by lower investment cost and are widely used, however, according to studies [58], [64], lithium-ion batteries present many technological advantages: higher energy density and lifecycle, low maintenance cost and they are more environment friendly too.

The technical and cost characteristics are summarized in Table 8, based on [65], the lifetime of the battery estimated is 15 years and a capital cost of 700 € is assumed. The initial state of charge is set to 100% and the minimum state of charge is 40% to avoid a damage to the storage back caused by excessive discharge [66].

Lifetime		15 years
Throughput		3000 kWh
Initial state of charge		100%
Minimum state of charge		40%
Costs	Capital cost	700 euro
	Replacement cost	700 euro
	O&M cost	10 euro/y

Table 16 - Battery data input for HOMER

3.1.5 Grid

The legislative framework which regulates the micro-grid energy production and the connection to the national grid is the authorization scheme. Decree 2016-1123 clearly states the terms for electricity production with renewable sources from private investors and defines that a resale price must be define by Ministry of Energy, Mines, and Renewables. This data is not publicly released on STEG or Ministry sites, hence here the resell prices for authorization regime are assumed equal to the auto-production ones. These values, reported in Table 6, are published by STEG and are expressed in milim TND per kWh according to different hours of the day: daytime tariff goes from 6.30 to 8.30 a.m. and from 1.30 to 7 pm; morning peak is from 8.30 am to 1.30 pm; evening peak from 7 to 10 pm; night goes from 10 pm to 6.30 am. The total number of hours per tariff in a year is specified in the table.

Hours	Number of hours in a year	kilowatthour price [thousandths TND]	kilowatthour price [€/kWh]
Daytime	3166	115	0,037
Morning peak	395	182	0,058
Evening peak	939	168	0,053
Night	4260	87	0,028

Table 17 - Sellback prices

HOMER allows to define different rates according to month and time of day, so that this scheduled table is reported on HOMER.

STEG publishes also electricity tariffs, which differs for types of customers (residential or non-residential) and for the maximum consumption per month. Residential household consuming less than 100 kWh/month are considerably subsidies, they pay a maximum price of 0,031 €/kWh, while, with increasing of monthly consumption, tariff increases until 0,13 €/kWh. Tariffs for non-resident are higher. Considering that the main demand comes from residential sector and street lighting while and lower part from business activities, the electricity price estimated is 0,13 €/kWh.

3.2 Economic evaluation

In this section, it is explained how HOMER performs the economic evaluation of the system [6]. This estimation can concern both renewable and non-renewable sources, which have diverse cost characterization: the first one has high investment costs and low maintenance while traditional technologies are characterized by higher operating and maintenance costs but low capital cost. Thus, it is critical the way these different systems are compared.

Life-cycle cost analysis contemplates investment and operation costs over entire the lifetime of the system analysed. For this purpose, HOMER estimates the Net Present Cost (NPC), which "condenses all the costs and revenues that occur within the project lifetime into one lump sum in today's dollars, with future cash flows discounted back to the present using the discount rate" [6]. When estimating NPC, investment cost is a positive value and revenues are negative. It contrasts with the net present value definition.

For the evaluation of the NPC, HOMER refers to the cost input parameters of each component (capital, replacement, O&M cost and salvages or revenues) and calculates the annualized cost of the components. These values are summed and the annualized cost of the entire system, $C_{ann,tot}$ is obtained. Hence, the NPC is estimated according to the following equation:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{3.2}$$

where CRF(i, R_{proj}) stands for capital recovery factor, R_{proj} is the lifespan of the system and i is the discount rate.

$$CRF\ (i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3.3}$$

where N is the number of years.

Finally, the other essential parameter to be evaluated is the levelized cost of energy (COE), which estimates how much costs producing a kWh for the system under investigation:

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \tag{3.4}$$

where E_{def} and E_{prim} are the yearly deferrable and primary load, while $E_{grid,sales}$ is the energy sold to the national grid every year. The sum of these quantities is the total amount of energy yearly produced by the plant.

Both NPC and COE are solid metrics to compare costs of different configurations, however HOMER refers to NPC to carry on this confrontation since its definition is universal and does not leaves room for ambiguous specifications (while COE can be referred to energy required by the load, instead to the electricity produced). The different system configurations are listed from the one with the lower NPC value to the one with the greater value: the optimum configuration identified by HOMER is the first one.

3.2.1 Economic inputs

Inputs required by HOMER are the inflation rate, assumed to be equal to 6,5% in 2019 [67], and the nominal discount rate, equal to 10,7%, which is the weighted average cost of capital [62] and is estimated considering the cost of equity and cost of debt. The calculated value falls in the range assumed by [62] in the African context. HOMER uses these two input quantities for the evaluation of the annual real discount rate, according to the following equation:

$$i = \frac{i' - f}{1 + f} \tag{3.5}$$

where *i'* is the nominal discount rate and *f* is the inflation. The real discount rate, *i,* is 3,94%. HOMER uses this value in order to evaluate discount factors and convert one-time costs in annualized costs [47].

The other variables required in this section are the project lifetime, assumed equal to 25 years, a suitable lifespan for the system considered [68]; system fixed capital cost is an expense t to meet at the beginning of the project life, which do not consider the size or the design of the project. It is a fixed cost added at the capital cost of the plant: it influences all system configurations considered and thus it has any consequence on the system rankings. This cost is assumed equal to the anaerobic digester costs which ranges between 250 €/m^3 and 700 €/m^3 [48]. According to [69] it is set equal to 272,2 €/m^3 and since the total amount of substrate entering the digester is 8,6 m^3/h, the volume of the digester, considering 30 days as time of residence, is assumed to be 6158 m^3, thus the total cost is equal to 1.675.227 €. This cost corresponds to construction cost and represents 65% of total investment. Facilities, labour, land and further installations count for 35% [69], so that the fixed capital cost become 2.577.272 €.

This investment is estimated according the correlation below [70]:

$$\frac{C_1}{C_2} = \left(\frac{Q_1}{Q_2}\right)^n \tag{3.6}$$

where C_1 is the cost of the system at size Q_1, C_2 is the system assumed as reference at a determined size and n is the scale exponent and it is the crucial parameter to be determined. According the study, when considering biogas plants of large scale in African countries, n is equal to 1 and so a constant return to scale exists.

Finally, the operation and maintenance cost considered is 1% of capital cost [69]. Capacity shortage penalty are not contemplated, and the currency is euro.

Nominal discount rate	10,7%
Expected inflation rate	6,5%
Project lifetime	25 years
System fixed capital cost	2.577.272 €
System fixed O&M cost	25.773 €
Capacity shortage penalty	-

Table 18 - Economics input

3.3 System design

Two system designs are considered during the simulation on HOMER pro.

During the first simulation, the chosen components that must meet the load are the biogas genset and the national grid. Hence only the biomass resource is modelled, plus the two components. This preliminary step allows to optimize the genset size, according to the available biomass, and when the genset is not able to totally meet the load, the grid intervenes. The system design is illustrated in Figure 17.

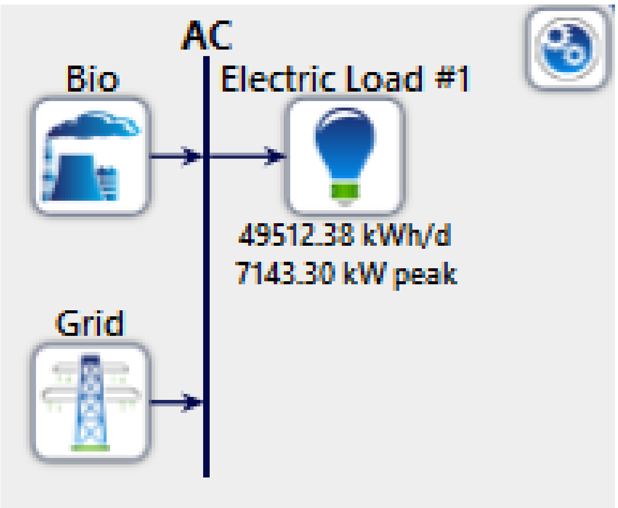


Figure 18 - First configuration: biogas genset

Then, the solar resource is added and thus the photovoltaic system. The other two components matched with PV are the inverter and the batteries.

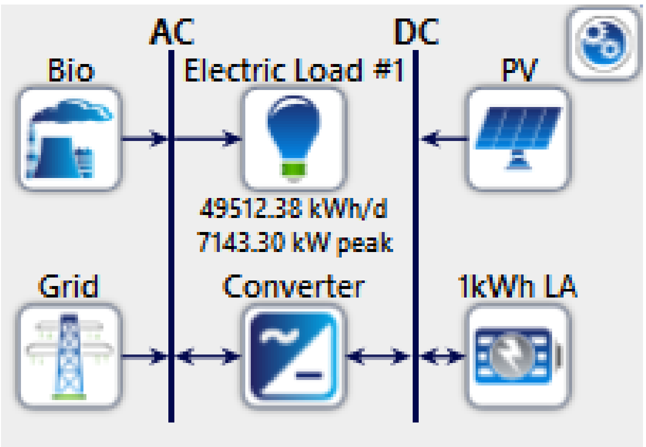


Figure 19 - Second configuration: biogas genset plus PV

Chapter 4

Simulation results and discussion

4.1 Optimization results

The description of how HOMER models the economic evaluation is shown in the previous chapter. The economic analysis is critical, in fact it is the basis for finding the optimal system configuration.

4.1.1 Scenario 1: Biogas genset

The first configuration comprises the biogas genset only. It is supposed that the daily available biomass feedstock is 78,1 tons. This resource enters the anaerobic digester for the biogas production, which in turn feeds the generator. Since Meknassy is a medium size town, the energy supplied by the genset cannot fully meet the load, hence the national grid intervenes when the demand is higher and during peak hours.

Architecture			**Cost**				**System**		**Grid**	
Bio (kW)	**Grid (kW)**	**Dispatch**	**NPC (M€)**	**COE (€)**	**Operating cost (M€)**	**Initial capital (M€)**	**Renewable Fraction (%)**	**Total Fuel (kg/y)**	**Energy Purchased (kWh)**	**Energy Sold (kWh)**
1100	999999	CC	35,7	0,126	2,06	3,29	42,1	27810	10461523	1567

Table 19 - Results for biogas genset

The table summarizes the configuration chosen elaborated by HOMER. The net present cost of the system is 35,7 million euros and the cost of electricity in this scenario is 0,126 euros. In the initial capital cost, the greater share is represented by the anaerobic digester plant, AD, as highlighted in Table 21. From this table it can be also noticed that the value that mainly affects the total cost is the electricity purchased by the national grid.

Other economic metrics are: the internal rate of return (IRR) 49,4%, return of investment (ROI) 40,2% and the payback time equal to 2 years. The system used as reference is the one where the load is totally supplied by the grid, called base case architecture by HOMER. Table 20 compares the two configurations: the base case and the optimized system with the biomass generator.

	Base case	Lowest cost system
Initial Capital	€2.58M	€3.29M
Operating Cost	€2.38M	€2,06M
Cost of Energy	€0.141	€0.126

Table 20 - Comparison with base case

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Biomass Generator	712.563	818.379	126.069	9.789.894	-126.749	11.320.157
Grid	0	0	21.221.066	0	0	21.372.390
AD	2.577.272	0	405.036	0	0	2.982.308
System	3.289.835	818.379	21.756.341	9.789.894	-126.749	35.674.855

Table 21 - Total system

The biogas system is a 1100 kW genset and it can supply half of the energy demand circa, as the renewable fraction amounts to 42,1%. Figure 20 shows the load profile of a sample week, it can be noticed that during night hours the genset works at a lower power respect to its rated power. During these periods the electricity produced is sold to STEG, however the resell price at night is the lowest thus the revenues are not too high.

Finally, an important factor to analyse is the emission in atmosphere, in fact HOMER estimates for each configuration the amount of polluting gasses released: the avoided carbon dioxide every year is equal to 4.758.151 kg_{CO2} (calculated respect to base case).

Quantity	Value
Hours of Operation	8.103 hrs/y
Operational Life	9,87 y
Capacity Factor	79,0 %
Electrical Production	7.612.064 kWh/y
Mean Electrical Output	939 kW
Fuel Consumption	27.810 tons/y
Specific Fuel Consumption	0,522 kg/kWh
Fuel Energy Input	23.087.715 kWh/y
Mean Electrical Efficiency	33,0 %

Table 22 - Generator operating condition

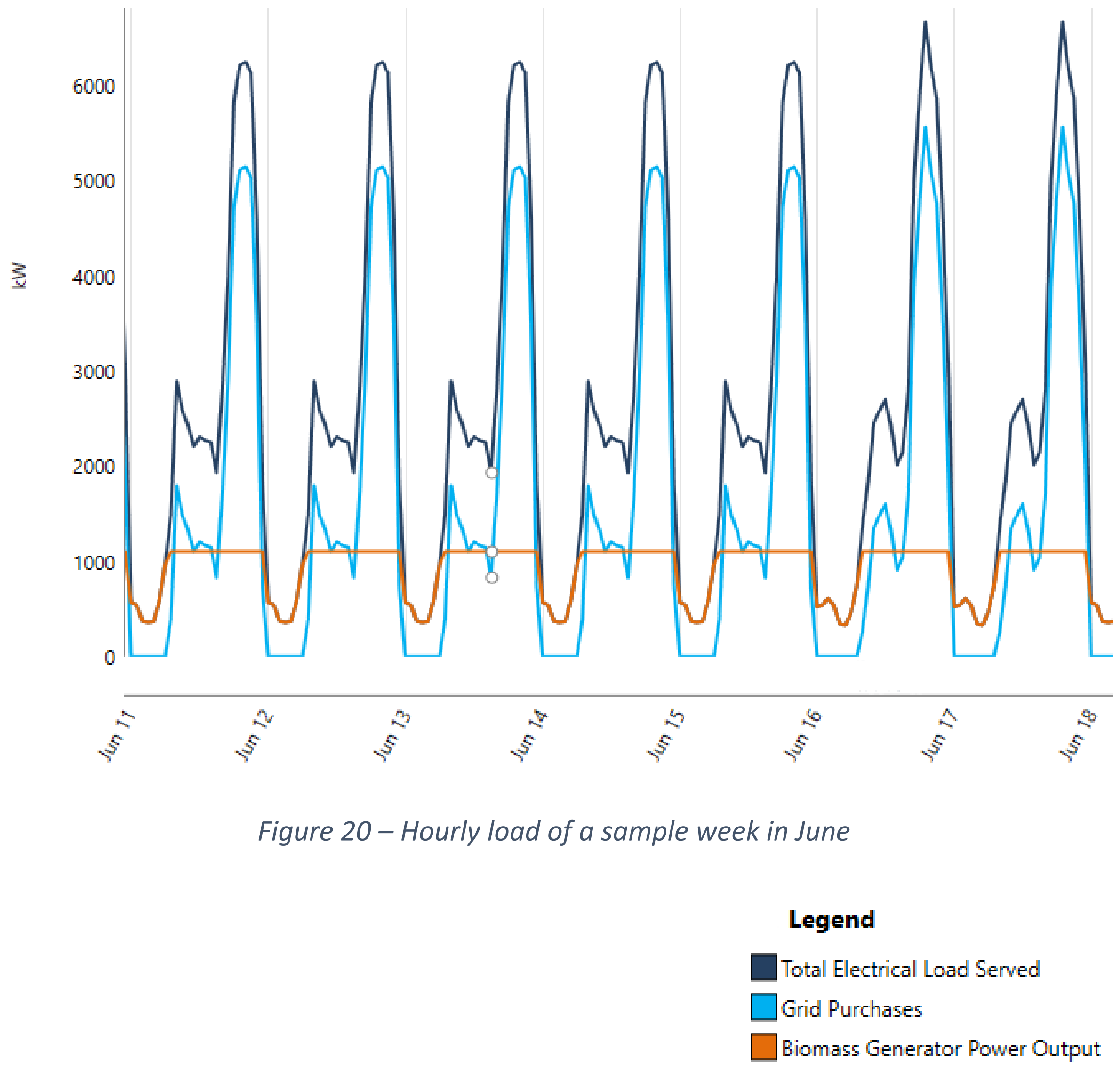


Figure 20 – Hourly load of a sample week in June

Figure 21 shows the discounted cash flow through the lifetime plant: it is provided the overall inflow, positive values, or outflow, negative values, for each year. The year zero, i.e. the first bar, represents the capital cost, in this scenario it is the sum of anaerobic digester and generator investment costs. The inflows are illustrated only the last year. They represent the save of component at the end of the life of the total project and the incomes from selling electricity.

Most of the operating cost is composed of electricity purchased by the grid.

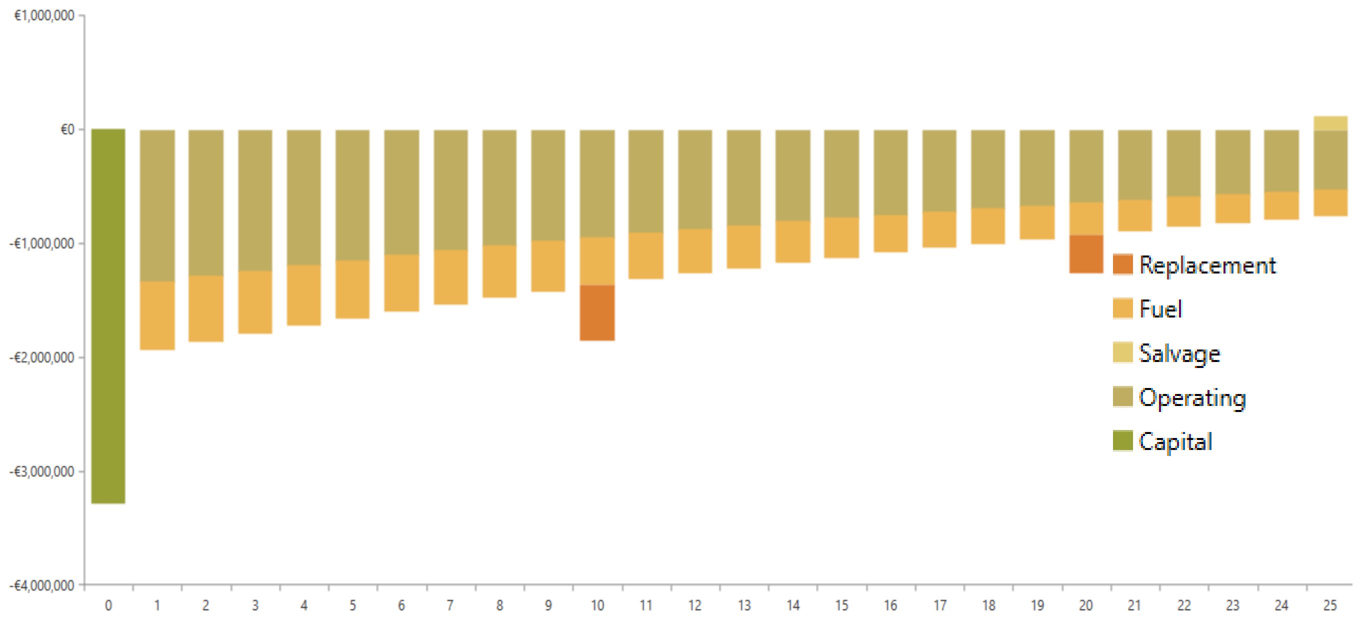


Figure 21 - Discounted cash flow

4.1.2 Scenario 2: Biogas genset and photovoltaic system

The first configuration includes a significant share of renewable sources, genset meets 42,1% of total load. However, considering the available solar irradiance in Meknassy, the second scenario foresees to incorporate photovoltaic panels in the configuration previously designed with the aim to increase the renewable fraction of the overall system.

Input data about PV panels, inverter and battery are uploaded in HOMER for the simulation, while the installed capacity is evaluated by the software. The optimized solution found, the one with the lowest net present cost, does not include a photovoltaic system, i.e. the optimized configuration remains the same of scenario 1.

The second optimal configuration includes photovoltaic too, but PV capacity is very low and equal to 30,2 kW, which is a negligible value compared to the required load. Therefore, in this scenario different values of photovoltaic capacity are investigated, even if they are not identified by HOMER as the optimal solution. The aim is to evaluate the investment costs and the cost of energy in this new configuration.

The considered options of PV installed power are the following. The maximum power, P = 6000 kW, is established according to the peak load. As shown in Table 23, NPC and LCOE values increase with increasing of the capacity. However, these parameters remain higher respect to the base architecture, that is the installation of PV modules is economically suitable and convenient respect to purchasing electricity from the grid, even if it does not represent the optimal solution. This is true for a PV power lower or equal than 4000 kW, while the last two alternatives are not feasible. Furthermore, in the view of an increase in power, there is not a substantial reduction in emissions of pollutants, Figure 24. See figure 23, where the base case (national grid only) is signed in black.

Figure 22 shows the output profile of the different components, with a 4000 kW PV.

PV capacity (kW)	NPC (M€)	LCOE (€)	Renewable penetration (%)	Emission factor (kg_{CO2}/y)
1000	36,4	0,128	49,5	6.028.725
2000	37,3	0,131	51,3	5.608.671
3000	38,4	0,135	53,6	5.348.365
4000	39,6	0,139	54,9	5.196.288
5000	40,9	0,143	55,9	5.105.869
6000	42,2	0,147	56,6	5.043.021

Table 23 – Costs for different PV capacities

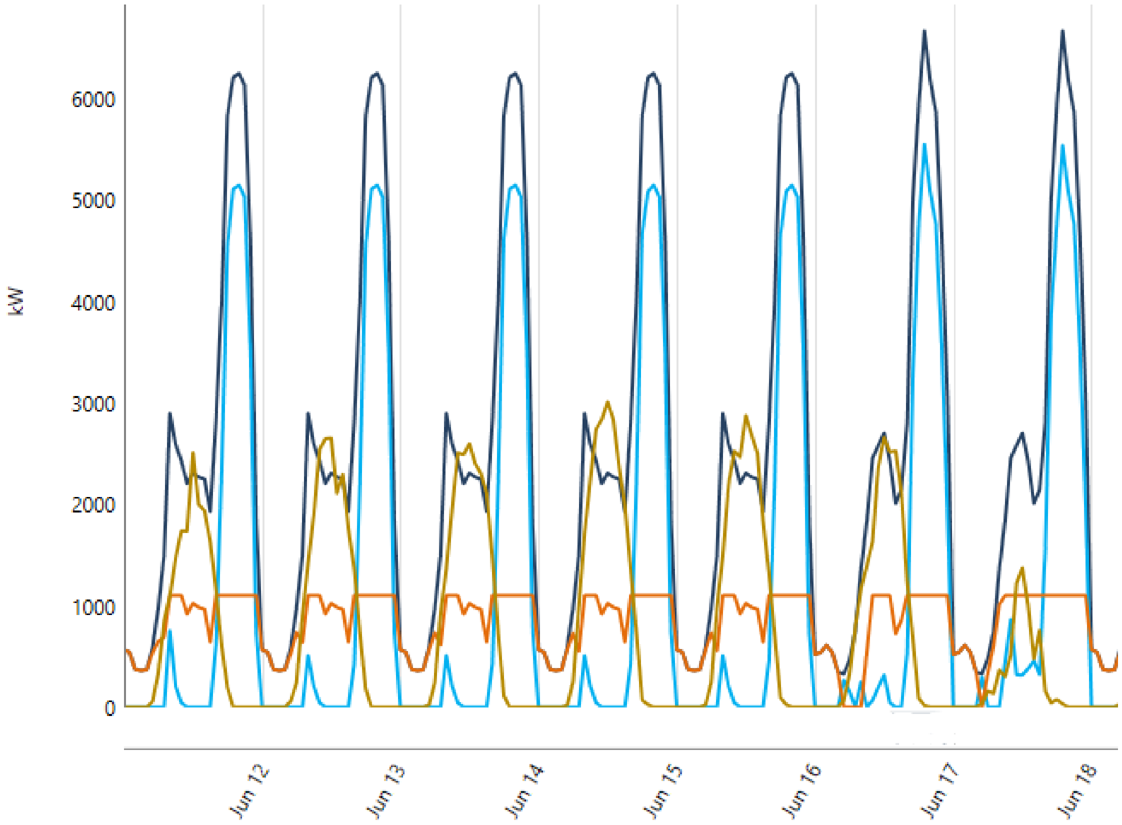
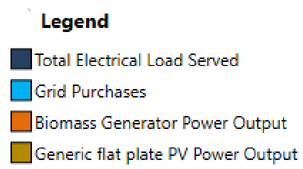


Figure 22 – Hourly load of a sample week with 4000 kW photovoltaic



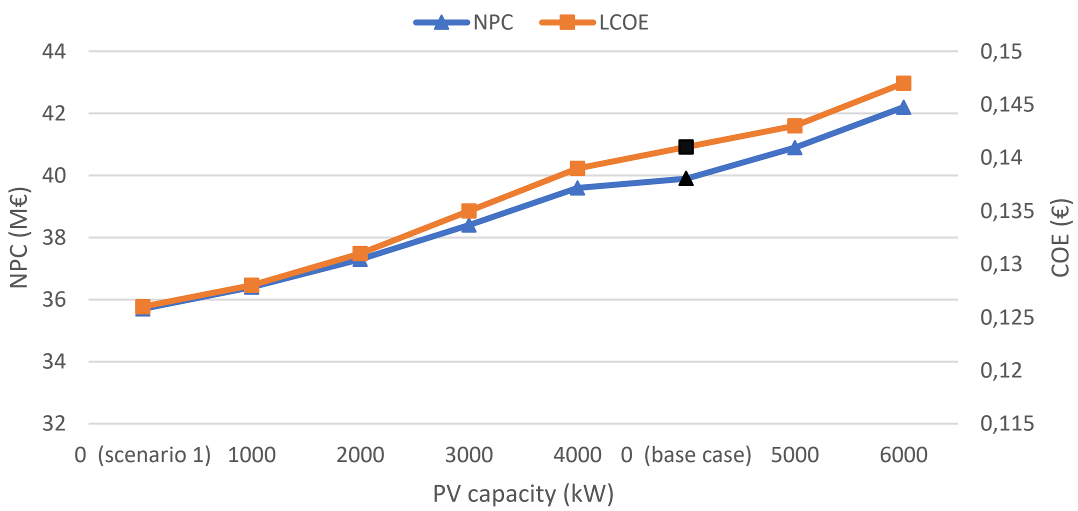


Figure 23 - Cost variations according to different PV capacities

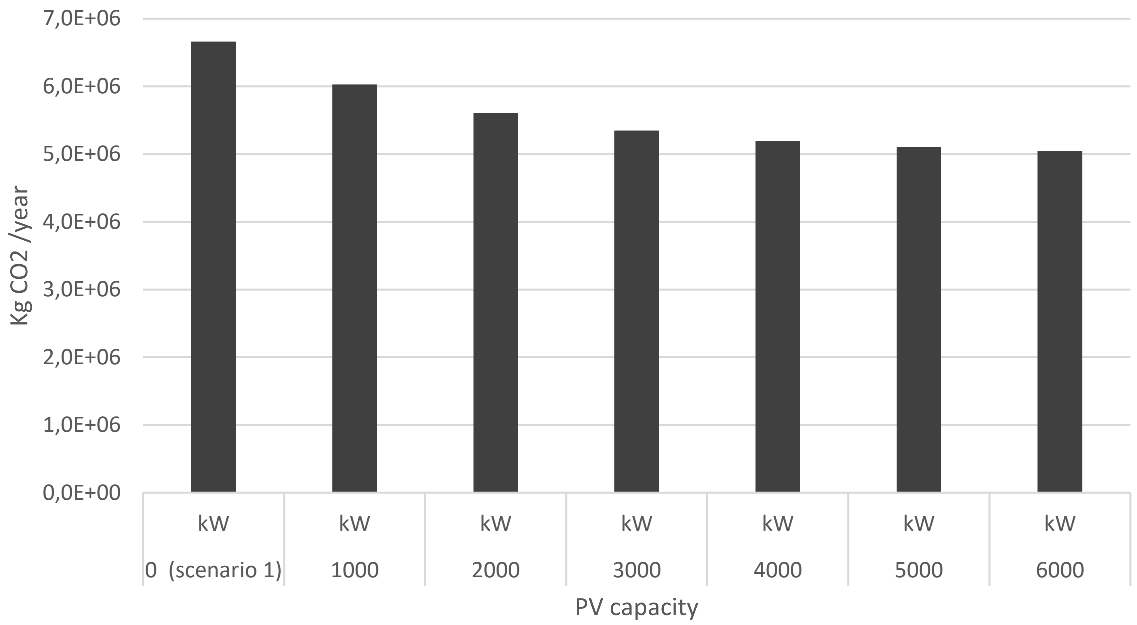


Figure 24 - Emission factors

Considering the context assumed in this work, the maximum feasible capacity of PV is equal to 4000 kW. The renewable fraction results to be 54,9% and the discounted cash flow is shown in the figure below.

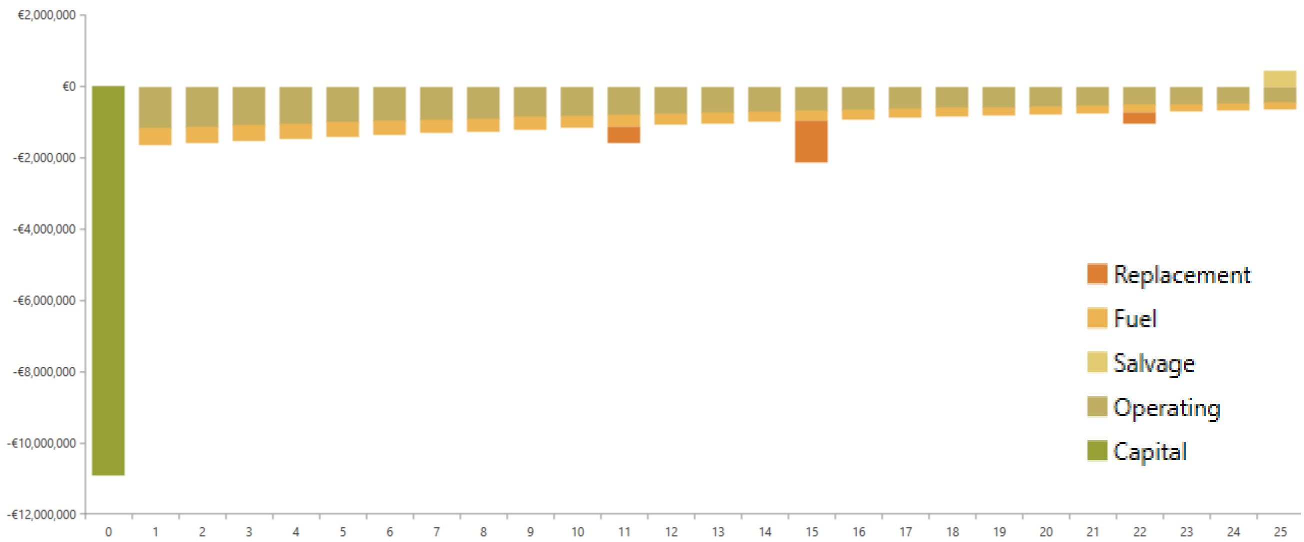


Figure 25 - Discounted cash flow: genset + 4000 kW PV

Now, it is carried on a sensitivity analysis in order to evaluate the parameters which determine if the photovoltaic system is feasible or not.

4.2 Sensitivity results

An investigation in sustainable energy technologies conducted by FAO [40] founds that in Tunisia the economic feasibility of a system based on renewable sources (the plant under investigation was a biogas power plant) was hindered by heavy subsidies dedicated to electricity from national grid. Thus, sustainable systems are profitable under a social and environmental point of view, but not in economic terms. Therefore, in conclusion, the study underlined that "a revision of the current electricity subsidy scheme would facilitate the adoption of clean technologies".

In this work, the sensitivity analysis seeks to evaluate the scenarios that can make photovoltaic investment profitable. Firstly, since the price of electricity is quite low compared to typical costs of the European market (according to Eurostat the average price in Europe is 0,22 €/kWh), the purchased electricity cost is gradually incremented. Then, the capital cost of photovoltaic panels is reduced: this reduction can be caused by the spreading of the technology in the country, and, in fact, PV prices have been reduced of 20% from 2010 to 2015 [60]. Another way that can lead to a reduction of the investment costs of photovoltaic is a public subsidy: this is a feasible scenario since in Tunisia does not exist big PV plants and this can be a way to increase investment in clean technologies.

During the sensitivity analysis the biogas genset capacity is assumed unchanged and equal to 1100 kW.

4.2.1 Electricity price

During the simulation, the assumed electricity cost is 0,13 €/kWh. This value is gradually incremented, of 20% each time, until reaching a price that doubles the initial one and corresponds to the average price of electricity in Europe according Eurostat database. The data in Table 24 summarize the best configurations found by HOMER for each value of electricity price.

Energy purchased cost (€/kWh)	PV installed (kW)	Renewable fraction (%)	NPC (M€)	COE (€)	Energy purchased (kWh)	Energy sold (kWh)
0,130	0	42,7	35,7	0,126	10461523	1567
0,163	0	42,7	41,1	0,145	10.349.157	349
0,195	0	42,7	46,3	0,163	10.349.157	349
0,228	1617	51,8	50,4	0,178	8.708.995	1020
0,260	2030	53,2	54,7	0,193	8.452.604	2563

Table 24 – Optimal configurations varying

For a price equal to 0,228 €/kWh the installation of PV modules becomes the most feasible. Figures below illustrate graphically the data in Table 24.

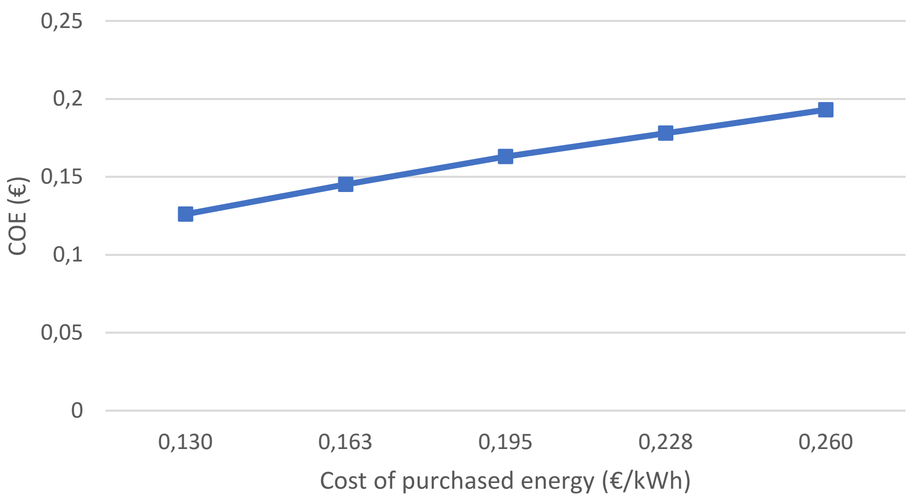


Figure 26 - Levelized Cost Of Energy

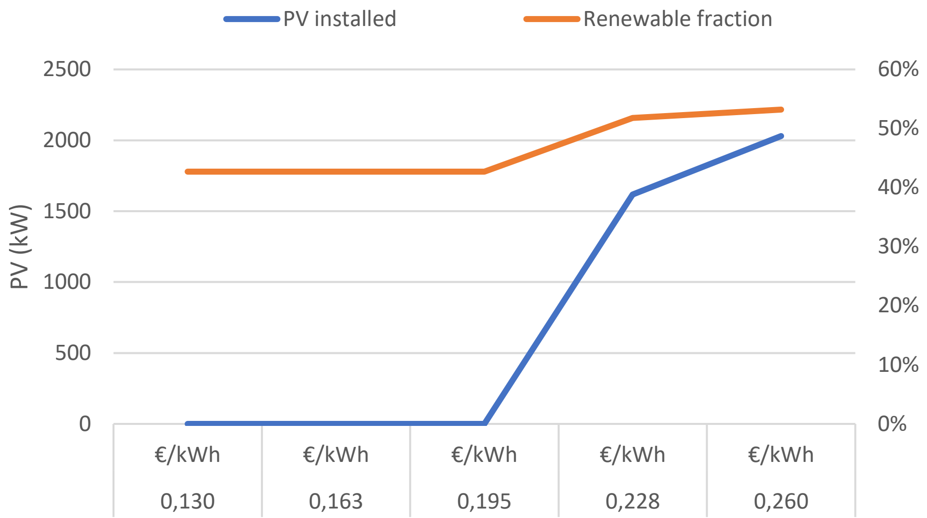


Figure 27 – PV capacity

4.2.2 PV capital cost

In this section, the capital cost of photovoltaic panels is decreased until a minimum threshold of total capex equal to 800 USD (2016)/kW, which is a cost estimated for the Indian scenario [71]. This value is referred to the capital cost of both PV module and the inverter: here it is assumed that 60% of capex concerns the photovoltaic and the remaining 40% the inverter. Hence, actualising the costs a value of 912,4 USD (2019)/kW is obtained and the cost for the components is in the table below.

PV capital cost	492,7 €/kW
Inverter capital cost	328,5 €/kW

Table 25 - Minimum capex

Starting from this threshold, the capex is increased of 30% each simulation. After a maximum value of 936 €/kW was found, the PV cost is gradually increased in order to find a threshold. The results are summarized in the following.

PV CAPEX (€/kW)	PV capacity (kW)	NPC (M€)	COE (€)
493	5760	32	0,106
640	4394	33,2	0,115
788	3459	34,2	0,12
936	2507	35	0,123
1000	1796	35,2	0,124

Table 26 - Optimal configuration by varying PV capex

The maximum threshold value of photovoltaic capital cost which makes the genset + PV configuration optimal is 1000 €/kW. This cost is not much lower respect to the one assumed as initial value, which represents the average capital cost for PV in Tunisia.

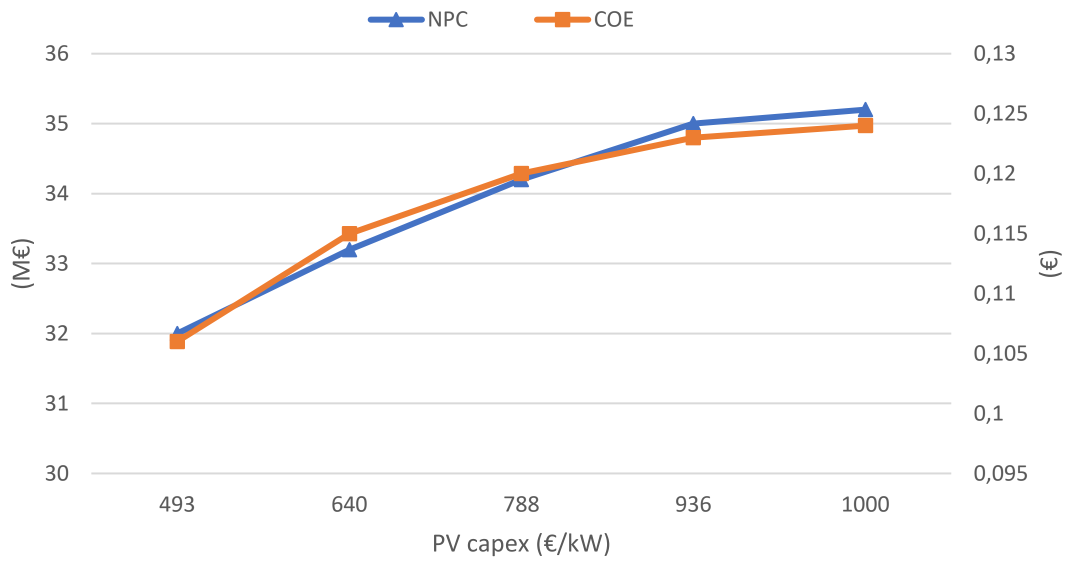


Figure 28 - Economic parameters

Finally, it is possible to notice that the system with the lowest NPC and LCOE is the one with 1100 kW biogas genset and 5760 kW of photovoltaic panels with a capex of 493 €/kW. The outputs are summarized below.

NPC (M€)	COE (€)	Renewable fraction (%)	Energy purchased (kWh)	Energy sold (kWh)
32,0	0,106	58,9	7.864.892	1.067.707

Table 27 - Output data of optimal configuration

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Biomass Generator	712.563	413.267	88.371	6.096.320	-60.961	7.249.560
Generic flat plate PV	2.838.136	0,00	669.902	0,00	0,00	3.508.038
Grid	0,00	0,00	15.438.960	0,00	0,00	15.438.960
Other	2.577.272	0,00	405.036	0,00	0,00	2.982.308
System Converter	797.757	446.581	1.646.219	0,00	-101.111	2.789.447
System	6.925.729	859.849	18.248.489	6.096.320	-162.072	31.968.316

Table 28 - Total system costs

The figure below shows the cash flows of this system compared to the base case (grid only). The payback time is higher respect to the case in scenario 1 and it is equal to 5,25 years, since the investment is more important. However, the other economic indicators (NPC and LCOE) are lower.

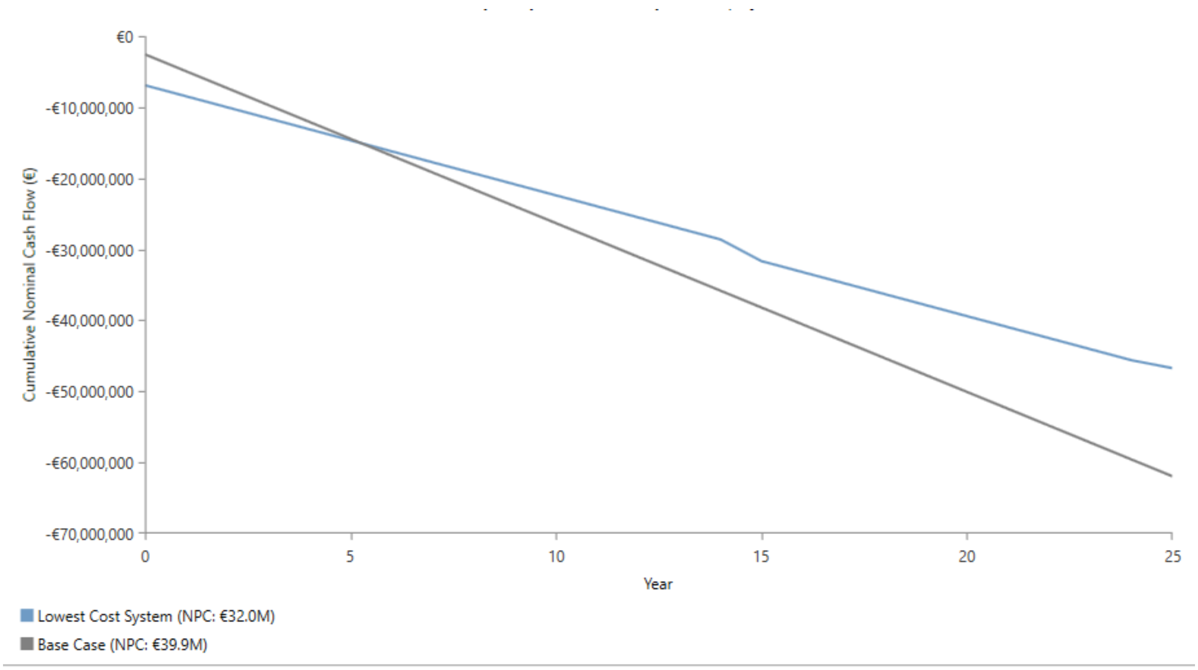


Figure 29 - Cumulative nominal cash flow

This last two figures want to highlight how high can be the share of renewables, and in particular photovoltaic, if the capital cost decreases respect to the actual values.

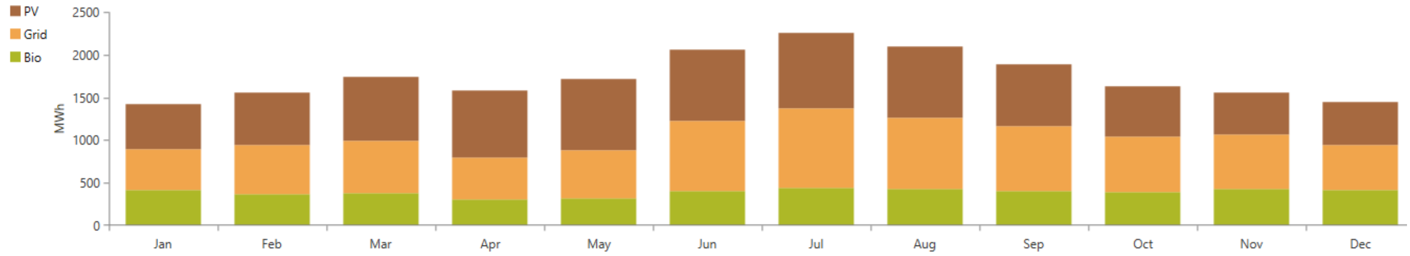


Figure 30 – Monthly electric production by component

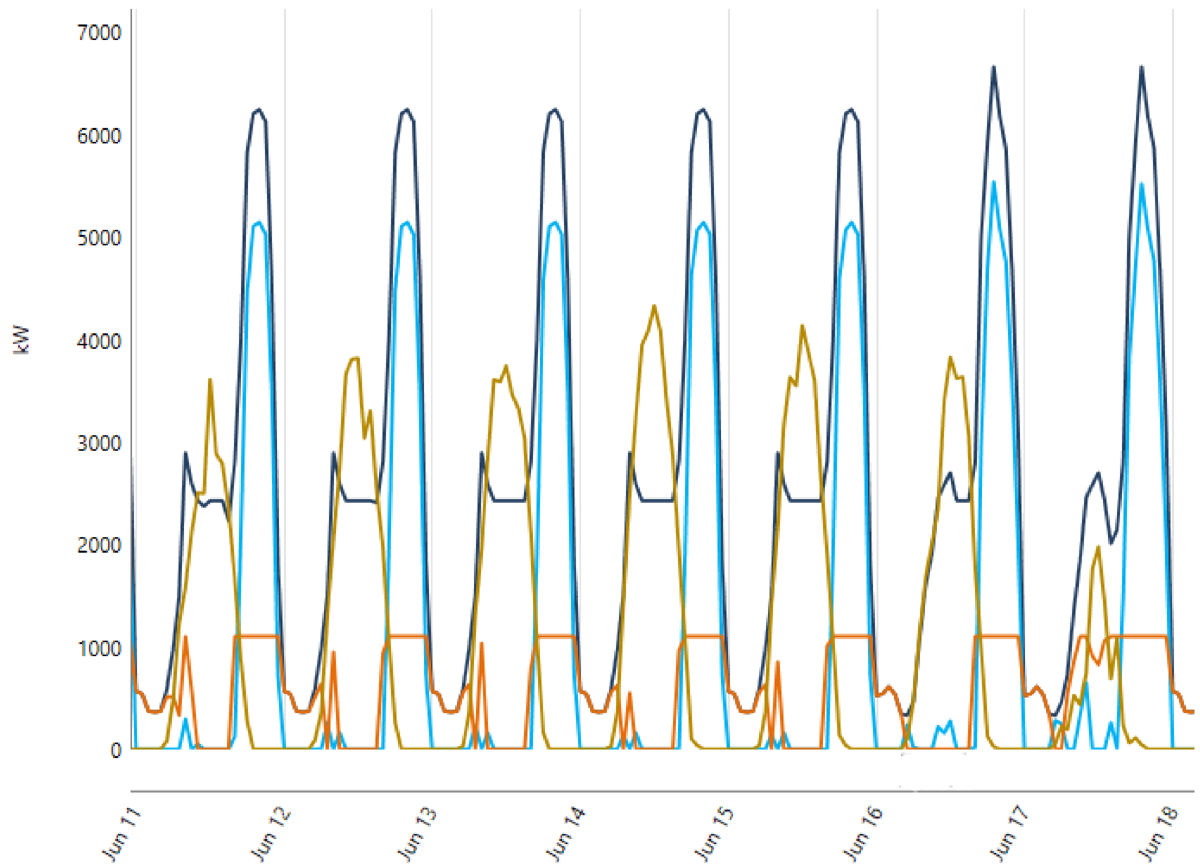


Figure 31 - Hourly load profile

Legend

Total Electrical Load Served
Grid Purchases
Biomass Generator Power Output
Generic flat plate PV Power Output

Conclusion

The present work aims at modelling a hybrid micro-grid for the town of Meknassy. The size and the energy production must meet the needs of the community in a more sustainable way, respect to the actual one.

In this section, the main steps that led to delineate the system configurations, illustrated above, are summarized.

The first essential step is the definition of the available resources: the solar resource for Meknassy is provided by HOMER, while the biomass resources were estimated by a research conducted in the area. The selection of the biomass was decided on the basis of the possible combination of substrates in the anaerobic digester. The manure and green waste were the ones with the higher potential and in the right proportion to feed the anaerobic digester.

Then, the technical and economic characteristics of the components are illustrated.

All these inputs are elaborated by HOMER to find the optimal system configuration.

During the first simulation scenario, the correct size of the biogas genset was estimated. In the following, this size was considered constant, since it was the optimal considering the biomass availability and the generator technical parameters.

According to the second scenario, the installation costs of the photovoltaic and inverter were too high, hence it was more economically convenient to meet the load requirements with the electricity purchased by the national grid. Therefore, the optimal solution delineated by HOMER during the optimization analysis corresponded the one in the first scenario.

The identified key parameters which hindered the feasibility of a genset+PV mini-grid are: cost of purchased electricity and capital cost of photovoltaic and inverter.

During the sensitivity analysis these two values are modified and HOMER identified systems where a portion of the electricity needed by the community was fulfilled by the photovoltaic modules.

The share of renewable production increases from 42,1% of the scenario 1 to 58,9 % of the highest value corresponding to the minimum PV capital cost.

The two sensitivity cases highlight how it is important the government support to these technologies by subsidising renewable sources. The electricity purchased by the grid is considered too subsidised and, since the Tunisian energy source mix is composed mainly by natural gas, that means that traditional fossil resources are favoured at the expense of newest technologies.

The two scenarios identified in the sensitivity analysis may be feasible in the future of Tunisia: the electricity cost may be increased a little, for example up to the European average value, in order to finance new projects. And simultaneously the increase of knowledge and the diffusion of such components may lead to a reduction of the investment costs.

Tunisian government will face some hurdles to fulfil the targets fixed for 2030 agenda. The scenarios evaluated in the sensitivity analysis may increase the renewable fraction not only at the level community of Meknassy, but at regional or national level.

Another faster way to reduce the capex of photovoltaic can be foresee a form of subsidy for this technology not only for the auto-production, but for bigger plants too.

The deployment of technologies powered by renewable resources is essential also to guarantee a better standard of life of the communities (for example, in Meknassy urges a conscious administration of municipal solid wastes, since it happens that the wastes are burned releasing chemicals in atmosphere).

This is a challenge at a global level too: reducing the investment cost of renewable technologies and enhancing their efficiencies with the aim to increase investments in this sector by private and public actors.

Appendix A

List of appliances in Loughborough (East Midlands, UK) model [19].

Appliance category	Appliance type	Proportion of dwelling with appliance
Cold	Chest freezer	16%
	Fridge freezer	65%
	Refrigerator	43%
	Upright freezer	29%
Consumer Electronics + ICT	Answer machine	90%
	Cassette / CD Player	90%
	Clock	90%
	Cordless telephone	90%
	Hi-Fi	90%
	Iron	90%
	Vacuum	94%
	Fax	20%
	Personal computer	71%
	Printer	67%
	TV 1	98%
	TV 2	58%
	TV 3	18%
	VCR / DVD	90%
	TV Receiver box	93%
Cooking	Hob	46%
	Oven	62%
	Microwave	86%
	Kettle	98%
	Small cooking (group)	100%
Wet	Dish washer	34%
	Tumble dryer	42%
	Washing machine	78%
	Washer dryer	15%
Water heating	DESWH	17%
	E-INST	1%

	Electric shower	67%
Electric Space Heating	Storage heaters	3%
	Other electric space heating	3%
Lighting	Lighting	100%

List of appliances in Delegation of Meknassy model [45].

Appliance category	Appliance type	Proportion of dwelling with appliance
Cold	Refrigerator	90,4%
Consumer Electronics + ICT	Cassette / CD Player	42,2%
	Clock	90,0%
	Cordless telephone	8,2%
	Personal computer	19,3%
	TV 1	92,3%
	TV Receiver box	86,3%
Cooking	Oven	56,1%
Wet	Dish washer	2,1%
	Washing machine	61,5%
Electric Space Heating	Storage heaters	1,3%
Cooling	Air conditioner	12,3%

Water heating systems considered are the same as the UK model, as no data was available. Other two consumer electronics appliances data (iron and vacuum) was missing and, as they are common in any developed county household, they were added to the list with a proportion equal to washing machine share.

In addition, lighting was included too.

Consumer Electronics + ICT	Iron	61,5%
	Vacuum	61,5%
Water heating	DESWH	17%
	E-INST	1%
	Electric shower	67%
Lighting	Lighting	100%

For each appliance the following parameters are estimated:

- Proportion of dwelling with appliance: probability that a household owns an appliance
- Base cycles/y: average time an appliance is used
- Mean cycle length (min): how much time an appliance is used
- Mean cycle power (W): capacity of the appliance
- Standby power (W): power utilized during standby
- Delay restart after cycle (min): for appliances characterized by a cycle function, as refrigerator
- Mean cycle energy demand (kWh): required electricity for each cycle
- Time running in a year (min): minutes an appliance is set on
- Time not running in a year (min): the complementary of the previous value
- Active occupancy dependent: this variable can assume two values YES or NO. If it is equal to yes, the appliance functioning depends whether there are people in the household or not (example: television or radio). Otherwise the appliance can be on even if during active occupancy (example: refrigerator)
- Proportion of time when starts can occur due to occupancy: connected to the previous value

- Minutes in year when event can start (min): number of times in a year on a one-minute basis when an appliance can be turned on
- Mean time between start events given occupancy (min): it defined as the ratio of minutes in a year when event can start and the cycles in a year.
- Lambda: it is the inverse of the previous value
- Short name
- Activity use profile: it is defined a profile
- Average activity probability: average probability of an activity to be performed by any of the active occupant
- Calibration scalar: calculated as lambda divided by the average activity probability
- Energy used when on (kWh/y): calculated by multiplying the mean cycle energy demand and the cycles in a year
- Energy used on standby: it represents the amount of energy utilized by the appliance during standby
- Total energy (kWh/y): it is the sum of the energy used during standby and the energy used when on
- Overall average per dwelling taking ownership into account (kWh/y): this is a crucial parameter. It is calculated by multiplying the total energy and the appliance proportion in dwellings
- Appliance mean power factor: power factor of appliances

Appendix B

Range of the characteristics of the substrates [48].

Substrates	**Total solids (%)**		**Volatile solids (% ts)**		**Nitrogen (% ts)**		**Biogas yield (m^3/ton vs)**		**CH_4 in biogas (%)**		**CH_4 (m^3/ton)**	
	from	to	from	to	from	to	from	to	from	to	from	to
Manure	20	28	75	90	1,8	2,0	450	550	60	65	41	90
Green waste	5	20	80	90	3	5	350	500	50	60	7	54
Organic fraction of private household	40	75	50	70	0,5	2,7	300	450	50	60	30	142

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