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"Techno-economic analysis of a hybrid microgrid system in semi-desertic areas of Tunisia"

Relatori

Prof. Pierluigi Leone
Dott.ssa Sonja Sechi

Candidato

Giovanni Tirri

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Abstract

Semi-desertic areas take up 10,6% of the land surface. This is a significant proportion of our land to disregard as wastelands, considering that they are habitable and part of the remaining land includes some mountains.

Access to electricity in semi-desertic areas of Tunisia, primarily located in the Midwest of the country, is a fundamental factor for improving the living conditions of the populations of these territories. The energy consumption of these areas is usually based on electricity supplied by the utility grid. The creation of a distributed power generation system (e.g. a microgrid) that provides electricity from locally available renewable energy resources such as solar energy and biomass might be a promising solution to reduce the grid dependence and improve access to a reliable supply of electricity.

The focus of this thesis is to perform the techno-economic analysis of grid-connected renewable energy systems consisting of photovoltaic (PV) and biogas generator set to provide electricity for Meknassy, a town and commune in the Sidi Bouzid Governorate, in the Midwest of Tunisia. HOMER simulator tool is used to recreate, simulate and optimize two proposed options of a grid-connected microgrid: biogas system (option A) and PV-biogas system (option B).

The optimization results show that the hybrid system for option B is economically a better choice than one including only biogas generator set with an anaerobic digester (option A). The best optimal system configuration is composed of the utility grid, 3.471 kW PV-Array, 2.480 kW converter and 2.500 kW biogas generator set. In this system configuration, the renewable fraction in power generation is 67%. The Levelized Cost of Electricity (LCOE) of generated electricity by this hybrid energy system (€0,077/kWh) is 29% lower than that calculated in the optimal system configuration for

option A (€0,109/kWh) and 32% lower than electricity cost from grid (€0,113/kWh). The sensitivity results illustrate that the grid-connected PV-biogas system appears to be the best optimal system type for the most sensitivity scenarios. As the grid electricity prices increase in the future, the integration of battery storage system to the grid-connected PV-biogas system represents an enhanced solution.

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INTRODUCTION

The socio-economic development of Tunisia passes through its electrification. Given the structural lack of infrastructure and indigence of semi-desertic area of Tunisia, to create a virtuous circle, low-cost and high-impact investments on the population are needed. Innovative distributed energy generation systems might represent the best tool to guarantee electrification in remote areas with low load density. In contexts such as that of the semi-desertic areas of Tunisia, a form of local energy, created for nearby customers, would represent a promising solution. Efficient generation technologies are fundamental but not sufficient to guarantee local development. Adopting inclusive business models that provide systems for the productive use of the energy generated is necessary to encourage growth.

Among various available renewable energy technologies (geothermal, ocean, wind, etc.), photovoltaic (PV) and biogas generators, in the form of distributed energy resources (DERs), have gained particular attention for their impact on the power system and for the ubiquitous abundance of primary resources. They can be a part of the large power system, small distribution system, and microgrid.

The reliability of power supply in semi-desertic areas can be ensured by the effective use of renewable energy resources. One way to contribute to the usage of cleaner energy is to use hybrid renewable energy source microgrid. The installed capacity of that microgrid can be based on the specific application. In many countries, grid-connected microgrid hybrid energy systems are in usage to connect and supply the electricity in remote areas. The development and diffusion of microgrids are becoming increasingly popular thanks to their control capacity, the various operational characteristics (technical aspect), and the economic and environmental advantages.

The main purpose of this thesis is to asses which is the most economical type of distributed power generation system (microgrid), that provides electricity from locally available renewable energy resources such as solar energy and biomass, for Meknassy, a town and commune in the Sidi Bouzid Governorate, in the Midwest of Tunisia. Therefore, a techno-economic analysis of two proposed options of a grid-connected renewable energy system consisting of photovoltaic (PV) and biogas generator set is performed.

The present study is structured as follows:

- Chapter 1: it discusses the context of the information discussed throughout the thesis: background. It provides general info about microgrid energy systems, a general picture of the regulatory framework which governs electricity network access in Tunisia and the current Tunisian renewable energy scenario.
- Chapter 2: it is dedicated to the core characteristics of the following study: system modelling. It provides a generic panoramic of HOMER simulation tool, a brief description of the selected site, a detailed electricity demand assessment, the modelling of the two primary local available renewable resources (solar and biomass) and the technic end economic components specifications.
- Chapter 3: it describes the optimization and sensitivity processes, discussing the corresponding results.
- Conclusion: it summarizes the thesis findings.

1 BACKGROUND

1.1 Introduction

The following chapter describes a microgrid energy systems overview briefly, providing general info about basic components, operation modes, classification and the renewable energy resources employment for this application. Then a general picture of the regulatory framework which governs electricity network access in Tunisia is provided, in order to understand which scheme applying to the electricity production from renewable energy sources. Finally, the Tunisian renewable energy scenario is provided, discussing the policy of the progressive integration of renewable resources into the energy mix as a priority axis of Tunisian development.

1.2 Microgrid overview

A microgrid is a localized group of distributed energy sources, including storage systems, that generally operate connected and in parallel with the utility electricity grid (grid-connected mode), but which can be disconnected and operate independently (islanded mode), depending on physical and economic conditions [1],[2]. The microgrid system is a way to integrate different distributed generation (DG) sources, in particular renewable energy sources (solar, wind, geothermal, ocean, waste-to-energy, etc.). It also provides an excellent solution to supply energy in case of emergency, ensuring energy supply to urban and rural communities. On the other hand, the control and protection activities in this type of network configuration are very complex [3],[2]. Two typical benefits of this kind of systems are the lowering greenhouse gas emission and the lowering strains on energy distribution and transmission [3].

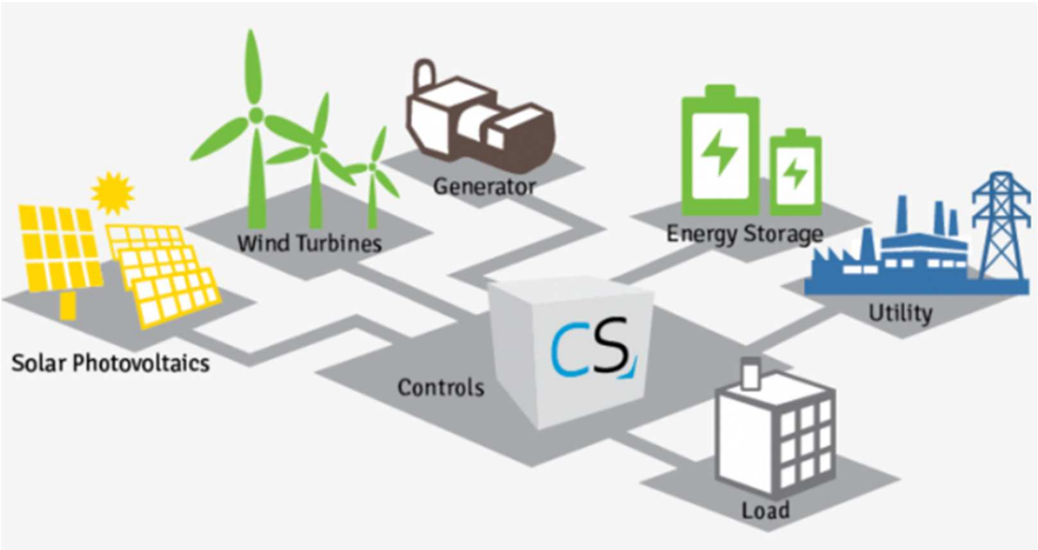

Figure 1: Basic components of a microgrid [4].

1.2.1 Basic components

The essential components of a microgrid are five: distributed generation (DG), loads, energy storage (ES), control devices and point of common coupling (PCC).
The distributed generation (DG) refers to electricity production of small electric power systems dispersed or located in several points of the territory and independents of traditional utility grids [2]. It includes internal combustion engine, microturbine, fuel cell, small hydropower system, photovoltaic (PV) generation, wind generation, waste generation, and biomass generation.
The loads include critical loads and common loads [1].
The energy storage (ES) technologies perform various functions such as ensuring the quality of the power produced, regulating the current frequency and voltage, stabilizing the output of renewable sources, ensuring the availability of a backup system and optimizing costs [2]. ES technologies are classified into physical form (pumped storage, CAES and flywheel), electromagnetic form (SMES, supercapacitor, high-energy-density capacitor), electrochemical form (lead-acid battery, nickel-hydrogen battery, nickel-cadmium battery, lithium-ion battery, sodium-sulfur battery, flow battery), and phase-change form (thermal ice storage) [1].
Control devices constitute the control system for distributed generations, energy storages, and transfer between grid-connected mode and islanded mode, facilitating monitoring and energy management [1].
The point of common coupling (PCC) is a single point in the electric circuit which connects the microgrid to the utility grid [2].

1.2.2 Operation modes

The key point of a microgrid is its capability to operate in two different modes: grid-connected mode and islanded mode.
Grid-connected mode means that the microgrid is connected to the main grid at PCC exchanging power and maximizing the advantages offered by the connection with the rest of the utility grid [1].
In islanded mode, the microgrid is disconnected from the utility grid at the PCC, and the distributed generations, energy storage systems, and loads within the microgrid operate independently. The critical loads need to be prioritized in order to avoid that the electricity supply is interrupted because the electricity produced is generally small and insufficient to meet the demand of all loads [1].

1.2.3 Classification

Microgrids can be classified according to function demand, capacity, and AC/DC type.
According to function demand, micro-grids are classified into simple microgrid, multi-DG microgrid and utility microgrid. Simple microgrid contains only one type of distributed generation, while multi-DG microgrid consisting of multiple simple microgrids or multiple types of distributed generations. Utility microgrid is the integration of all distributed generations and microgrids that meet specific technical conditions [1].
Table 1 illustrates that microgrids can also be classified into independent microgrid and grid-connected microgrid by capacity. Independent microgrids are typical of remote off-grid areas (village, island or mountainous areas). Grid-connected microgrids can be further classified into simple microgrid,

corporate microgrid, feeder area microgrid and substation area microgrid. Simple microgrids have a capacity below 2 MW and comprise loads of a small area (independent facilities and institutes). In comparison, corporate microgrids have a capacity of 2–5 MW and encompass small household loads. Feeder area microgrids have a capacity of 5–20 MW and include large commercial and industrial loads. Finally, substation area microgrids have a capacity above 20 MW and generally encompass all loads (household, commercial and industrial) [5],[1].

Type	Capacity (MW)	Grid to be Connected
Simple microgrid	<2	Common grid
Corporate microgrid	2-5	
Feeder area microgrid	5-20	
Substation area microgrid	>20	
Independent microgrid	Depending on remote off-grid areas	Diesel-fueled grid

Table 1: Classification of microgrids by capacity [1].

Finally, microgrids can be classified into DC microgrid, AC microgrid, and AC/DC hybrid microgrid. In DC microgrid, distributed generation, energy storage, and DC load are connected to a DC bus via a converter and the DC bus is connected to AC loads through an inverter. An AC microgrid is connected to the distribution network via an AC bus, and the distributed generation and energy storage are connected to the AC bus through an inverter. An AC/DC hybrid microgrid is composed of an AC bus and a DC bus which allow for direct supply to AC loads and DC loads [5].

1.2.4 Hybrid renewable energy sources for microgrids

The available renewable energy technologies (solar, wind, geothermal, biomass, etc.) in the form of distributed energy resources (DERs) can be part of a microgrid. The renewable energy sources (RESs) produced locally are most popularly used as distributed energy resources (DERs) in grid-connected and standalone microgrids. The hybrid combination of RESs represents an attractive worldwide because of its technical advancement, economical operation, and availability in abundance. In general, a hybrid renewable energy system (HRES) includes several forms of renewable energy which generate electricity as a unit and maximize the power capacity of a microgrid. A very general structure of an HRES may consist of any combination of renewable energy resources depending on the availability of resources in an individual area, load demand, and all the associated costs, including installation, operation, and maintenance costs [6].

1.3 Tunisian electricity market structure

In the sizing process of a microgrid system, several factors need to be assessed before proceeding to the techno-economic analysis.

An analysis of the access conditions to the Tunisian electricity market for foreign private investors is needed to identify the factors which can help the development of renewable energy projects. Thus, a general picture of the regulatory framework which governs electricity network access in Tunisia is provided in order to understand which scheme applying to the production of electricity from renewable energy sources.

The three main stakeholders are:

- Tunisian Minister of Energy, Mines and RES;
- Tunisian Company of Electricity and Gas (STEG);
- National Agency for Energy Conservation (ANME).

Figure 2 displays the structure of the Tunisian electricity market.

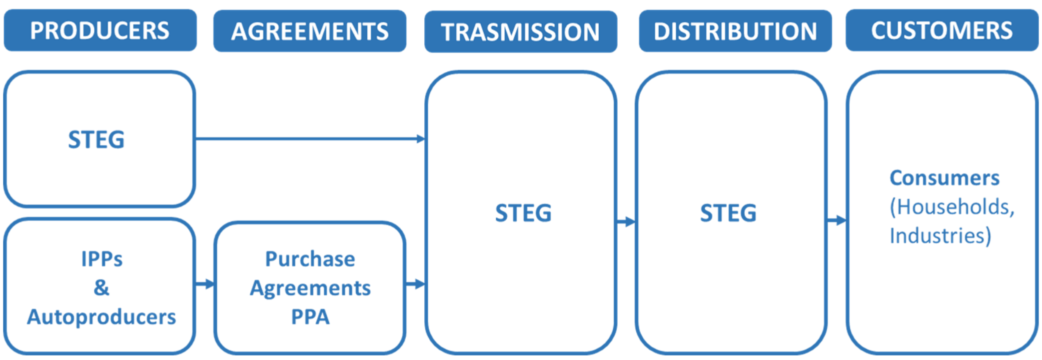

Figure 2: Structure of the Tunisian electricity market [7].

STEG currently holds the monopoly of the transmission, distribution, marketing, purchase and sale of electricity. In terms of electricity generation, STEG no longer holds the monopoly because the market is now open to:

- Independent power producers (IPPs) operating electricity generating plants under a government licence following an invitation to tender;
- auto-producers producing electricity from renewable energy sources;

STEG is regarded both the network manager and the buyer of electricity from both independent power producers (IPP) and auto-producers and agreeing for the purchase of energy (Power Purchase Agreement – PPA) with them.

1.3.1 Independent power producer regime

“Private persons are authorized to produce electricity to be sold exclusively to STEG under the terms of a contract entered into by the two parties” [8]. STEG operates as the single buyer under a PPA, and the conditions will define in the call for tender of the concession contract and part subject to the final negotiations. STEG needs to negotiate the amount of electricity to purchase. Thus, the IPP regime does not impose an obligation on STEG to purchase the overall amount of electricity generated. This scheme is not limited to any specific type of electricity production, either renewable or non-renewable, and it is well suited to large-scale projects.

1.3.2 Auto-producer regime

The self-producer regime provides that any industrial, agricultural or tertiary sector entity which produces electricity from renewable energy sources for self-consumption has the right to transmit the electricity produced through the national electricity grid to its consumption points. Any electricity surplus must be sold exclusively to STEG subject to certain upper limits under the terms of a standard contract (PPA) [8]. The decree must regulate the conditions of the transmission of electricity, the sale of surpluses and the decree upper limits.

1.3.3 Electricity generation from RES for self-consumption, local consumption or exports

Figure 3 shows the procedure to follow for each energy renewable production profile provided by law 2015-12:

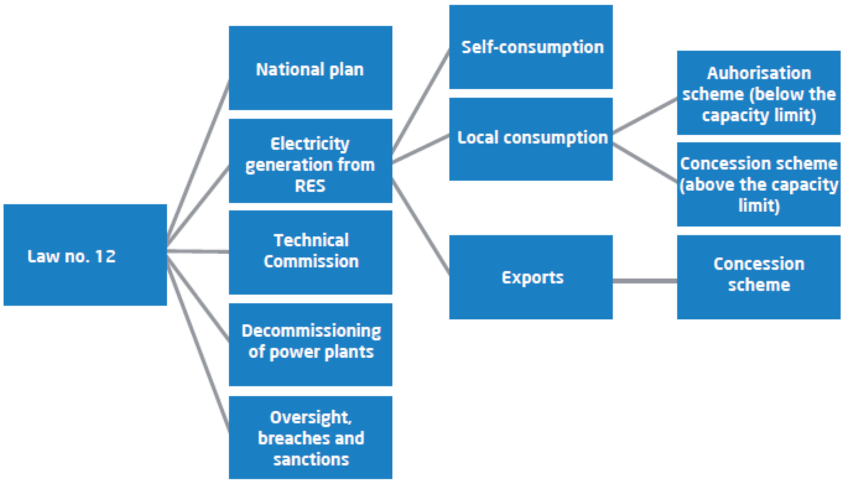

Figure 3: Law no. 12, enacted in May 2015, finalised the regulatory framework for RE project [7].

The decree of 9 February 2017 describes the standard agreements for selling electricity generated from RES to STEG.

1.3.4 Self-consumption projects

Any entity that is active in the industrial sector (local government, public or private institution) may generate electricity for self-consumption. Thus, any self-consumption project developer may transmit electricity over the national grid and sell its generation surpluses to STEG through a pre-defined purchase agreement. The law establishes if the point of consumption and production can be different or the same.

Concerning the standard sale agreement for self-generation plants, if the plant is connected to the LV grid, the sale of surpluses shall depend on the grid. The agreement shall specify the electricity supplied from a single point of supply on the LV grid.

If the plant is connected to the MV and HV grid, it shall be allowed to sell and transmit its electricity surpluses over the national grid exclusively to STEG (no more than 30% of annual production). The producer shall pay the costs of the connection to the grid and its improvement if necessary [7].

1.3.5 Projects subject to authorisation

Projects for local consumption of electricity produced within the capacity limit (set by decree no. 2016-1123 as shown in Table 2) shall be subject to an authorisation to be granted by the Minister of Energy, after hearing the opinion of the special commission.

Standard sale agreement for RE plants subject to authorisation specifies that all the electricity produced by authorised plants shall be sold exclusively to STEG. A decree of the Minister shall set the tariff applicable throughout the agreement and following the technical specifications [7].

RENEWABLE ENERGY SOURCE	CAPACITY LIMIT (MW)
Solar photovoltaic energy	10
Solar thermodynamic energy	10
Wind energy	30
Biomass	15
Other	5

Table 2: Maximum installed electrical power set by decree no. 2016 [9].

1.3.6 Projects subject to concession

Projects of electricity production to be sold locally that exceed the generating capacity limit set by the decree or projects of electricity production to be exported shall be subject to a concession to be granted by the State. The concession agreement includes some clauses, e.g. nature of the work to be carried out, duration of the concession or percentage share to be allocated to the State. Besides, for granting of the concession, the State shall receive a given share of the electricity generated by the plant [7].

1.4 Tunisian renewable energy scenario

Aware of the challenge posed by its energy security, Tunisia places a policy of progressive integration of renewable resources into the energy mix as a priority axis of development. The country ambition is to bring renewable energy to 30% of the energy mix in 2030, thus representing an installed capacity of 4.700 MW. The country has significant development potential, particularly in wind and solar, and a framework law, promulgated in 2015, defining a legal basis necessary for the implementation of private renewable energy projects [10].

1.4.1 Renewable energy resources potential

The electricity sector in Tunisia is characterized by the extreme dependence on natural gas, absence of interconnection with Europe, absence of large storage capacities and daily load peaks only in summer (massive use of air conditioning). In the summer of 2017, the Tunisian Gas and Electricity Company (STEG) recorded a peak consumption of 4.025 MW, thus exceeding the initially planned value of 3.900 MW [10]. This peak demand required a good part of gas turbines only during the summer period with losses during the rest of the year. Thus, renewable energies development represents an opportunity to consolidate Tunisian electricity production. Tunisia benefits of a high sunshine rate between 3.000 and 3.500 hours/year [10]. The solar radiation in Tunisia varies from 1.800 kWh/m^2/year to 2.600 kWh/m^2/year

[10]. Figure 4 illustrates the solar resource map of Tunisia, which provides a summary of the estimated solar photovoltaic (PV) power generation potential. It represents the average daily/yearly totals of electricity production from 1 kW-peak grid-connected solar PV power plant, calculated for 25 recent years (1994-2018) [11]. As can be seen, in southern Tunisia, the PV power generation potential is higher than in northern Tunisia.

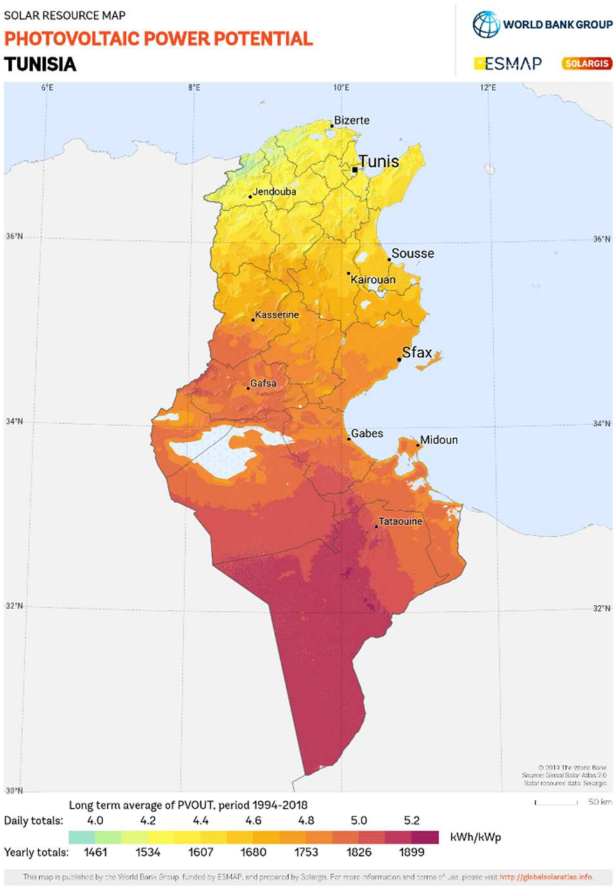

Figure 4: Photovoltaic power potential in Tunisia [11].

The Tunisia gross wind energy potential is estimated at 8 GW on an exploitable surface of 1600 km^2 [10], [12]. The regions of northern Tunisia are characterized by higher wind energy than in central and southern regions. In northern and north-eastern areas, the wind speed is between 7 (at the height of 60 m) and 10 m/s (at the height of 45 m) [13].

In 2017, the installed capacity in renewable energies represented 3% of the total power (311 MW) [10]. Tunisia is also exploring the potential of using marine energy, biomass and recovering waste.
Composting or biogas production from different waste sources such as municipal biowaste collected by households, industrial and commercial activities, sewage sludge and waste in the form of animal and vegetable by-products might solve the problem of municipal organic waste in Tunisian cities, and avoid the contamination from industrial and commercial effluents [14]. Taieb Wafi et al. study [15] provided a compositional and parametric characterization of the total waste generated in Tunisian cities with an estimation of the corresponding biogas potential and possible gain. Table 3 provides the typology of recoverable organic waste in Tunisia, and which are suited to material or energy recovery.

Typology of recoverable organic waste in Tunisia	Material recovery (composting)	Energy recovery (biogas)
Municipal and wholesale markets	✓	✓
Urban green spaces	✓	×
Fruit and vegetable canneries	✓	✓
The margins	×	✓
Forest waste	✓	×
Waste from the timber industry	✓	×
Vinification	✓	✓
Livestock slaughterhouses	×	✓
Poultry slaughterhouses	×	✓
Catering activities	×	✓
Manure	✓	✓
Solid and liquid droppings	✓	✓
Agricultural waste	✓	×
Wastewater treatment plants (sludge)	×	✓

Table 3: Tunisian waste classification [15].

The results show that, for example, the total waste produced in the region of Midwest of Tunisia was equal to 443.593 tons/year. The treatment of this quantity might produce 32,76 million of cubic meters of biogas, equivalent to 196,56 GWh, and the possible gain was estimated at $35,38 million [15].

1.4.2 An ambitious national and regional strategy

The Tunisian Solar Plan (2016-2030), valued at 15 billion dinars was the first strategy established in the area of renewable energy. In Autumn 2016, the Tunisian government held a conference, "Tunisia 2020", to present the national development strategy 2016-2020 for the transition to a green economy. The national strategy includes the development of the electricity network to facilitate the integration of renewable energies on the network. It identifies the main projects for the construction of production units: STEG will finance the construction of 5 photovoltaic stations with a global capacity of 300 MW in Tataouine, Médenine, Kébili, Gafsa and Djerba, as well as a wind farm in Tbaga (Cap Bon) and the pumped storage and power storage project in Oued El Melah (Béja) with a capacity of 400 MW. There is also a biomass power plant project with an installed capacity of 15 MW, in the Thyna region, financed by the private sector [10].

2 SYSTEM MODELLING

2.1 Introduction

The following chapter discusses the main characteristics of this study. After a generic panoramic of HOMER simulation tool, a brief description of the selected site and a detailed electricity demand assessment is provided. Then, the modelling of the two primary local available renewable resources (solar and biomass) are described. Finally, technologic end economic components specifications of the two proposed microgrid system options are provided. Assumptions regarding the electrical load, biomass resource and technical and economic component inputs are made considering average values from similar studies and literature.

2.2 HOMER simulation tool

In this work, the HOMER simulation tool is employed to search the optimized system configuration to meet the electrical demand of the proposed site and to assess the effect of changes in the input variables.
HOMER (Hybrid Optimization of Multiple Electric Renewables) is a microgrid software developed by HOMER Energy for optimizing microgrid design and comparing many different design options across a wide range of applications [16].
As mentioned above, a microgrid is a system that can employ any combination of electricity generation and storage technologies in order to meet the electrical demand. Power plants that supply electricity to a high voltage transmission system are not considered microgrid systems because they are not dedicated to a particular load. HOMER can model grid-connected and off-grid microgrid systems through any combination of photovoltaic modules, wind turbines, biomass energy, fuel cells, batteries and storage of hydrogen [16].

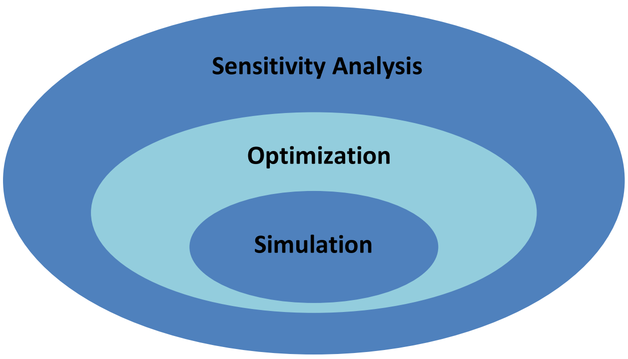

Figure 5: Conceptual relationship between simulation, optimization and sensitivity analysis [16].

Figure 5 shows the three principal tasks performed by HOMER: simulation, optimization, and sensitivity analysis. The simulation process consists of modelling the performance of a microgrid configuration each hour of the year to determine whether it can meet the electrical demand under certain conditions and estimate the life-cycle cost. The optimization process consists of simulating and comparing many different system configurations in order to determine the optimal value of the control variables. The least-costly system configuration identifies the optimum. In the sensitivity analysis process, HOMER simulates multiple optimizations under a range of input assumptions to assess the effect of changes in the input variables over which the modeller has no control [16].

2.2.1 Physical modelling

HOMER models the physical operation of a microgrid system that must include at least one source of electrical energy (resource), at least one destination for that energy (load), conversion and energy storage devices (components). The load refers to a demand for electric or thermal energy, and there are three types of loads: primary load, deferrable load and thermal load. The component is any part of a microgrid system that generates, converts, or stores energy. The resource refers to four renewable resources (solar, wind, hydro, and biomass) and any fuel used by system components to generate electricity [16].

2.2.2 Economic modelling

As mentioned above, one of the two purposes of simulation processes is estimating the life cycle cost of the system. At the same time, in optimization processes, the life cycle cost allows comparing the economics of various system configurations.

The life cycle cost is the total cost of installing and operating the system over its lifetime and HOMER uses the total net present cost *NPC* to represent that quantity [17]. The *NPC* includes all costs and revenues that occur within the project lifetime, with future cash flows discounted to the present. It is the opposite in sign of the net present value *NPV*. All other economic outputs are calculated in order to find the net present cost.
The total net present cost is calculated through the following equation:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{1}$$

where:

- $C_{ann,tot}$: total annualized cost [€/year];
- i: real discount rate [%];
- R_{proj}: project lifetime [year];
- CRF: capital recovery factor.

The total annualized cost $C_{ann,tot}$ is the sum of the annualized costs of each system component, plus the other annualized cost [17].
The annual real discount rate i is one of the HOMER inputs, which is also called the real interest rate or interest rate. It converts between one-time costs and annualized costs [17]. The discount factors and annualized costs are calculated from net present costs through the real discount rate. The real discount rate is related to the nominal discount rate i' and the expected inflation rate f through the following expression:

$$i = \frac{i' - f}{1 + f} \tag{2}$$

where:

- i': nominal discount rate,
- f: expected inflation rate.

The capital recovery factor *CRF* is a ratio used to calculate the present value of an annuity [17]. The capital recovery factor is calculated through the following equation:

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^n - 1} \tag{3}$$

where:

- i: annual interest rate [%];
- N: number of years [year].

The levelized cost of energy *COE* is the average cost for kWh of useful electrical energy produced by the system [17]. The *COE* is calculated by HOMER dividing the annualized cost of producing electricity by the total useful electric energy production. The levelized cost of energy is calculated through the following equation:

$$COE = \frac{C_{ann,tot}}{E_{prim,AC} + E_{prim,DC} + E_{grid,sold}} \tag{4}$$

where:

- $C_{ann,tot}$ total annualized cost [€/year];
- $E_{prim,AC}$ AC primary load served [kWh/year];
- $E_{prim,DC}$ DC primary load served [kWh/year];
- $E_{grid,sold}$ energy sold to the grid [kWh/year];

2.3 Selected site: Meknassy

The selected proposed site is Meknassy, a town in the Sidi Bouzid Governorate, in the Midwest of Tunisia. Figure 6 shows that the town of Meknassy is located on latitude 34° 36' N and longitude 9° 36' E. The town is placed far from the coast, it has a desertic climate, and consequently the landscape is mostly arid. It is the capital of homonym delegation and a marketing centre for agricultural production. The town is internationally known for breeding purebred Arabian horses.

Figure 6: Meknassy location.

In 2014 the town of Meknassy had a population of 14.773. Table 4 illustrates the total population and household distribution of the delegation of Meknassy [18]. As can be seen, more than 60% of the population and over 3,000 households live in the urban area.

The utility grid currently supplies the load demand of the Meknassy households.

Delegation	Rural/Urban	Population	Households	Dwellings
	Urban	14.773	3.206	3.475
Meknassy	Rural	9.016	1.960	2.828
	Total	23.789	5.166	6.303

Table 4: Meknassy delegation - population, households and dwellings distribution [19].

2.4 Primary load

The modelling of a microgrid system begins with the modelling of the load that the system must meet. In this work, the type of load is the primary load. The primary load is the electrical demand associated with lights, radio, TV, household appliances, computers, and industrial processes [16].
Lack of knowledge about the load condition and electrical demand during the sizing process may lead to oversized or undersized microgrid systems. If the microgrid is oversized, investment cost, payback time and operational costs increase, and the overall efficiency decrease. If the microgrid system is undersized the electricity supply would be unreliable, blackouts would be more likely, the service quality would be reduced, and dissatisfaction, operation and maintenance costs of the system would be higher [20].
The components and the corresponding investment cost are directly affected by demand assessment. Thus, detailed electricity demand assessment and accurate system sizing are crucial.
HOMER allows importing the assessed load profile via a CSV-file, with the time step being automatically detected. In this work, a data-file containing time series for the whole year (8760 h) is imported.

2.4.1 Techniques to assess energy demand

Techniques for modelling residential energy consumption are often classified into two categories: ‘‘top-down’’ and ‘‘bottom-up’’ as it is shown in Figure 7.

Top-down models utilize the estimate of total residential sector energy consumption and different variables to attribute the energy consumption to characteristics of the entire housing sector. In distinction, bottom-up models calculate the energy consumption of houses then extrapolate these results to represent the region or nation.

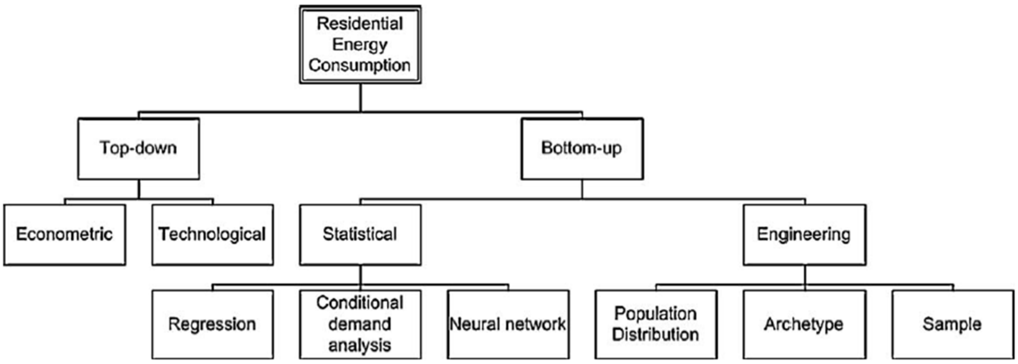

Figure 7: Top-down and bottom-up modelling techniques for estimating regional or national residential energy consumption [21].

The variables of top-down models include macroeconomic indicators, climatic conditions, housing construction rates, and appliance ownership and the number of units in the residential sector. Top-down models can be divided into two groups: econometric and technological. Econometric models are based mainly on the price of energy and appliances and income. Technological models attribute energy consumption to general characteristics of the entire real estate assets, such as the ownership trends of household appliances.

Typical input data to bottom-up models include dwelling properties such as geometry, equipment and appliances, climate properties, as well as indoor temperatures, occupancy schedules and equipment use. Bottom-up models can be divided into two groups: statistical and engineering. Statistical methods rely on historical information and types of regression analysis which are used to attribute dwelling energy consumption to specific end-uses.

Engineering methods explicitly account for the energy consumption of end-uses based on power ratings and use of equipment and system.
In this study, due to the availability of data, an approach, based on the equipment profile, considers all the devices (appliances and lights) that the households own in the area under study is employed (engineering bottom-up method).

2.4.2 The survey

Each household is characterized by a certain number of appliances and certain energy consumption habits. In these conditions, and depending on time, the construction of a method to determine electricity consumption by households becomes essential [22]. The design of the household survey form presents all the variables necessary to evaluate household electricity demand: household identification, dwelling characteristics, type, amount and power of appliances and time of use. The electricity demand can be determined by processing the information on the amount and use of electric appliances of each household or household category. The hourly aggregation of the power of all the appliances used by one household allows determining its typical load profile. Aggregating the load profiles of all households of the same class will result in the load profile per class. The aggregation of the load profiles of all categories results in the load profile of the town [20].

2.4.3 Available data

In this work, the available data are provided by the INS (Institut National de la Statistique), and they are the result of a survey conducted in 2014.

The available data regarding household appliance ownership of Meknassy delegation are shown in Table 5. The hybrid system must be able to provide electricity to the Meknassy town households. Table 4 shows that the number of inhabitants of Meknassy delegation urban area is about the same as Meknassy town. Thus, data referred to the urban area of Meknassy delegation are assumed to be the same as Meknassy town.

Appliance	Equipped households (%)		Number of households owning at least "one"	
	Rural	Urban	Rural	Urban
Refrigerator	87,9	92	1.723	2.950
Oven	40,08	65,94	786	2.115
Washing machine	42,6	73,12	835	2.345
Dish washer	0,41	3,15	8	101
Air conditioner	4,25	17,25	83	553
Computer	4,77	28,25	93	906
Radio	36,77	45,45	721	1.458
TV	90,41	93,45	1.772	2.997
Mobile phone	95,76	97,74	1.877	3.135
Lightning	99,39	99,97	1.948	3.206

Table 5: Households by ownership of electrical household equipment [19].

As can be seen, the typical electrical household equipment types are refrigerator, oven, washing machine, dishwasher, air conditioner, computer, radio, TV, mobile phone charger and lightning. It is fair to note that the iron is one of the most used household appliances in Tunisia, but unfortunately no data is available regarding the delegation of Meknassy.

Another available data is the percentage of dwellings according to the floor area, listed in Table 6.

Dwelling floor area	Percentage of dwellings (urban area)
less than 49 m^2	4,6%
between 50 and 99 m^2	33,0%
between 100 and 149 m^2	41,0%
between 150 and 199 m^2	15,3%
more than 200 m^2	6,2%

Table 6: Dwelling according to the covered surface [19].

The data regarding the number of appliances owned by each household, belonging to a specific class, are not available as well as daily appliance usage and hourly power consumption.

2.4.4 General assumptions

Starting from the number of urban area households, which own at least one type of appliance (Table 5), households are grouped in 10 classes per type of appliances, as shown in Table 7.

Class	Number of households	Appliances									
		Lightning	Mobile phone charger	TV	Fridge	Washing machine	Oven	Radio	PC	Air conditioner	Dish-washer
I	71	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
II	138	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
III	47	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
IV	605	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗
V	230	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗
VI	657	✓	✓	✓	✓	✓	✓	✗	✗	✗	✗
VII	552	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
VIII	353	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗
IX	452	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗
X	101	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 7: Households classes per type of electrical equipment.

It is assumed that households which are poorly equipped belong to low-income classes, and they live in dense neighbourhoods with poor infrastructure. Instead, households with necessary equipment belong to the middle classes, between the rich and poor classes. Finally, households owning quite complete equipment, including sophisticated lighting equipment and high-power devices, belong to the wealthiest classes of the town.

In a specific class, each household owns the same type of appliances and the same number per type, and the usage time and power consumption of each appliance are the same. In the absence of data, the following main assumptions are made:

a) all households belonging to the same k_{th} class own the same number of i_{th} appliances (n_i);
b) household classes with more types of appliances (wealthiest class) have a higher number per each type;
c) if the i_{th} appliance is in operation at time t, all i_{th} appliances in all households of all class k_{th} are in operation in that time t;
d) if the i_{th} appliance is in operation at time t, it is used for 1 hour;
e) appliances usage time and power consumption are the same for all households, regardless of the class they belong to;
f) daily usage time of domestic appliances (oven, washing machine, dishwasher, computer, radio, TV and mobile phone charger) is assumed for weekdays (Monday–Friday) and weekends (Saturday-Sunday) and repeated throughout the year;
g) weekdays and weekends usage time for air conditioner and lightning are not employed; the usage time of lightning depends on sunset/sunrise time and wake-up/bed time; the usage time of air conditioner depends on the season (only during the hot period);
h) weekdays wake-up and bed time are assumed to be 7 am and 10 pm, while for weekends they are assumed to be 9 am and 11 pm.

2.4.5 Appliances assumptions

The assumptions regarding each electrical equipment are taken from different sources in the literature.

Refrigerator

The average hourly power consumption of the refrigerator during operation can be assumed to be about 32 W [23]. The refrigerator is assumed to be active every hour all day (24 h). The average number of refrigerators per household is assumed to be one, for all households which own at least one.

Television

Television is the most popular medium in Tunisia: 98% of households own a TV [24]. The average hourly power consumption of the television during operation can be assumed to be about 55 W [23].
Tunisians spend an average of 26 hours per week listening to radio [24]. Thus, it is assumed that the television is watched for three hours during the weekdays (12:00-13:00/20:00-22:00) and 6h during weekends (10:00-11:00/13:00-14:00/17:00-19:00/21:00-23:00).
98% of Tunisians households own at least a television. Most of them (68%) own one television, 28% own two televisions, and 4% own more than two [25]. As shown in Table 4, all classes, except for class I and II, are equipped with television. Thus, it assumed that households of classes III, IV, V, VI and VII (70%) own one television, households of classes VIII and IX (27%) own two televisions, and households of class X (3%) own three televisions.

Radio

The radio is regarded as the second most popular media after television in Tunisia: 67% of households own a radio [24].
The average hourly power consumption of the radio during operation can be assumed to about 15 W [26].
Tunisians spend an average of 15 hours per week listening to the radio [24]. Thus, it is assumed that the radio has listened for two hours during the weekdays (7:00-8:00/12:00-13:00) and three hours during weekends (9:00-10:00/15:00-16:00/18:00-19:00).
Info about Tunisian household radio ownership is not available. Thus, the television info is employed for radio assumptions. It assumed that households of classes VII and VIII (62%) own one radio, households of class IX (31%) own two radios, while households of class X (7%) own three radios.

Mobile phone charger

The average hourly power consumption of the mobile phone charger during operation can be assumed to about 4 W [26].
It is assumed that the mobile phone charger is used during the night for a time interval between the bedtime and wake up time.
Info about Tunisian households mobile phone ownership are not available. Thus, television info is employed for mobile phone assumptions. It assumed that households of classes II, III, IV, V, VI and VII (71%) own one mobile phone, households of classes VIII and IX (26%) own two mobile phones, while households of class X (3%) own three mobile phones.

Computer

Computer usage increased rapidly from 13% in 2006 to 46% in 2016. [24]. The average hourly power consumption of the computer during operation can be assumed to be about 175 W [23].

Tunisians spend more time surfing the net: on average, 29 hours per week [24]. Thus, it is assumed that the computer is used for three hours during the weekdays (7:00-8:00/19:00-20:00/21:00-22:00) and six hours during weekends (10:00-12:00/15:00-19:00).

64% of Tunisians households own at least a computer. Most of them (72%) own one computer, and 28% own more than one [25]. As shown in Table 4, only class VIII, IX and X are equipped with a computer. Thus, it assumed that households of classes VIII and IX (89%) own one computer, while households of class X (11%) own two computers.

Washing machine

According to a recent study conducted in Egyptian households [27], the load sizes of each wash cycle and the total number increased with the increase in the size of households. The wash cycles per week are estimated equal to 5 (about 260 cycles per year) with an average consumption per cycle of 0,91 kWh. For some North Africa countries, mainly the New Member States, no specific information is available; therefore, the energy consumption per cycle of 0,97 kWh [27].

Thus, the average hourly power consumption of the washing machine during a washing cycle (30°C for 60 min) can be assumed to be about 970 W and the average number of wash cycles per week is assumed to be five, only during the weekdays (20:00-21:00).

The average number of washing machine per household is assumed to be one, for all households which own at least one.

Dishwasher

A typical washing program is the 65 °C power mode program with a washing time of 56 min. The amount of power consumed during the washing time is measured as 1113 W [23]. Thus, the average hourly power consumption of the dishwasher during operation can be assumed to be about 1100 W.
The frequency of use of the dishwasher is assumed to be two times per week, only during the weekends (21:00-22:00).
The average number of dishwashers per household is assumed to be one, for all households which own at least one.

Oven

Another home appliance that plays a significant role in energy consumption in the Tunisian home is the oven. Assuming that the average oven operating temperature is 180 °C, the total amount of power that the oven spent in one hour is measured as 1053 W during the cooking period [23]. Thus, the average hourly power consumption of the oven during operation can be assumed to be about 1000 W.
Due to the small distance between the housing and the workplaces, it is assumed that a generic Meknassy household cooks two times per day for one hour (12:00-13:00/20:00-21:00).
The average number of ovens per household is assumed to be one, for all households which own at least one.

Lightning

In general, incandescent lamps are by far the most common type of lamps in living rooms, bedrooms, bathrooms, corridors and warehouses [28]. Thus, incandescent bulbs are assumed to be the most common indoor lightning system in Meknassy dwellings. The average power rating of each bulb is assumed to be 75 W [28].

The average number of bulbs owned by each household belonging to a specific class is estimated considering the average amount of light needed to light up the average housing floor area. The Tunisia average number of households per dwelling is 1 [19]. Thus, the percentage of Meknassy dwellings according to the covered surface (Table 6) can be used to estimate the number of households according to the dwelling covered surface, as shown in Table 5. For each range of dwelling floor area, an average floor area A_{floor} is assumed (e.g. 25 m^2 for houses with a floor area less than 49 m^2, 75 m^2 between 50 and 99 m^2, end so on). The following equation can be used to calculate the average number of bulbs needed to light up the dwelling floor area:

$$N_{bulbs} = \frac{I_{mean} \times \ A_{floor}}{L_{(75W\ bulb)}} \tag{5}$$

where:

- I_{mean} is the average domestic buildings luminance level (150 lux) [29];
- $L_{(75W\ bulb)}$ the lumen produced by a 75 W incandescent bulb (1100 lm) [29].

As shown in Table 7, all ten classes are equipped with lightning. Thus, it shall be established which household class belongs to each dwelling floor area range. According to assumption b), household classes which own more types of appliance are allocated in that range with a higher average number of bulbs. Table 8 illustrates the following class distribution.

Dwelling floor area range [m²]	Percentage of dwellings/ households	Number of households	Average dwelling floor area [m²]	Average number of bulbs per dwelling/ household	Classes
Less than 49	4,6%	147	25	3	I
Between 50 and 99	33,0%	1057	75	10	II,III,IV,V
Between 100 and 149	41,0%	1314	125	17	VI,VII,VIII
Between 150 and 199	15,3%	489	175	24	IX
More than 200	6,1%	199	225	31	X

Table 8: Lightning household class distribution.

The electric lighting usage time depends on daylight and occupancy pattern. If the internal required lighting level is less than the available daylight illuminance level, then artificial lighting will be switched on when the house is occupied. The daily sunset and sunrise time of Meknassy are known. Assuming the wake-up and bed time for weekdays and weekends, the number of lightning consumption hours can be easily estimated.

Figure 8 and Figure 9 illustrates lightning assumptions during the year for weekdays and weekends, respectively.

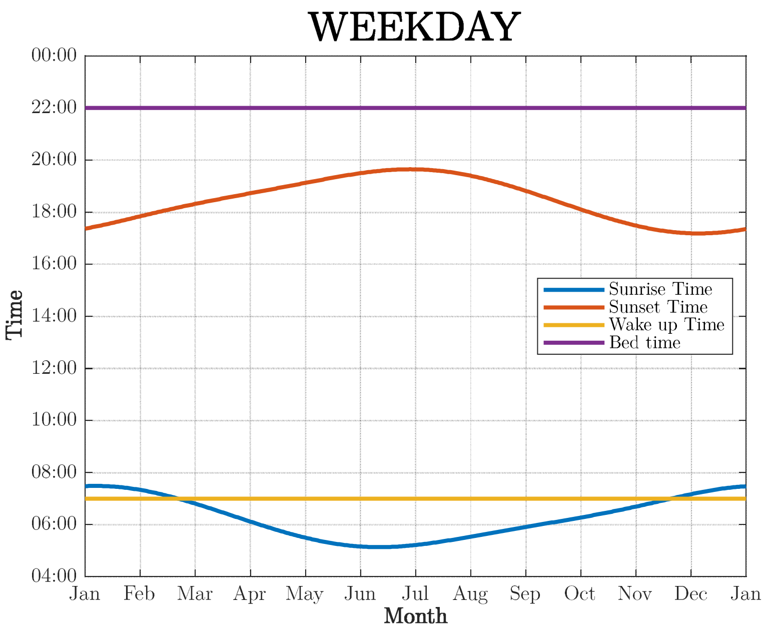

Figure 8: Lightning consumption time for weekdays.

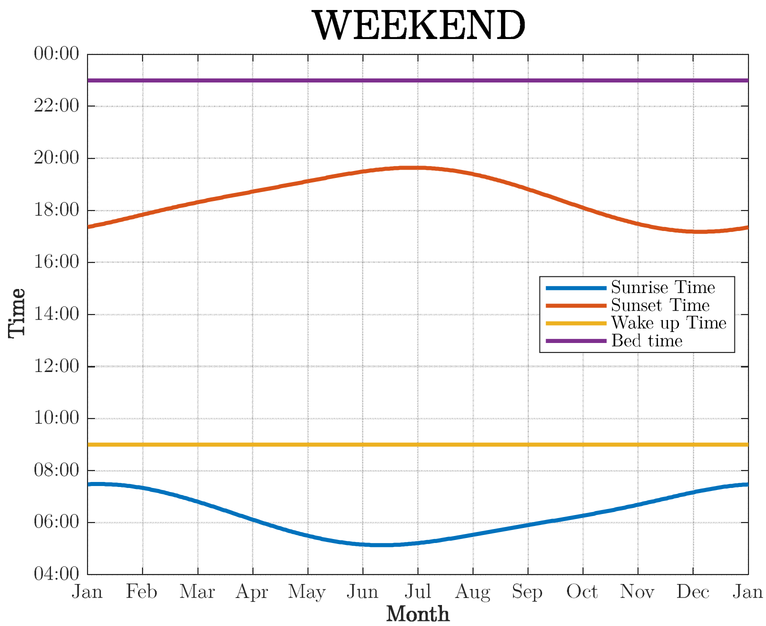

Figure 9: Lightning consumption time for weekends.

It is assumed that in the morning, the light will be switched on when sunrise time is later than the wake-up time until sunrise occurs. In the evening, the light will be switched on when bed time is later than sunset time until people go to bed.

Air conditioner

The Tunisian weather is sunny, and the temperatures are delightful throughout the year, particularly in summer. Temperatures sometimes exceed 40°C, and it causes an increase in the consumption of electricity mainly in June, July, August and September when using air conditioners.

The average hourly power consumption of the air conditioner is assumed to be 900 W [30]. As shown in Table 7, only households of class IX and X are equipped with air conditioner. The average number of air conditioners owned by each household belonging to both classes is assumed to be one.

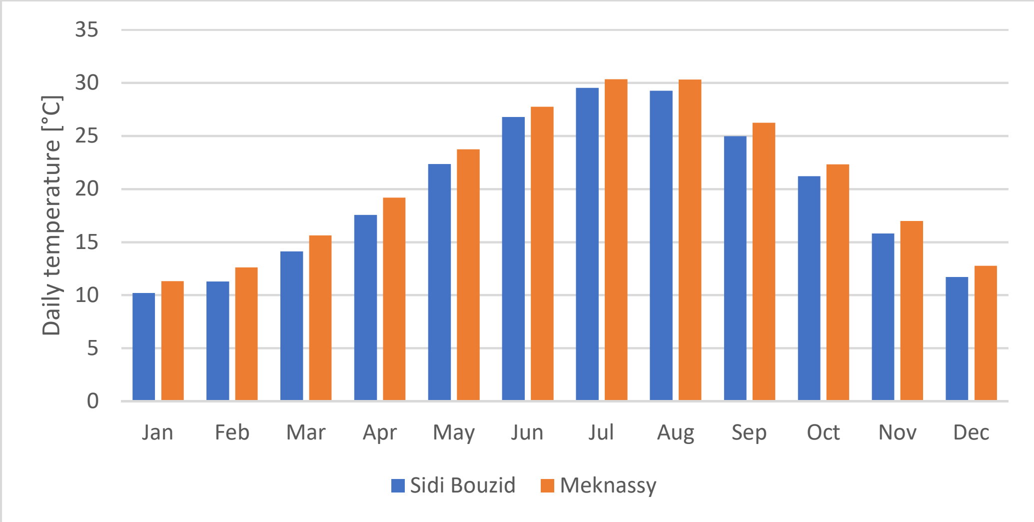

Figure 10: Monthly average air temperature data of Meknassy and Sidi Bouzid.

In order to determine the electric air conditioner on/off pattern during the year, hourly outdoor air temperature data are employed. The air conditioner will be switch on in the hours when hourly air temperature will be higher than the setpoint temperature assumed equal to 28 °C. The data regarding the hourly air temperature of Meknassy town are not available. As can be seen in Figure 10, the monthly average daily temperatures of Sidi Bouzid (40 km from Meknassy) are similar to Meknassy ones.

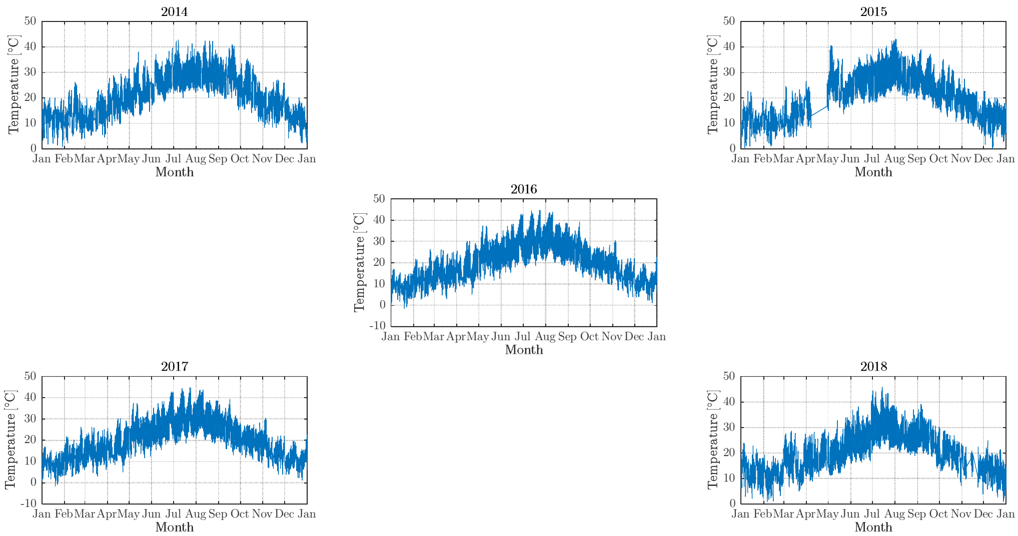

Figure 11: Hourly outdoor air temperature of Sidi Bouzid in 2014, 2015, 2016, 2017 and 2018.

Therefore, the hourly air temperature data of Sidi Bouzid city are employed [31]. They are referred to 2014, 2015, 2016, 2017 and 2018, as shown in Figure 11.

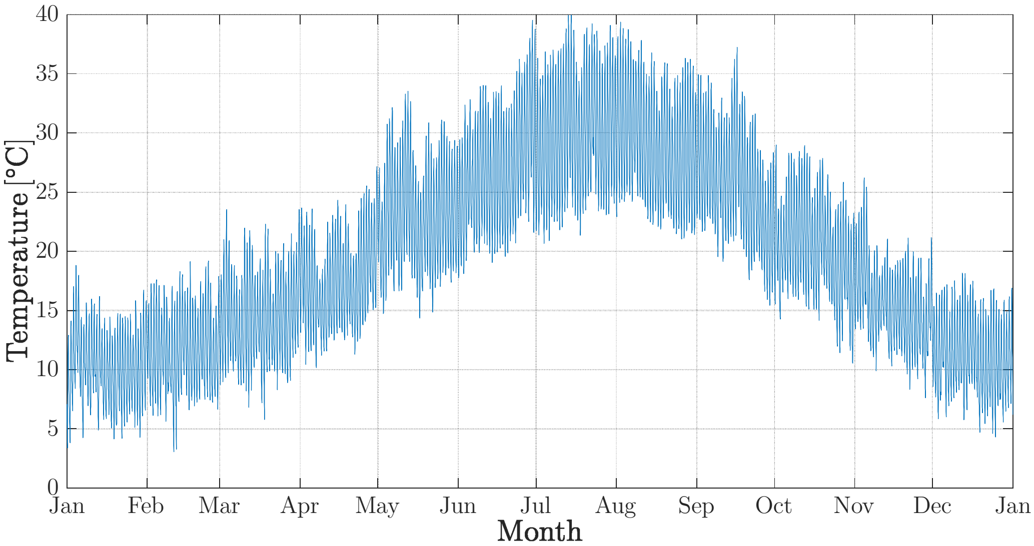

Figure 12: Hourly average outdoor air temperature of Sidi Bouzid.

The station does not report every hour, but once every 3 hours, and sometimes only during daylight hours. Thus, the intermediate hourly missing values are calculated by linear interpolation between the two adjacent values. The hourly average outdoor air temperature is illustrated in Figure 12.

2.4.6 Load curve estimation

The load curve for j_{th} household belonging to the k_{th} class is built with MATLAB through the following equation:

$$P_{jk}^{t} = \sum_{i=1}^{N_a} n_i^t \times p_i \tag{6}$$

where:

- P_{jk}^t: total power used by household j_{th} of class k_{th} at time slot t [W];
- N_a: number of types of appliances owned by the j_{th} household of class k_{th};
- n_i^t: number of i_{th} appliances owned by the j_{th} household of k_{th} class in operation at time t;
- n_i: total number of i_{th} appliances owned by the j_{th} household of k_{th} class;
- p_i: i_{th} appliance electrical power [W];
- t: time slots in a year [1, …, 8760 hours];
- i: 1, …, N_a appliance.

The following equation gives the load curve of all household categories:

$$P^t = \sum_{k=1}^{N_c} \sum_{j=1}^{N_h} P_{jk}^t \tag{7}$$

where:

- N_h: number of households in k_{th} class;
- N_c: number of classes;
- j: 1, …, Nh household in k_{th} class;
- k: 1,…, Nc class;
- t: time slots in a year [1, …, 8760 h].

2.4.7 Results

The yearly load curve of Meknassy town is shown in Figure 13. The load curve from scorching days of summer illustrates that the residential air conditioning is the major contributor to summer peak demand in Meknassy. It is also possible to observe the contribution of lighting in the early hours of winter weekdays when the sunrise time is later than the wake-up time (7 am) as shown in Figure 8. As can be seen, there are about 52 pairs of peaks (52 weekends) which demonstrate the higher energy use on weekends than on weekdays.

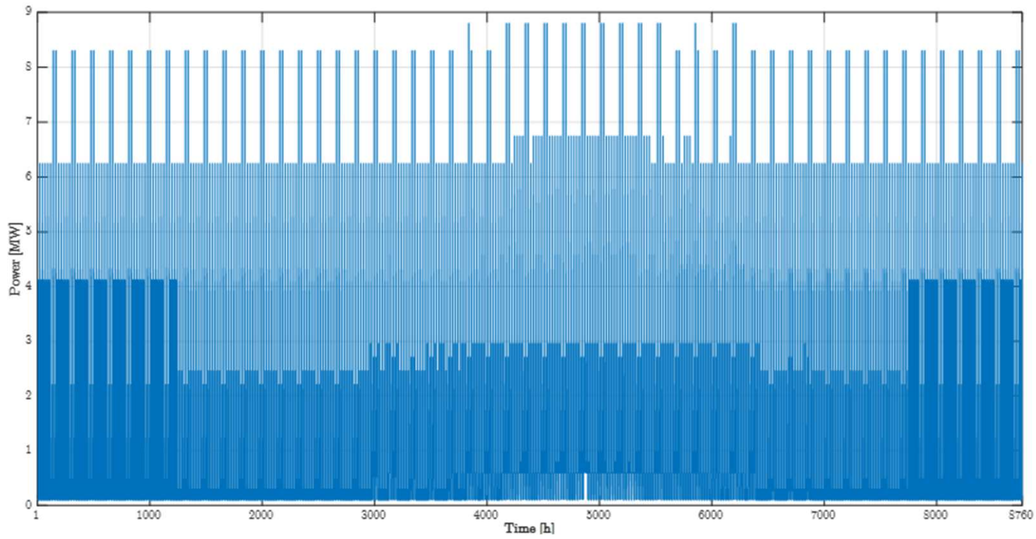

Figure 13: Yearly load curve of Meknassy town.

The average household size in Tunisia is decreased from 4.53 in 2004 to 4.05 in 2014. In detail, this value in the urban area is 3,91 persons and reached 4,37 in the rural area, making a difference of 0,46 points [19]. Electric power consumption (kWh per capita) in Tunisia was reported at 1.444 in 2014, according to the World Bank [32]. Thus, the yearly electric power consumption per Tunisian urban household per year can be assumed about 5.600 kWh.

Table 9 illustrates the electricity consumption per class and household belonging to different classes. As expected, the electricity consumption per household is higher for classes which own more type of appliances and a higher number per type. The electricity consumption per year of an urban Meknassy household is estimated on average 3.200 kWh. It is a reasonable value if it is compared to that of a generic Tunisian urban household estimated above.

Household class	Number of households	Class consumption (MWh/y)	Household consumption (kWh/y/household)
I	71	26	369
II	138	171	1.241
III	47	62	1.318
IV	605	967	1.598
V	230	391	1.699
VI	657	2.161	3.289
VII	552	1.823	3.302
VIII	353	1.284	3.638
IX	452	2.657	5.878
X	101	726	7.188
Total	3.206	10.267	3.202

Table 9: Electricity consumption per class and per households belonging to different classes.

The yearly load curve of Meknassy is imported on HOMER as time-series file contains 8760 lines (hourly data). The average 24-hour load profiles for each month of the year calculated by HOMER are shown in Figure 14.

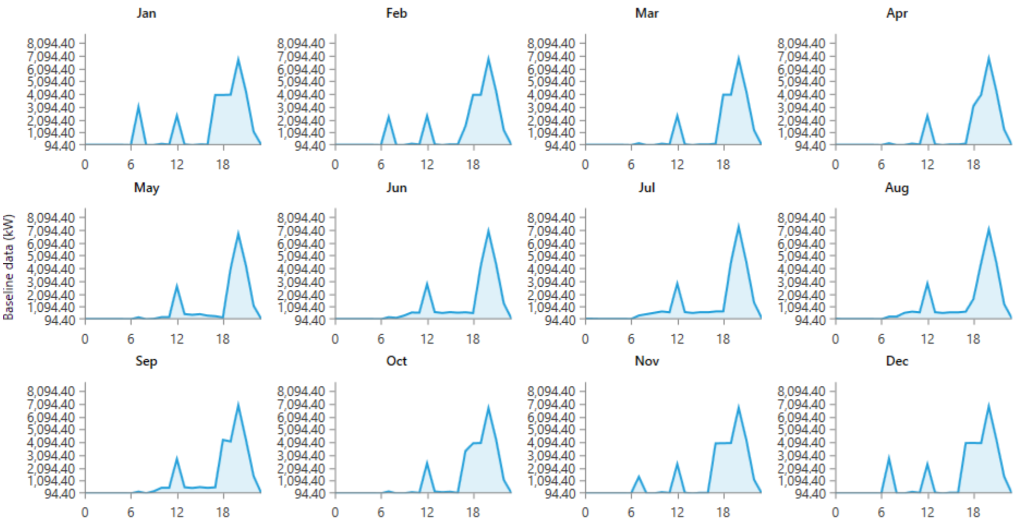

Figure 14: Monthly average daily profiles.

The daily average energy consumption of Meknassy town is calculated by HOMER equal to 28.130 kWh/day with a peak load 8.800 kW and a load factor (average load divided by the peak load) of 0,13.

2.5 Primary energy resources

In the following section, the two renewable resources, solar and biomass, used by the components of the system to generate electricity are described. The biomass resource depends on local availability, whereas solar resource on site location and weather, and this affects micro-grid systems. Thus, accurate modelling of them is vital.

2.5.1 Solar Energy

Due to the geographical location of Meknassy, solar energy potential is relatively high, and many studies have emphasized the importance of using solar energy as one of the most available primary energy sources in Tunisia. The modelling of system containing PV array requires solar resource data for the location of interest. Solar input data for HOMER are taken as monthly averaged daily insolation incidents on a horizontal surface ($kWh/m^2/day$) and monthly average clearness index provided by the NASA Surface Meteorology and Solar Energy web site. NASA gives monthly averaged values from 22 years of data, as shown in Table 10.

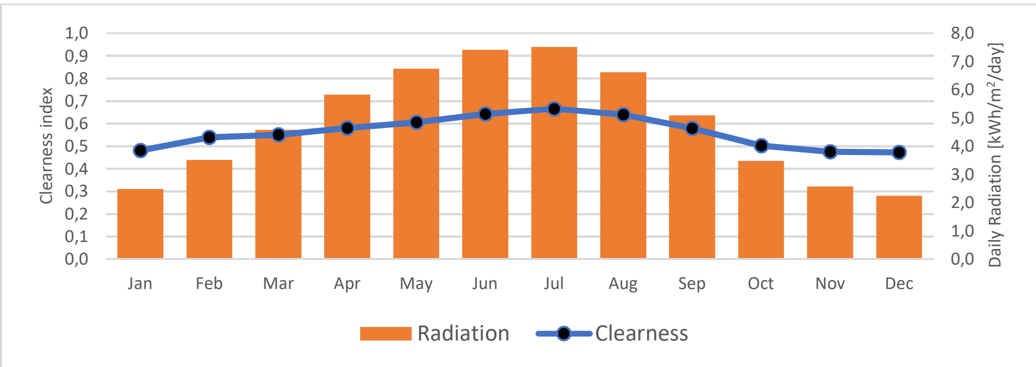

Figure 15: Global horizontal radiation, monthly averaged values over 22-year period (July 1983-June 2005).

The annual averaged daily solar insolation in this area is found to be 4,84 kWh/m^2. Figure 15 shows the monthly variation in global solar radiation. As can be seen, the maximum global solar radiation is reached during the period between the spring and summer season. Consequently, the monthly energy output from solar PV would vary from one month to another.

Month	Clearness index	Daily radiation (kWh/m^2/day)
January	0,481	2,48
February	0,540	3,51
March	0,550	4,58
April	0,580	5,82
May	0,606	6,74
June	0,643	7,41
July	0,666	7,51
August	0,640	6,61
September	0,579	5,08
October	0,502	3,48
November	0,476	2,57
December	0,473	2,24

Table 10: Monthly average solar global horizontal irradiance (GHI) data.

2.5.2 Biomass

The biomass resource takes various forms as food waste, animal waste, green waste, energy crops and may be used to produce electricity. The availability of the resource depends on several factors. It is consequently not intermittent, although it may be seasonal, and it is also often not free.
In this work, it is assumed that the biomass feedstock is fed into an anaerobic digester (AD) to create biogas that is supplied to the biogas generator producing electricity. The anaerobic digester is not a HOMER component, and

the feedstock conversion process is modelled explicitly entering biomass resource inputs.

Biomass resource inputs are defined in HOMER specifying the availability of the feedstock throughout the year using monthly averages for each month of the year (in tons per day), and four additional parameters: price, carbon content, gasification ratio, and the energy content of the biogas produced.

HOMER creates the synthesized values by assuming that the biomass availability is constant throughout each month, assigning the monthly average value to each hour in that month. In this study, the total amount of available biomass in tonnes per year is estimated in order to determine the month average biomass availability in tonnes per day.

2.5.2.1 Biomass resource availability

Meknassy has a significant biomass energy potential, and the biomass mainly is derived from several waste sources. Waste is generated mainly by the residential sector (private household waste and wastewater sludge), the agricultural sector (green waste) and the livestock sector (manure and droppings). Industrial activities developed in the study area do not generate organic waste [33].

Collection, transportation to the waste dump and elimination of household waste are organized by the municipality or individually by those who produce waste including manure and green waste. Using wheelbarrows, small tractors and small trucks, the collection rate in Meknassy is about 70 % with a frequency of 3 days per week. For these reasons, municipal landfills cannot be geographically located away from urbanized areas since transport will be expensive. The cost of waste collection in the commune of Meknassy varies between 60 to 80 TND/ton, according to the distance between the production source and the waste dump [33].

Organic fraction of private household waste

As shown in Table 11, the municipality of Meknassy produces nearly 5.440 tons/year of private household waste.

Municipality	Population (2016)		Waste production rate (kg/inhab/day)		Waste production (tons/year)
	Urban area	Rural area	Urban area	Rural area	
Meknassy	17.000	7.000	0,815	0,15	5.440

Table 11: Municipal solid waste production estimation [33].

Referred to the general characteristics of household waste in Sidi Bouzid the organic fraction, which is generated from private household is equal to 60,6% [33]. Thus, the total amount of organic fraction of municipal solid waste is estimated to be around 3.300 tons/year.

Figure 16: Uncontrolled wild dump [33].

Figure 16 shows how the waste is deposited in a massive wild dump located 3-4 km from the centre of Meknassy, where the waste is usually dumped in an uncontrolled way in the natural environment. Some people may have free access to the landfill in order to recover valuable products.

Figure 17: Burning waste in wild dumps [33].

As shown in Figure 17, waste is often burned in the landfill, creating an unhealthy atmosphere around it and environment pollution affecting the health of citizens. Rural areas have no infrastructure for waste management.

Wastewater treatment plant sludge

SONEDE provides water supply in the Municipal area and DGGREE in the rural area. Then a wastewater treatment plant operating by prolonged ventilation at low load ensures sanitation of Meknassy.

Figure 18: Wastewater treatment plant [33].

The station managed by ONAS serves the municipal areas for which the connection rate to the sewerage network is near 68 % [33].
The treated wastewater produced by the plant is near 810 m^3/day, and the station produces near 160 tons/year of dried biological sludge which comes from 2.530 tons/year of wet sludge [33]. Local authorities are already planned to build an anaerobic digester for the exploitation of these sludge.

Figure 19: Biological sludge storage area [33].

The wastewater coming from the station is exclusively urban water. It does not contain any industrial waste, so the stabilized and dried biological sludge is in high demand by the farmers who use it as soil fertilizer material. In rural areas, individual sanitation is applied either through septic tanks connected to lost wells or by discharging directly in the environment.

Green waste

Green waste is most usually composed of refuse from gardens such as grass clippings or leaves, and domestic or industrial kitchen wastes. In Meknassy it comes from weekly markets, fruit and vegetable sellers and annual fruit tree pruning. Table 12 shows the green waste quantity, estimated through the results of the survey given by municipal services, summarized in the reference [33].

Green waste source	Number	Specific production rate	Availability [%]	Quantity of waste [tons/year]
Fruit trees	1.413.030 [tree]	35 [kg/tree]	20	9.891
Vegetable crops	800 [ha]	0,85 [kg/m2/year]	50	3.400
Vegetable sellers	-	0,50 [kg/inh/week]	100	576
Total				13.867

Table 12: Green waste quantity estimation [33].

Manure and droppings from livestock

Another important waste source is manure and droppings from the livestock sector. Table 13 shows the number of cattle, sheep, goats and breeding horses in Meknassy. A large quantity of organic waste from livestock (almost 80% of manure) is often used as fertilizer [33]. The remaining quantity is deposed in wild dumps or natural environment. Thus, the availability rate is assumed as equal to 10%. The available quantity that can be recovered energetically from the livestock sector is estimated at 3.752 tons/year.

	Cattle	Sheep	Goats	Breeding horses
Numbers	216	20.000	3.800	200
Specific manure production by livestock [kg/day]	25	4	3	30
Production rate [kg/year]	5.400	80.000	11.400	6.000
Availability [%]	10	10	10	10
Production [tons/year]	197	2920	416	219
Total production [tons/year]		3.752		

Table 13: Waste production by the livestock sector [33].

2.5.2.2 Biomass resource summary

The total available quantities of fresh matter derived by each waste source are summarized in Table 14.

Waste Source	Fresh matter (FM) [tons/year]
Private household	3.300
Wet biological sludge	2.530
Green waste	13.867
Livestock manure and droppings	3.752
Total	23.449

Table 14: Available quantities of organic waste.

These quantities represent an important biomass resource with an unexploited biogas potential. Identifying the total available biogas from a given organic waste in cubic metres per year, it is possible to understand which waste source can be selected.

2.5.2.3 Biomass resource potential

The biogas is the product of the complex biochemical decomposition of organic materials. It consists of 60–70% methane, 30–40% carbon dioxide, and other gases (nitrogen, hydrogen, hydrogen sulphide, ammonia, water vapour). It is produced through an anaerobic digestion process which is considered one of the most efficient methods for conversion of biomass to methane [34]. A wide range of materials including green waste, agricultural waste, municipal solid waste, food waste, manure, industrial waste, wastewater, and crops may be considered as feedstock for the anaerobic digestion process. Each of them has their potentials for biogas production.

In this framework, understanding the correlation between a given feedstock and its potential biogas yield is necessary, and to do it, several factors should be considered. Total solids (%TS) refers to the overall amount of solids available in a sample, volatile solids (%VS) refers to the organic fraction of %TS available for biogas production, and fresh matter (FM) represents the actual amount of materials fed into digesters. Biogas yield is commonly expressed in cubic metres of biogas per ton of fresh or dry biomass. In contrast, biochemical methane potential (BMP) is commonly expressed in cubic metres of methane per tons of volatile solids. BMP normalizes available volatile solids for a given substrate indicating the relative richness of a substrate for biogas production. To accurately quantify the total available biogas from a given material for anaerobic digestion, both VS, TS as well as BMP are needed. VS and TS as well as BMP and concentration of methane expected in the biogas produced (C_{CH_4}) of each available feedstock are taken from the literature [34], [35], and are shown in Table 15.

Waste source	Q_{sub} [tons FM/ year]	TS [%FM]	VS [%TS]	BMP [m^3 CH_4/ tons VS]	C_{CH4} [%]	Biogas yield [m^3 biogas/ tons FM]
Private household	3.300	20	90	386	60	116
Wet biological sludge	2.530	5	75	400	60	25
Green waste	13.867	17	75	350	60	80
Livestock manure and droppings	3.752	25	76	236	60	75

Table 15: Composition, methane and biogas yield of available feedstocks from the literature [34], [35].

The quantities of biogas that could be produced per year by each feedstock can be calculated through the following equation [34]:

$$Q_{biogas_i} = Q_{sub_i} \times TS_i \times VS_i \times \frac{BMP_i}{C_{CH_4}} \tag{8}$$

where:

- i: i-th substrate used to feed the digester;
- Q_{biogas}: quantity of biogas produced in a year [m^3 biogas/y];
- Q_{sub}: quantity of material available in a year [tons FM/y];
- TS: initial total solids concentration [%FM];
- VS: volatile solids concentration referred to TS [%TS];
- BMP: biochemical methane potential [m^3 CH4/tons VS];
- C_{CH_4}: concentration of methane expected in the biogas produced [%].

2.5.2.4 Biomass resource selection

Table 16 shows that the biogas production depends both on the quantity of waste available and on biogas yield. As can be seen, the green waste could represent the primary biomass resource for biogas production, due to the massive amount of this biomass feedstock, even though it has not the most significant biogas yield. Green waste could produce about 1 million cubic metres of biogas per year, and consequently, it is taken as major biomass feedstock for anaerobic digestion.

Waste resource	Q_{biogas} [m^3/year]
Private household	382.140
Wet biological sludge	63.250
Green waste	1.105.027
Livestock manure and droppings	280.399

Table 16: Biogas production of available feedstocks.

In the past, anaerobic digestion was mostly referred to as a single substrate output process, but recently, co-digestion has become a standard technology in biogas production in many countries [34]. Co-digestion is the simultaneous conversion of a mixture of different feedstocks. The main goal of anaerobic co-digestion is to increase biogas, mainly biomethane for heat and electricity. A big range of feedstocks (see Figure 20) can be co-digested at a suitable mixture ratio to maintain optimum conditions required for metabolic activity and to improve biogas production for electricity and heat production. Anaerobic co-digestion may be a suitable option to solve problems related to mono-digestion, increasing methane production of materials characterized by a low yield or are challenging to digest [36].

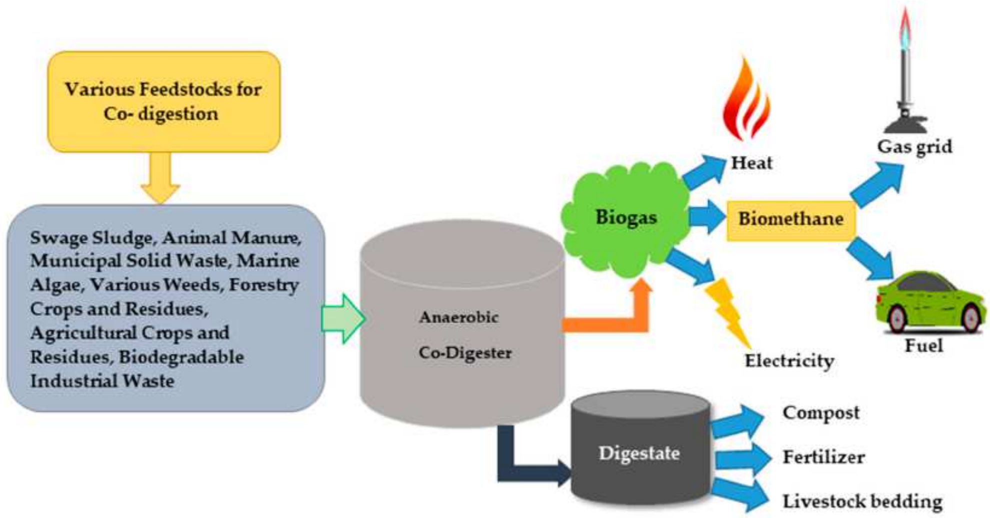

Figure 20: Co-digestion of multi feedstocks for waste reduction and energy recovery [36].

For the co-digestion process, care must be taken to select compatible co-digestion feedstocks and mixture ratio in order to enhance synergism and optimize methane production and digestate quality, avoiding materials that may inhibit methane. For instance, feedstocks characterized by higher C/N ratios (>50) can be co-digested by the feedstocks of lower C/N ratios to achieve optimum C/N ratios (20–30) and nutrient balance and avoid the reduction of biogas production.

An ideal co-substrate would be the organic fraction of municipal solid waste (OFMSW) characterized by organic matter concentration equivalent to green waste, high moisture content, high biodegradability due to the large fraction of food waste (FW) in it, presence of micro-nutrients, and high biogas generation potential [37]. As mentioned before, private household waste is deposited in a massive wild dump and often burned, creating an unhealthy atmosphere affecting the health of citizens and its possible non-polluting disposal could be a viable option to reduce the environmental pollution in the study area. Moreover, Table 16 shows that it represents the second biomass resource for biogas production, with a biogas potential of about 380.000 cubic metres per year.

For the reasons mentioned above that the organic fraction of private household waste is selected as co-substrate for anaerobic co-digestion.

2.5.2.5 Anaerobic co-digestion of biomass selected

When applying anaerobic co-digestion, the selection of the best blend ratio in order to enhance synergism must be considered.

"Data from Web of Science and Scopus revealed that of the total publications, 95% in co-digestion and 91% in OFMSW co-digestion were published in the latter period" [37]. For example, Pavi et al. [38] performed the anaerobic co-digestion of OFMSW and fruit and vegetable waste (FVW) with four different OFMSW:FVW ratios (VS basis) of 1:0, 1:1, 1:3, and 0:1. OFMSW in mono-digestion provides a smaller average cumulative biogas yield (215 Nml/g VS). FVW mono-digestion displayed an average cumulative biogas yield of 350 Nml/g VS, 63% higher than OFMSW. The average cumulative biogas yield of the OFMSW-FVW co-digestion, at the mixing ratio of 1:1, was 433,9 Nml/g VS. In this study, the optimum mixture ratio of OFMSW:FVW was 1:3, whose average cumulative biogas yield was 493,8 Nml/g VS. This represents an increase of 130% and 41% with respect to the mono-digestion of OFMSW and FVW, respectively. The increase of cumulative biogas yield was 14% for OFMSW-FVW ratio of 1:1. The compositions, the average methane content and the cumulative methane yield of the reactors with different OFMSW:FVW ratios are listed in Table 17 and Table 18.

Parameter	OFMSW:FVW ratio (VS basis)			
	1:0	1:1	1:3	0:1
TS [%FM]	19,94	19,74	19,64	19,54
VS [%FM]	19,19	18,99	18,9	18,8
pH	5,9	5,28	4,97	4,66
C/N ratio	22	30,5	34,7	93

Table 17: Characteristics of reactors with different OFMSW:FVW ratios [38].

OFMSW:FVW ratio (VS basis)	Biogas yield [Nml/g VS]	CH_4 [%]	Methane yield [Nml/g VS]
1:0	215,0	76,5	164,5
1:1	433,9	80,8	350,6
1:3	493,8	79,7	396,6
0:1	350,0	78,7	275,9

Table 18: Average methane content and cumulative methane yield of reactors with different OFMSW:FVW ratios [38].

OFMSW composition is heterogeneous and varies from region to region. The chemical composition data of the organic fraction of municipal solid waste and green waste of Meknassy are not available. Thus, data referred to Pavi et al. study are taken as reference in order to estimate the total amount of fresh matter fed into the digester per year and the corresponding amount of biogas produced per year. Table 14 shows that the total available amount of organic fraction of private household waste and green waste are 3.300 and 13.867 tons/year, respectively. Assuming that they have the same VS fraction of OFMSW and FVW reported in Table 17, the corresponding available amount of VS are assumed equal to 633 tons/year for private household waste and 2.067 tons/year for green waste. With different OFMSW:FVW ratios, the amount of VS of both substrates is selected in order to exploit the whole OFMSW mass of VS because it is less than that of FVW. The corresponding amount of FM for each type of waste is recalculated according to the VS percentage reported in Table 17. Mass of VS and FM with different mixing ratio are summarized in Table 19.

OFMSW:FVW ratio	**Mass of VS [tons]**			**Mass of FM [tons]**		
(VS basis)	OFMSW	FVW	Total	OFMSW	FVW	Total
1:0	633	0	633	3.300	0	3.300
1:1	633	633	1.267	3.300	3.368	6.668
1:3	633	1.900	2.533	3.300	10.105	13.405
0:1	0	2.607	2.607	0	13.867	13.867

Table 19: Volatile solids and fresh matter mass with different OFMSW:FVW ratios.

As can be seen, at OFMSW:FVW ratio of 1:1 the OFMSW and FVW mass of VS are both assumed equal to 633 tons/year for a total of 1.267 tons/year. The corresponding amount of FM fed into the digester, according to their composition, are 3.300 and 3.368 tons/year for OFMSW and FVW respectively, for a total of 6.668 tons/year. At OFMSW:FVW ratio of 1:3 the OFMSW mass of VS is assumed to 633 tons/year while the FVW mass of VS is 1.900 tons/year (3 times more), for a total of 2.533 tons/year. The corresponding amount of FM fed into the digester is 3.300 and 10.105 tons/year for OFMSW and FVW respectively, for a total of 13.405 tons/year. Assuming the organic fraction of private household waste and green waste have the same biogas yield of OFMSW and FVW reported in Table 18, the corresponding biogas production with different OFMSW:FVW ratios is calculated through the Equation (8).

OFMSW:FVW ratio (VS basis)	Total mass of VS [tons/year]	Total mass of FM [tons/year]	Biogas yield [Nm^3/ ton VS]	Biogas production [Nm^3/year]
1:0	633	3.300	215,0	136.153
1:1	1.267	6.668	433,9	549.552
1:3	2.533	13.405	493,8	1.250.835
0:1	2.607	13.867	350,0	912.449

Table 20: Total volatile solids and fresh matter mass and corresponding biogas production with different OFMSW:FVW ratios.

Table 20 shows that the optimum blend ratio 1:3 allows producing the highest amount of biogas, about 1.3 million of normal cubic metres per year, due to the highest biogas yield (493,6 Nm^3/tons VS) and significant mass of VS fed into the digester (2.533 tons/year). To sum up, the final mixture of fresh matter which is sent to the anaerobic digester per year is equal to 13.405 tons. It contains 24,6% of organic fraction of private household waste and 75,4% of green waste. The corresponding biogas production is estimated at 1.250.835 Nm^3/year.

2.5.2.6 Biomass feedstock inputs

As mentioned before, biomass resource inputs are defined in HOMER specifying the availability of the feedstock throughout the year and four additional parameters: price, carbon content, gasification ratio, and the low heating value of the biogas produced.

In order to specify the biomass availability throughout the year, twelve average values of biomass availability (in tons per day) must be entered: one for each month of the year. In this work, it is assumed that the total amount of available biomass (13.405 tons/year) is storable and uniformly distributed throughout the year. Consequently, the daily amount of available biomass is assumed constant throughout each day of the year and equal to 36,73 tons/day.

The gasification ratio is the fuel conversion ratio, indicating the ratio of the mass of biogas emerging from the fuel conversion process (in kg/year) to the mass of biomass feedstock entering the fuel conversion process (in kg/year). Assuming that the average normal density of biogas is 1,2 kg/Nm3 [39], the gasification ratio is estimated equal to 0,112 kg/kg.

The energy content of the biogas produced (in MJ/kg) is used to calculate the thermodynamic efficiency of the generator. The lower heating value (LHV) of pure methane is 9,94 kWh/Nm3, whereas, for biogas, it is conventionally assumed to be 60% of the said value [40]. Thus, the LHV is assumed to be 25,8 MJ/kg.

The biomass carbon content is the quantity of carbon contained in the biomass feedstock, and it is used by HOMER to calculate the emissions of carbon dioxide, carbon monoxide, and unburned hydrocarbons. In order to calculate the system gross carbon emissions, the gross carbon content of the biomass feedstock must be entered. A typically value is 50% (mass-based percentage) [17].

The biomass is usually free, but the cost of transporting from the generation point to the plant could be taken into account [36]. As mentioned before, the cost of waste collection, transport and landfill in the commune of Meknassy varies between 60 to 80 TND/ton, according to the distance between the production source and the waste dump. Assuming that this cost is the same according to the distance between the production source and the microgrid system site, the average price of biomass feedstock is assumed to be 70 TND/ton, equal 22,4 €/ton.

The biomass resource inputs are summarized in Table 21.

Available biomass [t/d]	Gasification ratio [kg/kg]	LHV of biogas [MJ/kg]	Carbon content [%]	Average price [€/t]
36,73	0,11	25,8	50	22,4

Table 21: Biomass resource inputs for HOMER tool.

2.6 System configurations

The study reported is focused on simulation and optimization of two micro-grid system options (A and B), based on renewable resources, for the electricity supply of the town of Meknassy, which is already connected to the utility grid. If load demand cannot meet by the microgrid system, the grid is used to purchase electricity at the purchase price. If there is excess electricity at a particular time, it can be sold to the grid at the sellback price. The electricity grid acts as a sort of back-up generator. In Section 2.7.6 grid electricity price and grid sellback price will be discussed in greater detail.

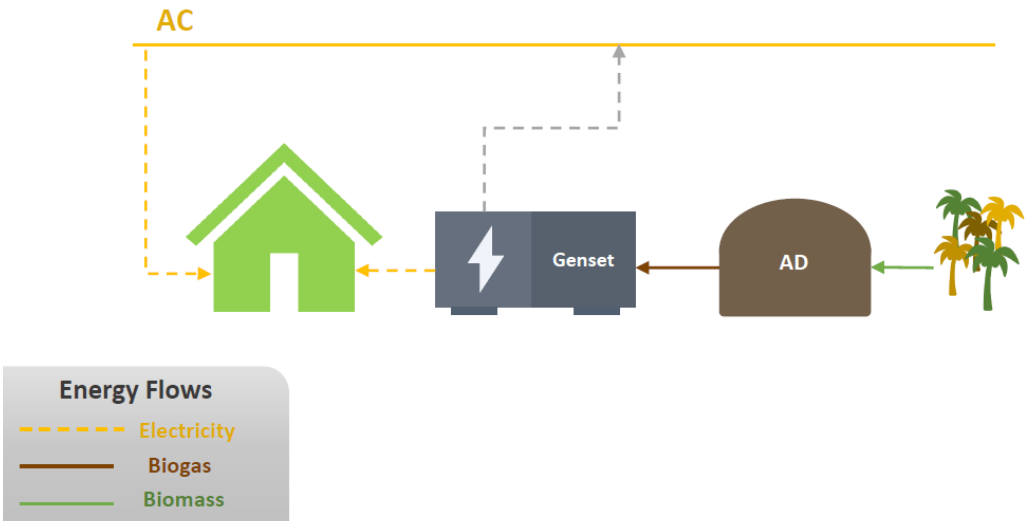

Figure 21: Configuration of grid-connected energy generation system for option A [41].

A schematic of the proposed micro-grid system for option A and B are shown in Figure 21 and Figure 22, respectively. For both options, the grid is added. The load demand and the grid are assumed to be AC. In the case for option A (Figure 21), the microgrid system consists of a biogas engine generator set, connected to an AC-Bus, with an anaerobic digester.

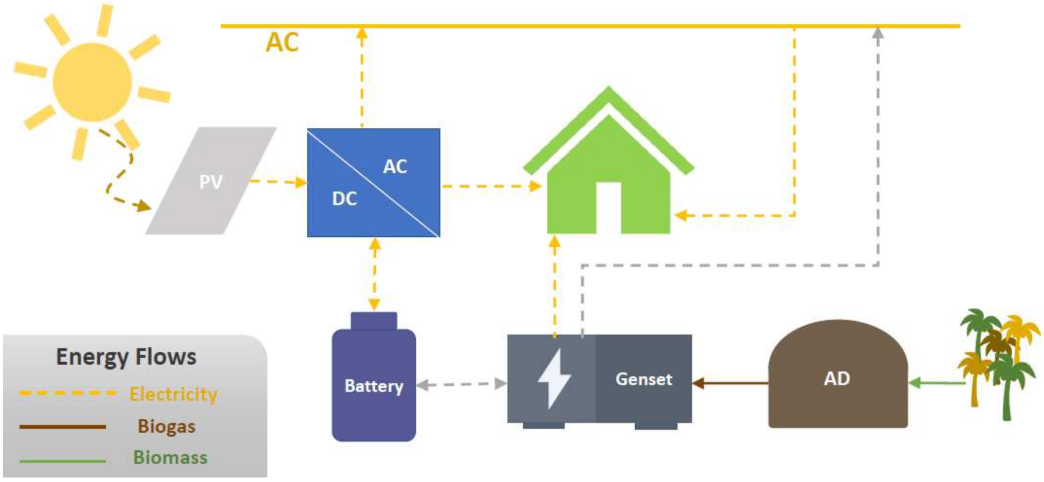

Figure 22: Configuration of grid-connected energy generation system for option B [41].

In the case for option B (Figure 22), the micro-grid system consists of PV array, biogas engine generator set with an anaerobic digester and battery storage (hybrid solution). The PV panels and battery bank are connected to a DC-Bus, and the biogas engine generator set is connected to an AC-Bus. These two buses are connected using a converter.

2.7 Components specifications

In the following section, the physical and economic properties of each component and how HOMER models them are described.
As mentioned above, four types of components are employed:

- Photovoltaic modules (PV), which generate electricity from an intermittent renewable source (solar);
- Generator and grid, which are dispatchable energy sources;
- Converter, which converts electrical energy into another form;
- Battery, which can store energy.

2.7.1 Solar photovoltaic module

In order to extract solar energy from the sun and convert it to DC electricity, PV array is required. PV array is modelled in HOMER as a device that produces DC electricity proportionally to the global solar radiation incident upon it. The power output of the PV array is calculated by HOMER through the following equation:

$$P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_S} \tag{9}$$

where:

- f_{PV} is the PV derating factor, a scaling factor which considers anything that can deviate the output of the PV array from expected ideal conditions;
- Y_{PV} is the rated capacity of the PV array (kW), in other words, the amount of power it would produce;

- I_T the global solar radiation incident on the surface of the PV array (kW/m^2);
- I_s is the standard amount of radiation used to rate the capacity of the PV array, and it is equal to 1 kW/m^2.

The selected solar PV module for this feasibility study is the STP 230-20 Wd module manufactured by SUNTECH Company [42]. That PV module is the same used in the feasibility analysis of a PV plant grid-connected system of 10 MW in the city of Tozeur in the South of Tunisia, and the technical specifications are provided by HOMER library. The lifetime of the photovoltaic modules is estimated to 25 years [42].

The cost for a 1kW PV module was assumed to be 2600 TND/kW equal to 838 €/kW, and the replacement cost is assumed to be 0 €/kW because system lifetime is assumed to be 25 years so panels will not be replaced. The operating and maintenance cost is assumed to be 52 TND/year equal to 17 €/year [42].

2.7.2 Converter

Since the power output from the solar PV module DC, power grid-connected inverter is required to convert the PV power output to AC power. The converter size refers to the inverter capacity. The inverter operates in parallel with the generator and the grid.

The selected converter is manufactured by SMA company (SUNNY CENTRAL 1000MV) [42]. The parameter specifications are shown in Table 22.

The lifetime of the inverter is assumed to be 15 years. The capital cost is assumed to be 150 TND/kW equal to 48 €/kW, and the replacement cost is supposed to equal to half the initial capital cost [42]. The operating and maintenance cost is assumed to be equal to 10 €/year.

Parameters	Value
Maximum efficiency [%]	98
DC input power [kVA]	1100
AC output power [kVA]	1000
Maximum input current [A]	2500
Output grid voltage [kV/Hz]	20/50 (3-phase)

Table 22: Technical specifications of the power converter [42].

2.7.3 Battery

Biomass resource is not an intermittent renewable energy source, but it may be seasonal. Photovoltaic modules generate electricity from an intermittent renewable energy resource: the sun. Thus, an energy storage unit as the battery is required in order to meet the electrical demand when the resources provide low energy.

A battery is modelled in HOMER as a device capable of storing a certain amount of DC electricity at fixed round-trip energy efficiency [16]. In HOMER, the physical properties of the battery are the rated voltage, the capacity curve, the duration curve, the minimum state of charge and the round-trip efficiency.

In this work, the lithium-ion battery bank is selected for its high cycle efficiency and rapid response times. Recent advances in technology development have made it competitive compared to traditional lead-acid battery [43]. The parameter specifications of a 1 kWh lithium-ion battery are shown in Table 23. The lifetime of the battery is assumed to be 15 years.

Parameters	Value
Throughput [kWh]	3.000
Nominal Voltage [V]	6
Maximum charge current [A]	167
Maximum discharge current [A]	500

Table 23: Technical specifications of the battery [44].

Concerning the economic properties of the battery, the capital cost is assumed to be 700 $/kW, equal to about 630 €/kW. The battery must be replaced twice during the project period, and the replacement cost is supposed to equal to the initial capital cost [44]. The operating and maintenance cost is assumed to be equal to 0 €/year.

2.7.4 Biogas generator set

A generator consumes fuel to produce electricity. A wide variety of generators can be modelled in HOMER: internal combustion engine generators, microturbines, fuel cells, Stirling engines, thermophotovoltaic generators, and thermoelectric generators. The physical properties of the generator are its maximum and mini-mum electrical power output, its expected lifetime (operating hours), the type of fuel it consumes, and its fuel curve, which relates the quantity of fuel to the electrical power produced.

In this work, the fuel consumed by the generator is the biogas derived from the biomass resource. To generate electricity from the biogas, gas generator and other associated devices are needed. The fuel curve is defined entering fuel consumption data and the size of the generator for which fuel consumption data are known. HOMER calculate the intercept coefficient and the slope and apply the fuel curve to a family of generators, over a range of sizes. It is necessary because multiple sizes will be entered in order to find the best one optimizing the system. The Cat-G3520C biogas generator set with a maximum power rating of 1966 kW is taken as reference in order to set fuel consumption parameters (Figure 23).

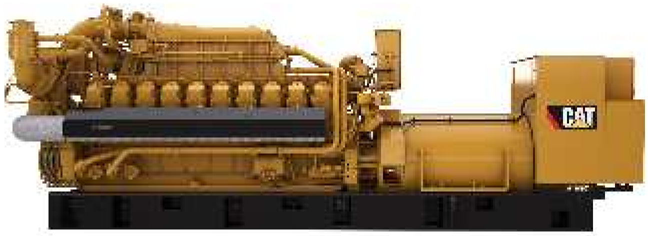

Figure 23: Cat-G5320 generator set 1966 kW.

Fuel consumption in MJ/(kW$_e$-h) at full load (100%) and part load (75% and 50%) of that Genset are provided by technical specification sheet [45] and are shown in Table 24. The corresponding fuel consumption curve is illustrated in Figure 24.

Data at:	Full load	Part load	
	100%	75%	50%
Electrical output [kW$_{el}$]	1966	1475	983
Fuel consumption [MJ/kW$_e$-h]	9,53	9,90	10,50
Fuel consumption [kg/h]	726	566	400

Table 24: Biogas genset fuel consumption [45].

The load factor and the operating hours are 30% and 90.000 hours, respectively [45].

Commercially available gas engines have total installed costs of 400 €/kW to 1100 €/kW and total O&M costs range from 0.010 €/kWh to 0.02 €/kWh [35]. Based on experience, the investment cost for the CHP of a simple plant for power generation is equal to 650 $/kW (587 €/kW) [39]. Thus, the capital cost and the replacement cost are assumed equal to 587 €/kW, respectively. The O&M cost is assumed to equal to 0.015 €/kWh.

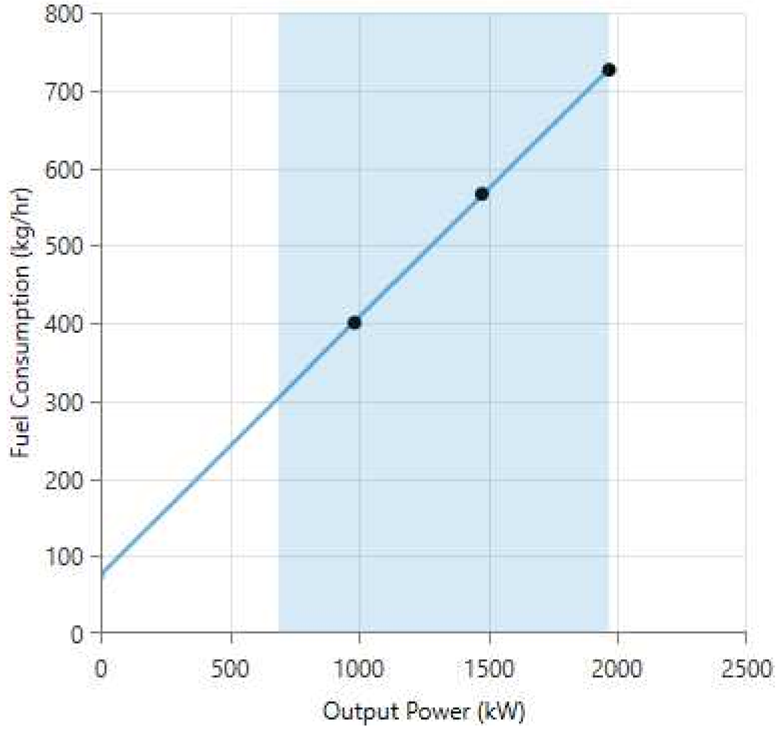

Figure 24: Fuel consumption curve.

2.7.5 Anaerobic Digester

As mentioned in Section 2.5.2, it is assumed that the biomass feedstock is fed into an anaerobic digester (AD) to create biogas that is supplied to the biogas generator set producing electricity. The anaerobic digester is not a HOMER component, and the feedstock conversion process is modelled explicitly entering biomass resource inputs. However, for general guidance, several of the most common digester technologies are briefly summarised in Table 25.

Typically, digester type is to be selected depending on the characteristics of the major feedstock used, mainly dry matter content [34].

	Feeding	Temperature	Agitation	Feedstock	Reliability	Climate
Wet continu-ous digestion	Continuous	Mesophilic or thermo-philic	CSTR with agitators, hydrau-lic digester without agitators	Easy pumpable, used for different feedstock	Impurities may cause technical problems	Worldwide, no limitation
Plug-flow re-actor	Continuous	Usually thermophilic, but mesophilic also possible	Along or transverse to the flow, vertical systems with-out agitators	Pumpable, mainly used for municipal biowaste	High tolerance to impurities	Worldwide, no limitation
Garage sys-tem	Discontinuous	Usually mesophilic, but thermophilic also possible	No agitators, percolation liq-uid distribution	Stackable, mainly used for municipal biowaste	Robust reactor without moving parts	Worldwide, no limitation
Lagoon biogas plant	Continuous with long re-tention time	Ambient temperature	Usually no agitation	Liquid, typically used for process or wastewater	Impurities may cause technical problems	Warmer lati-tudes like tropi-cal regions
Domestic di-gesters	Almost contin-uous	Ambient temperature	Usually no agitation	Locally available biowaste, manure, agricultural resi-dues	Impurities should not enter the process	Temperatures > 10°C

Table 25: Characteristics of different digester technologies [14].

Figure 25 shows an overview of technologies depending on dry matter content (TS) for the possible operating mode. It can be seen that the type of digestion process is dry continuous for dry matter content of feedstock ranging from 15% up to 45%. Dry continuous digestion takes place in plug-flow reactors [14].

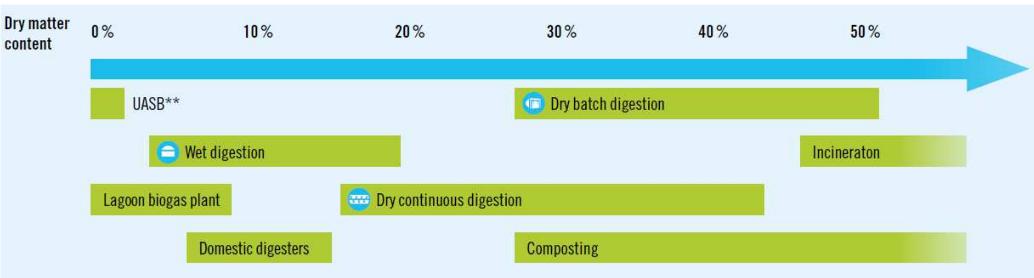

Figure 25: Overview of technologies depending on dry matter content for the possible operating mode [14].

Anaerobic plug-flow reactors are typically long rectangular channels, with the flow entering one end and leaving at the far end (Figure 26). The tanks, or channels, are generally placed above ground and are commercially used for treating diverse types of organic wastes including slurries of animal manure, distillery wastewater, and the organic fraction of municipal solid waste.

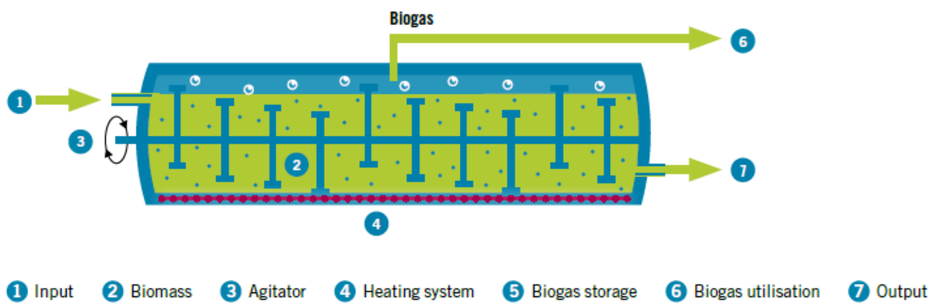

Figure 26: Plug-flow reactor.

As mentioned in Section 2.5.2, green waste is taken as major biomass feedstock for anaerobic co-digestion, and a typical value of dry matter content for green waste is 17% (see Table 15). Thus, an anaerobic plug-flow reactor could be representing a suitable digester technology option for this study. Digester costs will be considered as fixed costs which will be discussed in detail in Section 2.8.3 and 2.8.4.

2.7.6 Grid

In this study, the town of Meknassy is connecting to the utility grid. Thus, in all system types, the grid is added. The grid is a component from which the microgrid can purchase electricity and to which the system can sell electricity. The electricity grid acts as a sort of back-up generator. When the load demand is higher than the electricity generation from the micro-grid system in the town, the electricity is purchased from the grid. If there is an excess of electricity generation, electricity is sold back to the grid. The two main inputs are the grid electricity price and the sellback price. The grid electricity price is the price in euros per kWh that the electric utility charges for energy purchased from the grid and the sellback price refers to the price in euros per kWh that the utility pays for electricity sold to the grid [16].

As mentioned above, the Tunisian electricity grid is managed by the Tunisian Company of Electricity and Gas (STEG). The current is supplied to end-users in medium and low voltage because generally, in industries and dwellings, the equipment and machines that absorb electricity work respectively at these voltages. This work aims to provide electricity to Meknassy households. Thus, residential low voltage electricity tariffs for each monthly consumption bracket are taken into account to estimate grid electricity price at a fixed rate. The tariffs for low voltage electricity published on STEG website are given in Table 26.

<table>
<tr><th rowspan="2">Tariff</th><th rowspan="2">Sector</th><th rowspan="2">Power charge [mill TND/ kVA/month]</th><th colspan="6">Energy price for each monthly consumption bracket [mill TND/kWh]</th></tr>
<tr><th>1-50</th><th>51-100</th><th>101-200</th><th>201-300</th><th>301-500</th><th>500+</th></tr>
<tr><td rowspan="3">Economy rate 1 and 2 kVA and Consumption ≤ 100 [kWh/month]</td><td>Residential</td><td rowspan="3">700</td><td>62</td><td colspan="5"></td></tr>
<tr><td>Residential</td><td colspan="2">96</td><td colspan="4" rowspan="2"></td></tr>
<tr><td>Non residential</td><td colspan="2">104</td></tr>
<tr><td rowspan="2">Economy rate (1 and 2 kVA and Consumption ≥ 100 [kWh/month] Standard rate (>2 kVA)</td><td>Residential</td><td rowspan="2">700</td><td colspan="3">176</td><td>218</td><td>341</td><td>414</td></tr>
<tr><td>Non residential</td><td colspan="3">195</td><td>240</td><td>333</td><td>391</td></tr>
</table>

Table 26: Tunisian low voltage electricity tariff 2019 [46].

As we can see from Table 26, tariffs depend on the sector of the consumer (residential or non-residential) and the consumption per month in kWh and they are subject to a Value-added tax (VAT) applicable at the rate of:

- 19% on all charges and the energy price (net of tax) for all uses other than domestic and irrigation;
- 13% on the energy price (net of tax) for domestic uses;
- 7% on the energy price (net of tax) for irrigation uses;
- plus a “municipal surcharge” of 5 mill TND/kWh.

The electricity price for residential sector ranges from 0,062 TND/kWh to 0,096 TND/kWh for an electricity consumption less than 100 kWh/month, and from 0,176 TND/kWh to 0,414 TND/kWh for an electricity consumption higher than 100 kWh/month. Considering the average monthly consumption of a Meknassy household, the grid electricity price is assumed at a fixed rate and equal to 0,11 €/kWh (0,341 TND/kWh).
Concerning the "feed-in-tariff" or sellback price for renewable energy in Tunisia, Decision of the Minister of Industry, Energy and Mines on 2 June 2014 set multiple rates which are shown in Table 27.

Period	**Tariff mill TND/kWh (€/kWh)**
Day	115 (0,037)
Summer morning peak	182 (0,058)
Evening peak	168 (0,054)
Night	87 (0,028)

Table 27: Sellback price for renewable energy in Tunisia [47].

The electricity tariffs are arranged by time slots. As shown in Table 28, there are four-time slots: Day, Summer morning peak, Evening peak and Night.

Period	**September 1st - May 31th**	**June 1st - August 31th**
Day	7:00 - 18:00 pm	6:30 - 8:30 / 13:30 - 19:00
Summer morning peak	-	8:30 - 13:30
Evening peak	18:00 - 21:00	19:00 - 22:00
Night	21:00 - 7:00	22:00 - 6:30

Table 28: Tunisian four-time shifts regime [48].

In this case, the sellback price changes according to the time of day and the day of the year, thus more than one rate must be defined, and HOMER allows to define grid prices with a regular schedule as shown in Figure 27 and Figure 28.

	Price €/kWh	Sellback €/kWh
Day	0.1100	0.0370
Summer Morning Peak	0.1100	0.0580
Evening peak	0.1100	0.0540
Night	0.1100	0.0280

Figure 27: HOMER rate definition.

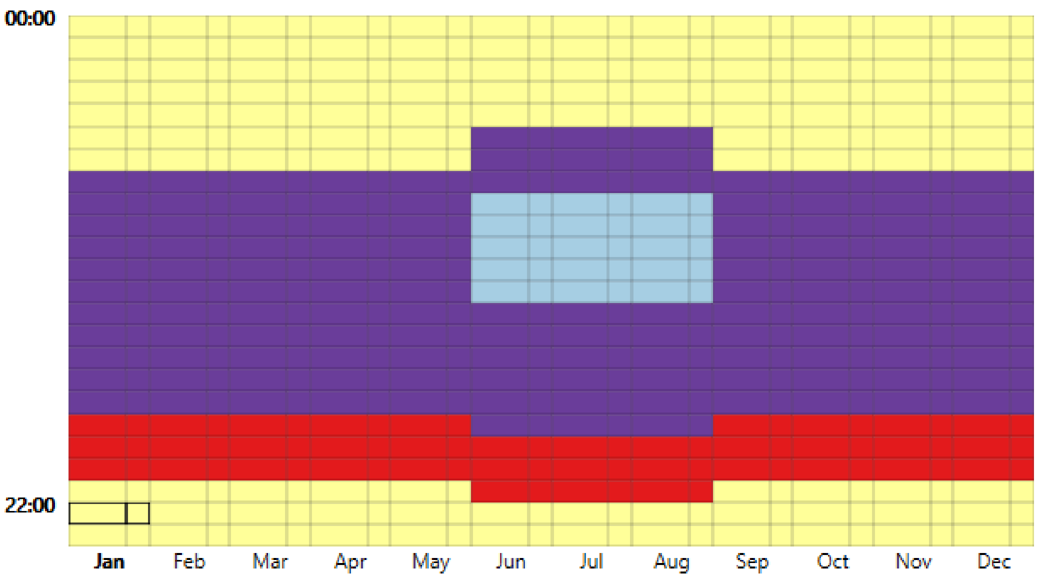

Figure 28: HOMER grid rate schedule.

2.8 Other inputs

2.8.1 Real discount rate

As mentioned in section 2.2.2, the annual real discount rate i is one of the HOMER inputs, which is also called the annual real interest rate. The annual real interest rate is related to the nominal interest rate and the expected inflation rate by Equation (2). The inflation rate in Tunisia is assumed to equal to 6,1%, according to “WACC EXPERT” website [49]. The weighted average cost of capital (WACC) is usually employed as nominal discount rate in order to consider to what extent an investment is financed through debt and equity [50]. As shown below, the WACC formula is:

$$WACC = K_d \frac{D}{D+E}(1-T) + K_e \frac{E}{E+D} \tag{10}$$

where:

- E: market value of the firm equity;
- D: market value of the firm debt;
- E+D: total market value of the firm financing;
- E/(E+D): weight of equity;
- D/(E+D): weight of debt;
- K_e: cost of equity;
- K_d: cost of debt;
- T: corporate tax rate.

The cost of equity is calculated based on the formula of the "Capital Asset Pricing Model" [51]:

$$K_d = R_f + \beta\ (R_m - R_f) \tag{11}$$

where:

- R_f: risk free rate of return;
- β: sensitivity to market risk;
- R_m: market rate of return;
- R_m-R_f: market premium.

The financial parameters and the WACC value for Tunisia country and utility sector are taken from "WACC EXPERT" webpage and are reported in Table 29. WACC EXPERT offers free and direct access to standardized WACC calculation.

Financial parameter	Value
Weight of debt [%]	24,60
Corporate tax rate [%]	25,00
Cost of debt [%]	5,48
Annual inflation rate [%]	6,10
Country risk premium [%]	3,20
Risk free rate [%]	1,28
Unlevered beta [%]	0,54
Market premium [%]	6,99
WACC [%]	8,34

Table 29: Financial data for Tunisia country and utility sector [49].

According to WACC EXPERT methodology, in Tunisia, the WACC for the utility sector is 8,34% and based on company specific characteristics, it can vary from 6,62% to 13,19%. Thus, the annual real interest rate is estimated equal to 2,11%.

2.8.2 Project lifetime

The project lifetime is assumed to be equal to 25 years, as is usually done in the project regarding energy investment.

2.8.3 System fixed capital cost

The fixed costs for a biogas unit include all expenses and lost income which are necessary for the erection of the plant, (e.g. land, excavation-work, construction of the digester and gasholder, piping system, gas utilisation system, the substrate storage system and other buildings). The cost of a specific item depends on size or scale and can usually be correlated by the following equation [52]:

$$\frac{C_1}{C_2} = \left(\frac{Q_1}{Q_2}\right)^n \tag{12}$$

where:

- C_1: item cost at size Q_1;
- C_2: item cost at size Q_2;
- n: scale exponent or cost capacity factor;

If the fixed capital cost (C_2) for a reference biogas plant capacity (Q_2) is known and the correct value of *n* is correctly chosen, the fixed capital cost (C_1) of the proposed biogas plant with specific capacity (Q_1) can be calculated through the Equation (12).

In this study, the biogas plant capacity (Q_1), is assumed equal to the bioreactor volume. A typical parameter used to calculate the digester volume is the organic loading rate (OLR). The OLR describes the amount of volatile solids introduced into the digester, expressed in kilogrammes of VS per day and per cubic metre of the digester (kg VS/m^3 day). The OLR is typically between 2 and 3 kg VS/m^3 day [35]. The formula for calculating the organic load is given by the following equation [35]:

$$OLR\ \left[\frac{kg_{VS}}{m^3 day}\right] = \frac{VS\ input\ \left[\frac{kg_{VS}}{day}\right]}{Digester\ volume\ [m^3]} \tag{13}$$

As mentioned in Section 2.5.2.5, the final mixture of fresh matter which is sent to the anaerobic digester per year is equal to 13.405, which corresponds to 2.533 tons of VS per year. Assuming that the daily VS mass in input is equal to 6.940 kg/day and the OLR is equal to 2,5 kg VS/m^3 day, the digester volume can be calculated through the Equation (13), and it is equal to 2.776 m^3

Regarding the cost capacity factor *n*, the use of the correct value for *n* is critical. Amigun et al. [52] investigate the significance of scale economies with increasing plant capacity on the capital investment cost of African biogas plants. For the small-scale–medium biogas plant (2–16 m^3), the cost exponent (capacity factor), is 1,21. In the case of large-scale biogas technology (>20 m^3), the cost capacity factor is 0,80. In this case, the value of the capacity factor is chosen equal to 0,80.

A biogas plant with a capacity of 5000 m^3, built in Nigeria in 2004, is chosen as reference [52]. The fixed capital investment cost (C_2) for that biogas installation is 420.000 \$. This value is corrected with the Engineering News Record construction cost indexes (ENR indexes) of 6.944 (2004) and of 11.281 (2019) [53] to account for cost escalation with time through the following equation [54]:

$$C_t = C_{t0} \frac{ENR_t}{ENR_{t0}} \tag{14}$$

where:

- C_t estimated cost at present time t (2019);
- C_{t0} cost at previous time t_0 (2004);
- ENR_t construction index value at present time t (2019);
- ENR_{t0} construction index value at previous time t_0 (2004).

The fixed capital investment cost for Nigerian biogas installation normalised to ENR index (2019) is 682.318 \$. Finally, the fixed capital cost of the proposed biogas plant is equal to 426.134 \$, which correspond to 385.637 €.

2.8.4 System fixed O&M cost

Fixed operations and maintenance (O&M) costs for bioenergy power plants typically range from 2-6% of total installed costs per year [55]. Fixed O&M costs include labour, scheduled maintenance, routine component/equipment replacement (for boilers, gasifiers, feedstock handling equipment, etc.), insurance, etc. The fixed O&M costs for biogas power plants with anaerobic digester is 2,1-3,2 % of CAPEX per year [55]. Assuming that it is equal to 2,5 %, the system fixed O&M cost is equal to 9.641 €/year.

2.8.5 Other inputs summary

The inputs mentioned above are summarized in the following table:

Parameter	Value
Nominal discount rate [%]	8,34
Expected inflation rate [%]	6,10
Project lifetime [year]	25
System fixed capital cost [€]	385.637
System fixed O&M cost [€/year]	9.641

Table 30: Inputs of the economic inputs window.

3 RESULTS AND DISCUSSION

3.1 Introduction

The following chapter reports the simulation results of two micro-grid system options (A and B) for the electricity supply of Meknassy urban area. For both cases, an optimization process is performed simulating and comparing many different system configurations in order to determine the best one with the lowest total net present cost. Then a sensitivity analysis is conducted to see what are the most important of the sensitivity variables that influence the optimal system configuration. Finally, a sensitivity analysis is incorporate with optimization to see how to change the optimal system types according to the most critical sensitivity variables.

3.2 Optimization results

As mentioned in Section 2.2, the optimization process consists of simulating and comparing different system configurations in order to determine the optimal value of the decision variables that identify the configuration with the lowest total net present cost [17]. The configuration of the two proposed system options is shown in Figure 29.

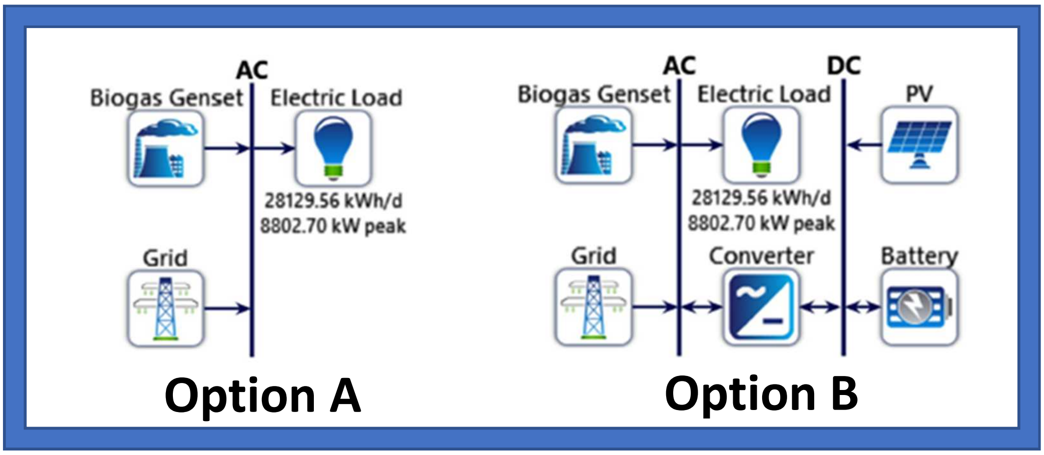

Figure 29: System configurations.

The decision variables are variables for which it is possible to consider multiple values in the optimization process. In the case for option A, the only decision variable is represented by the generator size that ranges from 0 to 3.000 kW. In the case for option B, the decision variables are the generator size, that ranges from 0 to 3.000 kW, the converter size, the PV size and the number of batteries. The search space of these last three variables is not specified because it is chosen automatically by HOMER optimizer. The decision variables of these two options are summarized in Table 31.

Decision variables	Option A	Option B	Search space
Generator size	✓	✓	0-3000 kW
PV size	×	✓	HOMER optimizer
Converter size	×	✓	HOMER optimizer
Number of batteries	×	✓	HOMER optimizer

Table 31: Decision variables and search space.

For both proposed options, the optimization process decides on the mix of components that the system should contain and the size or quantity of each component, creating different system configurations per category or type. For each possible system category, the optimization process rejects the infeasible configuration and ranks the feasible one with the lowest total NPC.

3.2.1 Best configuration for option A

Table 32 illustrates the optimization results for option A. The only possible system category consists of the existing grid and the biogas generator set (grid-biogas system). HOMER search for the best size of the biogas generator set and the found value is 2.100 kW.

Architecture					Cost
		Biogas Genset (kW)	Grid (kW)	Dispatch	NPC (€)
		2,100	999,999	CC	€21.6M

Table 32: Categorized optimization results for option A.

The total capital cost, the total net present cost and the levelized cost of electricity of this system configuration are €1.618.337, €21.616.135 and €0,109/kWh, respectively. Figure 30, which provide the cost summary of the optimal system configuration by cost type, shows that the operating cost of the grid represents the higher cost of the optimal system configuration.

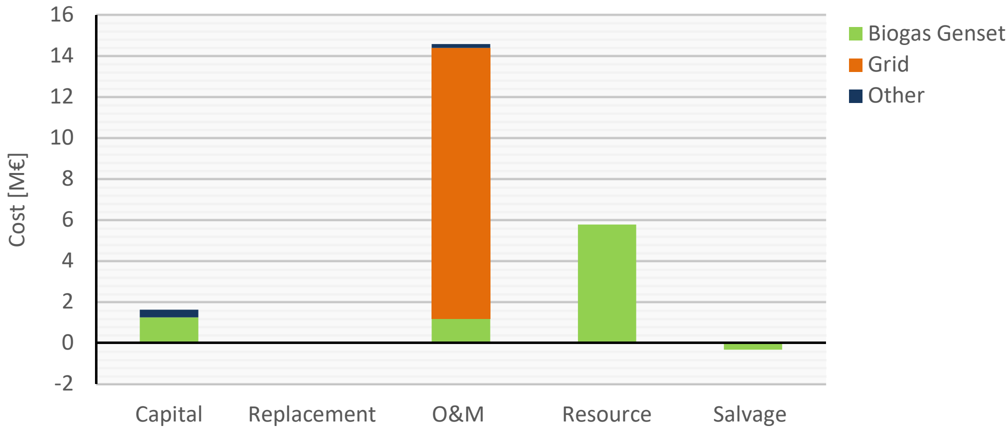

Figure 30: Cost summary of the optimal system configuration by cost type for option A.

Figure 31 shows the distribution of total electrical production. In this configuration, the electricity purchased from the grid is about 6,2 GWh/year. The grid dominates the power generation by providing 61% of the total generated electricity, whereas the electricity sold to the grid is equal to 0.

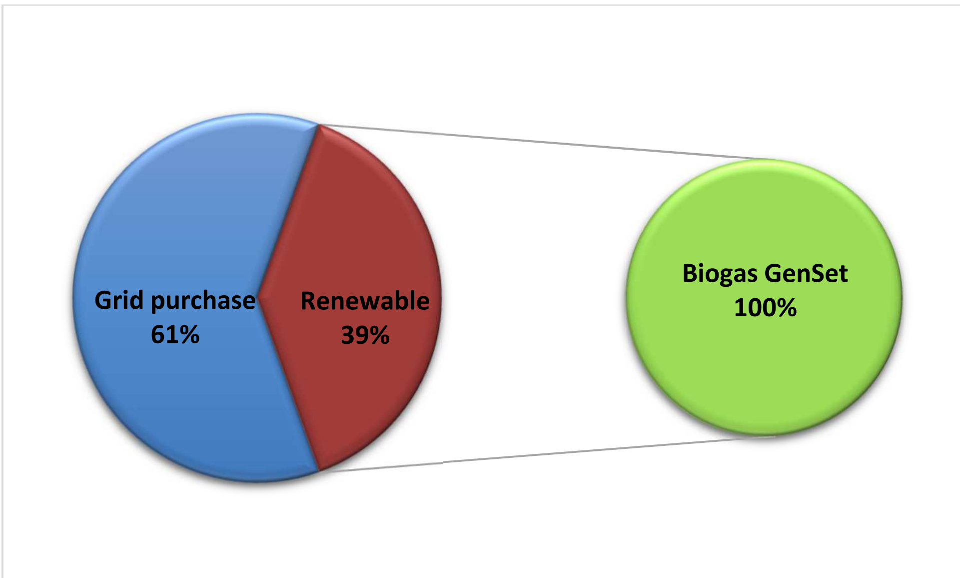

Figure 31: Distribution of total electrical production for option A.

On the other hand, the biogas Genset provides 39% of the total generated power, which represents the totality of the renewable fraction. The generator operates 1.930 hours per year, consuming almost all of the available

feedstock (13.374 tons/year). The mean electrical power output, the capacity factor and the mean electrical efficiency are equal to 2.090 kW, 21,9% and 38,3% respectively.
The primary load, the grid purchases and the amount of generated power by biogas generator in a generic week of September are shown in Figure 32. It is clear that the only biogas generator is not able to meet the load demand, but it contributes to reducing the grid purchases.

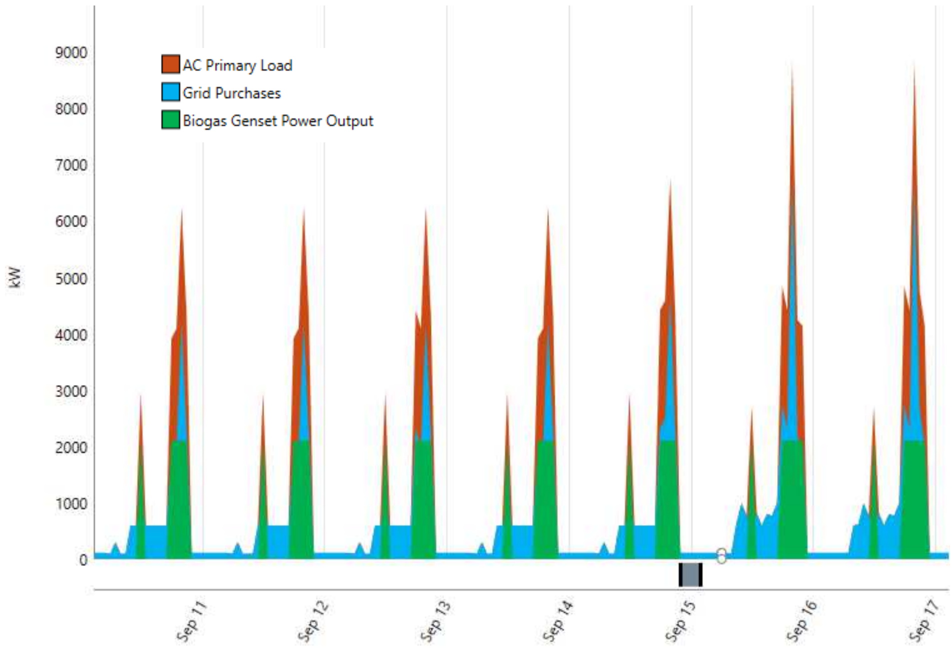

Figure 32: Primary load, grid purchases and generated power by biogas generator during a generic September week for option A.

3.2.2 Best configuration for option B

As can be seen in Table 33, the categorized optimization results for option B show that there are six possible system categories. For each of them, only the least-cost configuration within each system category is shown. The best system category is grid-PV-biogas. The second-ranked system category is the same as the except that it contains batteries (grid-PV-biogas-battery).

The optimal system configuration for option A (grid-biogas) ranks fifth in this case.

Architecture						Cost
PV (kW)	Biogas Genset (kW)	Battery	Grid (kW)	Converter (kW)		NPC (€)
3,471	2,500		999,999	2,480		€20.2M
3,371	2,300	21	999,999	2,415		€20.3M
3,471			999,999	2,480		€20.9M
4,052		31	999,999	2,633		€20.9M
	2,100		999,999			€21.6M
	2,100	52	999,999	17.2		€21.7M

Table 33: Categorized optimization results for option B.

The first row is the least-cost configuration within the grid-PV-biogas system category. In detail, it is composed of the grid, 3.471 kW PV-Array, 2.500 kW biogas generator set and 2.480 kW converter. In this configuration, the total capital cost, the total NPC and LCOE are €4.880.999, €20.246.879 and €0,077/kWh, respectively. A comparison between the best configuration system for option A and the best one for option B shows that the NPC and the LCOE are 7% and 29% lower in the optimal system of option B, respectively.

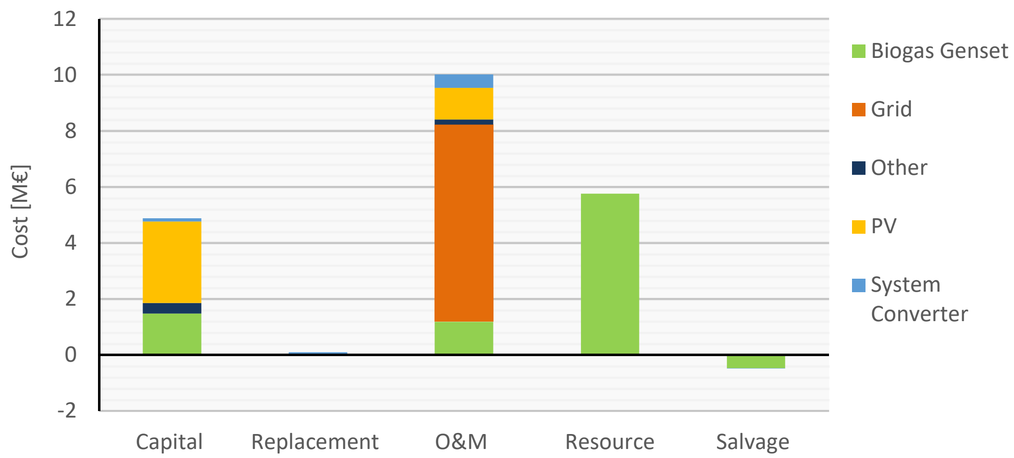

Figure 33: Cost summary of the optimal system configuration by cost type for option B.

Figure 33 illustrates the cost summary of the following optimal system configuration by cost type. The graph shows that slightly more than 50% of the capital cost goes to the PV array, and the replacement cost is very low because the only converter requires to be replaced during the system lifetime. As the case study A, the operating cost of the grid represents the higher cost of the optimal system configuration.

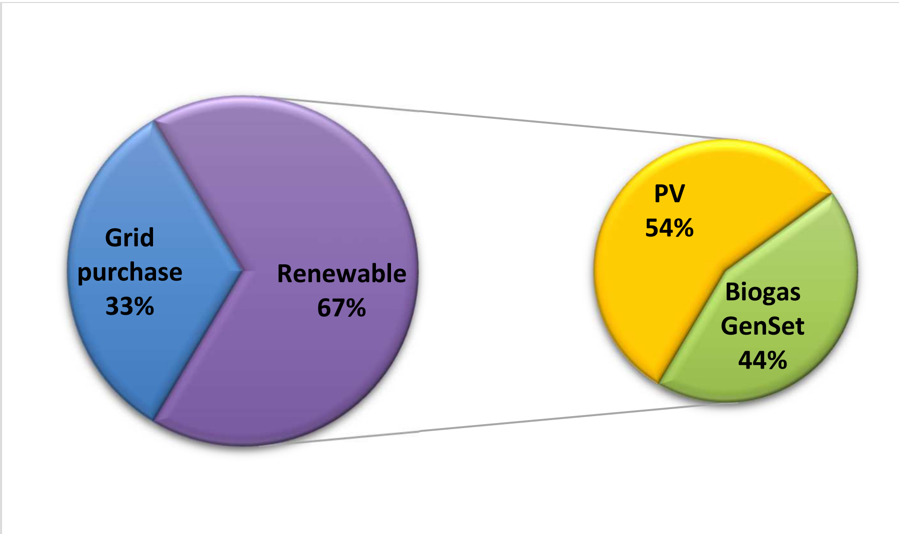

Figure 34: Distribution of total electrical production for option B.

The pie of pie chart illustrated in Figure 34 shows the distribution of total electrical production. The fraction produced by renewable sources amounts to 67%. The PV array contributes to providing about 5,2 GWh/year (38% of total electrical production, 56% of renewable fraction), while the biogas generator set about 4 GWh/year (29% of total electrical production, 44% of renewable fraction). The electricity purchased from the grid is about 4,5 GWh/year (33%). Moreover, the renewable fraction is increased by 28%, and consequently, the electricity purchased from the grid is decreased by the same percentage if compared to the best system configuration for case study A.

In this configuration, the total amount of electricity sold to the grid during the year is about 3,3 GWh/year. As can be seen from Figure 35, the higher amount of electricity sold to the grid usually occurs during the morning peak, due to the high solar insolation. Instead, the higher amount of electricity purchased from the grid happens during the evening due to the lack of solar insolation and because the only biogas generator is not able to meet the entire load demand.

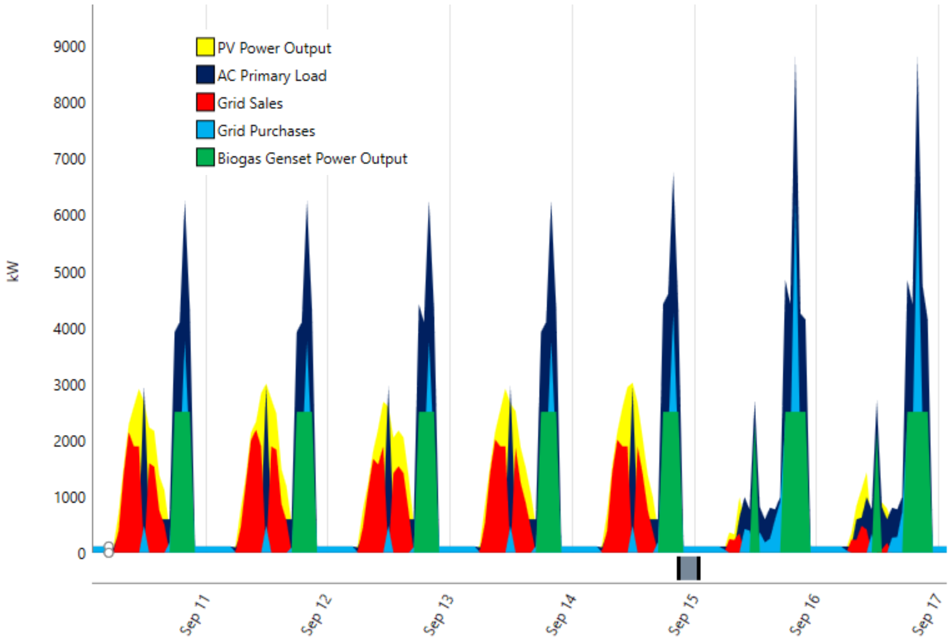

Figure 35: Primary load, grid purchases, grid sales and generated power by during a generic September week for option B.

Figure 36 illustrates the cumulative nominal cash-flow over the project lifetime, or in other words, how the system saves money over the project lifetime. The light blue line represents the optimal system configuration for option A, and the grey line represents the optimal one for option B. The intersection between the two lines identifies the simple payback, the number of years at which the cumulative cash flow of the difference between the two optimal systems switches from negative to positive [17]. In this case, the simple payback is equal to 14 years.

The internal rate of return (IRR) and the return on investment (ROI) are the other two economic measures which represent the value of the difference between the two systems. The IRR is the discount rate at which the base case and current system have the same net present cost [17], and it is equal to 5,3%. The ROI is the yearly cost savings relative to the initial investment [17], and it is equal to 3,4%.

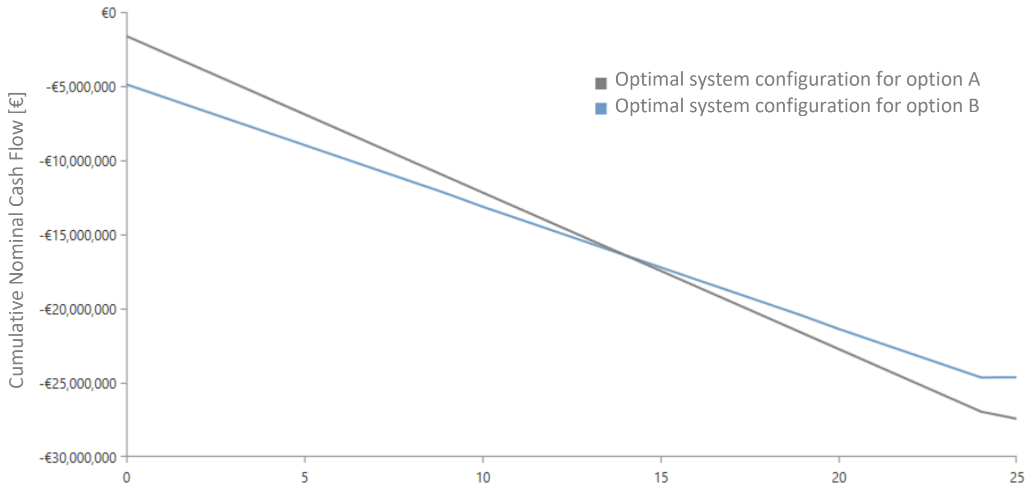

Figure 36: Cumulative nominal cash-flow over the project lifetime.

3.3 Sensitivity results

In the previous section, the optimization process finds the system configuration that is optimal under a particular set of input assumptions for both options. It is clear from optimization results that the optimal system configuration for option B (grid-PV-biogas) appears to be the best.

As is known, the optimization results are based on several assumptions taken from literature and different websites. Due to the uncertainties related to inputs assumptions, a sensitivity analysis has been performed to understand how the outputs are sensitive to the input changes. In detail, a first sensitivity analysis is performed fixing the best-optimized system configuration entering multiple values of input variables (sensitivity variables) for which the net present cost would appear more sensitive. Finally, a second sensitivity analysis is performed, incorporating the optimization to see how to change the optimal system types across a range of the most critical uncertain variables identified in the previous sensitivity analysis.

3.3.1 Sensitivity analysis 1

The following sensitivity analysis is performed fixing the system configuration to the grid-PV-biogas system that appears in the first row of Table 33. The best-fixed system configuration is shown in Table 34.

Component	Size [kW]
Biogas Genset	2.500 kW
PV	3.471 kW
Converter	2.480 kW

Table 34: Best-estimated system configuration.

The five sensitivity variables selected, for which the net present cost would appear more sensitive, range from 30% below to 30% above the corresponding values at best-fixed system configuration (best estimate values) and are shown in Table 35.

Sensitivity variable	Best estimate value
PV capital cost [€/kW]	838
Grid electricity price [€/kWh]	0,11
Nominal discount rate [%]	8,34
Biomass price [€/tons]	22,4
Generator capital cost [€/kW]	587

Table 35: Sensitivity variables and corresponding best estimate values.

The sensitivity results are shown in the spider graph of Figure 37.

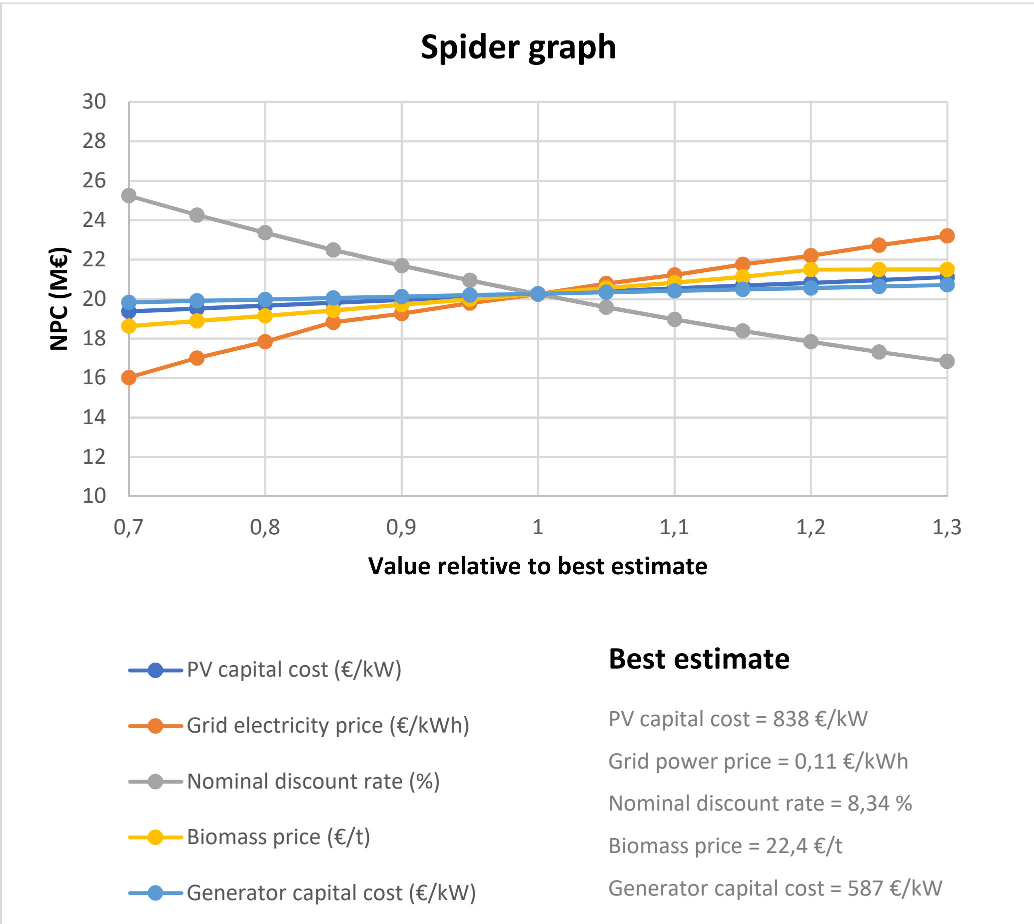

Figure 37: Spider graph.

As can be seen, the relative trend of the five curves shows that the total NPC is more sensitive to the nominal discount rate and grid electricity price than to the other three variables. A 30% increase in the nominal discount rate causes a 17% decrease in the NPC, while a 30% increase in the grid electricity price leads to a 15% increase in the NPC. Such information can help to understand what bounds of a confidence interval and which inputs assumptions need to be prioritized assessing the associated risks.

3.3.2 Sensitivity analysis 2

The previous sensitivity analysis has been underlined that the nominal discount rate and the grid electricity price are most critical variables. The second sensitivity analysis is performed incorporating the optimization process in order to determine which technologies, or combinations of technologies, are optimal across a range of the most critical variables. The search space of Table 31 is employed entering a range of grid electricity price and nominal discount rate above and below the best-estimate value of €0.11/kWh and 8.34%, respectively. In particular, nine values for the grid electricity price are entered, considering that the electricity price for residential sector ranges from €0,02/kWh to €0,13/kWh (see Section 2.7.6) and the growing trend of low voltage residential electricity tariff in the last 15 years [56]. Instead, eight values for the nominal discount rate are entered, considering that the WACC for the utility sector in Tunisia can vary from 6,62% to 13,19%, depending on company specific characteristics (according to WACC EXPERT methodology [49]). Each combination of those two sensitivity variables defines a distinct sensitivity scenario for a total of 72 sensitivity scenarios. For each distinct case, an optimization process is performed. The sensitivity results for the two selected variables are shown in Figure 38.

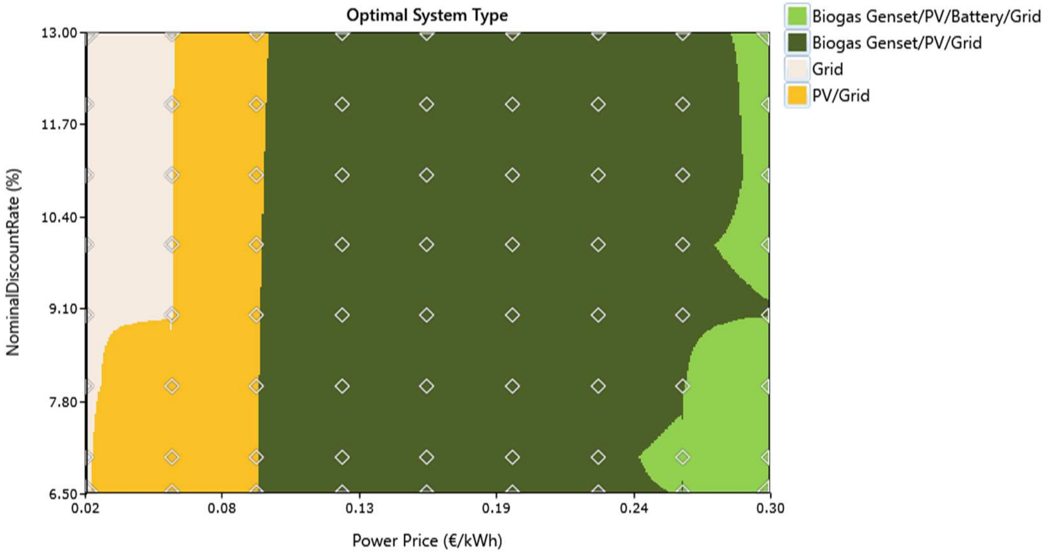

Figure 38: Sensitivity analysis in term of grid electricity price and nominal discount rate.

As can be seen, as grid electricity price increases, the optimal system type changes to the grid, grid-PV, grid-PV-biogas, and finally grid-PV-biogas-battery, whatever the nominal discount rate values. At high nominal discount rates and low grid electricity prices, the electrification of the town only with the electricity from the grid seems the optimal solution. The grid-PV-biogas system appears to be the best optimal system type for the most sensitivity cases. The possibility to integrate a battery storage system to grid-PV-biogas system can be taken into account only for high values of grid electricity price.

The surface plot of Figure 39 shows how the NPC is related to the nominal discount rate and grid electricity price for each sensitivity case. For example, at a nominal discount rate of 9% and a grid electricity price of €0,12/kWh, the optimal system type is grid-PV-biogas, and the NPC is amount €20 million.

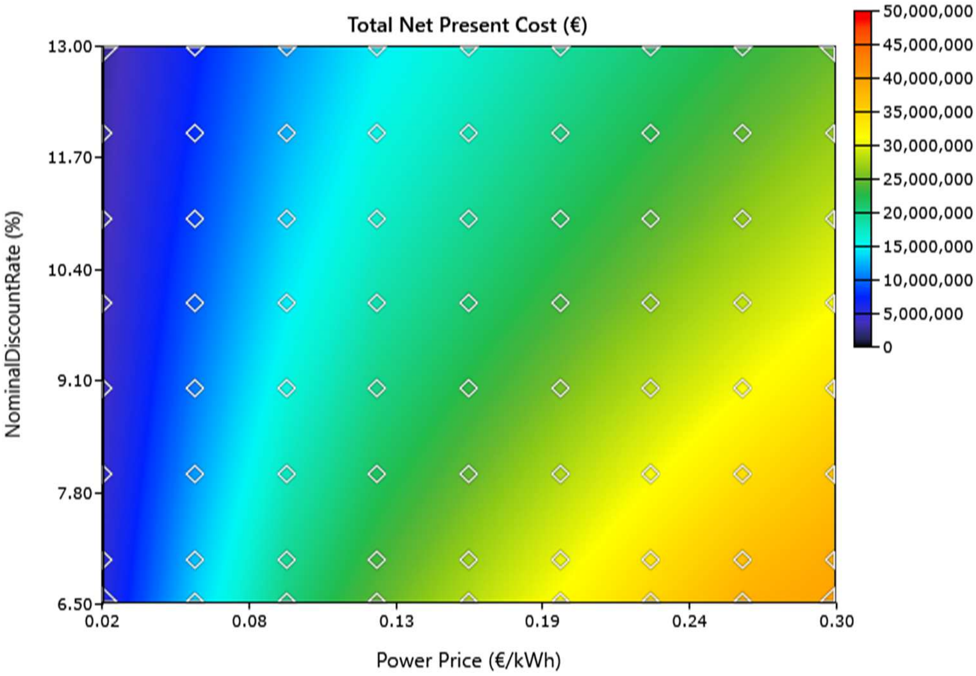

Figure 39: Surface plot of the net present cost.

CONCLUSION

The techno-economic evaluation of a grid-connected renewable energy system for the town of Meknassy in Tunisia has been performed. The generated electricity provides the power demand of 3.206 households living in Meknassy. In this work, a comparative analysis between two different micro-grid system options is considered. The optimal system configurations are analysed using HOMER simulation software and a MATLAB application. The optimization results determine the group of optimized systems for each proposed option according to the technic and economic assumptions. It is observed from the optimization results that the optimal system configuration for option B (grid-PV-biogas) is appeared to be the best. It is composed of the utility grid, 3.471 kW PV-Array, 2.480 kW converter and 2.500 kW biogas generator set, in which the biogas is produced locally by feeding an anaerobic digester with green waste and organic fraction of private households. In this system, the renewable fraction in power generation is 67%. The total NPC and the LCOE of generated electricity by this hybrid energy system are equal to €20,2 million and €0,077/kWh, respectively. They are about 6% and 29% lower than those calculated in the optimal system configuration for option A (grid-biogas). It means that the hybrid system option is economically a better choice than one including only biogas generator set with an anaerobic digester.

Two sensitivity analysis has been conducted to see what are the most critical input variables that influence the total NPC of the optimal system configuration, and how to change optimal system configurations according to the most critical sensitivity variables. The sensitivity results show that the total NPC is more sensitive to the nominal discount rate and the grid electricity

price values. The grid-PV-biogas system appears to be the best optimal system type for the most sensitivity scenarios. As the grid electricity prices increase in the future, the integration of battery storage system to the grid-PV-biogas system can be taken into account.
It is clear from the present work that the electricity produced by grid-connected renewable energy systems is significantly cheaper than the utility grid electricity. They represent a feasible and reliable solution to meet the energy demand of the urban households of Meknassy. More generally, they are a viable solution able to improve the living and economic conditions of habitants living in semi-desertic areas of Tunisia. This study may be helpful in the design, optimization and development of grid-connected PV-biogas systems for the study area. However, several possible limitations need to be considered, and proposed configurations need to be implemented in practice.

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