POLITECNICO DI TORINO

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DESIGN OF RENEWABLE ENERGY MINI-GRIDS FOR THE PRODUCTION OF ELECTRICITY IN RURAL COMMUNITIES

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ABSTRACT

Hybrid mini-grids are popular solutions in order to provide electricity in rural areas of developing countries. The number of these projects around the world increases every year and their huge potential market is attracting many private companies and public investors. These systems use the availability of local resources, as biomass or solar radiation, to generate electricity at low price for the customers and their economic convenience is due to low operational costs compared to the traditional systems powered by fossil fuels. The aim of this thesis is to design a mini-grid in a selected community called Toudgha El Oulia, situated in the central-eastern side of Morocco. The system exploits the availability of biomass produced by the cultivation of cereals, olive trees and date palms within the area and the availability of solar radiation to produce clean energy for the community in question. The techno-economic analysis of the project is performed using the software HOMER pro which calculates the most feasible solution including solar and biomass resources. The results of the simulation showed that the best solution for the community in question consists in a plant composed of photovoltaic and biogas generator able to cover about 40% of the demand.

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1. Sommario in italiano

L'obiettivo della tesi è il dimensionamento di un sistema alimentato da biomassa ed energia solare per alimentare una mini rete (mini-grid) che fornisca energia ad una comunità rurale del Marocco. Lo strumento utilizzato per svolgere l'analisi tecnico-economica e l'ottimizzazione dei componenti della mini rete è il software HOMER pro, un programma usato frequentemente per il corretto dimensionamento di questi tipi di impianti.

La tesi inizia con una presentazione generale delle mini-grids nel mondo (capitolo terzo). Questa tipologia di impianti rappresenta un'ottima soluzione per fornire energia elettrica in zone rurali dei paesi in via di sviluppo o in aree dove l'espansione della rete non è conveniente a causa del ridotto numero di consumatori. L'utilizzo di questi sistemi permetterà a molte persone che tutt'oggi vivono senza elettricità (si calcola che siano circa un miliardo e mezzo) di avere un accesso stabile all'energia, migliorando sensibilmente le loro condizioni economiche e sociali.

In generale le mini-grids possono essere definite come una serie di generatori elettrici e sistemi di accumulo interconnessi a una piccola rete elettrica che fornisce energia ad un ridotto numero di utenti. Il numero di questi progetti è in continuo aumento e il loro significativo potenziale economico sta attirando sempre più investitori da tutto il globo. Il paese con il maggiore numero di questi impianti è la Cina e si stanno diffondendo in molti altri paesi come l'India, la Cambogia, il Mali, le Filippine e il Marocco.

Ci sono diversi tipi di mini-grids che possono essere distinte sulla base della potenza o delle risorse che le alimentano; negli ultimi anni stanno riscuotendo sempre maggior successo le mini-grids ibride, impianti alimentati da risorse rinnovabili e che sfruttano i sistemi tradizionali, quali i generatori diesel, come back-up.

Mentre in passato solitamente venivano utilizzati generatori diesel per fornire energia in aree isolate e molti di questi sistemi sono ancora in funzione, adesso diverse società investono in soluzioni ibride che sono diventate economicamente più convenienti dei sistemi tradizionali in molti contesti. Questi impianti infatti permettono di sfruttare la disponibilità di risorse locali per generare energia pulita ed hanno minori costi operativi rispetto ai generatori diesel, non comportando la necessità di fornire grandi quantità di combustibile in zone remote. Diversi studi hanno dimostrato che l'opzione più conveniente in diverse realtà consiste nel trasformare i sistemi basati su generatori diesel già presenti e funzionanti in sistemi ibridi.

Nella figura seguente (corrispondente alla figura 3.2 del capitolo 3) è confrontato il costo di produzione dell'energia tra sistemi diesel e sistemi ibridi in diversi paesi del mondo.

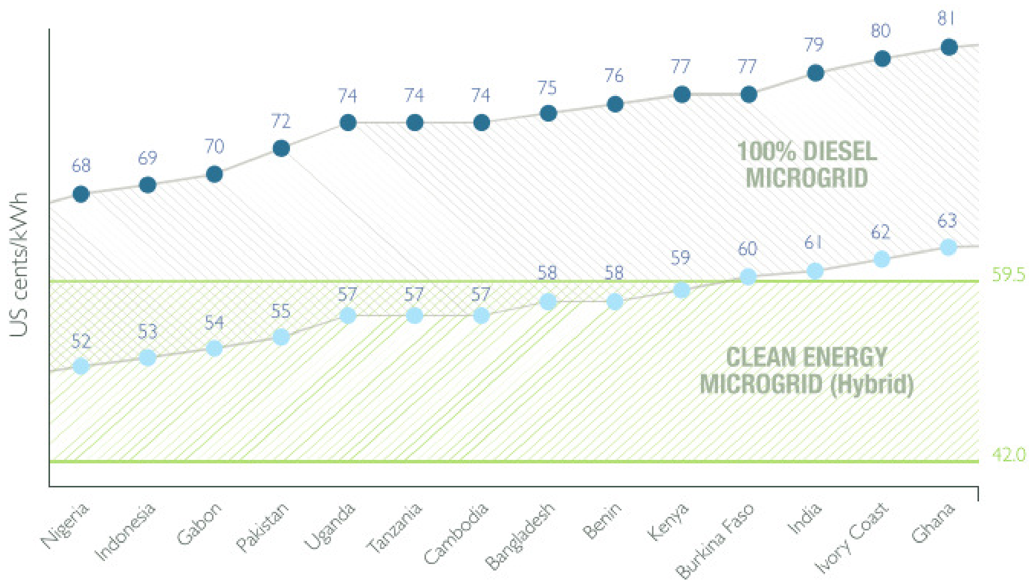


Figura 1.1: Confronto del costo di produzione dell'energia tra sistemi diesel e ibridi

Le mini-grids ibride dunque presentano vantaggi di tipo economico, di tipo ambientale poiché riducono l'emissione in atmosfera di gas inquinanti, incrementano la diffusione delle energie rinnovabili nei paesi in via di sviluppo e garantiscono una maggiore affidabilità nella fornitura di energia in quanto, essendo basate su generatori alimentati da fonti diversificate, nel caso di malfunzionamento o rottura di uno di questi, la produzione può continuare utilizzando gli altri componenti.

Nonostante i notevoli vantaggi appena esposti, questi impianti presentano ancora diverse problematiche che ne limitano il pieno sviluppo. Molto spesso essi vengono proposti in aree caratterizzate da instabilità politica, regolamentazione incerta e popolazione povera e con basso grado di istruzione. Questa instabilità rende difficile trovare investitori disposti a impiegare grandi risorse finanziarie in situazioni caratterizzate da un così alto grado di incertezza. Un'altra grande difficoltà riscontrata da diverse aziende del settore è quella di riuscire a formare sul luogo tecnici ed operatori che garantiscano il corretto funzionamento dell'impianto e che sappiano intervenire in modo efficace in caso di guasto. Infine, molto spesso questi progetti falliscono a causa di strategie economiche o modelli di gestione errati, per cui risulta molto importante in fase progettuale definire in modo accurato i modelli operativi e di business per garantire un investimento di successo.

Esistono principalmente due strategie di business adottate dalle grandi società per questi investimenti, "*l'extensive strategy*" e "*l'intensive strategy*".

La prima strategia (*extensive strategy*) tende a ridurre al minimo il tempo di ritorno dell'investimento, punta su componenti di taglia di ridotta che siano in grado di soddisfare gli attuali carichi elettrici della comunità in questione ma non i futuri incrementi.

La seconda (*intensive strategy),* invece, tende alla massimizzazione delle rendite a lungo termine, investe su componenti di taglia maggiore rispetto ai carichi elettrici attuali e spinge per aumentare i consumi della comunità e quindi le rendite per la vendita dell'energia.

I modelli di gestione di questi sistemi sono quattro: l'utility model, il private sector model, il community model e l'hybrid model; la scelta del modello corretto dipende dalle caratteristiche politiche, economiche e sociali della comunità in questione.

1) Nell'utility model il controllo e la gestione dell'impianto vengono affidati dal governo ad utility regionale o nazionale.
2) Nel private sector model invece la costruzione, la gestione e il controllo delle operazioni sono di competenza di una società privata.
3) Nel community model i responsabili della mini grid sono un gruppo di utenti finali della stessa.
4) L'hybrid model combina caratteristiche dei modelli precedenti tramite contratti che regolano i compiti e le responsabilità dei diversi operatori.

Come detto in precedenza questi progetti molto spesso coinvolgono comunità rurali dei paesi in via di sviluppo caratterizzate da una forte instabilità politica, legislativa ed economica. Queste instabilità possono scoraggiare i grandi investitori e per questa ragione sono state sviluppate delle procedure di analisi del rischio dirette a valutare, sotto diversi aspetti, la stabilità socio-politica di una certa area in modo tale da indirizzare meglio i vari soggetti intenzionati ad investire.

Nel terzo capitolo è proposta una procedura di analisi del rischio che viene utilizzata per diversi di questi impianti chiamata "*standardized risk management procedure for mini grid*". Questa procedura valuta cinque diversi aspetti della comunità in esame e ad ognuno di questi assegna un punteggio; la valutazione finale sarà data dalla media dei cinque punteggi. I cinque aspetti che vengono misurati sono la situazione politica e sociale, la situazione economica, la situazione tecnologica, la situazione finanziaria e la situazione educativa ed ognuno di questi aspetti contribuisce alla valutazione finale.

Una caratteristica importante riguardante le mini-grids è la valutazione del profilo di carico, poiché per potere dimensionare in modo corretto i vari componenti dell'impianto è indispensabile avere delle stime accurate della domanda di energia elettrica.

Nel caso non vi siano delle misurazioni dei consumi, possono essere utilizzate alcune strategie per fare una stima della domanda; una di queste è "*l'interview-based method*" che consiste nel presentare un questionario agli abitanti della comunità in esame in modo da fare un inventario degli apparecchi elettrici domestici, della loro potenza e del loro tempo di utilizzo. Partendo da questi dati viene costruito il profilo di carico medio di ogni abitazione e successivamente il profilo di carico delle piccole-medie imprese e dei carichi elevati. Il profilo finale della comunità verrà ottenuto dalla combinazione dei precedenti profili. Questa tecnica presenta però lo svantaggio di ottenere delle stime non troppo accurate della domanda energetica.

Un metodo più preciso è il "*data-driven proxy method*" che utilizza le misurazioni dei consumi di diverse mini-grids per predire i profili di altre comunità con caratteristiche simili.

Il terzo capitolo termina con una presentazione degli aspetti necessari ad una mini-grid per essere un investimento di successo. Questi aspetti includono l'utilizzo di componenti tecnologici e sostenibili, misure di efficientamento energetico, valutazione degli interessi della popolazione e della crescita dei consumi, sostegno del potere politico, utilizzo di tariffe progressive per includere nel progetto anche i consumatori meno abbienti e la formazione sul luogo di tecnici ed operatori specializzati.

La tesi prosegue con una descrizione della comunità in esame e della situazione energetica del Marocco. Il Marocco è lo stato del Nord Africa con le minori riserve di combustibili fossili ed importa la maggior parte di questi dai paesi vicini. Questa povertà energetica ha creato un deficit nelle finanze dello stato ed ha spinto il paese a concentrarsi su fonti di energie alternative. Il consumo di energia del paese è in continuo aumento e il settore che consuma maggiormente è quello dei trasporti. Circa l'89% della produzione totale di energia primaria deriva dall'utilizzo di fonti fossili; di queste più del 61% viene importato dall'estero, mentre le rinnovabili pesano solamente per il 9%. Questi dati sono graficamente rappresentati nella seguente figura (corrispondente alla figura 4.3 del capitolo 4)

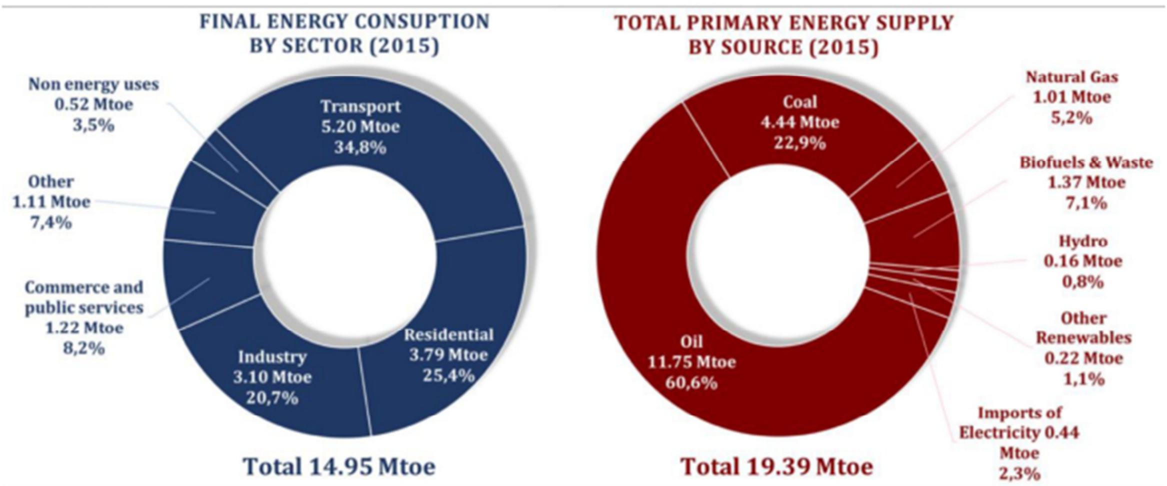


Figura 2.1: Consumo di energia finale per settore e fornitura di energia primaria per fonte in Marocco

Per fare fronte al continuo incremento dei consumi la strategia del governo si basa sulla diversificazione del mix energetico, sullo sfruttamento delle risorse rinnovabili, sull'incremento delle misure di efficienza energetica e sul rafforzamento delle infrastrutture che importano combustibili fossili dai paesi vicini. Nell'ambito di questa strategia le rinnovabili giocano un ruolo fondamentale, in particolare il governo punta molto sul solare, l'eolico e l'idroelettrico; per quanto riguarda le fonti convenzionali invece si prevede un forte aumento del consumo di gas naturale grazie al potenziamento delle condutture che trasportano il gas dall'Algeria al Marocco.

Il settore energetico in Marocco è dominato dall'utility ONEE (*Office National de l'Electricitè et de l'eau potable*) posta sotto il diretto controllo del governo. ONEE è stato per molto tempo il monopolista nella compravendita di energia elettrica, finchè alcune liberalizzazioni, caldeggiate dalla Banca Mondiale ed attuate dallo stato marocchino, hanno permesso anche a produttori minori di produrre e vendere energia elettrica sulla rete nazionale. Inoltre, negli stessi anni vi è stata una privatizzazione del settore di distribuzione dell'energia.

In questi ultimi anni il Marocco ha attuato un piano di capillare elettrificazione delle aree rurali, che ha permesso di passare da un tasso di elettrificazione nelle zone rurali del 18% (1996) ad un tasso attuale superiore al 99%. Questo piano si è basato sull'espansione della rete nazionale già esistente dove conveniente e sull'implementazione di sistemi off-grid dove l'estensione della rete nazionale era anti-economica.

Secondo le previsioni ministeriali ci sarà un forte aumento dei consumi nei prossimi anni dovuto in modo particolare all'aumento della popolazione ed all'aumento degli elettrodomestici. Per fare fronte a questo incremento e per ridurre le emissioni di gas inquinanti si fa affidamento su un forte contributo delle rinnovabili, in particolare del fotovoltaico, dell'eolico e dell'idroelettrico (il governo ha dichiarato l'obiettivo di raggiungere il 52 % della capacità installata alimentata da fonti rinnovabili entro il 2030), su un aumento del consumo di gas naturale ed è stata anche contemplata l'opzione del nucleare.

Il quarto capitolo termina con una descrizione della comunità di Toudgha El Oulia. L'economia della comunità si bassa essenzialmente sull'agricoltura (olive, datteri e cereali) e sul turismo. Il consumo elettrico per persona è particolarmente basso nella zona, molto al di sotto della media nazionale, anche se, stando alle misurazioni di ONEE, c'è stato un progressivo aumento della domanda negli ultimi anni.

Al fine di stimare la quantità di biomassa disponibile, tutti i calcoli sono stati eseguiti ridimensionando le informazioni regionali e provinciali fino al livello del comune. Più in particolare, i dati sulle produzioni agricole provinciali e regionali sono stati ridimensionati al comune confrontando la popolazione e la superficie di Toudgha El Oulia con quelle della provincia di Tinghir e della regione di Drâa Tafilalet. Dal momento che questa rappresenta una stima non ancora validata, durante la simulazione verrà eseguita un'analisi sensibile al variare della biomassa disponibile per tenere conto di possibili errori sull'effettiva disponibilità della risorsa.

Nel quinto capitolo vi è la presentazione del software "HOMER pro" utilizzato per il corretto dimensionamento dei componenti.

Questo programma riceve come input cinque tipi di dati relativi:

1) al carico elettrico
2) alla disponibilità delle risorse utilizzate
3) ai dati economici dell'impianto
4) alle caratteristiche dei componenti
5) alle strategie di utilizzazione

HOMER utilizza questi dati di input per esaminare tutte le configurazioni possibili dei sistemi in questione con la funzione obiettivo di ridurre al minimo il costo totale netto attuale (NPC). Successivamente, seleziona la soluzione più fattibile rispettando i vincoli indicati nei dati di input (capacità minima e massima, contributo delle rinnovabili, costi per la produzione di elettricità) ai costi totali più bassi.

Il programma esegue un bilancio energetico per ognuna delle 8.760 ore dell'anno solare e per ogni ora confronta la domanda elettrica nell'ora con l'energia che il sistema può fornire in quell'ora. Calcola i flussi di energia da e verso ciascun componente della mini-grid ibrida e, per i sistemi che includono le batterie, può anche decidere in quale ora caricare o scaricare il sistema di accumulo.

HOMER può essere utilizzato per svolgere tre compiti: eseguire simulazioni, eseguire analisi di sensibilità e ottimizzare il sistema simulato.

Inizialmente sono stati inseriti i dati della domanda elettrica della comunità utilizzando le misurazioni disponibili dall'*Office National de l'Electricité*. In questo modo HOMER ha calcolato il profilo di carico annuale e diverse altre informazioni utili sul carico elettrico.

Successivamente sono stati inseriti i dati relativi alla risorsa solare disponibile e alla temperatura della zona ottenibili tramite "*NASA Surface Meteorology and Solar Energy Database*" ed i dati relativi alla biomassa disponibile ottenuti precedentemente. Nella seguente figura (corrispondente alla figura 5.7 del capitolo 5) è rappresentata la radiazione solare per mese della comunità in esame.

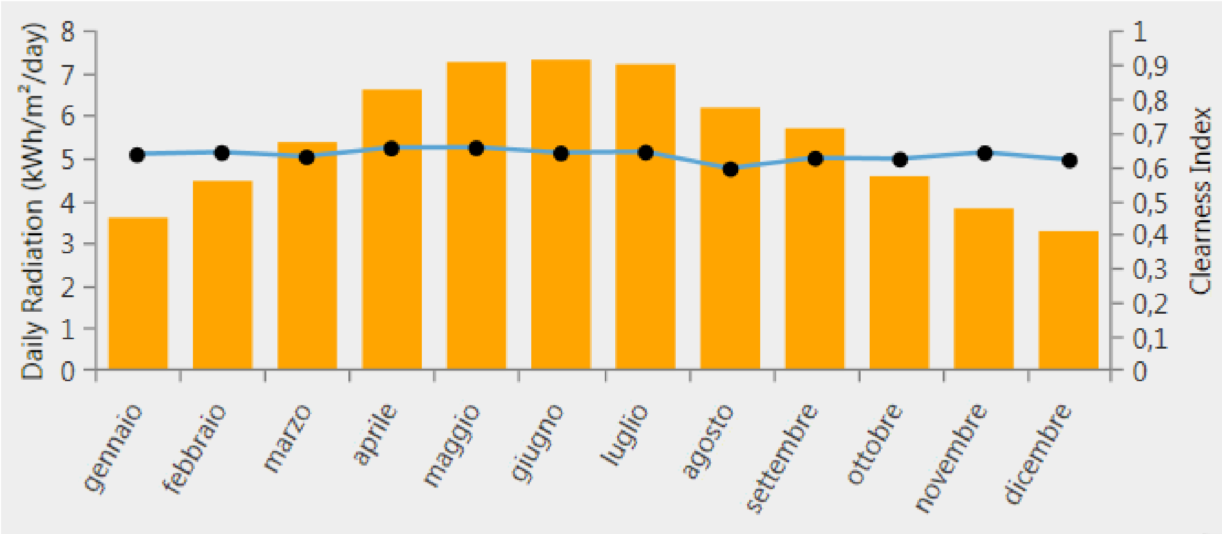


Figura 1.3: Radiazione solare per mese di Toudgha El Oulia

Dopo i dati relativi alle risorse è necessario inserire i dati economici e tecnici dei vari componenti, cioè del pannello fotovoltaico, del generatore biogas, delle batterie per l'accumulo, dell'inverter e della rete dalla quale il sistema compra o vende energia.

Nella seguente figura (corrispondente alla figura 5.10 del quinto capitolo) è rappresentata la finestra di modellazione del pannello fotovoltaico su HOMER.

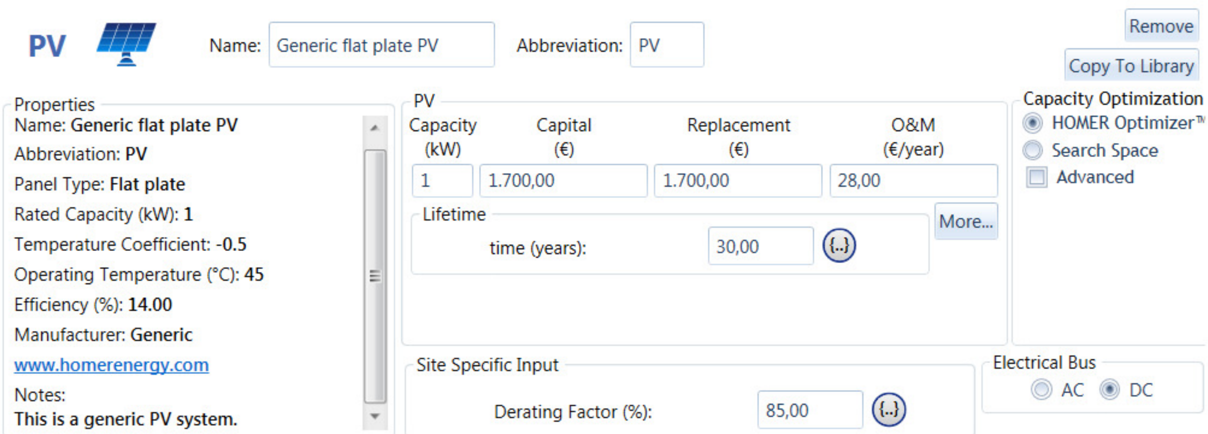


Figura 1.4: Finestra di modellazione del pannello fotovoltaico su HOMER

Come si può notare dalla rappresentazione grafica vengono inseriti parametri relativi a 1 kW di potenza del componente; sarà il programma, in seguito alla simulazione, a individuare la giusta taglia del componente che minimizza il costo totale netto (NPC) del sistema. Lo stesso procedimento è stato eseguito anche per tutti gli altri componenti dell'impianto.

Per quanto riguarda il componente della rete è necessario inserire i prezzi a cui viene venduta e comprata l'energia. Il prezzo di acquisto è stato confrontato con diverse fonti e può essere fissato in modo adeguato, mentre il prezzo di vendita dell'energia prodotta in esubero non può essere conosciuto in modo esatto in quanto la legislazione non è ancora chiara su questi aspetti. Perciò il prezzo di vendita è stato inizialmente ipotizzato ad un valore inferiore al prezzo di acquisto e, successivamente, è stata svolta un'analisi sensibile che tiene conto di possibili variazioni del valore.

Il quinto capitolo termina con l'inserimento dei dati relativi ai vincoli, al tasso di inflazione, alla vita dell'impianto ed altri parametri utili per poter effettuare l'analisi economica.

A questo punto vengono svolte le simulazioni per diversi tipi di impianto. HOMER calcola il costo totale netto (NPC) rappresentato dal valore attuale di tutti i costi sostenuti dall'impianto durante la sua vita, meno il valore attuale di tutti i ricavi (compresi i risparmi e le entrate della rete) ottenuti nel corso della sua durata. Il software simula tutte le possibili configurazioni di sistema che soddisfano la domanda elettrica della comunità in base alle risorse energetiche disponibili, scarta le soluzioni irrealizzabili, classifica quelle realizzabili in base al costo totale netto attuale (NPC) e presenta la soluzione migliore con il minore NPC. Oltre al NPC, HOMER calcola diverse altre informazioni utili come LCOE ("levelized cost of energy"), l'utilizzo delle rinnovabili e le caratteristiche di funzionamento di ogni componente.

Inizialmente è stato simulato un sistema che include solamente l'utilizzo della biomassa coma risorsa. La biomassa, trasformata in biogas all'interno di un digestore anaerobico, è utilizzata come combustibile per un generatore. I risultati della simulazione mostrano che con un sistema di questo tipo la taglia del generatore ottimale è di 50 kW ed è in grado di coprire solamente il 15,1 % dei consumi mentre la restante parte è coperta dalla rete. La seguente figura (corrispondente alla figura 6.1 del capitolo 6) mostra i risultati della simulazione.

Architecture					Cost				System	
		Bio (kW)	Grid (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€/yr)	Initial capital (€)	Ren Frac (%)	Total Fuel (L/yr)
		50,0	999.999	LF	€ 0,130	€ 4,32M	€ 267.859	€ 125.000	15,1	266
		50,0	999.999	CC	€ 0,130	€ 4,32M	€ 267.859	€ 125.000	15,1	266
		100	999.999	LF	€ 0,140	€ 4,63M	€ 285.952	€ 150.000	13,5	266
		100	999.999	CC	€ 0,140	€ 4,63M	€ 285.952	€ 150.000	13,5	266
		200	999.999	LF	€ 0,140	€ 4,64M	€ 283.264	€ 200.000	13,5	266

Figura 1.5: Risultati relativi all'impianto con generatore biogas

Successivamente è stato considerato un diverso impianto per sfruttare la biomassa disponibile. In questo sistema la biomassa viene trasformata in syngas all'interno di un gassificatore tramite un processo termo-chimico. Il syngas prodotto alimenta un generatore che produce energia elettrica per la comunità, anche in questo la rete elettrica interviene per coprire la parte della domanda non soddisfatta dal generatore. Lo scopo di questa seconda simulazione è capire quale impianto risulti più conveniente per lo sfruttamento della risorsa.

La seguente figura (corrispondente alla figura 6.4 del capitolo 6) e rappresenta i risultati delle simulazioni per l'impianto syngas.

Architecture					Cost				System	
		Syngas (kW)	Grid (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€/yr)	Initial capital (€)	Ren Frac (%)	Total Fuel (L/yr)
		50,0	999.999	LF	€ 0,133	€ 4,40M	€ 269.615	€ 175.000	14,5	266
		50,0	999.999	CC	€ 0,133	€ 4,40M	€ 269.615	€ 175.000	14,5	266
		10,0	999.999	LF	€ 0,139	€ 4,62M	€ 284.513	€ 155.000	4,14	74,5
		10,0	999.999	CC	€ 0,139	€ 4,62M	€ 284.513	€ 155.000	4,14	74,5
		100	999.999	LF	€ 0,142	€ 4,69M	€ 286.605	€ 200.000	13,3	266

Figura 1.6: Risultati relativi all'impianto con generatore syngas

In entrambi gli impianti la soluzione migliore include un generatore con potenza 50 kW, ma il sistema alimentato a biogas ha un minore NPC e LCOE rispetto alla soluzione che sfrutta il syngas. Inoltre, con l'impianto biogas si ha un maggiore utilizzo delle rinnovabili per cui si è scelto di utilizzare questo sistema per ottimizzare lo sfruttamento della biomassa.

A questo punto si sono aggiunti al sistema anche pannelli fotovoltaici, sistemi di accumulo ed un converter per poter sfruttare la risorsa solare ampiamente disponibile nella comunità. Lo scopo di quest'altra simulazione è quello di valutare se, aggiungendo questi nuovi componenti all'impianto, si hanno risultati migliori rispetto all'utilizzo della sola biomassa. I risultati di questa nuova simulazione sono proposti nella seguente immagine (corrispondente alla figura 6.5 del capitolo 6).

PV (kW)	Bio (kW)	1kWh LI	Grid (kW)	Converter (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€/yr)	Initial capital (€)	Ren Frac (%)
423	50,0		999.999	283	LF	€ 0,114	€ 3,94M	€ 194.996	€ 886.323	42,2
423	50,0		999.999	283	CC	€ 0,114	€ 3,94M	€ 194.996	€ 886.323	42,2
419	50,0		999.999	281	LF	€ 0,114	€ 3,94M	€ 195.415	€ 879.813	42,0
419	50,0		999.999	281	CC	€ 0,114	€ 3,94M	€ 195.415	€ 879.813	42,0
433	50,0		999.999	290	LF	€ 0,113	€ 3,94M	€ 193.797	€ 905.214	42,7

Figura 1.7: Risultati relativi all'impianto solare e biogas

Come si può vedere dalla figura 1.7, l'introduzione di questi nuovi componenti comporta un prezzo iniziale maggiore ma permette di avere un costo totale netto molto minore rispetto agli impianti precedenti. Questo vantaggio è dovuto al fatto che, grazie all'utilizzo della risorsa solare, si riesce a coprire circa il 30 % della domanda riducendo di molto l'energia acquistata dalla rete; quest'ultima infatti è la componente che pesa maggiormente sui bilanci dei precedenti impianti. In questo sistema la taglia del generatore biogas rimane la stessa anche se il motore viene fatto lavorare a carichi minori.

Nell'ultima simulazione viene effettuata un'analisi sensitiva del sistema per tenere conto della possibile variazione di alcuni parametri che sono stati stimati in precedenza come il prezzo a cui si vende l'energia elettrica prodotta alla rete e la biomassa disponibile nella località.

I risultati mostrano che leggeri incrementi sul prezzo di vendita dell'energia alla rete comportano un aumento della dimensione dell'impianto fotovoltaico che permette di avere un maggiore sfruttamento delle rinnovabili e ridurre il costo totale netto. Gli stessi benefici sono riscontrabili con l'aumento della biomassa disponibile, la dimensione del generatore rimane la stessa ma riesce a lavorare con capacity factor più elevati. Per questa ragione risulta molto importante il sostegno del governo che favorisca, tramite incentivi, questi sistemi che sfruttano risorse rinnovabili.

L'utilizzo del software HOMER pro ha permesso di valutare diversi tipi di impianti che sfruttino le risorse disponibili sul territorio e di trovare quello al minore costo totale netto e col maggior sfruttamento di rinnovabili. Questo tipo di procedimento può essere utilizzato per ottimizzare il dimensionamento delle mini reti ovunque nel mondo, garantendo l'accesso all'energia elettrica ad un numero sempre maggiore di persone. Inoltre, lo sviluppo di tecnologie rinnovabili può portare ad ottenere componenti sempre più efficienti e meno costosi favorendo notevolmente il diffondersi delle mini-grids.

2. Introduction

The purpose of this thesis is to size a hybrid system powered by solar and biomass resources in order to produce electricity for a selected rural community.

Systems that provide electricity in rural zones with a small number of customers are called mini-grids and their role is becoming very important to supply energy in areas far from the grid or with weak infrastructures. Hybrid mini-grids are a promising solution to solve the problem of energy poverty but remain a very young sector with many technical and economic challenges. The design of mini-grids involves several project parameters such as mix of renewables, component sizing and network design; the correct sizing of the components of a mini-grid is a priority in order to reach the financial viability of the project.

The tool used in this thesis for the sizing of the mini-grid is the software HOMER Pro; this software is a powerful tool for the optimal designing, sizing and planning of hybrid renewable energy systems because is able to perform the techno-economic analysis for connected or non-connected mini-grids through optimization algorythims.

The thesis is divided into several chapters in which are presented the main aspects related to the mini-grid in question.

In chapter 3 a general description about mini-grids is proposed; this section describes the main types of mini-grids with the related problems and advantages and, as the financial viability is a top priority for the investors, presents the business development strategies and the operation models used for the management of these systems. Another important point described in this chapter is the evaluation of the load profile in rural mini-grids and the main methods used to estimate it. The chapter ends with a presentation of several characteristics that a mini-grid must feature to be a successful investment.

In chapter 4 there is the presentation of the selected community, Toudgha El Oulia, a rural community located in the central-eastern side of Morocco at the frontier with Algeria. In this chapter there is the description of the current and the future trends of the energy system in Morocco with an outlook on the power sector of the country. After that, it is shown the energy national strategy and the future projections of the energy system. In the last part of this chapter the selected community is described with particular attention to the social aspects, economic activities, energetic consumption and the available biomass for energetic purposes.

In chapter 5 the software HOMER pro used in the project is described. In order to perform a correct simulation on HOMER, we have to find several data regarding the load profile, the available resources, the economic aspects and the techno-economic characteristics of the main components (solar modules, biogas generator, storage system, converter). In this chapter is presented the way in which the software works, the methods and the equations it uses to size the system and how to find the input data for the operations.

In chapter 6 are shown the results of the simulation; in this section is described how the system ranks the different results and is proposed the best configuration with optimal techno-economical features for the community in exam. For each configuration is shown the size of the components, the net present cost, the levelized cost of energy, the share in use of renewables and many other useful aspects. This section ends with a sensitivity analysis performed to take into account possible variations on the available biomass and on the price the system sells electricity to the grid.

The thesis ends with the conclusions in which are summarized the results obtained and are proposed the future developments of such system.

3. Mini-grids

Today, while in the most advanced countries access to electricity is practically guaranteed to everyone, in the developing countries about 2.2 billion people haven't a stable supply of energy and among them more than one billion lacks any service [1]. This problem is called power poverty and occurs usually in developing countries, in rural areas or where it is not convenient the expansion of the grid.

	Population without electricity	Electrification rate	Urban electrification rate	Rural electrification rate
	million	%	%	%
Africa	589	40	66.8	22.7
- North Africa	*2*	*98.9*	*99.6*	*98.2*
-Sub-Saharan Africa	*587*	*28.5*	*57.5*	*11.9*
Developing Asia	809	77.2	93.5	67.2
- China and East Asia	*195*	*90.2*	*96.2*	*85.5*
- South Asia	*614*	*60.2*	*88.4*	*48.4*
Latin America	34	92.7	98.7	70.2
Middle East	21	89.1	98.5	70.6
Developing countries	**1453**	**72**	**90**	**58.4**
OECD and Transition economies	**3**	**99.8**	**100.0**	**99.5**
World	**1456**	**78.2**	**93.4**	**63.2**

Figure 3.1: Access to electricity in the world [2]

The access to energy could be very useful in fighting the poverty of the rural areas in developing countries and several studies have shown the positive impacts on the population driven by the growth of energy consumption [3]. The access to electricity can promote the economic growth, the education and the health situation of these populations. Electricity can make more efficient various activities (milling, carpentry…) in these rural areas and can lead to the creation of new business (internet cafés, electrical equipment shops, battery charging stations …) essential for economic development [4].

Mini-grids are considered an excellent solution to supply energy in these areas until the growth of consumption makes the expansion of the national grid more convenient. A mini-grid, also sometimes called *"micro-grid or isolated grid"*, can be defined as a series of electric generators and storage systems connected to a distribution line in order to supply energy to a certain group of consumers isolated from the national grid. Mini-grids can be powered by several types of energy resources and power plants. However, usually mini-grids use low AC voltage (220-380V), a centralized production, a storage system and have an installed capacity between 5 and 300 kW even if are present systems with different features [5].

Several companies are especially promoting hybrid solutions that include renewable sources and energy storage with the aim to reduce local pollution and to reduce the project costs. The renewable sources are already competitive with fossil fuel technologies in many countries. Mini-grids are characterized by high business and technical risks in the investments, however the huge potential market of USD 200 billion/year is making interested in these systems non-governmental organizations, research institutions, public investors and private companies [1] .

At present there are 1681 mini-grid projects in the world with a potential capacity of 16.5 GW. There is an increase of these systems of 17% on 2015 and more than three times on 2013, led in particular by a strong dynamic of solar projects [6]. A lot of those are based in North America, while China is becoming the global leader in the development of mini-grids by installing 4 GW of additional capacity between 2016-2020 [6]. Other countries where there is a big number of these systems are Bangladesh, India, Cambodia, Philippines, Morocco and Mali [7].

As said before, mini-grids can be connected to larger grids when the energy demand make it profitable and in this case they can sell electricity to the major grid. Before making the connection between the grids it must be taken into account that this can cause the rapid increase of intermittent power with consequent system fluctuations. To avoid this problem it is necessary to invest in balancing technologies during the design step [8].

These systems are often located in remote areas with difficult terrains and impoverished customers; for this reason their sustainability is difficult to guarantee. The main problems are limited local technical and managerial skills, low energy demand, poor availability of components and unproven financing models. Mini-grids have to provide affordable energy for the rural population in their service area with an acceptable level of reliability and financial viability, in particular the financial viability is the most considered parameter by the proponents of the project.

For a successful project it is necessary taking into account several critical project parameters such as mix of renewables, component sizing and network design. These parameters have a large impact on the financial model and determine the net present cost and the levelized cost of energy; these two values must be minimized to make the mini-grid profitable. In this context planning tools are really useful to find the most suitable system for the area in question; a common software used for the design of mini-grids is HOMER pro [9].

3.1 Types of mini-grids

Mini-grids can be classified in different ways:

1) Grid-connected or off-grid (they can be connected to the main grid and exchange energy with it or be disconnected)
2) Depending on power (nano-grids whose power is less than 5 kW, mini-grids whose power is between 5-100 kW and large mini-grids whose power is larger than 100 kW [6]).
3) Based on the sources (clean mini-grids are fed only by renewable sources, hybrid mini-grids are fed by renewable and non-renewable sources and diesel mini-grids that are fed by diesel generators).

Clean and hybrid mini-grids are already competitive with diesel systems in many contexts thanks to lower operating costs. "*Nowadays, for most sites in Africa, renewable energy and hybrid solutions have a lower Levelized Cost of Energy (LCOE) than diesel generators*" [6].

Another big advantage of clean and hybrid systems is that they can exploit the availability of local resources, while for the correct functioning of diesel generators it is necessary to deliver large amount of fuel in remote areas, with consequent economic and logistical issues. In the following figure is represented a comparison between diesel and hybrid mini-grids in different countries made by USAID [6].

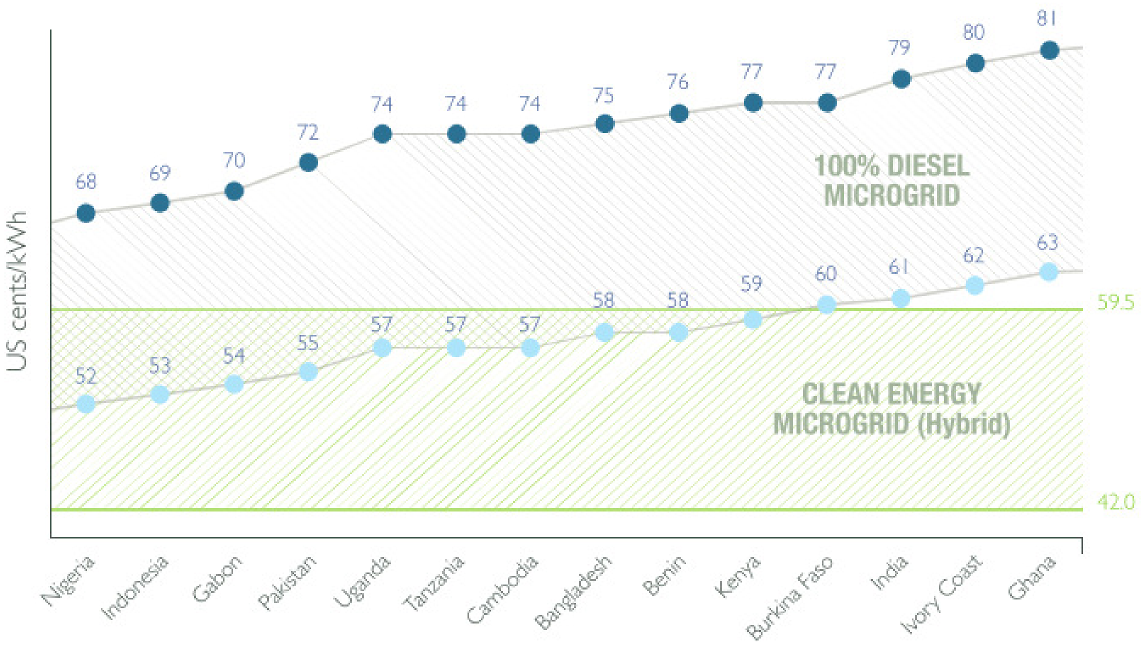


Figure 3.2: Comparison of LCOE between diesel and hybrid mini-grids [6]

Today in many areas there are still systems powered by diesel generators that continue to use expensive and polluting fossil fuels; this happens because in the past electricity in remote rural areas or in island communities was provided almost exclusively by these systems [7]. "*Diesel system accounts for the second largest share of the installed off-grid generation capacity*" [7]. The main advantage of diesel powered mini-grids is the possibility of producing energy at any time if the fuel is available.

A report by the Alliance for Rural Electrification shows that converting the mini-grid based on diesel generator to hybrid system is a good solution from an economic point of view in order to provide electricity in rural communities [7]. Another study conducted by the Frankfurt School of Business, based on an analysis of several case studies, showed that hybridisation could reduce the average cost of generation by assuming market-based financing rates [7]. The total installed capacity of these systems powered by diesel that can be converted into hybrid mini-grids is in the range between 50 GW and 250 GW. At present there are 100 GW of diesel gen-sets in operation worldwide that are smaller than 0.5 MW [7].

The installed capacity of clean and hybrid mini-grids depends on the technology and on the maturity of the components. Mini hydroelectric systems (1-10 MW) have an installed capacity of about 75 GW worldwide [7]. Other systems such as wind, solar and biomass technologies have a lower installed capacity than diesel and mini-hydro. Thanks to the continuous technological improvement in recent years, the hope is that the percentage of mini-grids powered by renewables increases more and more.

Hybrid and clean energy mini-grids are a promising solution but remain a young sector with limited experience. Many companies started to invest in these systems since 2010 but, because of the time required to identify sites, recruit clients and install connections, there are few players with adequate experience [6].

"Husk", which is one of the biggest company in the sector, has tested different solutions in the past. It controls different types of these systems such as 100% biomass micro-grids, hybrid solar-biomass micro-grids and solar nano-grids; now it focuses the attention on the hybrid systems which considers the option with the highest commercial viability [6].

3.2 Challenges and opportunities

Mini-grids have to face different challenges in order to succeed in the market; in particular there are three important challenges to overcome . The following information are based on [6].

The first challenge is that business environments are often unstable and submitted to ambiguous regulation. Micro-grid companies have to do long term investments in areas with uncertain characteristics and with a declared payback usually between 5 and 10 years. They have to face four types of uncertainties:

1) Grid extension or reinforcement: in many contexts it is not possible to predict the arrival of the grid and until feed-in tariffs are not regulated, the arrival of the grid can cause at best reduced consumptions, at worst a loss of subscribers.
2) Regulation instability: even if the governments of developing countries are trying to lighten regulation, very often the laws are unclear and this fact can lead investors not to risk large amounts of capital.
3) Technology: there are two types of risks that involve technology, the underestimation of failure and maintenance that increase the costs of the system and the emergence of cheaper technology (prices of panels and batteries are decreasing fast) which within few years, may threaten the tariffs of the operating mini-grids because of the competition with more efficient system, such as SHS (solar home system), at low cost.
4) Customers: at the beginning for most operators the revenues per customers could be too low and they hope that consumption will increase over time thanks to greater trust in the project.

The second challenge is the ownership and management of the network.

Regarding ownership, there are different types of operation models such as utility model, private company model, community model and hybrid model that are used around the world and that will be explained in detail in the following chapter. Usually it is not easy to find the correct model for each situation and the experience from other sectors, such as village-level water treatment plants, shows that the choice of the correct model depends on several variables such as the environment, the geography, the socio-economic context and the political environment [7].

Regarding the management, companies usually use scalable hardware and software to control and monitor the entire system. In order to guarantee the correct functioning of the project it is especially important the recruitment, training and management of skilled taff. As said before the shortage of skilled staff represents one of the biggest problems for the development of mini-grids in rural areas.

The third challenge to overcome is to ensure the financing. "*Because of the relatively small size of all actors in rural areas, the debt financing (local or international) is out of reach and investors are moving cautiously at this early stage*" [6]. In the near term it could be very useful to borrow from local banks with concessional lending. A big issue today is that many investors consider the risk-return ratio insufficient; this because it is a long-term investment (>6 years) with multiple risks (political changes, technology risks, etc.).

On the other hand, there are a lot of opportunities that have been observed with hybrid mini-grids . These information are based on [5].

1) They can be used to guarantee the reliability of energy supply. Thanks to the low dimension of such system it is possible to reduce the problem of power theft that is usually associated to bigger grids.
2) Hybrid mini-grids usually involve different components that produce energy and for this reason the supply of electricity is more guaranteed compared to systems with a

single technology; they ensure availability of power when a component is broken and can lower the net present cost of the project thanks to reduced operating costs.

3) The use of renewable energy sources limits the emission of climate- altering gases in the atmosphere and can improve the efficiency of the system.
4) Evaluations indicate that the renewable technologies (biogas, geothermal, photovoltaic, wind and micro-hydro systems) are the more economical solutions for mini-grids in developing countries, assuming that sufficient renewable energy resources are available [5]. In particular, technologies based on biomass as renewable source, such as biogas digesters and biomass gasifiers, are a promising solution from an economic point of view, thanks to their high capacity factor and availability in size range matched to mini-grid load [5].
5) For countries where the grid system is not well developed and characterized by a strong private sector, mini-grids can initially be used to supply energy in non-electrified areas and then be connected to the main network when it expands.

3.3 Business development strategies and operation models

Observing the strategies of real companies it is possible to define two different business development approaches for mini-grids. The following information are based on [6].

- The extensive strategy
- The intensive strategy

The aim of the extensive strategy is to minimize the payback time. It reduces the generation capacity per site in order to minimize the risk of unproductive assets with the disadvantage that it will only be able to serve current village uses.

The aim of the intensive strategy is to maximize long-term revenues. It invests in larger generation capacity in order to promote electricity consumption and support customers in "*moving up the energy ladder*" [6]; it means that the purpose of this strategy is to ensure that the community increases energy consumption over time in order to increase the revenues by selling electricity.

The following table summarizes the main features of the two business models.

Table 3.1: Intensive vs extensive model for mini-grids [6]

Model	Intensive	Extensive
Strategy	Revenue maximisation	Payback time minimisation
Demand sizing	Focused on potential use based on activity and comparables	Focused on current use and ability to pay
Risk	Stranded assets	Customers satisfaction
Source of performance	Sales volume	Diversification and number of sites
Impact	Improved business productivity	Access to electricity

In environments characterized by high risks and uncertainties a good strategy could be the extensive and short term option even if this model has the disadvantage that deprives communities of opportunities to increase the energy consumption. Fortunately there are many entities who invest in the intensive strategy, with advantages for both consumers and operators. Customers can "*move up the ladder*" by progressively increasing their consumptions [6].

There are four main mini-grid operation models used around the world.

The following information are based on [7]. These operational models are different from a point of view of organisation and deployment. There isn't a method better than another and the success or failure of mini-grids operation models depends on the specific context and on many different variables such as the political situation, the geography, the socio-economic situation and the regulatory environment. Mini-grids can do the job of two different entities, they can be a small power producer (SPP) and a small power distributor (SPD); usually an operator fulfils both roles because they generate electricity and then sell it to customers.

The four main mini-grid operation models are:

1) Utility model
2) Private sector model
3) Community model
4) Hybrid model

In the **utility operation model,** the national or regional electricity utility owns and operates the mini-grid. The utility must perform various tasks such as the installation, the repair, the maintenance, the operation management and the tariff collection of the system. The government could require the utility to use similar tariffs in the community of those paid by customers connected to the national grid and the money earns from the larger consumers of the main grid could be used as cross-subsidise for the end-user of the mini-grid. The financing could be provided initially by the utility and subsequently could be received subsidies from the government or from external donors.

In the **private-sector operation model,** the private sector is responsible for building, managing, and operating the mini-grid. The potential sponsors could obtain funding from several actors such as equity, commercial loans, public sector (governments), donors through grants, subsidies or loan guarantees. Nowadays the number of mini-grids in which the financing is provided entirely by private companies is very limited and the installed capacity of these systems by the private sector is lower than the capacity installed by national utilities. In order to increase the private sector operated model, it is necessary the improvement in the field of technology and innovations and greater support from the government and donors.

In the **community operation model** the mini-grid is operated and managed by a group of customers of the local community. The customers can be organised in a company that respects the government regulations and different studies have shown that the participation of end-users in the project could have positive impacts. In this type of model the financing is primarily grant based while the community contributes at the project providing land or with the work of the customers. "*In some circumstances community-managed and -operated mini-grids may be able to provide cheaper electricity to rural communities*" [7].

As said before one of the main issues is the lack of technical experience in these rural communities; for this reason the tasks of planning, design and implementation of the system are entrusted to specialized technicians. In order to guarantee the sustainability of the community model, it is important that tariffs could cover the main cost of the project such as the maintenance and operation costs. At this point it becomes important to train specialized technicians in the area who can intervene in case of malfunctions.

The **hybrid model** combines different aspects of the three previous models. In this type of model are involved different actors for investments, management and operation of the mini-grid. The responsibilities of the different actors can be granted through joint ventures or other contractual arrangements. For example the generation and distribution of electricity can be divided between utility controlled by the government, the private companies or local communities in the form of small power producers (SPPs) and small power distributors (SPDs) [7].The regulatory framework must be very clear to guarantee the correct functioning of this model. There are several examples of contractual arrangements that are a part of hybrid models:

1) Public-private partnerships: In this arrangements the government could build, operate and manage the mini-grid while the private company has the task of maintaining the system.
2) Renewable energy service companies: Assets are owned by the government and the service company is responsible for operation, maintenance and for tariff collection.
3) Concessions: The concessionaires who provide electricity in the rural areas can be advantaged with beneficial terms such as geographic monopolies or preferential tariffs.
4) Power purchase agreements: In this contract the distribution and generation are owned and controlled by different entities that sign a power purchase agreement for providing electricity.

The main advantages and disadvantages of these models are summarized in the following table.

Table 3.2 : advantages and disadvantages of the operation models [5]

Models	Advantages	Disadvantages
Utility model	Greatest experience of the utility in generation, distribution and administrative process.	They are influenced by the market so they could not prioritize decentralized systems in rural areas.
	Better legal system	Corruption and inefficiencies in some cases
	Major access to spare parts and maintenance.	Depend on political agenda .
Private model	Great efficiency	lack of support for covering financial cost
	Better operation and management services.	Difficulty in finding companies with a lot of experience in the field
	Companies have an incentive to promote financial sustainability of the mini-grids when they are driven by market dynamics rather than government subsidies	
	Not influenced by political interferences .	
Community model	Sense of ownership in the community that improve interest in the project	Lack of technical experience for the management and operation of the mini-grid
	The system is most likely to fit in with the community's requirement	The governance of the mini-grids need to be clear and well managed.
	This model empowers the local people	Social interests conflicts
	Reduction of bureaucracy	
Hybrid model	Combine the positive aspects of the previous model.	The difference in management for each entity can increase the transaction costs for the scheme.
		Strong framework is required to balance the interest of each involved parties and establish the interface between them.

3.4 Risk management procedure for mini-grids

Mini-grids have to face different challenges and often the projects fail because of poor suitability to user needs, instability conditions and different other risks. One of the main reasons that could cause the failure of the project is an inadequate business model [10]. The correct functioning of mini-grids involves complex financial and organizational features in the fields of sales, technology and finance. A successful project is able to satisfy the demand of the consumers with high quality and availability, the technology involved must be economic and easy to maintain and the funding are provided by the private and by the public sector [10].

The major stakeholders of a mini-grid are typically:

1) Customers and small or medium sized enterprises (SME)
2) Suppliers for the technological equipment including operation & maintenance as well as communities for capacity building, training and education
3) Public and private investors responsible for funding

"*Without an assessment of the different risks influencing the economic performance of a mini-grid, the uncertainty given by the complex structure of a mini-grid could discourage investments in decentralized electrification*" [10]. The risk evaluation procedure has the aim to analyze the community in question and establish its strengths and weaknesses in order to make investors as informed as possible [11].

In the following pages it will be described a methodology often used to evaluate a rating measuring the risk of a mini-grid. The following information are based on [10]. This methodology is called standardized risk management procedure (SRMP) for mini-grid and it is based on five criteria:

1) Regulatory framework
2) Economic environment
3) Technology equipment
4) Finance situation
5) Education measurements

During the evaluation it is assigned a score to each criterion depending on the features of the community, the final score will be obtained by combining the single scores.

The scores are given on a scale from 1 until 6.

Table 3.3: Score categories [10]

Valutation	score
very low risk	1
low risk	2
Intermediate risk	3
Moderately high risk	4
High risk	5
Very high risk	6

The regulatory framework score is combined with the economic score to generate the "*framework and economic effectiveness profile*", while the remaining three scores (technology, finance and education scores) account for 33% of the overall "*flexibility and performance profile*". The scores of the two intermediate profiles are then combined in a final score that represents the mini-grid final rating.

The final rating results from an equal 50% each weighting of the "*framework and economic effectiveness profile*" and the "*flexibility and performance profile*" and the classification goes from AAA to D. This type of classification (from AAA to D) corresponds to the commonly applied credit ratings used in capital markets and released by the international rating agencies (Standard & Poor's and Moody's and Fitch typically reported the rating levels in this way). The purpose of this classification is to present an evaluation model which large investors are accustomed to; this because the intentions of the SRMP mini-grid rating is to encourage private companies in investing in such projects.

3.4.1 Regulatory framework score

The purpose of this score is to evaluate how favorable the local authorities are to the electrification project. This score is influenced by several criteria allocated in the primary factor and secondary factor. In the primary factor are evaluated the effectiveness, the stability and the predictability of the political situation, with particular attention to the population and to the local mayor. Another aspect that can influence the primary factor is the crime rates of the community which can have a negative potential on the electrification process.

The aspects involved in the secondary factor are the level of transparency, the accountability, the process reliability, the conflict of interests and the respect of the rules of the other involved institutions. The final criterion that influences the secondary factor are the sustained issues between entities on state level and local level. The primary and secondary criteria generate the regulatory framework score.

3.4.2 Economic score

The economic score is evaluated on the basis of the purchasing power of the population (retail score) and on the basis of the diversity of economic activities (commercial score). Both scores contribute to the final economic score.

The parameter to measure the retail score is the village income level per capita. It represents the average monthly income per person of the village and this value is compared to the corresponding average income level of a reference group which is typically given by the region.

The commercial score measures the differentiation of economic activities in a community; this parameter is important because if a sector goes into crisis, the economy of the community can rely on other more stable sectors. For this reason the concentration in one sector is seen as negative; rural community,based exclusively on agriculture, have low values of commercial score.

Another important factor affecting the commercial score is the share of commercial customers revenues compared to total revenues of the mini-grid, it is used to measure the commercial strength of the community and a higher share contributes to lower risk for the mini-grid. Both ratios contribute to the commercial profile and are combined to produce an overall commercial score.

3.4.3 Technology score

The technology score is based on the maintenance costs and the share of renewable energy in order to evaluate the reliability and the resource efficiency of the system; these two factors are selected to measure how much attention is paid to provide a reliable technology and to measure the resource efficiency of a mini-grid. The maintenance costs are calculated in relation to the investment and the share of renewable energy is calculated as the fraction between the yearly energy produced by renewables and the total yearly energy produced. In this score we must take into account that any additional technology, in particular based on renewables, can lead to inefficient supply structures and additional sources of technical failures.

3.4.4 Finance score

The finance score is measured in a similar way of the technology score. In this evaluation it is given an initial score to the financial situation of the community that can be subsequently improved or worsened. The initial score calculate the average of the share of debt and the cost of debt during the previous three years. "*In this way the financial flexibility and independence is measured by the amount of the net debt as percentage of the total capital and the interest expenditures as a percentage of the revenues*" [10].

As said before the initial score can be changed by a positive or a negative adjustment. For example if a grant is provided to finance the project, the initial score could be improved, this because usually a grant can reduce the financial pressure over long period of time. Another important factor is the participation of private investors, whose support is essential for the financial viability of the project and to avoid to undervalue profitability targets. If private investors don't participate at the program a negative adjustment is assigned.

3.4.5 Education score

This criterion has the aim to evaluate the ability of the community in training experts for system control and management in order to ensure continued economic performance and to keep technical failures in check. In this score aren't present positive or negative adjustments as for the finance score. An important factor that contributes to this evaluation is the capability to actively drive and affect the technological quality through a planned educational policy. "*The quality of the educational efforts is assessed by the number of education measures and the cost of education activities in relation to the total costs averaged over the previous three years*" [10]. Both these values are combined to generate a final education score.

3.4.6 Total SRMP mini-grid rating

As said at the beginning of chapter 2.4 the five different scores of the mini-grid rating which have been divided into two profile categories (the "Regulatory framework effectiveness and economic profile" and the "flexibility and performance profile") will be summarized and combined to produce a final mini-grid rating.

In the following table is reported an example of mini-grid rating in India.

Table 3.4: example of final mini-grid rating [10]

Factor	Score	Profile	Score
Regulatory framework	4	Regulatory framework effectiveness and economic profile	3,25
Economic	2,5		
Technology	5	Flexibility and performance profile	3,7
Finance	3		
Education	3		
Total rating			bbb+

A mini-grid rating is a way to address and help all the entities that intend to invest in a certain mini-grid. Because of the complexity of all the risks involved, no mini-grid rating should be taken as infallible or should be considered as a perfect method to estimate the validity of a certain community. Therefore the proposed mini-grid rating should be considered as a method to clarify the economic, political and financial situation of a certain area to help investors in making decisions [10].

3.5 Load profile in rural mini-grid

"*One of the major challenges relating to the dissemination of mini-grids is their poor economic performance, leading to an inability to cover operating and expansion costs*" [4]. The capacity factor is a very important parameter in order to reach the financial viability of the project. This parameter is defined as the ratio between the actual generation of electricity and the maximum electricity generation, in order to use a mini-grid in a efficient way, the capacity factor should be maximized [4].

To obtain this result the components that produce electricity must be sized with regard to the current load and future developments of the demand; for this reason it is necessary using accurate methods to estimate both short-term variations (such as daily load profiles) and long-term developments. Once the load profile is known, the component can be sized in order to maximize as possible the capacity factor.

If the estimates are higher than the real consumption, the system is oversized with excessive costs and reaching the financial viability of the project becomes a difficult target. In the best situation initially there will be a low usage of the system and, as consumption increases, it can be used more efficiently and increases revenues for the owners [4].

On the other hand if the consumption is under-estimated, the reliability and availability of the system decrease and it can cause many technical problems such as the reduction in battery lifespan and many problems to the community. Lack of energy in a hospital for example can cause loss of life and this can decrease the community's confidence in the project; as consequences some customers could procure diesel generator in order to produce energy for their needs and decrease the usage of the system [4].

There are different methods to estimate load profiles; in the best situations measured data of electric consumption are available and can be used to build the electric profile of the rural community. A common method to generate load profiles when measurements are unavailable is the interview-based method. The following information is based on [4].

3.5.1 The interview-based method

This method is based on a questionnaire provided to the inhabitants of the community to take an inventory of all the electrical equipment with the relative powers and time of usage; an estimate of future devices is usually also made to take into account the growth in consumption. Using these data and multiplying the powers of the devices for the respective times of usage, it is possible to predict an average daily energy requirement for the entire mini-grid. If the data collected on the time of usage of the equipment are accurate, it is possible to construct a profile on a hourly basis, useful for the use of HOMER Pro. This method can provide information on the energy consumption of a community in a simple way but often presents not too accurate results.

A typical interview starts with predefined questions on household size, economy and electricity usage. The question about the electricity usage regards the number and the type of the electrical equipment, the usage time and on which days these appliances are used. For example it could be asked if the house has a TV, what is the size of the TV and during which hours it is used. Subsequently, open-ended questions are formulated to verify the correctness of the previous answers; for example it could be asked which TV programs they usually watch and compare the answer to the previous one. Sometimes some customers do not know the time of usage of a certain appliance; in this case one can use the average time of usage of this appliance taken from other interviewed. When the power of a certain appliance is not specified, more information are collected about the object (for example the size) and the power is estimated on the basis of similar equipment.

Regarding the small and medium enterprises (SME), additional information are collected such as the daily duration of operation and the working hours.

An example of interview collected data is shown in the following picture.

Appliance type	Mean number of appliances per customer	Average rated power (W) (that was verified by inspection)	Usage			
			Start time (average)	Standard deviation (hours:min)	Stop time (average)	Standard deviation (hours:min)
Households						
TV	0.81	88	16:00	5:00	22:00	0:45
DVD	0.6	14.3	17:30	2:15	21:30	1:00
Stereo	0.5	100	19:00	8:30	21:30	1:15
Lights	8.6	29.5	18:00	4:45	21:00	4:00
Iron	0.4	1000	7:15	2:30	10:15	1:00
SMEs						
Lights	1	27	14:30	5:30	20:30	1:15
Stereo	0.4	75	9:30	3:45	20:45	1:30
DVD	0.2	- (14.3)	10:45	5:00	21:30	1:45
TV	0.3	60	10:30	4:30	21:15	1:30
Computer	0.16	Intel Pentium 4[a]	8:00	1:30	19:30	0:45
Trimmer	0.21	- (15 W)	8:00	1:30	21:30	2:00
Hairdryer	0.16	65	14:00	*	16:00	*

Figure 3.3: example of data from interview [4]

In order to construct appliance-specific load profiles the data relative to the power rating and running times of each appliance are extracted by the interview. After that an average household load profile is built with the aim to generate a load profile for the total household load. The average household load profile is done taking into account all appliances which are used at time i scaled by the ratio between interviewed household customers (n) and total number of household customers (N). The way in which is calculated the load (E_i) at time i is shown in Eq.(3.1). Usually an household is selected (considered average in terms of the socio-economic attributes) in order to make a specific comparison with measurements on household level.

$$E_i = \frac{N}{n} * \sum P_{m,i} \qquad (3.1)$$

Regarding the appliances used at high power for short period the equation 3.2 is used to calculate the contribution of the load at time i dividing their rated power (P) by their usage time (t_{usage})

$$E_i = P/t_{usage} \qquad (3.2)$$

This procedure is not suitable for the large loads, because of their irregular power demand and running times (for example electric machines), so it is necessary using a different method to determine these load profiles. The load's daily energy consumption is calculated using the rated power of the load and the daily usage time (t_{usage}), obtained by the respondents as the number of hours the machine is used each day. As it is not easy for the operators to specify at what times their machines are running, the daily energy consumption is uniformly distributed during their work's hours (t_{open}), resulting in a constant power demand. The calculation for the load at time i, is shown in Eq. 3.3.

$$E_i = \sum P_m * t_{usage}/t_{open} \qquad (3.3)$$

In order to generate the load profile for the smaller SME appliances it can be used the same procedure used for the households. The entire mini-grid system load profile is then obtained by combining the load profiles for households, SMEs and the large loads [4].

3.5.2 Accuracy of the interview-method and alternative prediction approaches

Different studies [4] [9] show distinct differences between load profiles based on interviews and measured data. The largest differences rely in the calculated energy demand, in particular during the morning and the night. These issues can be observed in the load factor (a systems load factor is the fraction between average load and peak load) and in the capacity factor, which are underestimated using the interview-based method.

A more accurately predicted parameter is the peak load, which shows small variations respect to the measured data. These differences are caused by two factors: lack of correct identification of appliances and errors in time of usage [9].

An alternative prediction approach is the use of the data-driven proxy method, which uses mean customer consumption from known mini-grid to predict customer consumption from other mini-grids [9]. The average consumption of one mini-grid should provide a reasonably accurate prediction of another mini-grid with similar features [9]. "*This is a more accurate approach that reduces error in load profile prediction and highlights the importance of sector-wide sharing and aggregation of mini-grid consumption data*" [9]. It means that mini-grid developers can use, if available, the data about the other mini-grids to better predict the load profile of their community than using the common interview method [9].

3.6 Success factors for mini-grids

A study has compared different features of mini-grids in Africa in order to identify success factors of these installations to guide future implementations of such systems in rural communities. The following information is based on [12].

The study concludes that:

1) Technology is a very important factor and needs the support of population and government for the successful implementation and sustainability of components.
2) In order to guarantee long term sustainability of these projects the population growth, the business interests and the increase of the consumptions have to be accommodated.
3) The adoption of energy efficiency measures is essential for sustainable operations and the creation of awareness on such measures should convince new customers not to use inefficient equipment.
4) In order to include in the project also the poorest people it is required a progressive tariff system.
5) As mentioned several times it is essential to train the locals in the management, maintenance and control of the system for a more sustainable program.
6) In order to avoid the electricity theft the prepaid metering system could be more effective for revenue collection.

Furthermore the design of rural electrification programs should be scalable to take into account increasing population and business interests. The accumulation of spare parts or primary resources can be a good solution to reduce downtime in case of failure and ensure more efficient operation. Initially the management of the project can be entrusted to the government which has the financial capacity to send it forward and later it is possible to hand over to an independent service provider.

4. The community

The community in question is situated in Draa Tafilalet, one of the 12 regions of Morocco, located in the central-eastern side of the country at the frontier with Algeria. The region has an extension of more than 88 thousand square kilometers and is organized in five provinces: Errachidia (the regional capital), Ouarzate, Midelt, Zagora and Tinghir. The chosen community falls within the province of Tinghir and more specifically in the Toudgha El Oulia rural municipality. This municipality has a total population of 5.665 people living in 939 households and most of them are involved in activities related to agriculture and tourism [13].

Figure 4.1: Toudgha El Oulia

Toudgha El Oulia is situated near the "*Gorges du Todra*", a canyon carved by the Todra River over the years. In the last part the canyon becomes spectacular, the two rocky walls reach their minimum distance equal to a minimum of 10 meters, with overhanging rocks that reach 160 meters in height.

Figure 4.2: Gorges du Todra

In order to understand the economic and energetic situation of the area into consideration in the following chapters the energy system in Morocco will be described.

4.1 Current and future trends in the energy system of Morocco

Morocco is the country with the lowest estimated reserves of recoverable oil in Northern Africa and imports more than ninety percent of his energy need (Morocco is the largest importer of fossil fuels in the region) [14].

The country's poverty of domestic supply of oil, coal and gas places a burden in the finances of the government, which has been running a budget deficit since 2009. The deficit peaked at 9,7 % of the gross domestic product (GDP) in 2012, when the increase in the oil prices caused the Moroccan subsidies system to impact on the government's account by the unprecedented level of 6,6% of GDP [15].

The excessive vulnerability of the Kingdom to the price volatility of the imported commodities called in question the sustainability of the national system of subsidies. In February 2014 the elimination of subsidies to gasoline and fuel oil started and in the end of 2015 occured the total liberalization of liquid fuel products. The government started to invest in the energy sector with the aim of diversifying the country's energy mix, accelerating the development of renewables, limiting CO_2 emission, strengthening the existing transport (electricity and gas) infrastructure and supporting the exploration of local oil reserves.

4.1.1 Energy demand

Total final consumption (TFC) of energy in Morocco increased at the average pace of 3,9 % from the beginning of 2000s up to today. In 2015 the TFC amounted to 15.0 Mtoe [14]. The sector with the highest energy consumption is transportation (34,8% of TFC), followed by the residential sector (25,4% of TFC), industry (20,7% of TFC), commerce and public services (8,2% of TFC), agriculture (7,4% of TFC) and the remaining (3,5%) part is attributed to non-energy uses of the resources.

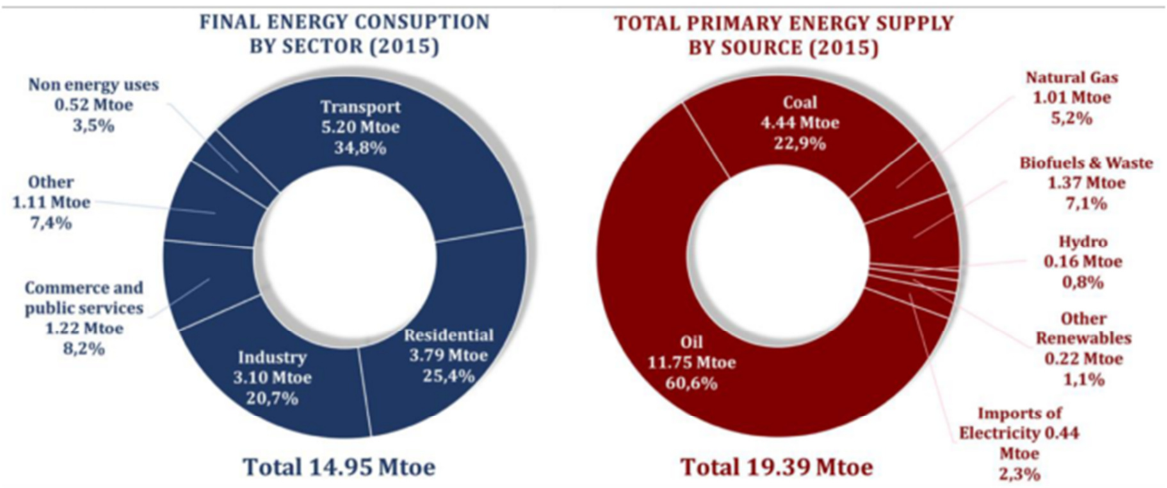


Figure 4.3: Final consumption by end-use sectors and primary energy supply by source in Morocco [14]

4.1.2 Energy supply

In the last decades the total primary energy supply (TPES) of Morocco has grown reaching the value of 19,4 million tonnes of equivalent oil (Mtoe) in 2015. Yet (MJ/$) is the country indicator for the intensity of primary energy consumption, it reaches the value of 3,15 MJ/$ in 2011 and is below the average of Middle East and North Africa countries [16].

Renewable sources accounted for 9% of TPES in 2015 thanks to a high deployment of biofuels and wastes. Biofuels, wastes and hydroelectricity are sources of longer tradition while wind and solar technologies started to develop in 2001 and 2010 respectively [17].

The 89% of TPES is composed by fossil fuels and in particular the imported crude oil and oil products account for 61% of the total. Almost half of the national supply of oil products are used for transport while the remaining part is consumed by residential and industrial users. Natural gas provides only the 5,2 % of TPES in 2015 while primary and derived coal-based fuels cover 23 %. Excluding minor shares destined to industrial application, all the provisions of coal and natural gas are used for power generation and constitute the principal sources of the sector.

The natural gas was introduced in the energy mix of the country in 1996 after the inauguration of the Maghreb-Europe gas pipeline which delivers Algerian natural gas to Spain and Portugal through the Strait of Gibraltar. Morocco's proven reserves of natural gas are small and Maghreb-Europe gas pipeline remains the main infrastructure of supply to Morocco which in 2016 imported about 1,1 billion cubic meters of Algerian natural gas [18].

4.1.3 Emissions

The World Bank estimates that Moroccan yearly carbon dioxide emissions amounted to 60 million tons in 2014 and represent the 0,17% of world total, having increased by 50% since 2000. Per capita emissions amount to 1.7 tonnes of CO_2 / person, which is rather low comparing to the world's average (5 tonnes CO_2 /person) [19]. The data has constantly increased at the average pace of 3 % since 2000.

4.2 Future trends and national energy strategies

Projections illustrated by Morocco's national energy strategies indicate that Morocco's primary energy need will grow at an average pace between 4-5% in the future years, reaching 43 Mtoe in the base scenario for 2030 [20]. Matching the country's increasing demand will require considerable investments in infrastructures and additional power generation capacity, besides diversifying away from fossil fuel imports. The country's energy strategy of 2009 has been structured around these issues and declares four fundamental objectives:

1) Achieve universal access to electricity at competitive and affordable prices
2) Control the growth of energy demand through demand side management measures
3) Preserve the environment and control greenhouse gases emissions (GHG)
4) Increase the security of supply

The government's guidelines to cope with these challenges are summed up as follows :

1) Diversification of the energy mix
2) Exploitation of the country's potential of renewable sources
3) Elevation of energy efficiency into a national priority
4) Reinforcement of the infrastructural integration with neighboring countries
5) Pursue of sustainable development

4.2.1 The role of renewables

Renewable energy sources (RES) have a crucial role for overcoming part of the fundamental objectives declared by the Moroccan NES (National Energy Strategy). The government expects that the cumulated contribution of solar, wind and hydro over the national primary energy demand will be up to 12,5 % by 2020 and up to 18 % in 2030 (6.8 Mtoe) [20].

Morocco will lead the capacity of renewables along the 2017-2022 period in the MENA region and, according to the International Energy Agency (IEA), in the same time range the additional installations of RES will amount to 3500 MW. The leading technologies are onshore wind (+1200 MW from 2017 to 2022), solar PV (+ 850 MW) and concentrated solar power (+ 500 MW) [20].

4.2.2 The role of conventional sources

In the NES of 2009 the Ministry of energy, mines, water and environment (MEMEE) contemplates two options for the development of the natural gas utilization in the country. One option limits natural gas consumption to the current supplies from the Maghreb-Europe gas pipeline and to the domestic production. In this scenario coal and oil cover 38,5% and 39,1 % of 2030 national TPES [20].

The second option (illustrated in figure 4.2) foresees a considerable growth of the natural gas sector to be realized through the extension of the MEG (Maghreb-Europe gas pipeline) capacity or the creation of new interconnection pipelines, the construction of LNG regasification terminal (for a total capacity of 5 billion cubic meters) and the consequent development of national transmission and distribution networks. The consumption of natural gas has constantly grown since 2009 (with yearly average increases of 13% from 2009 to 2015), demonstrating that the Kingdom has already committed in enhancing the role of NG in the national energy system. In these perspective the NG consumption is expected to increase to about 3.7 Mtoe (14% of TPES) in 2020 and 5.1 Mtoe (still 14% of TPES) in 2030 reducing the need of other fossil fuels.

In the two described scenarios, coal and oil still represent the principal primary sources of energy. In the energy strategy it is contemplated the introduction of nuclear, which might cover 4% of TPES in 2030 (there is already a 2 MW experimental reactor). The government, supported by the International Atomic energy Agency, announced its plan to build a 1300 MW nuclear power plant near Sidi Boulbra [21].

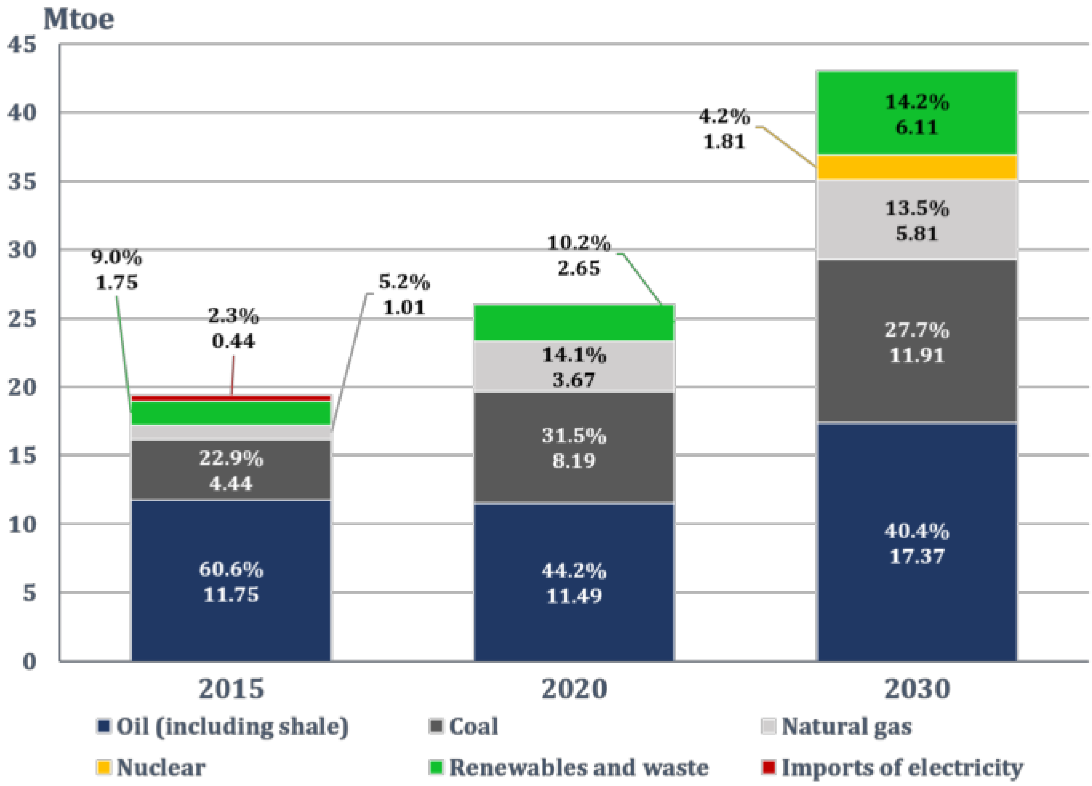


Figure 4.4: Evolution of Morocco's primary energy supply [14]

4.2.3 CO_2 targets

According to a Business as usual (BAU) scenario, if no preventive measure were taken Morocco's emissions of equivalent CO_2 would increase up to 171 million tonnes/year. The government has committed in reducing the carbon dioxide emission by 32 % with respect to BAU scenario in 2030, which means a cumulative reduction of 301 million tonnes of equivalent CO_2 [22].

4.3 Outlook on the power sectors of Morocco

Moroccan power sector is dominated by the state-owned utility ONEE (*Office National de l'Electricité et de l'eau potable)*, placed under the administrative and technical control of MEMEE. ONEE owns the totality of the transmission network and large part of the distribution. It represents the single buyer and seller for most of the electricity trading. Legislation has been posed in 1994, under suggestion of the World Bank [23], to permit the national power monopoly (ONE, Office Nationale de l'Electricité) to stipulate power purchase agreements (PPAs) with both independent power producers (IPPs) and private owners of smaller generation plants of up to 10 MW capacities [24]. As a result of this step towards the liberalization of the sector, today (2016) 65% of the power generation is sold to ONEE by IPPs. In the same years (1990s) the process of privatization of the distribution sector began. In accordance to a scheme which would gain the name of "*transferred* *management*", private companies were permitted to take control over public distribution utilities under a concession agreement with the local authorities.

The position of the state-owned operator has been reduced after the introduction of Law 13-09 in February 2010, which permits direct exchanges of renewable-based electricity between producers and customers connected to the very high-voltage, high-voltage (VHV/HV) and medium voltage (MV) electric grid. In the framework of the Law 58-15 (ultimate completion of Law 13-09) promulgated at the beginning of 2016, the access to the electric grid has been also extended to the renewable generators connected to the low-voltage (LV) distribution network [25]. Private plant owners contemplated by the two laws are allowed to inject into the grid a maximum share of 20% of the yearly production. The electricity is therefore sold to ONEE, to private distribution utilities or to other municipal distribution operators (known as régies).

Electricity prices in Morocco are differentiated by user category, voltage and consumption. In the case of households connected to the distribution grid the retail price of electricity increases with the monthly consumption and ranges between 0.901 MAD/kWh and 1.4407 MAD/kWh [17] .This pricing system does not take into account the socio-economic situation of the residential consumers. For industries, prices are differentiated by daily time slots and are generally lower. Despite the total elimination of fossil fuels subsidies, electricity prices in Morocco still do not represent the real cost of production, as they are below average costs of production and transmission. IEA estimates that this gap implies a "hidden" subsidy of 0.30 MAD/kWh, being around one third of the unit price paid by an average residential customer [17].

4.4 Rural electrification: policies and achievements

In the last decades, Moroccan electricity network has expanded dramatically. In the 1990s the governments undertook an ambitious plan for increasing the rate of rural electrification from 18% (1996) to 80% by 2010 [26]. PERG (Programme d'Electrification Rurale Global) was conceived with an utility-led model (according to which the responsibility for the actuation of the plan would be completely posed on the state-owned utility ONE) and with an integrated approach including both connected and off-grid options in the framework of a single project. The target to achieve 80% of electrification rate was accomplished in 2005 and surpassed in the following years. Nowadays (2016) the electrification of the rural population is over 99%, with more than two million households (estimated 12.7 million people) having gained access to electricity since 1996 [24].

The financing scheme for the implementation of the program is based on a shared participation between ONEE, the local authorities and the beneficiaries (the households). The vast majority of the electrification has relied on the extension of the existing grid, which has also included efficient solutions for cutting the costs of construction (such as lowering the height of the LV poles and placing the transformers on the poles).

However, also decentralized off-grid solutions have been implemented as a cheaper alternative to grid extension for remote and dispersed villages, settled excessively far away from the existing infrastructure. ONEE accepts extending the grid to a certain village if the estimated resulting cost of connection per household keeps below a predefined threshold; if the connection cost per household surpasses the budget for grid extension, the mini-grid or standalone solar home systems (SHS) solutions are adopted. In 2006 the breakeven cost between the off-grid and the connected solutions was 27,000 Dh/household. Depending on the type of use and on the amount of energy required, the electricity prices for rural customers vary between MAD 1.07/kWh and MAD 1.391/kWh, and the service is provided afterwards an upfront payment, following a fee-for-service model [17].

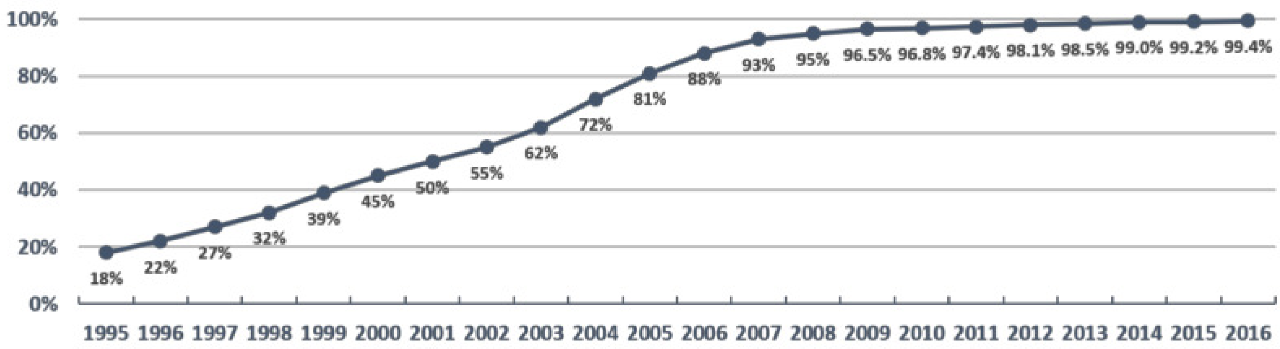


Figure 4.5: Evolution of rural electrification rate during PERG in Morocco [24]

4.5 Electricity demand, generation and infrastructure

Morocco's power sector transforms and produces around one third of the national supply of primary energy. Electricity demand has grown since 2000, with an average rate of 6%. In 2016 the country's electricity consumption reached 35.4 TWh, 2.90% more than the previous year [24]. The sector is going to face dramatic further growth and renovation in the future years, driven by a growing population with increasing access to electric energy and improving standards of living, infrastructural investments, enabling regulatory framework and economic growth.

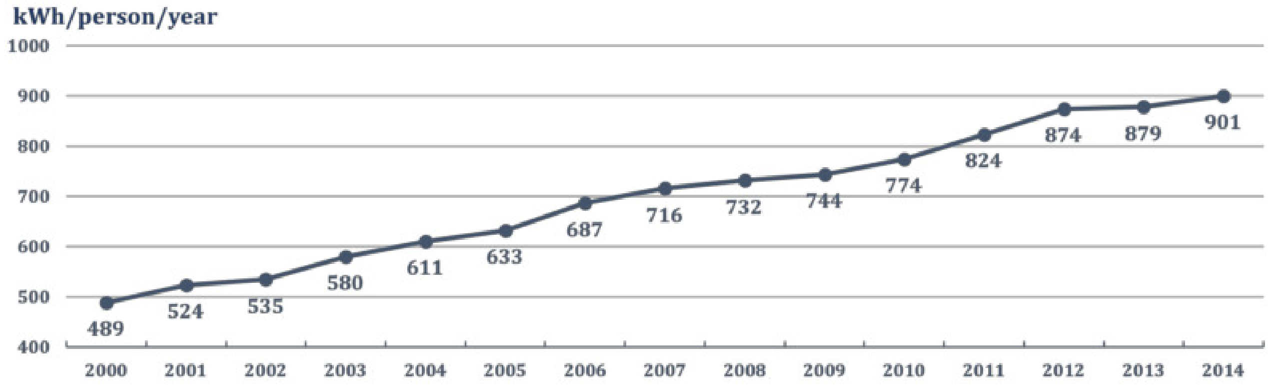


Figure 4.6: Evolution of consumption of electricity per capita in Morocco [19]

Today (2016), 72% of the electricity consumed in Morocco has fossil origins [24]. Coal leads the energy mix of the power sector and provides 48% of the electricity, followed by NG (17%) and fuel oil (8%). Renewable energies covered 14.3% of the demand in 2016. Wind farms deliver 8.5% of the national demand of electricity and constitute the principal source of renewable power of the country, while hydropower plants provide 4.7%, a quarter of which derives from pumped hydroelectric storage. Generation from utility-scale solar facilities is limited to 1.1%, predominantly owed to the commissioning of the CSP plant NOOR I (160 MW) which produced around 400 GWh in 2016. In the same year estimated additional 279 GWh have been generated by small-scale solar PV systems, distributed to 70,000 households in the framework of PERG [26] .

Roughly 15% (5.3 TWh) of Moroccan electricity consumption is covered by imports. Neighbouring Spain and Algeria constitute the third "source" of energy of Morocco's power sector, which benefits from a high capacity of interconnection (1400 MW with Spain and 600 MW with Algeria) and competitive electricity prices of the Spanish market.

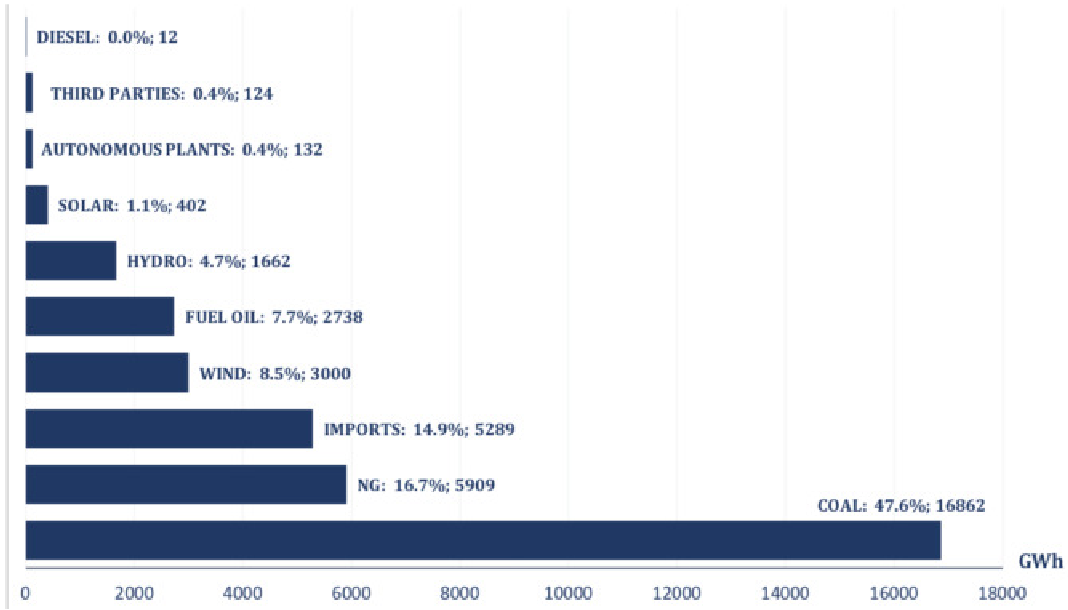


Figure 4.7: Electricity supply by primary source of energy in Morocco (2016) (Elaboration from ONEE)

Morocco's electricity transmission infrastructure extends for more than 25,000 km, covering the whole country with exception of some desert and southern areas. With a total capacity of more than 29 GVA in 2016 [27], the network is under continuous development and expansion. In the framework of the reinforcement and expansion program realized between 2014 and 2017, at the end of 2016 the transmission grid has gained additional capacity by 2300 MVA and 1880 km of lines. Extra investments for 12 million MAD were subsequently realized throughout 2017 [26]. The responsibility for the expansion of the transmission network is completely laid on the utility ONEE, which retains the monopoly over the grid and acts as transmission system operator (TSO).

Interconnections with Spain and Algeria are well developed with a cumulative transmission capacity of around 2000 MW. With the aim to enhance the regional integration and to provide the Moroccan power system with more flexibility, plans for the developments of future interconnections include a 1000 MW connection with Portugal, an additional 700 MW link with Spain and the first interconnection with Mauritania, the Morocco's southern neighbour. In this last regard, ONEE is currently already expanding towards South with a 400-kV line connecting Boujdour to Dakhla [28].

The distribution subsector is shared between the national office (ONEE), three private companies ("*Gestionnaires délégués*") and seven municipal utilities ("*Régies*", owned by municipalities, communes or groups of neighbouring communes). ONEE owns the majority (52%) of the distribution infrastructure and distributes and supplies 58% of the electric energy [28]. In the case of private owned utilities, the local authorities provide the private sector with a long-term concession during which the utility needs to comply with performance objectives and assumes the responsibility for all the investments in the infrastructure, the construction and the operation of the grid. All the distribution utilities also act as retailers of electricity.

4.6 Future projections

According to ministerial projection, the electricity demand in Morocco is going to drastically increase in the medium-term future, reaching up to 133 TWh in 2030 (almost 4 times the current needs) and a maximum load of up to 22 GW (about 3 times the current values). Yet, more conservative projections slightly lower 2030 estimated demand to 95 TWh, and the 2030 national load to 12 GW. Under the same forecasts, the electricity demand should double in the next 10 years.

In order to cope with the technical, economic and environmental challenges deriving from the required expansion of the power system, the subsector is already undergoing a deep and rapid renovation supported by an increasingly enabling regulatory framework and predominantly based on the integration of new RES capacity. The national agenda for the installation of RES has been illustrated on two main horizons: the NES of 2009 declared the target to achieve 42% of installed capacity from RES by 2020; later, right before the COP 22 held in Marrakech, the objective was extended to 2030 and increased to 52% [20].

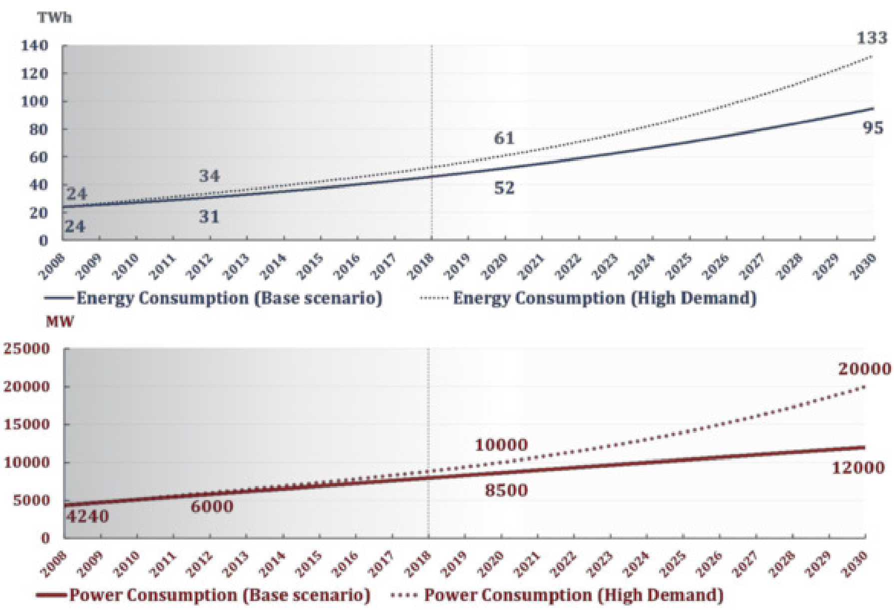


Figure 4.8: Evolution of Morocco's electricity demand and national load [20]

Afterwards the completion of NOOR Ouarzazate (580 MW of total capacity), two additional solar plants will be erected, namely NOOR Boujdour et Laâyoune (100 MW) and NOOR Midelt and Tata (1200 MW). Thanks to these and other projects, the government foresees to install more than 4500 MW of solar technologies (both PV and CSP) in the period 2016-2030, meaning 20% of the total installed capacity. Another 20% of the generation capacity will be provided by wind farms. Ministerial projections indicate that the wind capacity installed between 2016 and 2030 will amount to 4200 MW, of which 1700 MW from 2016 to 2021 and 2500 MW between 2021 and 2030. Additional 1330 MW of hydropower plants are also expected to be integrated in the same period.

As a means to cut GHG emissions and to provide the power system with additional flexibility, Morocco has committed in increasingly rely on natural gas for the generation of electricity. MEMEE foresees the installation of 3000 MW of additional capacity from combined cycle (CC) gas-fired power plants in the period 2021-2025, which would lead the power industry to require up to 3.5 billion cubic meters of NG per year [20]. Morocco is making an effort to develop its nuclear infrastructure, developing institutional network and research in the field. The option of nuclear power as a long-term alternative is becoming more and more realistic as the government announced its plan to build a 1300 MW nuclear power plant near Sidi Boulbra .

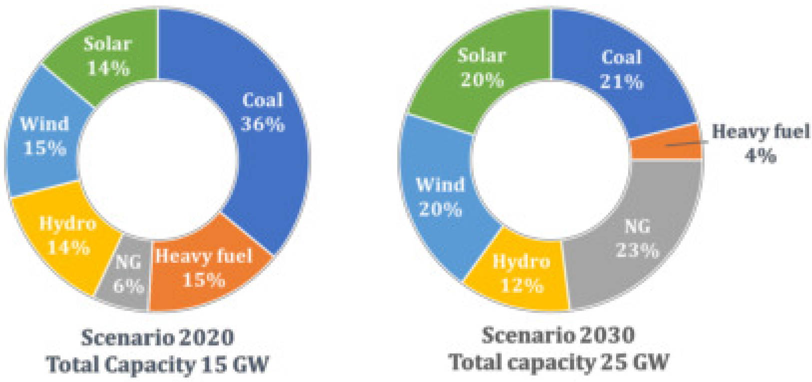


Figure 4.9: Energy mix of Moroccan power sector in 2020 and 2030. Elaboration from [28]

4.7 Description of the target community: Toudgha El Oulia

As said at the beginning of chapter 4, the selected community is the rural municipality of Toudgha El Oulia, situated in the province of Tinghir and in the region of Draâ Tafilalet.

The population of the region amounts to about 1.6 million and is predominantly involved in agriculture and tourism related activities. The agricultural sector of the region is principally based on the cultivation of cereals (among which wheat, barley and corn), olive trees and date palms. In this last regard, Draâ Tafilalet is the largest producer of dates in Morocco (116,000 tons in 2016), with 4.3 million date palms constituting 90% of the country's total [29] .

Drâa Tafilalet exhibits a per capita consumption of electricity considerably below the national average. The total electricity demand in 2016 amounted to 619 GWh, meaning a per capita consumption of 0.38 MWh/person [30] (for comparison, in the same year the national average was 1.00 MWh). In addition, the degree of electricity utilization within the region is not uniformly distributed, indicating the presence of asymmetries in terms of socio-economic development among its provinces. The per-capita electricity demand is particularly low in the province of Tinghir, where it reaches the value of roughly 240 kWh/person/year. The following table reports data directly collected from the *Office National de l'Electricitè*, referring to the community of Toudgha El Oulia.

Table 4.1: Evolution of the electric consumption for the last three years in Toudgha El Oulia

Year	Consumption (MWH)
2017	2120
2016	2067
2015	1964

Monthly data of electric consumption in 2017 (collected from the *Office National de l' Electricitè*) are reported in the following table.

Table 4.2: Evolution of electricity consumption per month of Toudgha El Oulia in 2017

Month	Consumption (MWh)
january	117
february	124
march	185
april	132
may	161
june	216
july	191
august	256
september	241
october	173
november	161
december	163

The objective of the study is to size a mini-grid powered by solar photovoltaic and biogas product by the local biomass. In order to estimate the quantity of available biomass all the calculations have been performed scaling regional and provincial information down to the level of the municipality. More specifically, data on the provincial and regional agricultural productions have been scaled down to the municipality comparing the population and the surface area of Toudgha El Oulia with the ones of the province of Tinghir and the region of Drâa Tafilalet. In the following table are reported information about biomass in the region.

Table 4.3: Biomass data in Draâ Tafilalet [31]

	Toudgha El Oulia	Province of Tinghir	Region of Draâ Tafilatet
Population	5500	322400	1635008
% (province,region)	-	1,71%	0,34%
Area (km2)	165	13,007	88,836
% (province,region)	-	1,27%	0,19%
Number of date palms	-	-	4,320,000
Surface of olive tree cultivation (hm2)	-	-	17,613
Production of cereals (tons/year)	-	-	252,000

The choice of considering only the cultures of date palm, olives and cereals is justified by their predominant role in the agricultural sector of the region, in terms of yearly production [13]. Due to the differences in the type of biowastes produced by the above cultures, different methodologies have been adopted for their quantification. Scaling the values reported above on the basis of the share of the surface area of Toudgha El Oulia over the regional total has been done under the hypothesis that no differences in terms of agricultural intensity and yields exist within the region. Under this assumption, the estimated number of date palms planted within the municipality is 8035, the estimated surface cultivated with olive trees is 32.8 hm2 and the estimated yearly production of cereals amounts to 468.7 tons/year.

Starting from these values, the quantity of wastes produced by the cereal crops has been assessed applying a residue/product fraction of 130% [32]. Woody residues of olive tree pruning have been estimated applying a unit surface yield of 1.7 tons (waste) / hm2 [32]. The quantity of bio-wastes from date palm has finally been calculated considering that each tree produces 16.75 kg of dry fronds each year [33].

In order to take into account for shares of the biomass production non-usable for energy purposes, the obtained quantity for date palm waste has been reduced by 40%. The same has been done for olive trees [32]. A usable share of 25% has been considered for the wastes from cereal crops [32].

It is worth mentioning that until a validation of the data adopted for the calculation of biomass availability results may carry some errors. The real potential of electricity generation may vary due to inaccuracies in the estimation of the waste production from the considered cultures. More accurate (possibly official) information on the number of date palms, olive trees and hectares cultivated on cereals may provide more reliable information.

As a last remark it is worth pointing out that, although proper fractions of usable wastes have been applied, in the analysis it is assumed that all the bio-wastes produced in the area are accessible. Given the high number of small farms in the region, this may be not totally true.

Scaling the biomass-based power generation would be more straightforward if the plant owners could rely on infrastructures of agricultural cooperatives embracing all the producers of the municipality and managing the production and the wastes of all the considered cultures.

5. HOMER Pro

HOMER (Hybrid Optimization Model for Electric Renewables) software has been developed by NREL (National Renewable Energy Laboratory, USA) and has been used in this thesis for the techno-economic feasibility analysis and for the optimal design of the mini-grid in Toudgha El Oulia. "*This software is a powerful tool for the optimal designing, sizing and planning of hybrid renewable energy systems by carrying out techno-economic analysis for off-grid and grid connected power systems*" [34]. This software can be employed in several types of renewable technologies (PV, wind, fuel cell, hydro…) and is able to do hourly simulations.

In order to determine the optimal size of components of the mini-grid, the program takes five types of input data [35]:

1) Meteorological data (wind speed, solar radiation, temperature, hydro and steam flow data)
2) Hourly or sub-hourly electric and thermal demand profile data
3) Economic cost data (operation and maintenance cost, capital cost, replacement cost, fuel price, transaction electricity price, interest rate, lifetime, system fixed capital cost, maintenance cost and emissions penalty)
4) Technical data (dispatch strategy and operating reserve)
5) Equipment characteristics data

The software using these input data examines all the feasible configurations of the system in question with an objective function that minimizes the total net present cost (NPC). Subsequently, it selects the most feasible solution respecting the specified constraints given in the input data (minimum and maximum capacities, fuel prices, costs for generating electricity…) at the lowest total costs [35].

The software performs an energy balance calculation for each of the 8,760 hours in a year and for each hour compares the electricity demand to the energy that the system can supply. It calculates the flows of energy to and from each component of the hybrid mini-grid and, for systems that include batteries, can also decide in which hours to charge or to discharge the storage system. [36].

HOMER performs the feasibility analysis and optimization of the micro-grid system before the installation. The methodology utilized for the complete feasibility analysis is indicated in the following figure.

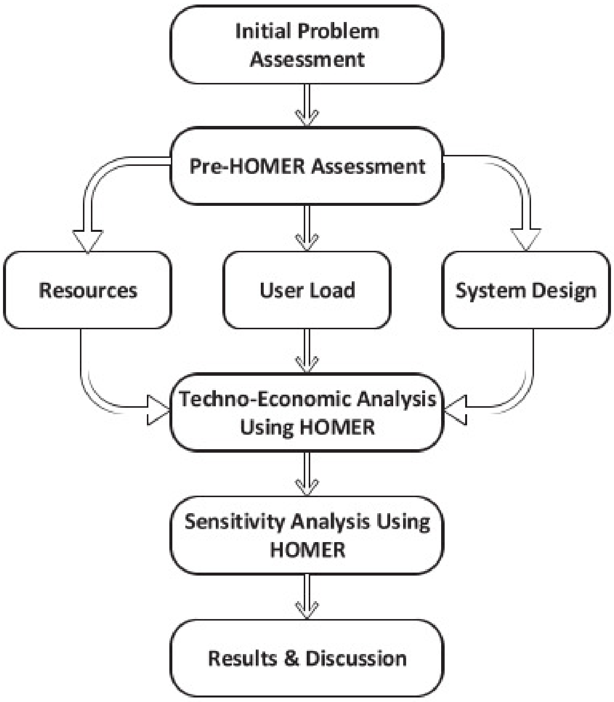


Figure 5.1: Schematic diagram indicating methodology utilized for the analysis [34]

HOMER can be used to perform three tasks: running simulations, performing sensitivity analysis and optimizing the simulated system [34].

5.1 User load assessment

As said in chapter 3.5 the evaluation of the electric load profile is very important for the correct sizing of the mini-grid. In Toudgha El Oulia the electric consumption is mainly associated to public lighting, equipments related to agriculture and domestic appliances.

The community under consideration is connected to the main grid and the monthly consumption data are available directly from the *Office National de l'Electricité*. In 2017 the consumption amounts to 2120 MWh and the monthly data are reported in the following table equal to table 4.2.

Table 5.1: Electricity consumption per month of Toudgha El Oulia in 2017

Month	Consumption (MWh)
january	117
february	124
march	185
april	132
may	161
june	216
july	191
august	256
september	241
october	173
november	161
december	163

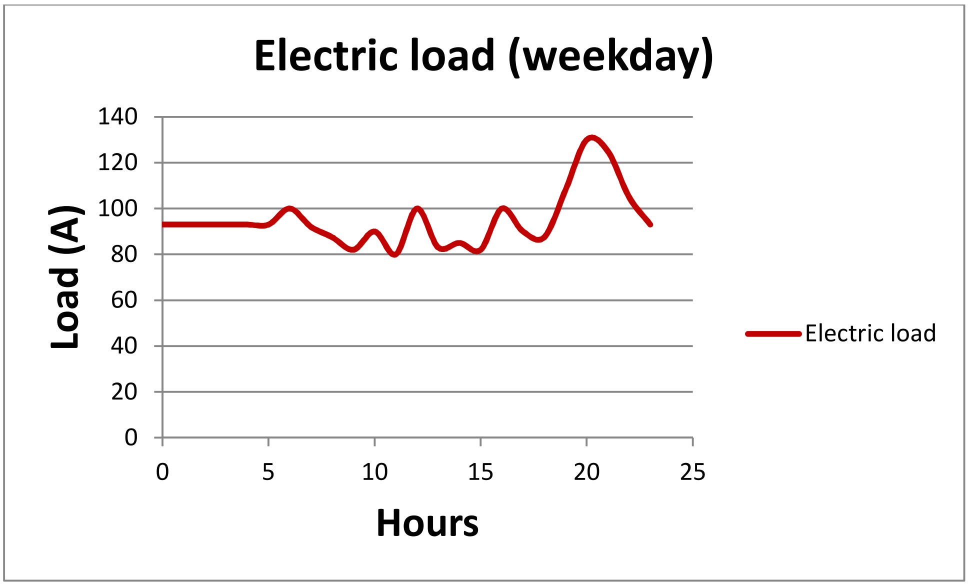
HOMER simulates the hybrid energy system by making energy balance calculations for each of the 8,760 hours in a year and for each hour compares the electrical demand to the energy the system can supply; in order to perform the simulation we have to know hourly consumption data. HOMER also distinguishes between weekdays and weekends; therefore, proper differences in the load must be taken into account.

As the hourly data are not known, a data-driven proxy method has been adopted to build the hourly consumption profile. This method, explained in chapter 3.5.2, uses the profile of a known mini-grid in order to predict the consumption of another mini-grid with similar features.

In the present study, the description of the community's load has relied on the profile of a known rural mini-grid situated in Tanzania [4] with a similar number of inhabitants (Toudgha El Oulia has roughly 5.500 inhabitants while the mentioned village 4.000), similar weather (temperature, solar irradiance, clearness index …) and similar activities. In the rural mini-grid of Tanzania the main activity is agriculture and the electrical consumption is mainly due to public lighting, domestic appliances and electric machines involved in agriculture activities as well as for the Moroccan community.

In order to build the load curves of the case study community, available measured hourly consumption data of the Tanzanian reference mini-grid have been used and adapted to the monthly electricity consumption data of Toudgha El Oulia, provided by *Office National de l'Electricité.*

The following images show the electrical profile of the Tanzanian community.



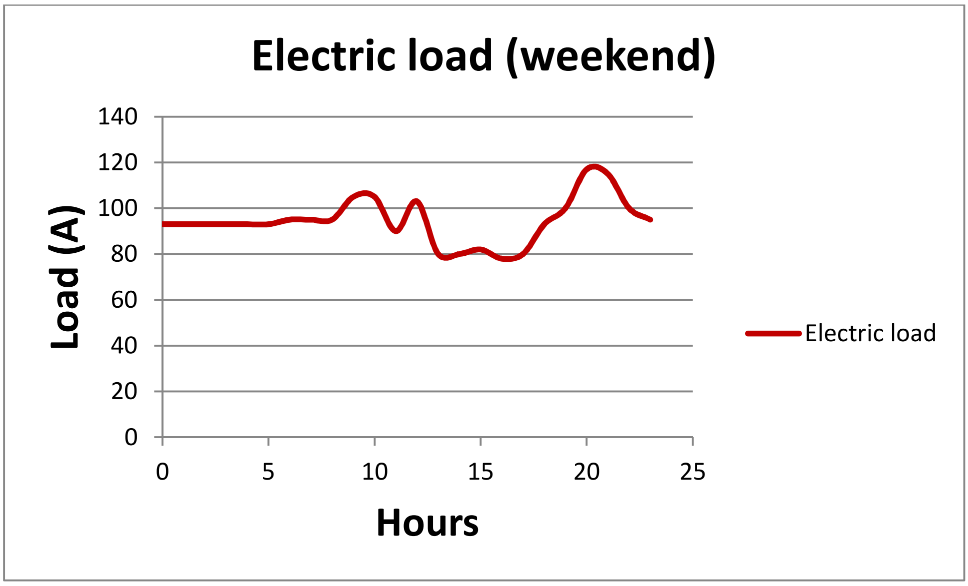


Figure 5.2: Load profiles for the Tanzanian village for a weekdays (top) and weekends (bottom). Elaboration from [4]**.**

The measured monthly consumption is divided by the corresponding number of days in order to obtain a daily consumption for every month of the year. In this operation we assume the consumption of every day of a certain month is constant.

As a result, the hourly profile of each day of the year exibits the same (normalized) profile as the hourly load of the Tanzanian grid. This procedure was carried out both for weekdays and weekends.

The resulting hourly load profile of the community is described in figure 5.3, as represented on HOMER Pro.

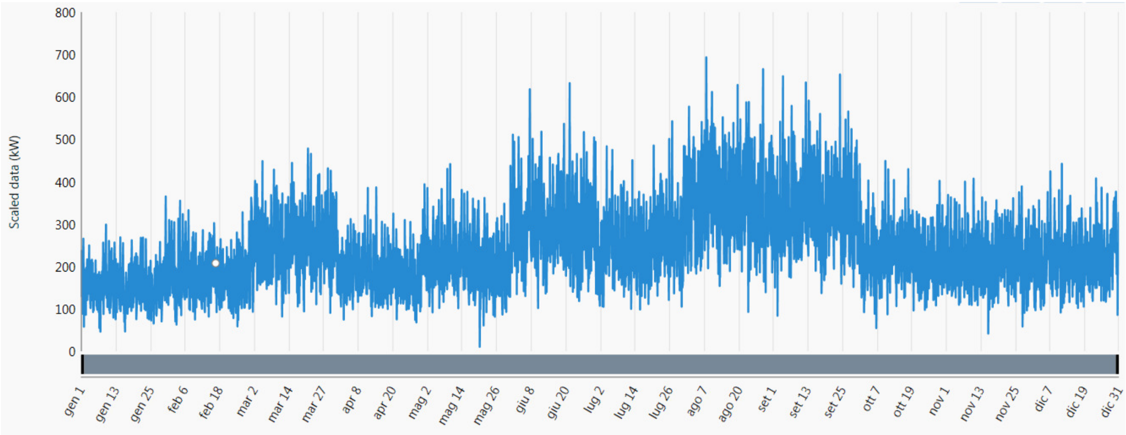


Figure 5.3: hourly load profile of Toudgha El Oulia on HOMER

The following picture reports the monthly profile of the community on HOMER:

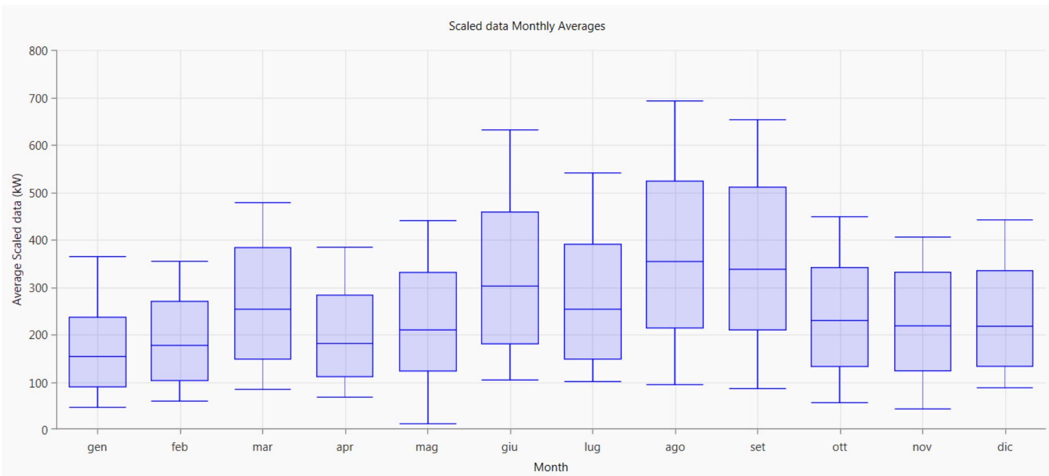


Figure 5.4: monthly profile on HOMER

Other information of interest obtainable by the software is the frequency of the power consumption of the community. The frequency and cumulative frequency distributions are respectively shown in figures 5.5 and 5.6.

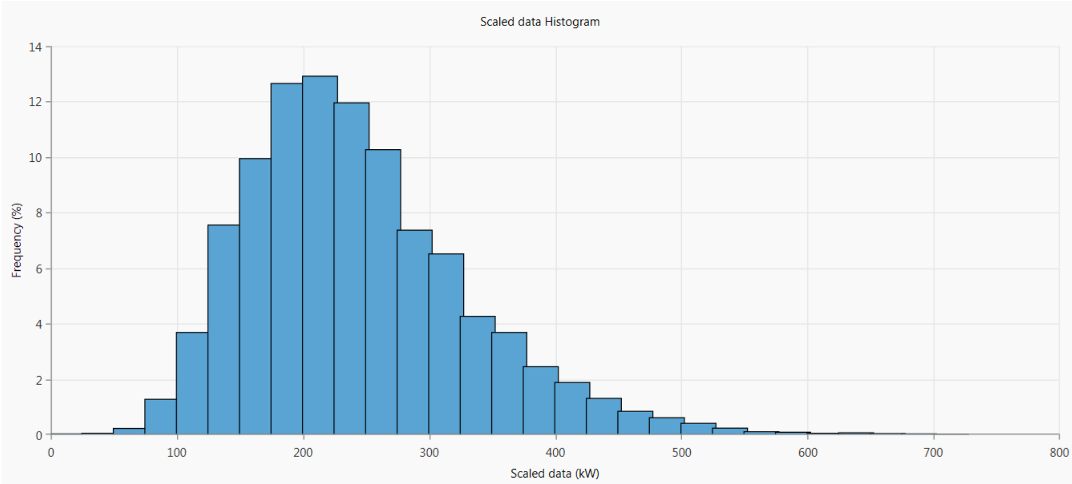


Figure 5.5: Frequency of the power in the community

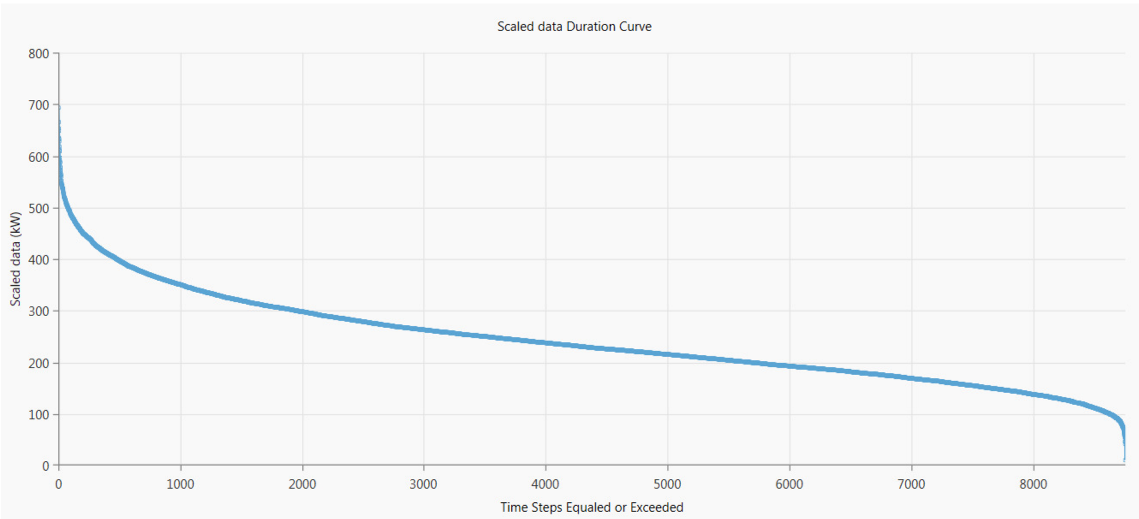


Figure 5.6 : Cumulative curve of the community

HOMER provides some useful information regarding the load profile that are summarized in table 5.2. The average daily consumption is 5796,5 kWh/day although this value varies depending on the months (in September and August this value is higher). Even if the average power has a value of 241 kW the peak power reach a value of 693 kW during the months with higher consumption.

Table 5.2: Information about the load profile

Average daily consumption (kWh/day)	Average power (kW)	Peak power (kW)	Load factor
5796,5	241	693	0,35

5.2 Available resources assessment

For the current case a hybrid solar/biomass electric system is considered. The complete assessment of the available solar and biomass resources is given below.

5.2.1 Available solar radiation

The solar radiation data are downloaded by the software for the location of "Toudgha El Oulia" using the "*NASA Surface Meteorology and Solar Energy Database*". The annual scaled average solar radiation is 5,44 kWh/m2/day and the maximum solar radiations is 7,31 kWh/m2/day. The annual scaled average solar radiation is the average energy emitted by the sun that reaches Earth's surface per square meter per day.

Data show that the location has good solar potential and can produce a lot of energy using photovoltaic (PV) panels. A profile indicating solar radiation and clearness index created by HOMER for the location is shown in figure 5.7.

The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. It is a dimensionless number between 0 and 1, defined as the surface radiation divided by the extra-terrestrial radiation [37]. The clearness index has a high value under clear and sunny conditions and a low value under cloudy conditions; it can be defined on instantaneous, hourly or monthly basis. The clearness index values in HOMER's solar resource inputs window are monthly average values. The symbol for the monthly average clearness index is K_t.

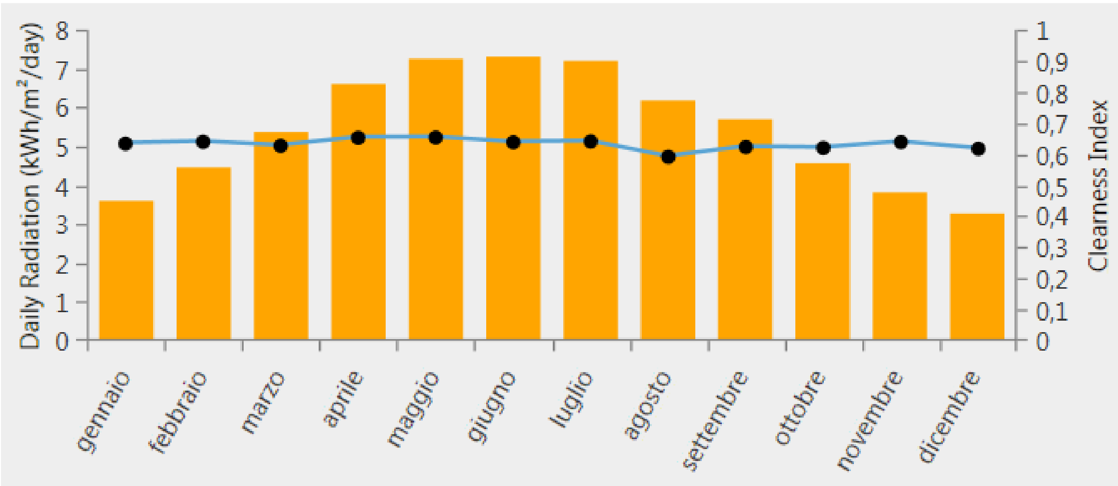


Figure 5.7: Solar radiation and clearness index profile

Table 5.3 reports the exact values of the clearness index and of the daily solar radiation, as from Figure 5.7.

Table 5.3: Monthly average daily incident irradiance and clearness index

Month	Clearness index	Daily solar radiation (KWh/m^2/day)
January	0,634	3,59
February	0,639	4,43
March	0,626	5,39
April	0,652	6,62
May	0,653	7,26
June	0,638	7,31
July	0,641	7,21
August	0,591	6,19
September	0,623	5,67
October	0,62	4,59
November	0,638	3,79
December	0,617	3,25

Another factor to be considered when solar energy potential is assessed is the ambient temperature, since it affects the performance of PV modules. The average monthly temperatures of the selected village are downloaded from "*NASA Surface Meteorology and Solar Energy Database*" and are represented in figure 5.8.

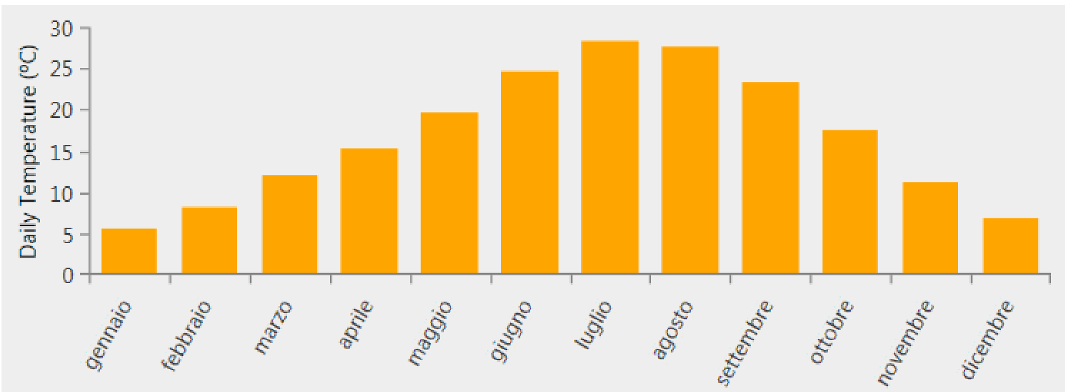


Figure 5.8: Temperature variation of the selected location from HOMER

In addition, tabulated monthly averaged daily temperatures are reported in table 5.4.

Table 5.4: Monthly average daily temperature

Month	Daily Temperature (°C)
January	5,62
February	8,27
March	12,05
April	15,38
May	19,55
June	24,63
July	28,32
August	27,62
September	23,27
October	17,5
November	11,28
December	6,93

5.2.2 Available biomass resource

Biomass is the oldest source of energy in the world, it is composed by the organic matter of agricultural residues, wood, animal and human wastes. It can be used to produce biogas, a mixture of gases such as carbon dioxide (CO2) and methane (CH4), which is produced by biomass in a process involving micro-organisms in the absence of oxygen (anaerobic digestion).

HOMER assumes the biomass feedstock is fed into an anaerobic digester to create biogas [37]. On the program the data to be considered to include the biomass resource are the available biomass (tons/day), the gasification ratio (kg/kg), the carbon content (%), the average price (€/ton) and the lower heating value (MJ/kg).

The available biomass in the location is illustrated in chapter 4.7. The quantity of biomass for energy purposes is 33,456 tons/year from olive trees, 80,75 tons/year from date palms and 152,32 tons/year from cereal crops.

The total is 266,5 tons/year and assuming a sufficiently large storage, this quantity uniformly distributed throughout the year. As said in chapter 4.7, until a validation of the data adopted for the calculation of biomass availability, results may carry some errors; for this reason in the simulation a sensitivity analysis is carried out with the aim of considering the errors on the estimate of biomass.

The biomass conversion ratio is the ratio of biogas generated to biomass feedstock consumed in the digester. HOMER assumes this value is constant and according to [38] this value is set 0,70 kg/kg. The biomass carbon content is the amount of carbon contained in the produced biogas, expressed as a mass-based percentage. HOMER uses this value to calculate the emissions of carbon dioxide, carbon monoxide and unburned hydrocarbons. In the present work, a carbon content of 55% has been considered for the biogas composed by 60% of CH4 and 40% of CO2. The lower heating value of biogas represents the energy content of the biogas produced by the digester and assuming it composed by 60% of CH4 and 40 % of CO2, the value of LHV (lower heating value) is 18 MJ/kg [39]. The average price is the average cost per ton of the biomass feedstock. Based on [40], an average price of 23 €/ton is assumed.

Figure 5.9 represents the input information relative to biomass resource on HOMER pro.

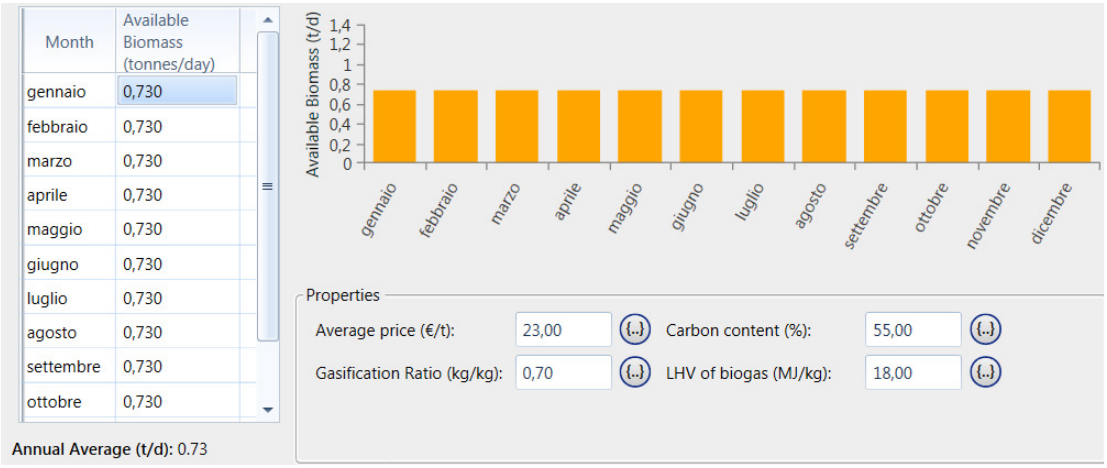


Figure 5.9: Biomass resource on HOMER

5.3 Components

In order to design the hybrid mini-grid on HOMER it is necessary to size the different components involved in the project.

5.3.1 Solar modules

In this case we indicate parameters relative to 1 kW of PV and HOMER will find the correct size of the system in order to minimize the NPC (net present cost). For the simulation HOMER requires different economic and technical parameters. According to [41] and the International Renewable Energy Agency, the average panel lifetime is 30 years. The capital cost of the modules has been set 1700 €/kW equal to the replacement cost and the O&M costs(Operation & Maintenance costs) has been set 28 €/year; these parameters are provided by the platform pvXchange and by [41].

Another important input data is the derating factor; the photovoltaic derating factor is a scaling factor that HOMER applies to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated [37]. In our simulation we assume this value 85% on the basis of [34].

Other input data are the efficiency at standard condition, assumed equal to 14% (general efficiency of PV panels), the normal operating temperature (downloaded from "NASA Surface Meteorology and Solar Energy Database") and temperature effect on power (assumed -0,5 %/°C). The performance of the PV system decreases with the increase of ambient temperature and the accumulation of the dust on the solar panels. The power output and the efficiency of the PV panels are given by:

$$P_{pv} = Y_{pv} * f_{pv} * \left(\frac{G_T}{G_{T,STC}}\right) * [1 + \alpha_P * (T_C - T_{C,STC})] \quad (5.1)$$

$$Efficiency = Y_{PV}/(A_{PV} * G_{T,STC}) \quad (5.2)$$

Where P_{PV} is the power output of the PV array (kW),Y_{PV} is the rated capacity of the PV array (power output under standard test conditions (kW)), f_{PV} is the de-rating factor (account for soiling of the panels, wiring losses, shading and aging), G_T is the solar radiation incident on the PV array in the current time step (kW/m2), $G_{T,STC}$ is the solar radiation at standard test conditions (kW/m2), α_P is the temperature coefficient of power (%/°C), and T_C is the PV cell temperature at the current time step (°C), and $T_{C,STC}$ is the PV cell temperature under standard test conditions (25°C) [42].

Figure 5.10 reports the PV modeling window on HOMER Pro

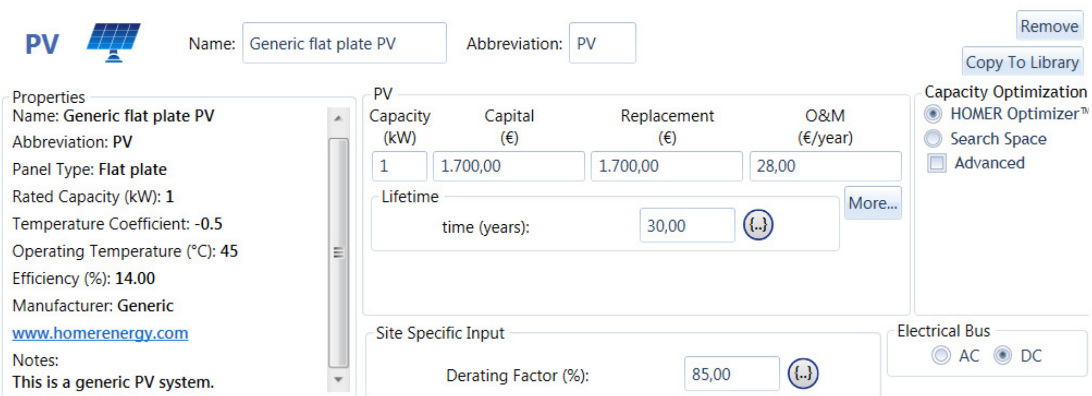


Figure 5.10: PV modeling window on HOMER Pro

5.3.2 Biogas fuel generator

The biogas generator uses biogas as fuel to produce electricity. For the correct sizing of the biogas generator we consider different modules. Looking at the cumulative curve in figure 5.6 modules of 50,100,200,300,400 kW are chosen. Homer will simulate the system for each module e will find the one that minimizes the net present cost of the system.

For each module a lifetime of 15.000 hours and a minimum load ratio of 30 % are specified. On HOMER the minimum load ratio is defined as the minimum allowable load on the generator, as a percentage of its rated capacity. Specifying a minimum load does not prevent the generator from being shut off; it simply prevents it from operating at too low load. This input exists because some manufacturers recommend that their generators must not be run below a certain load. [37]

The other technical and economical parameters have been defined according to [42]. The capital cost has been considered 500 €/kW, equal to the replacement cost. O&M costs increase with the size.

Table 5.5: Economic parameters of the different size of biogas generator

Capacity (kW)	Capital cost (€)	Replacement cost (€)	O&M (€/op.hr)
50	25000	25000	0,03
100	50000	50000	0,035
200	100000	100000	0,04
300	150000	150000	0,045
400	200000	200000	0,05

In figure 5.11 is represented the generator modeling window on HOMER Pro.

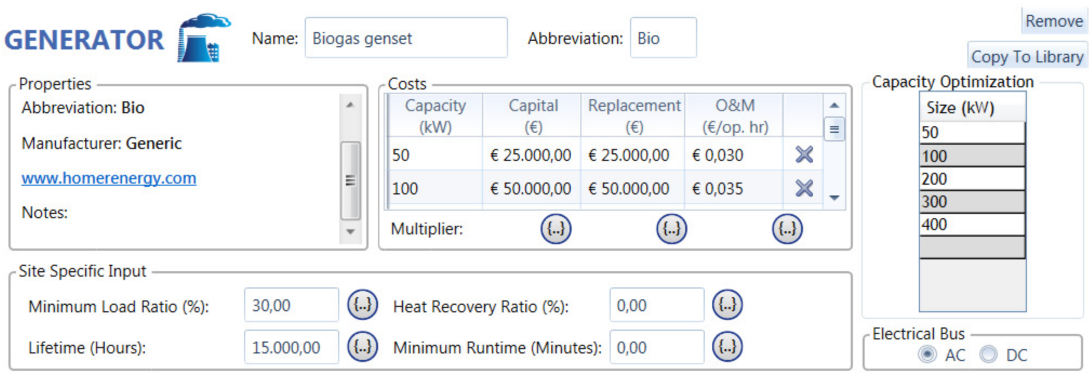


Figure 5.11: generator modeling window on HOMER Pro

In addition, the fuel consumption curve and the efficiency curve of the selected generator are also reported. The two curves have been generated according to [43]

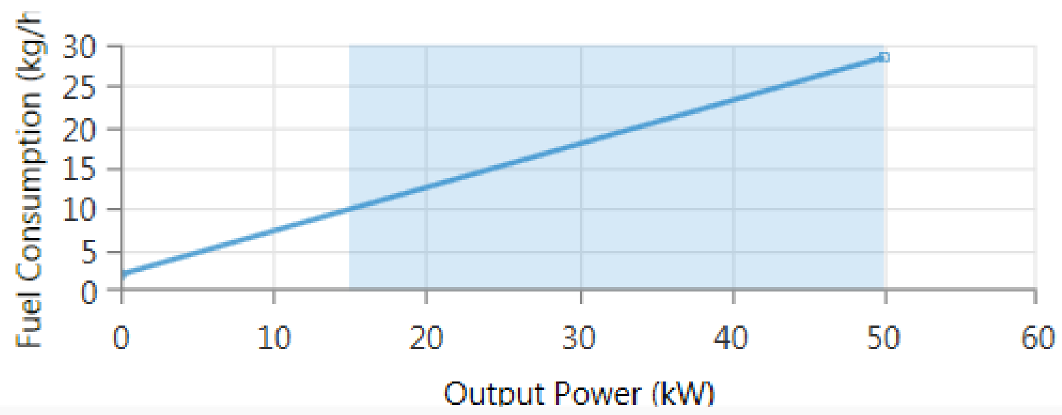


Figure 5.12: Biogas generator fuel consumption curve

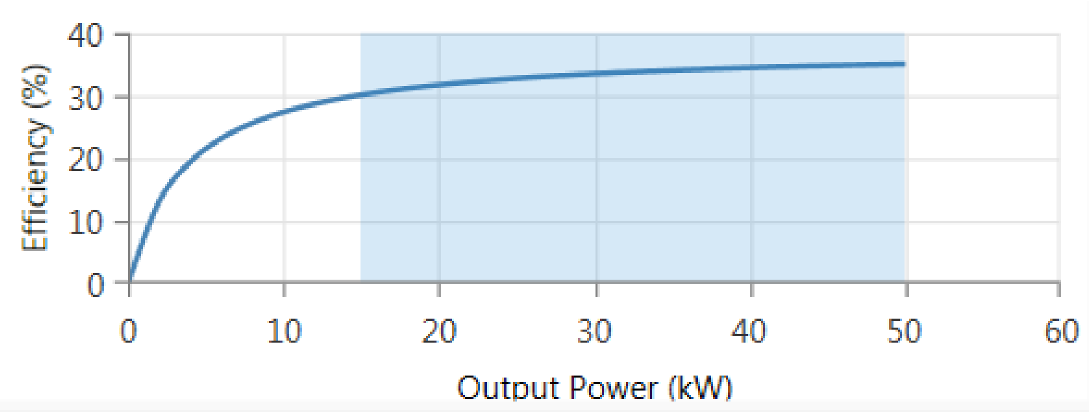


Figure 5.13: Biogas generator efficiency curve

5.3.3 Storage batteries

The function of the batteries is to store the energy produced by photovoltaic during the day and use it in the absence of solar radiations. The storage batteries can also be used as a backup system when other components do not work.

HOMER Pro requires as input information the type, the size and the costs of the battery. The present work contemplates a generic 1 kWh Li-Ion battery with a lifetime of 10 years, a capital cost of 600 € equal to the replacement cost and a O&M costs of 10 €/year. The round trip efficiency has been set 90 %. Other features are the voltage of 6 V, the throughput (kWh) of 3000 kWh and the initial state of charge and minimum state of charge chosen 100% and 40 % respectively. All this data are based on [41].

Figure 5.14 represents the battery modeling window on HOMER Pro:

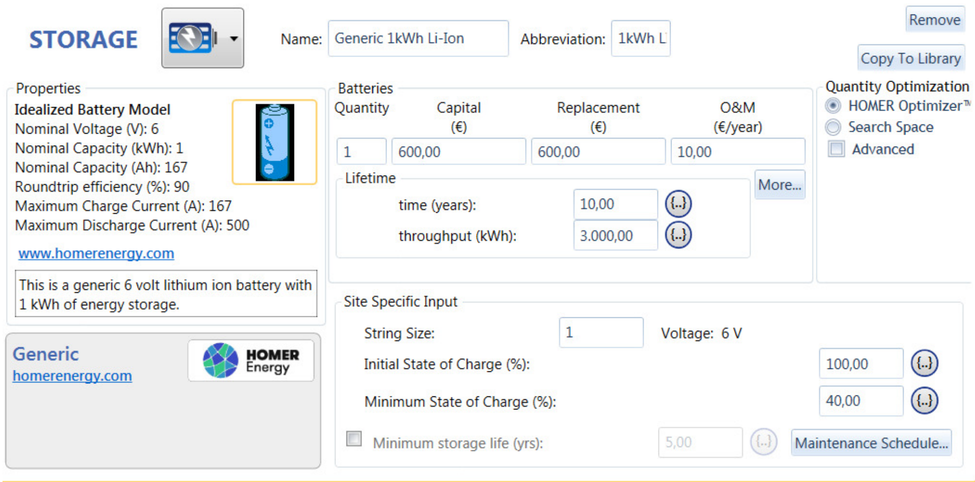


Figure 5.14: Battery modeling window on HOMER Pro

5.3.4 The converter

In the systems that include both AC and DC current a converter also known as an inverter is necessary for converting DC electricity into AC. In this case the converter is used to convert the DC power obtained from solar panel to AC power.

The price of the converter has been set 150 €/kW equal to the replacement cost, O&M costs of 5 €/year and a lifetime of 10 year. Another characteristic is the efficiency set equal to 90 %. Data based on [41].

In figure 5.15 is represented the converter modeling window on HOMER Pro

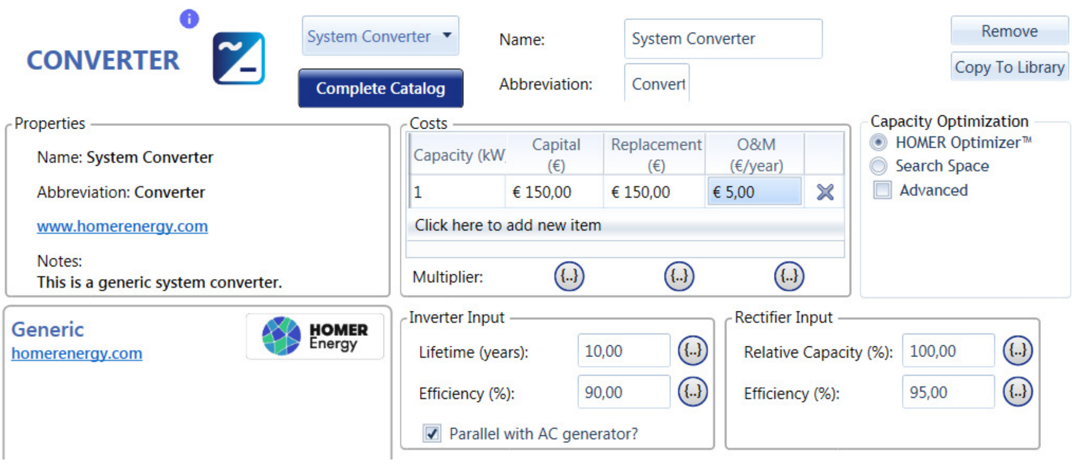


Figure 5.15: Converter modeling window on HOMER Pro

5.3.5 The grid

As the community is connected to the grid, we have to specify the grid power price in €/kWh and the price the system sell the energy produced to the utility that owns the grid (Grid Sellback Price) in €/kWh.

"*Electricity tariff depends on the type of use and is subject to a Value-added tax (VAT) of 14%*" [41]. In the considered community public lighting and equipment related to agriculture represent the majority of the power consumed by the system and, according to [41], the energy price has been estimated 0,138 €/kWh.

Considering the grid sellback price, Morocco has introduced two laws, called 13–09 and 58-15, which allow anyone to produce energy from renewable sources in high, medium or low voltage and sell it to buyers with adequate connections. Unfortunately the application decree is still being drawn up and the grid sellback price is not specified [41]. In this study initially we estimated it lower than the Power Price equal to 0,04 €/kWh. This assumption has been done because in Italy the price we sell electricity to the grid (produced for example by a PV system) is about a quarter of the price we purchase energy from the grid. Since this value can't be confirmed accurately will be performed a sensitivity analysis based on the variation of this parameter.

In figure 5.16 is represented the grid modeling window on HOMER Pro

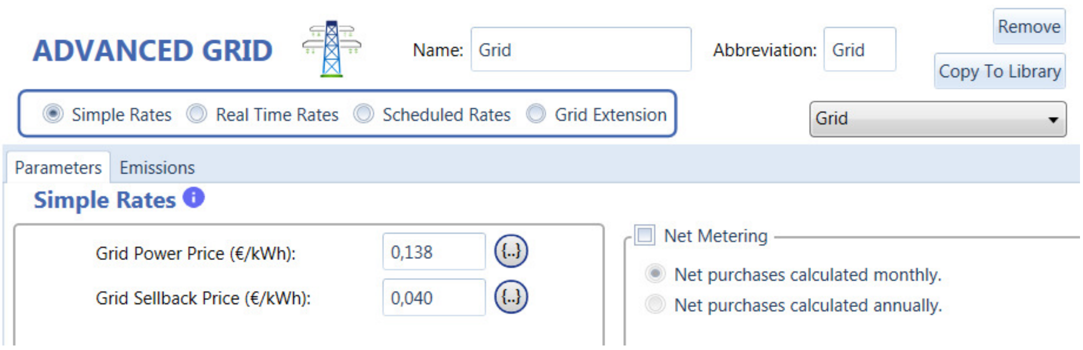


Figure 5.16: Grid modeling window on HOMER Pro

5.4 Economic assessment

In order to perform the economic analysis, HOMER requires several input data as the nominal discount rate (%), the inflation rate (%), the project lifetime (years), the system fixed capital cost (€) and the system fixed O&M costs (€/year).

The system fixed capital cost is the capital cost that occurs at the start of the project regardless of the size or architecture of the power system [37]. The system fixed capital cost is added to the total initial capital cost of the system and, therefore, to the total net present cost. Because it affects the net present cost of all system configurations in the Search Space by the same amount, it has no effect on the system rankings.

In the simulation we include in the fixed capital cost the price of anaerobic digesters, biomass storage and equipment for pre-treatment and post-treatment of the fuel. The price of these components is about 2000 €/kW according to [44]. It means that for a 50 kWe system their price will be 100.000 €.

The system fixed operation and maintenance (O&M) cost is the recurring annual cost that occurs regardless of the size or architecture of the power system [37]. The system fixed O&M costs affects the total net present cost of each system configuration equally, so it has no effect on the system rankings. In this factor we include the ordinary maintenance costs of the plant for the production of biogas. According to [38] we assume this cost equal to 0,03 €/kWh.

The project lifetime is assumed to be 20 years (average lifetime of biomass plants) and the inflation rate for Morocco in 2018 is 2,5% [45].

The discounted rate is the cost of capital, that is the expected rate of return of investors [46]:

1) Stakeholders that share private equity capital (K_e) expect to achieve a rate that is equal to the risk-free discounted rate plus a premium from the specific investment.
2) Stakeholders that share debt capital (K_d) expect to achieve a rate that is equal to the cost of the debt of the specific investment.

The discount rate can be calculated with the following equation that includes cost of equity (K_e) and the cost of debt (K_d):

$$Discount\ rate = k_e * x + k_d * (1 - x) \tag{5.3}$$

Assuming K_e equal to 4%, K_d equal to 6% and x equal to 50 % the discount rate is 5%.

In the following figure is shown the economic modeling window on HOMER.

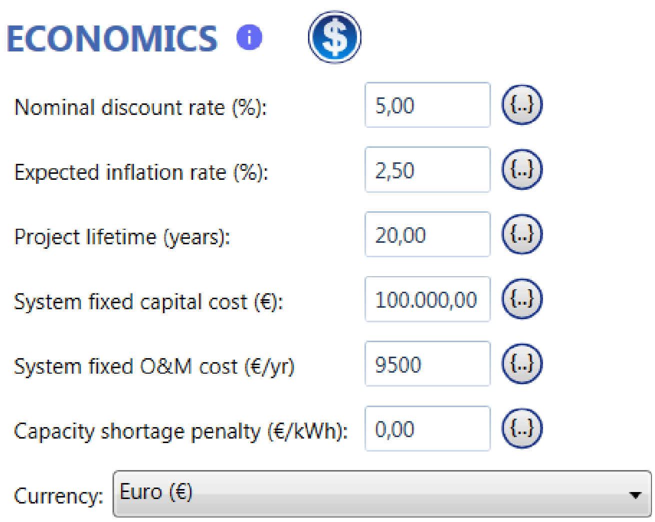


Figure 5.17: Economic modeling window on HOMER

In the simulation is possible to add some constrains as the maximum annual capacity shortage and the minimum renewable fraction. The maximum annual capacity shortage is the maximum allowable value of the capacity shortage fraction, which is the total capacity shortage divided by the total electric load. HOMER considers infeasible (or unacceptable) any system with a higher value of the capacity shortage fraction [37]. The minimum renewable fraction is the minimum allowable value of the annual renewable fraction in %.

For our simulation we decide not to include constraints.

Figure 5.18: Constrains modelling window on HOMER

5.5 System design

In the simulation are considered different types of plant powered by solar and biomass resources with the aim to find the most convenient.

1) In the first simulation is considered a plant that produce electricity thanks to a biogas generator, the main grid intervenes during the hours in which the generator doesn't cover completely the load.

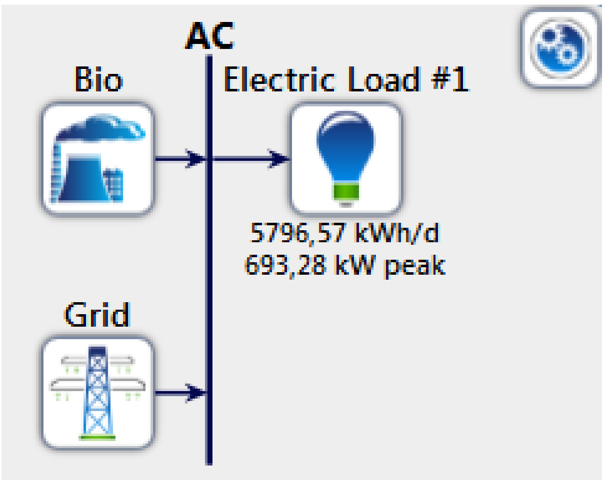


Figure 5.19: Configuration of the biogas system on HOMER

2) Subsequently it has been considered a syngas powered plant to understand which was the best for the exploitation of the available biomass. The configuration of this system is equal to figure 5.19.
3) After that have been introduced in the plant photovoltaic panels, storage batteries and a converter to exploit the solar resource.

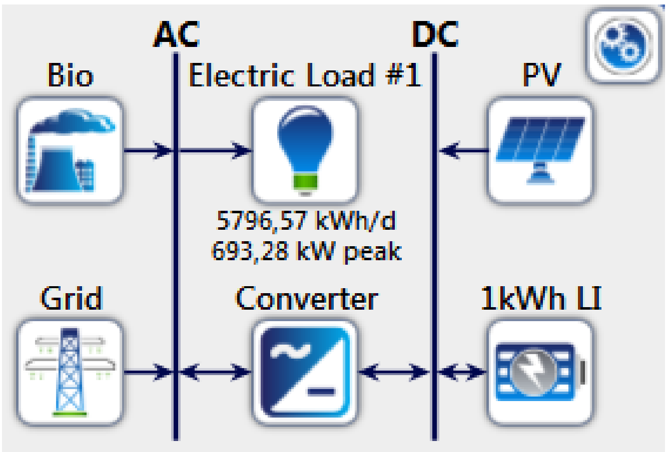


Figure 5.20: Configuration of the system with biogas and PV

6. Simulation results

The target in this project is to find the best system configuration consisting of renewable energy sources with the lowest net present cost. Economics modelling is essential in the simulation. As hybrid mini-grids have higher initial capital costs and low O&M (as explained in chapter 3) compared to system powered by conventional fossil fuels, the levelized cost of energy (LCOE) analysis must be performed in order to evaluate the economic viability throughout the entire life of the plant.

HOMER Pro finds the optimum system configuration that minimizes the net present cost (NPC) and the average cost of 1kWh (LCOE) of energy generated as both include all the costs incurred during the lifetime of the system.

On HOMER the total net present cost (NPC) is defined as the present value of all the costs the plant incurs over its lifetime, minus the present value of all the revenues (including salvage value and grid sales revenue) it earns over its lifetime. Costs include capital costs, installation costs, replacement costs, O&M costs, fuel costs, emissions penalties and the costs of buying power from the grid. It is by the total NPC value that HOMER categorizes by ranks all system configurations in the optimization results and the basis from which it calculates the total annualized cost and the levelized cost of energy (LCOE) [37].

HOMER calculates the total net present cost using the following equation:

$$NPC = \frac{C_{TOT}}{CRF(i,N)} - \frac{R_{TOT}}{CRF(i,N)} \tag{6.1}$$

Where NPC is the net present cost in €, C_{TOT} is the sum of all the costs the plant incurs over its lifetime in €, CRF is the capital recovery factor (function of the interest rate i and the project lifetime N) and R_{TOT} is the sum of all the revenues during the life of the plant [41].

$$CRF(i,N) = \frac{i*(1+i)^N}{(1+i)^N - 1} \tag{6.2}$$

Another very important output variable is the levelized cost of energy (LCOE). HOMER defines the levelized cost of energy as the average cost per kWh of useful electrical energy produced by the system. In order to calculate the LCOE, HOMER divides the annualised costs of the produced electricity by the total useful electric energy production [37].

$$LCOE = C_{ann,tot}/E_{serv} \tag{6.3}$$

Where E_{serv} is the total electrical load served (kWh/year) and $C_{ann,tot}$ is the total annualized cost of the system (€/year).

The software simulates all the possible system configurations that satisfy the electricity demand of the community under its available energy resources, discards the infeasible solutions, ranks the feasible ones according to the total net present cost and presents the feasible one with the lowest total net present cost as the optimal system configuration .

6.1 Biogas plant

In the first simulation it has been considered a plant that produces energy only using the biomass resource. The available biomass is sent into an anaerobic digester in which is produced the biogas. The biogas is used as fuel for the generator that produces electricity for the community and the grid intervenes during the hours in which the generator can't cover the energy demand. The design of this plant on HOMER is shown in figure 5.19.

Architecture					Cost					System	
		Bio (kW)	Grid (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€/yr)	Initial capital (€)	Ren Frac (%)	Total Fuel (L/yr)
		50,0	999.999	LF	€ 0,130	€ 4,32M	€ 267.859	€ 125.000	15,1	266
		50,0	999.999	CC	€ 0,130	€ 4,32M	€ 267.859	€ 125.000	15,1	266
		100	999.999	LF	€ 0,140	€ 4,63M	€ 285.952	€ 150.000	13,5	266
		100	999.999	CC	€ 0,140	€ 4,63M	€ 285.952	€ 150.000	13,5	266
		200	999.999	LF	€ 0,140	€ 4,64M	€ 283.264	€ 200.000	13,5	266

Figure 6.1: Results of the biogas plant

In figure 6.1 are represented the first results also if the program has calculated much more configurations. The best configuration includes a 50 kW biogas generator, has a NPC of 4,32 millions of euros and the renewable source cover the 15,1 % of the demand.

On HOMER is possible to obtain more detailed information about the best configuration as the cost of each component and the operating conditions of the biogas generator.

Table 6.1: Cost summary

Component	Capital (€)	Replacement (€)	O & M (€)	Salvage (€)	Total (€)
Biogas genset	25.000	216.521	4.120	-4.940	336.790
Grid	0	0	3.888.000	0	3.888.000
Anaerobic digester	100.000	0	0	0	100.000
System	125.000	216.521	3.892.000	0	4.324.845

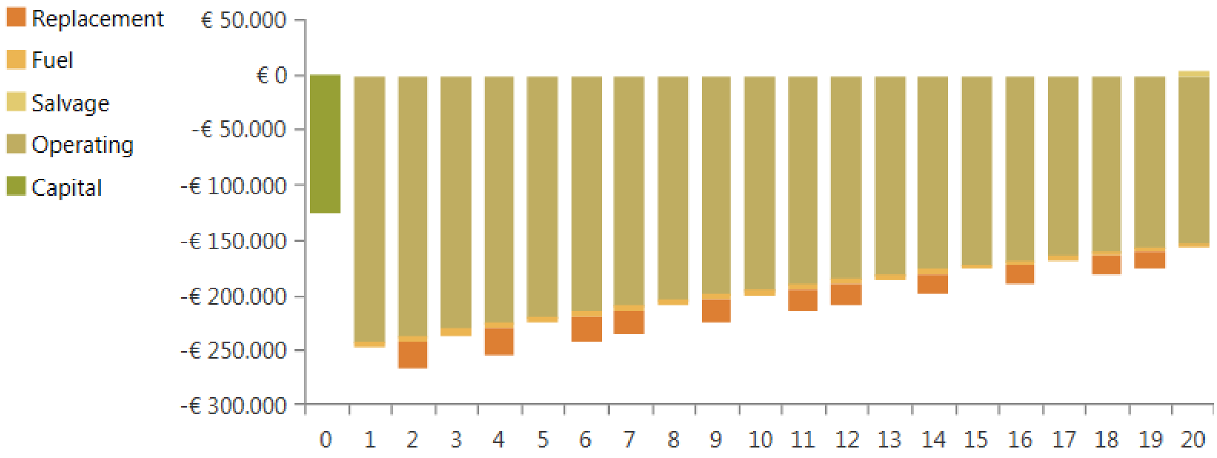


Figure 6.2: Discounted cash flow of the system

As shown in table 6.1 the expense needed to buy electricity from the grid is the factor that most influences the cost summary. This happens because unfortunately the biomass resource is limited and is able to cover only the 15 % of the demand.

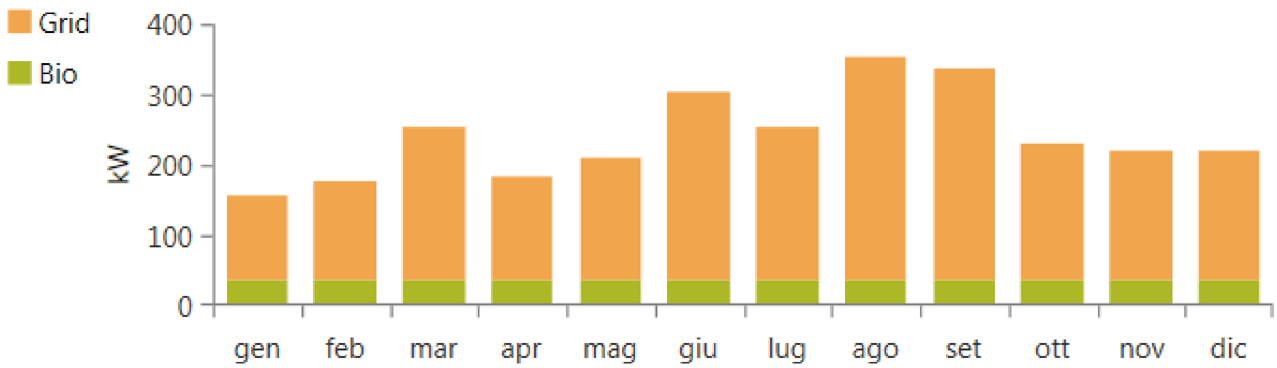


Figure 6.3: Monthly average electric production

In the following table are summarized the information about the operating conditions of the generator obtained by HOMER.

Table 6.2: Biogas generator operating conditions

Quantity	Value
Hours of operation (hours/year)	8.760
Number of starts (starts/year)	1
Capacity factor (%)	72,8
Electrical production (kWh/year)	318.858
Mean electrical output (kW)	36,4
Fuel consumption (tons/year)	266
Specific fuel consumption (kg/kWh)	0,585
Fuel energy input (kWh/year)	932.575
Mean electrical efficiency (%)	34,2

As shown in table 6.2 in this configuration the generator works continuously for every hour of the year with a mean electrical power of 36,4 kW and a mean electrical efficiency of 34,2 %. In these working conditions the system consumes all the available biomass.

The following image shows the operating conditions of the system during a typical week.

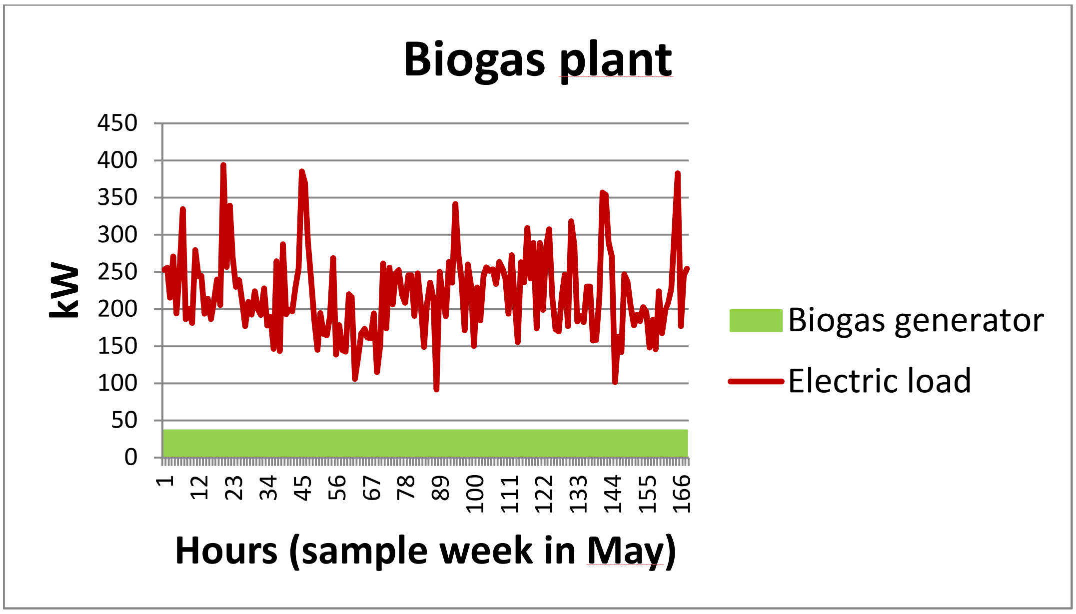


Figure 6.4: Operating condition of the generator during a sample week

6.2 Syngas plant

During the simulation it has been also considered a syngas plant that exploits the available biomass with the aim to find which type of plant is more convenient. The syngas is a mixture of several gases such as H2, CO, CH4, CO2 and N2 in different quantities and is produced by a process called "*gasification*"; the gasification is a complex chemical and physical process through which is realized the partial oxidation at high temperature of carbon compounds in the presence of air and / or water vapor [47].

In order to use the syngas on HOMER, is necessary to make some changes. According to [48] we assume that the produced syngas is composed by 15 % of H2, 25 % of CO, 10% of CO2 , 10% of H2O, 5% of CH4 and 40% of N2 with a lower heating value of 5 MJ/kg. The gasification ratio has been set 2,2 according to [47] and the carbon content is 10%. The generator has the same efficiency of the generator used for the biogas but as the LHV is lower, it will be higher the fuel consumption. The O&M costs are higher and in the system fixed capital cost has been introduced the price of the gasifier instead of the price of the anaerobic digester. We assume a price for the plant of gasification of 3500 €/kW and the cost of plant maintenance of 0,04 €/kWh according to [49]. Using these variations it is possible to perform the simulation with the new type of plant.

Architecture					Cost				System	
		Syngas (kW)	Grid (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€/yr)	Initial capital (€)	Ren Frac (%)	Total Fuel (L/yr)
		50,0	999.999	LF	€ 0,133	€ 4,40M	€ 269.615	€ 175.000	14,5	266
		50,0	999.999	CC	€ 0,133	€ 4,40M	€ 269.615	€ 175.000	14,5	266
		10,0	999.999	LF	€ 0,139	€ 4,62M	€ 284.513	€ 155.000	4,14	74,5
		10,0	999.999	CC	€ 0,139	€ 4,62M	€ 284.513	€ 155.000	4,14	74,5
		100	999.999	LF	€ 0,142	€ 4,69M	€ 286.605	€ 200.000	13,3	266

Figure 6.5: Results of the syngas plant

The optimal size of the generator is the same for the two types of plants but the syngas plant has an higher NPC, an higher LCOE and a lower renewable fraction compared to the biogas plant.

Table 6.3: Cost summary

Component	Capital (€)	Replacement (€)	O & M (€)	Salvage (€)	Total (€)
Syngas genset	25.000	216.516	5.493	-4.900	338.125
Grid	0	0	3.914.250	0	3.914.250
Gasifier	150.000	0	0	0	150.000
System	175.000	216.516	3.919.742	-4.900	4.402.375

As for the biogas plant the greatest expense is due to the energy bought by the grid. The information about the operating conditions of the syngas generator are reported in the following table.

Table 6.4: Syngas generator operating conditions

Quantity	Value
Hours of operation (hours/year)	8.750
Number of starts (starts/year)	2
Capacity factor (%)	70
Electrical production (kWh/year)	306.400
Mean electrical output (kW)	35
Fuel consumption (tons/year)	266
Specific fuel consumption (kg/kWh)	1,91
Fuel energy input (kWh/year)	814.060
Mean electrical efficiency (%)	37,6

The electrical production is slightly lower compared to the biogas generator also if it works with higher efficiency. Comparing the results of the two plants it is more convenient to exploit the biomass available through a biogas plant than the one just proposed.

6.3 Photovoltaic and biogas system

As the available biomass is low and it is able to cover about the 15% of the demand, are introduced in the plant photovoltaic panels, storage batteries and a converter. This simulation needs to understand if the introduction of these new components can have positive impacts on the overall system. The design of this new configuration is shown in figure 5.20.

PV (kW)	Bio (kW)	1kWh LI	Grid (kW)	Converter (kW)	Dispatch	COE (€)	NPC (€)	Operating cost (€/yr)	Initial capital (€)	Ren Frac (%)
423	50,0		999.999	283	LF	€ 0,114	€ 3,94M	€ 194.996	€ 886.323	42,2
423	50,0		999.999	283	CC	€ 0,114	€ 3,94M	€ 194.996	€ 886.323	42,2
419	50,0		999.999	281	LF	€ 0,114	€ 3,94M	€ 195.415	€ 879.813	42,0
419	50,0		999.999	281	CC	€ 0,114	€ 3,94M	€ 195.415	€ 879.813	42,0
433	50,0		999.999	290	LF	€ 0,113	€ 3,94M	€ 193.797	€ 905.214	42,7

Figure 6.6: Results of the photovoltaic-biogas plant

In the image are reported only the first configurations also if the system has calculated much more of these. Looking at the first row of figure 6.5, the best configuration is composed by a 423 kW photovoltaic system, a 50 kW biogas generator and doesn't include storage system. It has a NPC lower than the other two proposed systems as well as the LCOE. The renewable fraction increase a lot reaching a value of 42,2 %.

This type of simulation proposes a dispatch strategy LF (load following). Under the load following strategy, when a generator is needed, it produces only enough power to meet the demand. Load following tends to be optimal in systems with a lot of renewable power that sometimes exceeds the load [37]. The other type of strategy is the cycle charging CC. Under the cycle charging strategy, whenever a generator is required, it operates at full capacity, and surplus power charges the battery bank. Cycle charging tends to be optimal in systems with little or no renewable power [37].

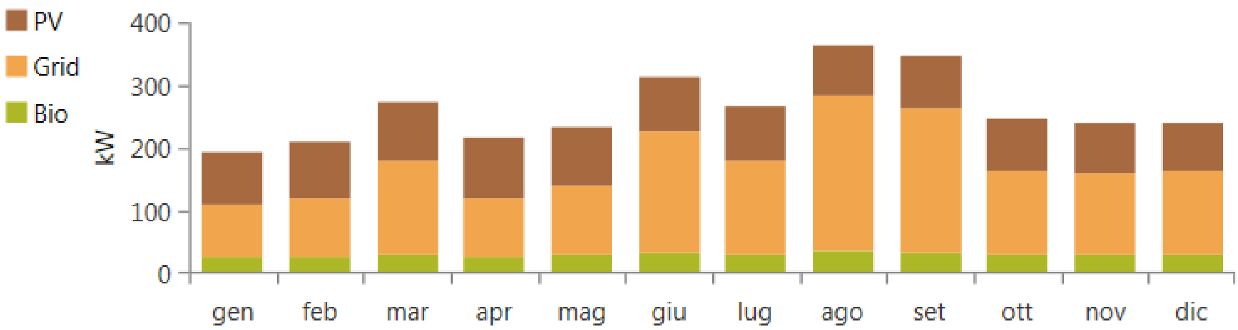


Figure 6.7: Monthly average production

In figure 6.7 it can be seen that, during the months in which the consumption is lower, the contribution of the renewables is higher, while when the demand increases, such as in August or September, the energy bought from the grid increases a lot and this has negative consequences on the NPC.

Table 6.5: Production by components

Production	kWh/year	%
PV	751.921	32,7
Biogas genset	267.562	11,6
Grid purchases	1.277.911	55,6

As the reduced availability of biomass the contribution of biogas is very low, while the photovoltaic is able to cover 32,7 % of the demand.

Table 6.6 : Cost summary

Component	Capital (€)	Replacement (€)	O & M (€)	Salvage (€)	Total (€)
Biogas genset	25.000	177.378	3.457	-3.067	283.402
PV	718.903	0	185.655	-147.992	756.565
Grid	0	0	2.705.828	0	2.705.828
Other	100.000	0	0	0	100.000
Converter	42.420	33.366	22.170	0	97.926
System	886.323	210.714	2.917.111	-151.060	3.943.722

In this configuration, the price at which electricity is purchased from the grid is again the biggest expense of the plant even if it is significantly reduced compared to the system in which only the biogas genset operates.

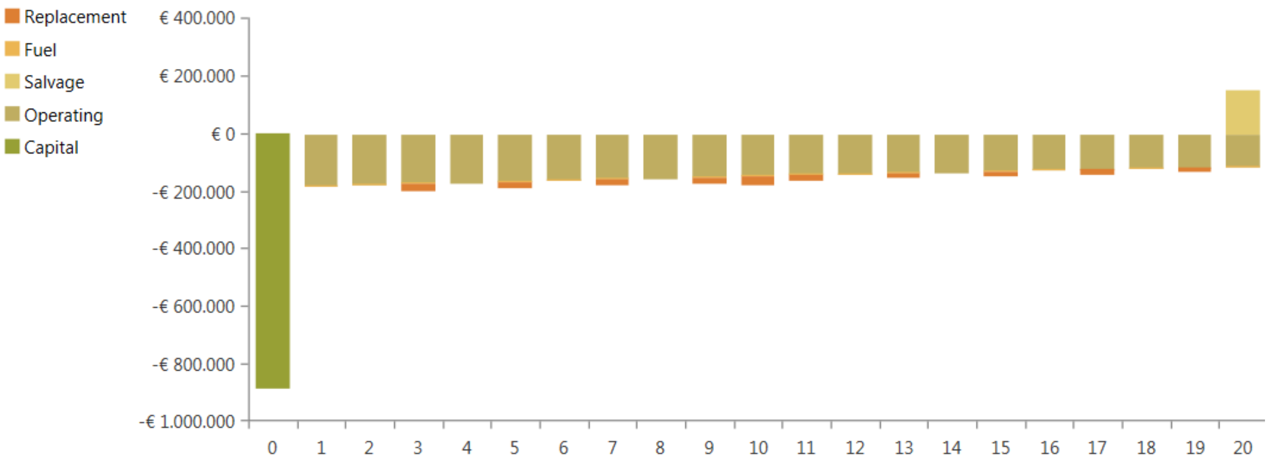


Figure 6.8: Discounted cash flow

HOMER calculates more accurate information about the operating conditions of each component. The characteristics of the biogas generator are shown in table 6.7

Table 6.7: Biogas generator operating conditions

Quantity	**Value**
Hours of operation (hours/year)	7.351
Number of starts (starts/year)	424
Capacity factor (%)	61,1
Electrical production (kWh/year)	267.562
Mean electrical output (kW)	36,4
Fuel consumption (tons/year)	224
Specific fuel consumption (kg/kWh)	0,585
Fuel energy input (kWh/year)	782.575
Mean electrical efficiency (%)	34,2

In this configuration decrease the hours of operation, the capacity factor, the electrical production and the fuel consumption of the generator compared to the solution powered only by biogas. This happens because during the day the demand can be covered completely by the photovoltaic and the generator is used mainly during the night or in the early morning.

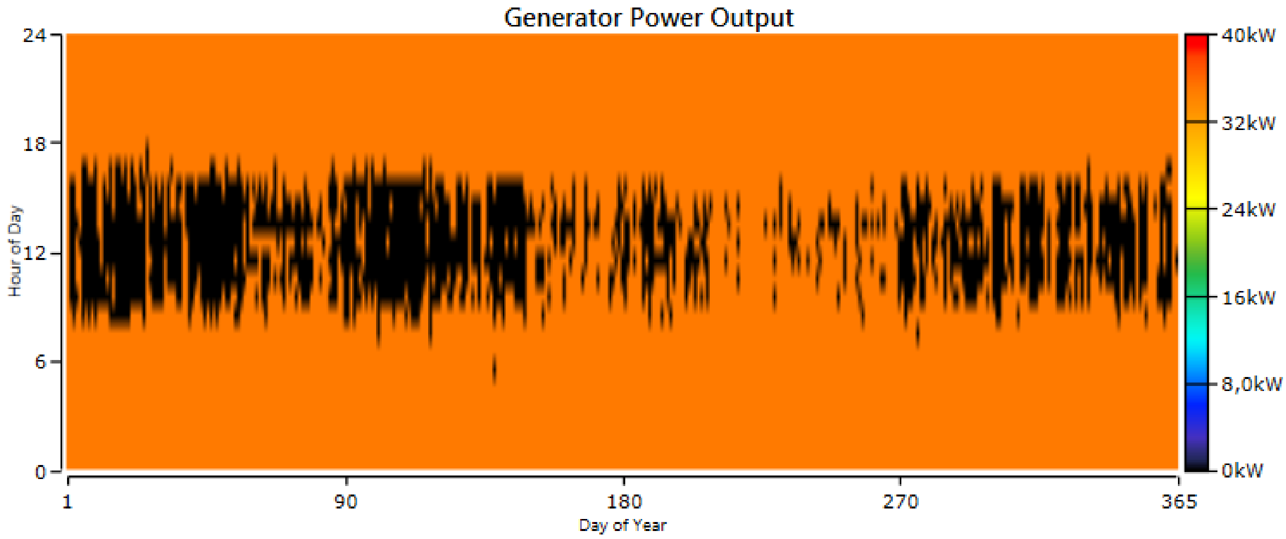


Figure 6.9: Generator power output

Figure 6.9 confirms what just said, in the central hours of the day the engine is switched off, in particular during the months with low demand.

The same information about the photovoltaic panels are available.

Table 6.8: PV operating conditions

Quantity	Value
Rated capacity (kW)	423
Mean output (kW)	85,8
Mean output (kWh/day)	2.060
Capacity factor (%)	20,3
Total production (kWh/year)	751.921
PV penetration (%)	35,5
Hours of operation (hours/year)	4.377

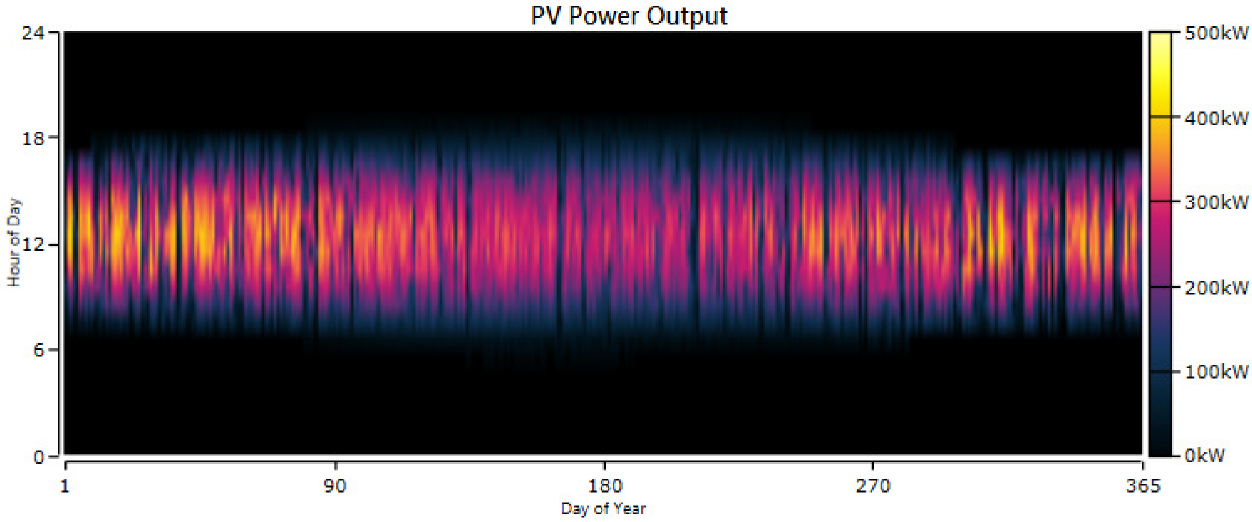


Figure 6.10: PV power output

Obviously the PV system produces energy only during the central hours of the day when the solar radiation is available. Finally are represented the operating conditions of the grid.

Table 6.9: Grid information

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Peak demand (kW)	Net energy cost (€)
January	60948	18686	42263	329	7663
February	63278	13661	49617	319	8185
March	111899	5864	106034	442	15207
April	67210	15432	51778	350	8657
May	84268	9987	74281	405	11229
June	139392	2010	137383	596	19155
July	111285	3940	107345	506	15199
August	184687	743	183904	657	25451
September	164323	1050	163273	617	22634
October	99252	6196	93056	413	13448
November	93340	8389	84952	371	12545
December	98068	8510	89558	406	13192
Annual	1277911	94468	1183443	657	172572

Table 6.9 confirms what said previously; during the months in which the demand increases, the energy purchased from the grid increases while the energy sold to the grid decreases with negative consequences on the NPC of the system.

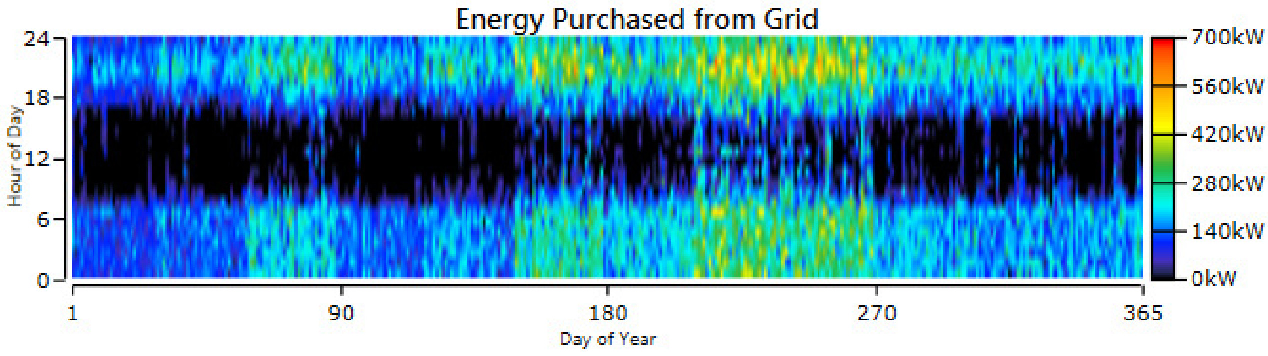


Figure 6.11: Energy purchased from the grid

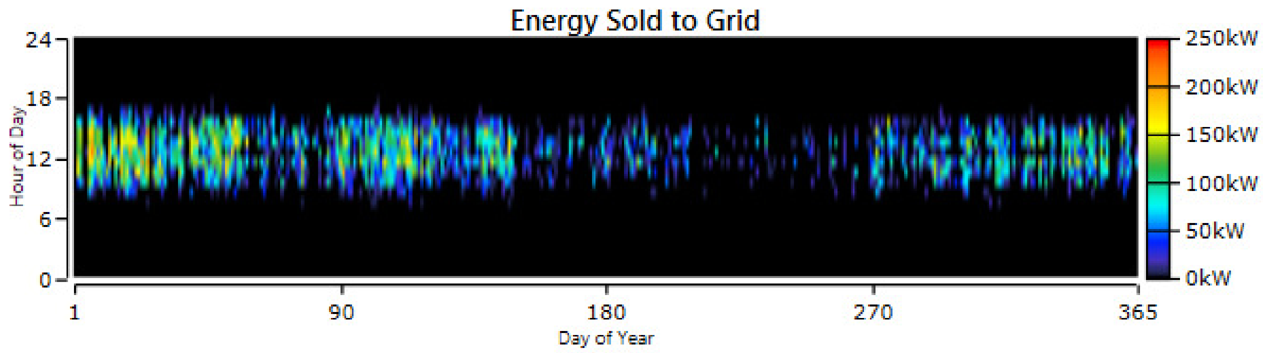


Figure 6.12: Energy sold to the grid

The photovoltaic is able to cover the consumptions during the central hours of the day and can sell the extra energy produced at the grid reducing the NPC of the system. The power is bought from the grid during the night and in the early morning, in the same period in which works the biogas genset. It happens because the engine isn't able to satisfy the electrical demand in these periods because of poor availability of the resource. These information are confirmed in the following image that represents the operating conditions of the system during a typical week.

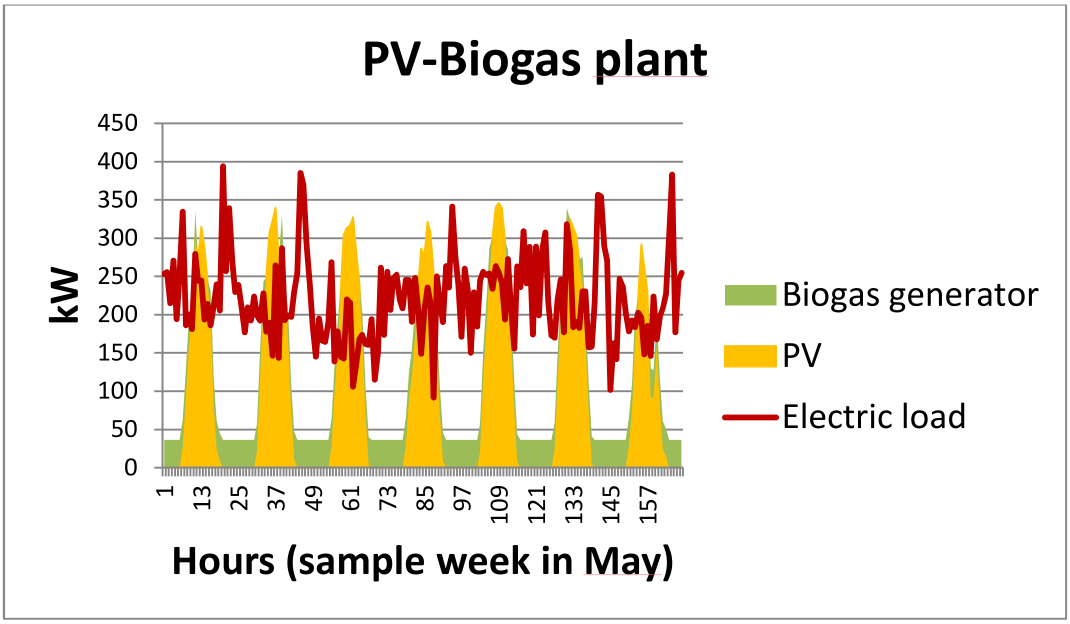


Figure 6.13: Operating condition of the generator during a sample week

This plant, powered by solar and biomass resources, has better characteristics than the two presented previously. The introduction of photovoltaic entails higher initial costs but is a more convenient investment as it considerably reduces the energy bought by the grid (higher expense of this system). This can be seen from the fact that the NPC is significantly lower as well as LCOE. Another big advantage is the increase of the renewable fraction, in particular thanks to the great availability of solar resource. The extra energy produced is sold to the grid, especially in the months with low consumption, further reducing the NPC. In this configuration the contribution of the biomass is slightly low because the generator is used only during the night and is not consumed all the available biomass.

Table 6.10: comparative results table

	Biogas plant	Syngas plant	Biogas +photovoltaic plant
NPC (M€)	4,32	4,4	3,94
LCOE (€/kWh)	0,131	0,134	0,114
Renewable fraction (%)	15,1	14,5	42,2
Initial capital (€)	125000	175000	886323
Operating Cost (€/year)	267859	269615	194996
PV size (kW)	0	0	423
Generator size (kW)	50	50	50
Biomass consumption (tons/year)	266	266	224

6.4 Sensitivity analysis

In the last simulation has been taken into account possible variations of two parameters that has been used previously. The two parameters are the sell back price (the price the system sells the extra energy to the grid) and the available biomass. HOMER performs the sensitivity analysis taking as input several values of these two factors. For each couple of values it calculates the most feasible solution with the same procedure carried out in the previous simulations. During the simulation we move away from the nominal values from + 50% to - 50% for the grid sellback price and from + 20 % to – 20 % for the available biomass.

Table 6.11: Sensitivity parameters

Grid sellback price (€/kWh)	Available biomass (tons/day)
0,02	0,6
0,03	0,65
0,04	0,73
0,05	0,8
0,06	0,9
0,07	

In the following table will be reported the results of the sensitivity analysis, for each couple of values are indicated the NPC, the LCOE, the size of the components and the renewable fraction. So it is possible to understand in which way to change the best system configuration when the two parameters vary. We expect an increase in the renewable fraction and a decrease in the NPC as the two values increase.

Table 6.12: Results of the sensitivity analysis

Sellback rate (€/kWh)	Biomass availability (ton/day)	PV (kW)	Bio (kW)	LCOE (€/kWh)	NPC (M€)	Renewable fraction (%)
0,02	0,6	439	50	0,112	3,92	42,4
0,03	0,6	463	50	0,111	3,91	43,8
0,04	0,6	497	50	0,109	3,89	45,6
0,05	0,6	593	50	0,103	3,86	49,9
0,06	0,6	560	50	0,103	3,89	47,6
0,07	0,6	732	50	0,0933	3,83	54,2
0,02	0,65	427	50	0,111	3,88	42,9
0,03	0,65	465	50	0,11	3,87	44,8
0,04	0,65	501	50	0,107	3,85	46,8
0,05	0,65	593	50	0,102	3,82	50,9
0,06	0,65	534	50	0,103	3,85	47,4
0,07	0,65	680	50	0,0946	3,79	53,2
0,02	0,73	385	50	0,113	3,87	40,2
0,03	0,73	404	50	0,112	3,86	41,1
0,04	0,73	423	50	0,111	3,84	42,2
0,05	0,73	461	50	0,109	3,83	44
0,06	0,73	532	50	0,105	3,8	47,2
0,07	0,73	673	50	0,0937	3,76	54,1
0,02	0,8	367	50	0,112	3,82	40,7
0,03	0,8	401	50	0,111	3,81	42,3
0,04	0,8	414	50	0,11	3,79	43,1
0,05	0,8	455	50	0,107	3,78	45
0,06	0,8	521	50	0,104	3,75	47,9
0,07	0,8	666	50	0,093	3,7	55
0,02	0,9	367	50	0,11	3,74	42,6
0,03	0,9	385	50	0,109	3,73	43,5
0,04	0,9	395	50	0,108	3,72	44
0,05	0,9	443	50	0,106	3,7	46,3
0,06	0,9	483	50	0,1	3,68	49,6
0,07	0,9	655	50	0,0904	3,63	56,2

As the sellback rate increases, the size of PV grows up as well as the renewable fraction. This happens because it becomes more convenient selling energy to the grid. The higher initial costs due to a larger size of photovoltaic are covered during the life of the plant thanks to the reduced use of the grid and revenues from the sale of energy.

The same behavior occurs when the available biomass increases; as the resource grows, the NPC decreases thanks to a reduced use of the grid and obviously increases the fraction of renewables.

The table shows that the sellback price is a very important parameter for the sustainability of the system, a small increase in this parameter generates significant variations in the size of the photovoltaic and on the NPC. It confirms what just said in chapter 3: government support and incentives on these types of systems can strongly encourage their development.

7. Conclusion

The aim of the thesis was to correctly size an energy production plant for the community of Toudgha El Oulia exploiting local resources. These types of plants have been frequently used in Morocco in the last few years allowing to reach an electrification rate in the countryside of over 99%. As very often these systems risk to fail from the economic point of view, the correct sizing of the components is essential.

Initially the available resources and the electric load of the community were estimated.This information was used as input for the HOMER pro, software used for the optimal sizing of the system. Subsequently the technical and economic parameters of the various components included in the plant were also assessed.

Thanks to the use of HOMER, it has been possible to evaluate different types of biomass and solar powered plants. The aim was to find the type of plant that would exploit renewable resources at the lowest cost, managing to meet the consumption of the community.

In the first simulations, only the biomass obtained from the cultivation of dates, olives and cereals within the community to produce energy was used. The simulations have shown that the best plant for the exploitation of biomass is composed by an anaerobic digester and a biogas generator. In fact, this system results in a lower net present cost and a greater use of the resource compared to a plant powered by syngas that has been simulated as well.

Unfortunately, due to the lack of biomass availability in the area, the biogas system is able to cover only 15% of the demand, while the remaining part is purchased from the grid with high costs.

In the following simulation, photovoltaic panels, batteries for the accumulation and a converter were introduced to exploit the solar resource. The results of this simulation have shown positive effects by reducing the NPC, the LCOE and significantly increasing the use of renewables. The great advantage of this system has been the significant reduction of the energy bought by the grid; this is the factor that affects in the worst way the net present cost.

A sensitive analysis carried out later showed how this plant is strongly influenced by the price at which it is possible to sell the extra energy produced to the grid. For this reason it is very important the support of the government for the development of such systems.

Thanks to HOMER it has been possible to evaluate different types of plants and find the most convenient for the community under examination. The use of this program is of considerable importance for the correct planning of these projects and requires accurate estimates to have valid results.

The continuous development of these systems in recent years has allowed to bring electricity to many rural areas of the planet improving the living conditions of many people and allowing greater use of renewable sources.

The improvement of renewable technologies is essential to ensure the continuous development of mini-grids worldwide. Components with greater efficiencies and lower costs can make these systems more economical and attract investments from private companies or public bodies.

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