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B. El Amrani

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## Feasibility evaluation of a Hybrid Renewable Power Generation System for sustainable electricity supply in a Moroccan remote site

H. El-houari<sup>(a,b,e)</sup>, A. Allouhi<sup>(a)</sup>, S. Rehman<sup>(c)</sup>, M.S. Buker<sup>(d)</sup>, T. Kousksou<sup>(e)</sup>, A. Jami<sup>(a)</sup>, B. El Amrani<sup>(b)</sup>

<sup>(a)</sup>Ecole Supérieure de Technologie de Fès, U.S.M.B.A, Route d'Imouzzer, BP 242, Fez, Morocco

<sup>(b)</sup>Ecole Normale Supérieure Fès de Fès, U.S.M.B.A, Route Bensouda, BP. 5206, Fez, Morocco

<sup>(c)</sup>Center for Engineering Research, King Fahd University of Petroleum and Minerals, Dhahran-31261, Saudi Arabia

<sup>(d)</sup> Energy and Semiconductors Research Group, BITAM, Konya NEU University, Konya, Turkey

<sup>(e)</sup>Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Electrique (SIAME), Université de Pau et des Pays de l'Adour – IFR – A. Jules Ferry, 64000 Pau, France

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### Abstract

Renewable energy sources **can constitute an important alternative** solution to fulfil the energy requirements of isolated rural areas in the near future. Although power supply to these areas poses a great challenge, off-grid hybrid energy systems exploiting renewable sources might pave way towards more sustainable solution. In this paper, various combinations of standalone Hybrid Renewable Energy Systems (HRES) are technically and financially assessed to ensure continuous power supply for 10 houses in a remote village, Tazouta located in the Moroccan Fez-Meknes region. The renewable energy sources considered are solar, wind and biomass. Findings reveal that for an average energy requirement of 91.38 kWh/day and a peak load of 6.44 kW, unit energy cost of the optimum configuration scenario A (PV-Wind-Biomass-Battery) is found to be 0.2 \$/kWh and hence, design, development and implementation of the proposed system imply a promising solution for energy supply security. For a 100% renewable energy penetration, the HRES produces electricity according to the following distribution: 11% from wind, 41 % from solar and 48 % from biomass. From an environmental perspective, the proposed HRES is able to reduce up to 26.48 tons **and 28.814 tons of CO<sub>2</sub> equivalent greenhouse-gas emissions annually compared to the grid extension and conventional diesel generator only scenarios, respectively.**

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**Keywords:** off-grid; Hybrid system; feasibility; HOMER; Morocco

## Nomenclature

$m_i$	amount of manure per head [-]	$P_{out}$	power output of the wind turbine [kW]
$Z_{anem}$	anemometer height [m]	$f_{PV}$	Rated PV capacity [%]
$V_b$	annual volume of biogas received in manure [m <sup>3</sup> ]	$G_{ref}$	solar energy incident on the photovoltaic [1kW/m <sup>2</sup> ]
A	area in [m <sup>2</sup> ]	$e_{bi}$	specific heat energy obtained from the manure [kWh/m <sup>3</sup> ]
$D_d$	battery's depth of discharge [-]	$B_c$	storage capacity of the battery [Ah]
$V_{bi}$	biogas production of the material organic [m <sup>3</sup> /tons]	$K_T$	temperature coefficient of the maximum power [-]
$K_e$	coefficient of electric efficiency of the plant [-]	$T_{ref}$	temperature on the photovoltaic at 25°C [°C]
$K_{OMi}$	content of organic matter [-]	$N_i$	total annual manure [tons]
$D_a$	daily autonomy [-]	A	total number of animals [-]
$\rho$	density of air [kg/m <sup>3</sup> ]	$T_C$	total operation hours of the plant throughout the year [-]
$D_{ele}$	daily electrical energy demand [kWh/day]	V	wind velocity [m/s]
$\rho_{water}$	density of water [1000 kg/m <sup>3</sup> ]	$U_{anem}$	wind velocity at anemometer [m/s]
$K_{DMi}$	dry matter content in manure [-]	$U_{hub}$	wind velocity at the hub height [m/s]
$\eta_b$	efficiency of the battery [%]	<b>Abbreviations</b>	
$\eta_{inv}$	efficiency of the converter [%]	AC	Alternative Current
$\eta_g$	efficiency of generator [%]	BAD	Bank of Africa of the Development
P	electric power generation from the biomass [kW]	DC	Direct Current
$Z_{hub}$	hub height of the wind turbine [m]	HRES	Hybrid Renewable Energy Systems
$C_p$	performance density of air [-]	IEA	International Energy Agency
$E_b$	potential of obtainable energy from manure [kWh]	ONE	National Office of Electricity
$P_{PV}$	power at the output of the cell [kW]	NREL	National Renewable Energy Laboratory
		PV	Photovoltaic
		WT	Wind Turbine

## 1. Introduction

Exponentially growing global population and equally increasing energy needs have become a matter of social, economic and environmental concern as our planet's resources dwindle. Socially, the imbalance between the energy demand and the supply is somehow responsible for social deterioration. It can further be inferred from the world energy statistics that there are approximately 1.3 billion population currently without any access to the utility grid. Moreover, of these, more than 85% of the inhabitants resides in rural sector (Allouhi et al., 2019). In Africa, there are about 620 million people without electricity and almost two-third of the Continent has unsteady energy infrastructure (Ouedraogo, 2017). According to the Bank of Africa for the Development (BAD), about 315 million inhabitants are thought to get access to electricity, which makes only 30% of the overall African population having access to the electrical network.

In the current scene, the production of electrical power is based essentially on non-renewable fossil fuel resources that cause significant environmental issues including alarming level of greenhouse gases dumped into the atmosphere (Allouhi et al., 2015). In accordance with the International Energy Agency (IEA) report, temperature of the earth is expected to increase by 3.5°C in the 21<sup>st</sup> century (Rajbongshi et al., 2017). Owing to technological advancement and commercial acceptance of renewable power systems, utilisation of these clean and green technologies for distributed and remotely located applications has become effortless and cost-effective (Allouhi, 2020). Renewable sources such as wind, solar, hydro, biomass are abundant in nature, regenerate naturally, and have no political and geographical boundaries and hence, can be used everywhere either through grid connected or stand-alone applications. Hybrid systems comprise more than one source of energy and are more reliable than a single-source power system (Allouhi, 2019; Billinton, 2005; Rehman et al., 2012). Likewise, standalone hybrid systems (SAHS) based on renewable energy sources can ensure power generation permanently (Shahzad et al., 2017). This scenario proves the concept for the deployment of autonomous power systems in Africa with abundant renewable source.

In the recent times, hybrid power systems and energy storage techniques have been the focal point of many energy research and development activities. Several studies have been carried out based either on a single source or hybrid systems (several renewable sources). Khan and Iqbal (2005) studied the feasibility of stand-alone hybrid systems in Newfoundland supported by storage technologies (batteries, and electrolyser-tank). Authors reported a wind-diesel-

battery hybrid power system claiming the best convenient configuration for an isolated grid with energy utilization of 25 kWh per day. Singh et al. (2017) studied a hydrogen fuel cell (HFC) and hybrid solar power system to fulfil the annual energy demand of a university research building. The study revealed that the proposed system is able to supply 20.7 MWh of energy annually. Qolipour et al. (2017) has presented a complete study on the power supply of the electric load for the Hendijan region in south-western Iran. The results showed that the studied case could generate 3.15 GW annually and store 31,680 kg of hydrogen based on a PV/wind hybrid system with a hydrogen storage tank. Sen and Bhattacharyya (2014) analysed the optimum strategy for hybrid technology in order to meet electricity requirement of an isolated rural zone in India. Four types of energy sources (hydropower, PV, wind turbines and biodiesel generators) were envisaged economically and the designed system was found to be more profitable compared to grid extension. From the same sources, seven different system configurations as well as a comparison between the autonomous PV/Diesel/Wind system with and without storage was examined for the ambient conditions of Johor Bahri, Southern Peninsular Malaysia. Despite that, the proposed designs were not competitive against the fuel-only configuration, they were able to mitigate up to 34.5% of greenhouse gasses (Ngan and Tan, 2012). Rajbongshi et al. (2017) performed an optimization of a biomass-diesel-PV hybrid system for an energy requirement of 178 kWh/day and a peak load of 19 kW and found the cost of energy as 0.145 \$/kWh. Kumar and Deokar (2018) conceived a wind-solar-diesel system for an ATM machine in India for an isolated location and reported the cost of energy as 0.307 \$/kWh, net present cost of 82,775 \$, and initial capital cost of 48,384 \$. Amutha and Rajini (2015) proposed a wind-solar-hydro hybrid system to ensure continuous supply of energy throughout the year. The proposed system was able to fulfil energy demand of the village with 25 kWh/day for commercial and industrial loads, 15kWh/day for irrigation, 35 kWh/day for base transceiver station and 252 kWh/day for domestic household loads. Shahzad et al. (2017) presented a technical-economic evaluation of an off-grid solar-biomass system for agricultural and residential utilizations in Pakistan. Authors reported that the system was more convenient for small communities with cost of energy of 5.51 PKR/kWh. Halabi et al. (2017) assessed the performance of two power stations located in Pulau Banggi and Tanjung Labian, Sabah, Malaysia. From technical aspect, PV/Diesel/Battery hybrid system was the most favourable in their study. El-Houari et al. (2019) proposed a design of an autonomous photovoltaic system to ensure the electrical demand of a rural house located in the Moroccan village of Tazouta. It was found that a PV-DG combination leads to the optimum scenario with the lowest electricity cost estimated at to 0.356 \$/kWh. Also, the

optimum configuration with lower PV penetration level could achieve up to 42.38% of the total power requirement from renewables. Most recent attempts similar to previous investigations can be found in (Baseer et al., 2019; Nag and Sarkar, 2018; Rehman et al., 2020).

The hybrid power system sizing and optimization tools are very well developed and have been used successfully globally. Among these software and modelling tools, HOMER is largely utilized for simulating renewable based hybrid technologies accurately (Shezan et al., 2016). It is mainly exploited for pre-feasibility studies and has the capability of handling several technologies including hydroelectricity, PV, wind, biomass with a large meteorological database permitting its usage in various zones around the world. Currently it is widely used by more than 120,000 users in more than 193 countries. Further, among several approaches for techno-economic analysis relating with acquiring, operating, maintaining and disposing cost of a system, HOMER is useful for techno-economic optimization of the hybrid systems based on least net present cost (NPC), (Kousksou et al., 2015).

As observed from the cited literature, numerous investigations have proposed feasible optimum configurations of hybrid renewable systems to meet the energy needs of various isolated locations. Accordingly, the site specifications, available energy resources, and economic considerations are the main determinants in the optimization process of the feasible hybrid power systems. Also, the production of energy through renewables is strongly influenced by climatic conditions (Buker et al., 2014).

Various locations in Morocco have high intensity of renewable sources for longer durations that can be utilized for clean power generation at highly competitive costs. Assessment studies and identifying optimum configurations of hybrid renewable power generation systems are crucial for decision-making.

The present research proposes a standalone Hybrid Renewable Energy System to supply electricity to a remote Moroccan area. Biomass, solar and wind are the available power sources in the targeted zone and therefore, it is within the interest of this paper to assess the feasibility of various combinations of these resources to achieve the optimum implementation option. The techno-economic optimization is carried out using HOMER software by considering actual energy loads of the remote village of Tazouta, Morocco. Simulations are based on a real time data with updated market costs. Moreover, meteorological data of the region and the village's resources are used as the problem inputs to examine the likely

combination of renewable energy system. In terms of discussing different scenarios, this study therefore can bring useful conclusions to the research community in this aspect.

As demonstrated by the presented literature review, the applicability of hybrid renewable energy systems for powering remote areas was undertaken for several case studies worldwide. However, the examined system based on the combination of PV-Wind-Biomass renewable sources under the Moroccan context have not been assessed before, despite the considerable resources the country enjoys. As such, useful guideline related to implementation of hybrid energy systems is presented which, can help policymakers in reaching the targets of the national energy strategy. The paper reviews not only the financial and energetic benefits of such systems but also sheds light on the positive environmental impact that can bring through emissions mitigation potential comparing the renewable hybrid system with various electrification scenarios.

## **2. Methodology**

The adopted methodology in this work is shown in **Fig. 1**. The **proposed** system is an autonomous hybrid system containing biomass generator, solar PV field and wind turbines as power generation options. A data collection and preliminary assessment of the village characteristics in terms of energy demand, available energy infrastructure, current and future renewable projects underway in the region have been conducted. System configuration is determined and optimum size of each power generation technology is achieved based on the local economic and energy requirement inputs.

### **2.1. Site description**

The concerned site appertains to the Sefrou zone, the rural village of Tazouta which is located in the Middle-Atlas of Fes-Meknes region of Morocco. This area is located 36 km from the town of Sefrou and 65 km from the city of Fez. The total area of Tazouta village is 174 square kilometers, which is equivalent to 4.36 % of the area of the Sefrou zone. The ground of this region consists of a range of mountains, plains and plateaus characterized by sufficient underground water source. The studied site is a small residential zone belonging to Tazouta.

### **2.2. Load assessment**

According to the data collected from the Moroccan National Office of Electricity (ONE), the electricity consumption of Tazouta was approximately 18 GWh in 2016. The electrical

consumption covers several end-uses (**Fig. 2**). It is obvious that the household takes the majority of the load by 72%, public lighting in second position with 13%, commercial use by 8%, agriculture with 4% and the administrative state by 2% and industrial consumption with 1%, respectively.

The proposed system seems to be a promising option to supply households with electricity need for domestic purposes. The studied zone consists of 10 separated traditional houses which are already connected to the electricity grid. However, the main purpose of this manuscript is to analyse the possibility of implementing centralized stand-alone HRES in similar rural regions without access to electricity network.

**Fig. 3** shows the distribution of the monthly electricity consumption throughout the year 2016 for the 10 houses. A maximum of monthly consumption is seen over the months of July and August with an average value of 1891.2 kWh and the minimum in January with the average of 1140.12 kWh. This trend clearly shows the seasonal aspect of the electricity consumption in this zone.

The distribution of the average electric load per hour for the year 2016 is depicted in **Fig. 4**. A maximum load of 6.44 kW (at 23:00 h) is identified in the summer season.

### **2.3. Resources assessment**

The village Tazouta possesses a high potential of renewable energy resources notably biomass, wind and solar. The details of these resources are covered in the following paragraphs.

#### **2.3.1. Solar irradiation data**

Solar energy data for the region under examination is collected from NASA (surface meteorology and solar energy database). The geographical coordinates of the village are 33°40'12" N latitude, 4°38'2" W longitude and has an elevation of 1146 m. **Fig. 5** displays the daily irradiation and clearness index throughout the year. The annual average solar global horizontal irradiance is 5.07 kWh/m<sup>2</sup>/day with maximum of 7.18 kWh/m<sup>2</sup>/day observed in June and a minimum of 2.74 kWh/m<sup>2</sup>/day in December. **Fig. 5** indicates an average clearness index of 0.597 at the site under study.

#### **2.3.2. Wind data**



The monthly mean wind speed is obtained from NASA Surface meteorology for the village studied is shown in **Fig. 6**. The monthly average wind speed is found to be 4.16 m/s with a maximum and minimum of 4.54 m/s and 3.72 m/s in the month of April and October, respectively.

### 2.3.3. Biomass resource

Biomass is among the oldest power sources in the world and through which methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) gases **are produced** in the absence of oxygen by microorganisms. It is obtained from agricultural residues, animal waste, wood, and human waste etc (Zafar and Owais, 2006). The village Tazouta has around 7400 hectares of forest, which is equivalent to 50% of the total area and has abundant biomass resources. The useful agricultural land is about 3491 ha or 20% of the total area of the village. Of this, 250 ha land is irrigated as the primary occupation of the people in this village is agriculture.

It is considered in the analysis that there are total number of 27 cows in possession of the 10 houses. The electricity production based on manure from livestock is carried out using the anaerobic digester method. The estimated annual production of manure is calculated using **Eq. (1)** as given by (Plūme et al., 2012);

$$M = \sum_{n=1}^i N_i * m_i \quad (1)$$

where M represents the total annual manure in tons, n is the number of groups of animals, m<sub>i</sub> is the amount of manure per head and N<sub>i</sub> is the total number of animals. The estimated annual production of biogas from manure is given by

$$V_b = \sum_{n=1}^i N_i * m_i * K_{DMi} * K_{OMi} * V_{bi} \quad (2)$$

Where V<sub>b</sub> is the annual volume of biogas, in m<sup>3</sup>, obtained from the manure, K<sub>DMi</sub> is the dry matter content in manure of certain animals, K<sub>OMi</sub> indicates the content of organic matter in the dry matter and V<sub>bi</sub> is the specific biogas production of the organic material in m<sup>3</sup>/tons. **Eq. (3)** gives the energy of biogas (E<sub>b</sub>) generated from animal manure while **Eq. (4)** provides the power (P) produced from the manure.

$$E_b = \sum_{n=1}^i N_i * m_i * K_{DMi} * K_{OMi} * V_{bi} * e_{bi} \quad (3)$$

$$P = \frac{E_b}{T_c * K_e} \quad (4)$$

Here,  $e_{bi}$  is the specific heat energy obtained from the manure (kWh/m<sup>3</sup>),  $K_e$  is the coefficient of electrical efficiency of the plant considered equivalent to 40% as indicated in (Rajbongshi et al., 2017), and  $T_c$  is the total operational hour of the plant throughout the year. From the above equations, the estimated power capacity is found to be around 3.03 kW/day (**Table 1**) while the estimated waste emitted by the cows is 0.243 tons/day. The variability in the produced power stems from the variation in the quantity depending on the season.

## 2.4. HRES detail and equipment specification

The autonomous Hybrid Renewable Energy System proposed in this manuscript is illustrated in the **Fig. 7**, which contains five major components: biomass generator, PV Modules, wind turbines, converter, and batteries for storage.

### 2.4.1. Solar photovoltaic system

The photovoltaic modules are polycrystalline silicon connected to each other, oriented towards the south and tilted at 33°, which is the optimum inclination in the studied region. Photovoltaic panels do not have a tracking system. The generating power by the PV modules is dependent on the upcoming solar radiation as well as ambient temperature. The initial price in the Moroccan market is approximately 1600 \$/kW and considering that the module lifespan equals to the project life and the replacement price is taken to be zero. The operating and maintenance costs are estimated at 15 \$/yr which is a reasonable value in the Moroccan scenario. The project lifespan is considered as 25 years. Power generated by PV modules is calculated as follows;

$$P_{PV} = Y_{PV} * f_{PV} * \left( \frac{G_{PV}}{G_{ref}} \right) * [1 + K_T (T_c - T_{ref})] \quad (5)$$

where  $P_{PV}$  is the produced power,  $Y_{PV}$  is the PV generation under standard test conditions [kW],  $f_{PV}$  is the rated PV capacity [%],  $G_{PV}$  and  $G_{ref}$  represent the solar energy incident on the photovoltaic field in the current time and under the standard conditions [1kW/m<sup>2</sup>],

respectively.  $K_T$  is the temperature coefficient of the maximum power [%/°C] and  $T_c$  and  $T_{ref}$  are temperatures of the photovoltaic surface at standard tests conditions [25 °C], respectively. The derating factor considered is around 80%. In this study, the ground reflectance is equal to 20 %.

### 2.4.2. Wind Turbine

The wind turbine considered in this study is of horizontal axis type, producing nominal 5.1 kW of AC current at the output. Technical specifications are tabulated in **Table 2**. The hub height of the wind turbine is 12 m and has a lifetime of 25 years. The wind velocity at the chosen hub height  $U_{hub}$  and the corresponding power output  $P_{Wout}$  are calculated using the following equations (Kennedy et al., 2017).

$$U_{hub} = U_{anem} * \left( \frac{Z_{hub}}{Z_{anem}} \right)^\alpha \quad (6)$$

where  $U_{anem}$  represents the wind velocity at anemometer height, respectively.  $Z_{hub}$  is the wind turbine hub height,  $Z_{anem}$  is the anemometer height, and  $\alpha$  is the power law exponent.

$$P_{Wout} = \frac{1}{2} * \rho * A * V^3 * C_p(\lambda, \beta) * \eta_t * \eta_g \quad (7)$$

where  $\rho$  is the air density,  $A$  is the rotor area in m<sup>2</sup>,  $V$  is wind velocity in m/s,  $C_p$  is performance density of air coefficient of the turbine and  $\eta_t$  and  $\eta_g$  are the efficiencies of wind turbine and the generator, respectively. The initial cost according to the Moroccan market of the wind turbine unit is considered as \$10,775 with the replacement cost of \$0 considering the equality between the project life and the wind turbine lifespan and the operation and maintenance cost of 20 \$/year.

### 2.4.3. Biogas generator

The gasification reaction takes place under very high temperature conditions (>1000°C) (Heydari and Askarzadeh, 2016). Syngas is used as a source of electricity production from gas turbines. In this case, the cost of fuel is not considered because the fuel is the animal waste, which can be found abundantly. The initial price of biomass generator is taken as 1600 \$/kW, the replacement and operating costs are assumed as 1250 \$/kW and 0.1 \$/h, respectively. The

life of the biogas generator is taken as 20,000 hours so as the lower heating value of 5.5 MJ/kg, and the percentage carbon content as 5%.

#### 2.4.4. Converter

The converters are among the most important components of the hybrid system utilised to convert alternating current (AC) to direct current (DC) or the opposite way. To do this, it is placed between the AC and DC segments. The efficiency of the latter relies on the other devices of the hybrid system (Eroglu et al., 2011). In the present case, the initial, replacement, and maintenance costs per kW capacity are taken as \$400, \$400, and \$0 per year, respectively. The lifetime of the converter is taken as 15 years. Efficiency of the inverter and rectifier are considered as 90 % and 95%, respectively.

#### 2.4.5. Battery

In hybrid systems, which are not usually connected to the electricity network, batteries play an important role as they ensure the continuous power supply during the periods when there is no or inadequate electricity production and maintain constant voltage during the peak loads. The storage capacity of the battery,  $B_c$ , is calculated using **Eq. (8)** (Malheiro et al., 2015). In **Eq. (8)**,  $D_{ele}$  is the daily electrical demand in [kWh/day],  $D_d$  is the battery's depth of discharge,  $N_a$  is the daily autonomy, and  $\eta_b$  and  $\eta_{inv}$  are the efficiencies of the battery and converter, respectively.

$$B_c = \frac{D_{ele} * N_a}{\eta_b * D_d * \eta_{inv}} \quad (8)$$

In this work, the battery employed has a capacity of 167 Ah with a nominal voltage of 6V. The capital cost and the replacement cost in Moroccan market of this battery is \$330, the maintenance cost is equal to 10 \$/year, with the expected lifetime of 15 years. **Table 3** summarizes the specifications of the selected battery.

### 2.5. Simulation process and economic considerations

For the economic analysis, the life of the project is equal to 25 years; the discount rate and inflation rate are considered as 5% and 2.5%, respectively (Allouhi et al., 2016). **Table 4** summarizes the capital, replacement, and operating and maintenance (O&M) fees for each component of the hybrid system. It should be noted that most of the assumed costs are estimated based on the Moroccan market and other technical data is taken from the literature

(Amutha and Rajini, 2015; Rajbongshi et al., 2017; Rehman et al., 2012; Sen and Bhattacharyya, 2014).

### 2.5.1. Net Present Cost

The hybrid power system optimization tool, HOMER, is exploited to optimize the system rested on the minimum net present cost (NPC) that can be evaluated as follows.

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad (9)$$

with

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (10)$$

where  $C_{ann,tot}$  and  $C_{NPC}$  represent total annualized cost (\$/year) and total net cost (\$), CRF is the capital recovery factor,  $R_{proj}$  is the project life time in years and  $i$  is the interest rate (%).

### 2.5.2. Levelized Cost of Electricity

The levelized COE is a very important indicator for economic analysis of any hybrid system. The COE means the cost of a kWh electricity generated by the system. The COE is calculated by Homer by dividing total annualized cost (TAC) with respect to the total annualized primary served load (kWh/yr)  $E_{prim}$ , as following;

$$TAC = NPC * CRT(i, N) \quad (11)$$

$$COE = \frac{TAC}{E_{prim}} \quad (12)$$

### 2.5.3. Avoided CO<sub>2</sub> emission

#### 2.5.3.1. Compared to a scenario of grid-extension

In this first approach, the quantity of CO<sub>2</sub> emission avoided by the HRES is going to be discussed with the hypothesis of 1 kWh generated by HRES is equivalent to 1 kWh obtained from the Moroccan electricity grid. The expression below calculates the mass in tonnes of CO<sub>2</sub> avoided as

$$EM_{AV,grid} = \frac{E_{PV}(F_{C_{grid}} - F_{C_{PV}}) + E_{WT}(F_{C_{grid}} - F_{C_{WT}}) + E_{Bio}(F_{C_{grid}} - F_{C_{Bio}})}{10^6} \quad (13)$$

where  $F_{CPV}$ ,  $F_{CWT}$  and  $F_{CBio}$  are emission factors related to PV technologies, WT and Biomass generator respectively. The HRES emission factor was estimated considering carbon footprint of renewable energy systems to be respectively, estimated at 50 g CO<sub>2</sub>/kWh for PV technologies, 13.7 g CO<sub>2</sub>/kWh for wind conversion systems and 16.5 g CO<sub>2</sub>/kWh for biomass generation (Allouhi et al., 2019; Lund and Biswas, 2008).  $E_{PV}$ ,  $E_{WT}$  and  $E_{Bio}$  represent the energies produced by each technology as PV, WT and Biomass generator respectively. In Morocco, the emission factor is considered equal to 746 g CO<sub>2</sub>/kWh is represented by  $F_{Cgrid}$ .

### 2.5.3.2. Compared to a scenario of diesel power generation

The second approach quantifies the amount of avoided CO<sub>2</sub> emissions comparing with the scenario of diesel-based power generation. Homer calculates CO<sub>2</sub> emissions caused by a diesel generator using the following equation (Shezan et al., 2016).

$$EM_{AV,DG} = (3.667 \times m_f \times HV_f \times X_f \times CEF_f) - EM_{HRES} \quad (14)$$

where  $m_f$  represents the fuel volume (liter),  $HV_f$  refers to the calorific number of the fuel (MJ/L),  $X_f$  means fraction of the oxidized carbon and  $CEF_f$  means the carbon emission factor (tonne of carbon /TJ),  $EM_{HRES}$  and means the emissions emitted by the system.

## 3. Results and discussion

In this work, a hybrid system is designed and its performance characteristics are carefully examined to successfully fulfil the energy demand of the studied site. The proposed hybrid power system is optimized using HOMER, which delivers outcomes regarding the system optimization, performance and sensitivity analysis. HOMER identifies the optimum configuration of the off-grid taking into account the solar, wind and biomass renewable energy sources.

HOMER performs simulations to describe the operation of each possible configuration by considering energy balance computations in each time step. At each time, HOMER predicts the energy demand to the corresponding energy from the proposed system, and evaluates the flows of energy between all system components. It is also interesting to state that for configurations employing batteries, the algorithm decides instantly how to manage the generators and whether to charge/discharge the batteries. According to the computations,

HOMER indicates whether a configuration is viable first in terms of satisfying the electric load under the given conditions. Then, it gives a detailed financial evaluation of costs during the whole project lifetime. As such, for each possible configuration, HOMER sorts by net present cost of the investigated options and indicates optimum scenarios inducing lowest life cycle expenditures. **Table 5** describes the different scenarios examined by the simulation process.

### **3.1. HRES optimization results**

**Table 6** shows the possible configurations of supplying the electric load to the studied zone based on the available energy sources. It also indicates design options and installed capacities with respect to each configuration.

The most cost-effective system (Scenario A), as described in **Table 6 and Fig. 8**, consists of PV-Wind-Biomass-Battery as it yields the lowest Net Present Cost (NPC) of \$123,887.00 and accordingly the lowest Cost of Energy (COE) of 0.2 \$/kWh, respectively.

Switching to scenario B that excludes the utilization of wind power does not generate a considerable difference in NPC at around 2.18 %. As seen, Scenario B is characterized by a larger PV field to substitute energy production from the wind turbine as compared to scenario A.

The use of wind energy, photovoltaic panels and the battery (scenario C) will generate an additional NPC of 74.4 %. The NPC of scenarios D, E and F remains costly options compared to scenario A.

All scenarios have 100% renewable fraction since there is no diesel or other engine. Under unmet load and excess production, scenario E presents 0 kWh/yr for unmet load with an excess production of the order of 253 kWh/yr. Following, scenario A has unmet load and excess production 21.4 kWh/yr and 2,071 kWh/yr, respectively.

The last scenario engenders the higher annual electricity production that surplus is estimated to be 52,605 kWh/year.

In the rest of the discussion, the scenario A consisting of the Solar-Wind-Bio sources will be analysed, forming the optimum HRES configuration. Such a configuration is of a particular interest, particularly for guiding strategic policies for diversifying energy mixes in remote areas of Morocco.

### **3.2. Analysis of the optimum scenario (A)**

The capital cost, the NPC, and operations costs of the suggested system (scenario A) which contains PV-Wind-Biomass-Battery are found to be \$49,524, \$123,887, and \$4,008,

respectively. The levelized (COE) is considered to be 0.2 \$/kWh (**Table 6**). The scenario A consists of a wind turbine with 5.1 kW capacity, 9.11 kW of PV panel, 3 kW of biomass generator, 53x167 Ah of accumulator, 4.7 kW converter with the strategy of cycle charging load. This optimal configuration emits about 9.58 kg/year of CO<sub>2</sub>. **Table 7 shows the pollutants and their concentrations for the optimal configuration. The very low quantity of CO<sub>2</sub> emissions can be attributed to the fact that the proposed system does not contain non-renewable energy sources.**

### 3.2.1. Electricity production and economic analysis for system A

**Fig. 9** illustrates the monthly average energy generation produced by scenario A. It is observed that the average monthly electricity generation is nearly constant for the biogas generator and solar panels throughout the year. Solar energy generation experiences a slight decrease in October, November, December and January (rainy season with low radiation values, rain and overcast conditions) and the maximum generation is reached in June and July (peak of the summer season). For the production of electricity generated by biomass decreases in June/July and its maximum is predicted in December.

The **relative** contribution of each component is as 11 % of wind power, 41 % of solar power and 48 % of biomass power, respectively (see **Fig. 10**). The biomass generates more power with annual production of 17,701.00 kWh than other components in the proposed system. PV panels have annual energy contribution of 15,106.00 kWh. The lowest amount of energy is derived from the WT, which is envisaged to be 4,167.00 kWh. **Table 8** shows that there is energy surplus totalling of 2,071 kWh, that is to say 5.6 % of overall production. This excess energy can be used to support the increasing energy needs of the population (increase in household appliances and use durations, as well as the connection of neighbouring villages). Unmet load electric for this scenario is around 21.4 kWh/yr, **(equivalent to 0.0642 %) which is insignificant value proving the effectiveness of the proposed architecture.**

As for the corresponding cost figures, **Table 9** provides the capital, replacement, O&M, and salvage costs for each element of the hybrid energy system which are found to be \$49,524.40, \$32,779.54, and \$46,142.01, respectively.

**Fig. 11** shows the NPC of each element of the hybrid power plant. Highest NPC values belong to the Biogas generator and the battery. The converter system has the lowest initial investment cost. As indicated previously, the levelized COE is 0.2 \$/kWh.



### 3.3. Sensitivity analysis

In this study, for a complete technical-economic evaluation of the proposed HRES (scenario A), it is critical to carry out sensitivity analyses on key operating/financial parameters. The first sensitivity deals with the impact of the variation of the discount rate and the inflation rate on the cost of energy and the net present cost of the system. Both parameters were varied from 0% to 10% with an increment of 0.5%.

The cost of electricity (COE) generated by the system hybrid (PV/Wind/Biomass/Battery) is illustrated in a surface plot as shown in **Fig. 12**. The discount rate (%) is taken along x-axis and the inflation rate (%) along y-axis. According to this figure, the inflation rate and discount rate have an influential effect on the economic performance of the HRES. In other words, by increasing the inflation rate and decreasing the discount rate decreases the unit cost of the energy produced (Nyeche and Diemuodeke, 2020).

The second sensitivity study is to evidence the effect of capital cost reduction on the HRES financial performance. The initial cost according the current market considerations (presented earlier) was decreased gradually up to 40%. It should be indicated that the discount rate and inflation rate were kept constant at 5 % and 2.5 %, respectively.

**Fig. 13** shows the variation of the levelized COE with respect to the capital cost reduction of the HRES. As can be seen, the capital cost reduction has a remarkable effect on the system's COE. When the capital cost of the hybrid system decreases from the value given by the Moroccan market to a value corresponding to a 40 % price reduction, the COE drops from 0.2 \$/kWh to 0.15 \$/kWh respectively.

### 3.4. Environmental and carbon market analysis

Morocco was committed to COP21 to reduce its GHG emissions in 2030 by 40% compared to projected emissions by 2030. This goal corresponds to a cumulative reduction of 523.5 Mt CO<sub>2</sub>-eq over the period between 2020 and 2030. The integration of systems based on renewable sources to produce electricity is vital to reduce greenhouse gas emissions and fossil fuel based resources (Anvari et al., 2018). Quantification of CO<sub>2</sub> emissions avoided by the proposed system is introduced and compared to the different power generation modes.

#### 3.4.1. Scenario based on grid extension

The avoided CO<sub>2</sub> emissions that can arise from replacing grid electrification by the PV-wind-biomass system are calculated based on **Eq. (13)**. The quantity of CO<sub>2</sub> emissions in this case was estimated to be around 26.48 tonnes of CO<sub>2</sub> per year.

### **3.4.2. Scenario based on diesel power generation**

An additional simulation was carried out considering the same electric demand at the same region. The proposed system contains a non-renewable energy source consisting of the DG-battery to assess the CO<sub>2</sub> emissions avoided due to the utilization of the hybrid system based on renewable energy resources. The capital cost and the replacement cost of the diesel generator are considered as 300 \$/kW while the maintenance cost is taken equal to 0.03 \$/hours.

The simulation results are illustrated in **Table 10 (Scenario 1)**. It is an interesting configuration since it allows assessing the amount of CO<sub>2</sub> avoided by the PV-Wind-Biomass Battery system discussed above. That is to say, the production of electricity in this case will only be ensured by the diesel generator.

In addition to the environmental damage that will be caused by this system, the price of the electricity produced is equal to 0.354 \$/kWh which is 77% higher than the unit electricity price determined for the PV-Wind-Biomass-Battery system.

The DG-Battery system emits 28.824 tonnes of CO<sub>2</sub>/year as it shown in **Table 11**. This shows the environmental benefit of the proposed system leading great quantity of CO<sub>2</sub> emissions avoided each year.

### **3.4.3. Carbon market analysis**

A simulation model is launched to the effect of the penalty for CO<sub>2</sub> emissions in tonnes per year, introduced by the DG-Battery only system. The specific price of penalty issues introduced in the software is 0.021 \$/kg (**Almutairi et al., 2016; Wang et al., 2019**).

The results in **Table 10 (Scenario 2)** show that the price per kWh is negatively affected after applying the penalty on CO<sub>2</sub> emissions. The comparison between (DG-battery only) before and after applying CO<sub>2</sub> penalty showed that the price per kWh changed from 0.354 \$/kWh to 0.372 \$/kWh. This indicates that considering CO<sub>2</sub> emissions penalty in the analysis improves the competitiveness of the HRES against conventional alternatives since the deviation between corresponding COE becomes significant.

Switching into the presented hybrid renewable energy system instead of grid extension and diesel-based power generation can save indirect costs up to 556.08 \$/year and 605.304 \$/year, respectively with substantial environmental benefits.

#### **4. Conclusions**

The main purpose of this paper is to ensure the fulfilment of energy demand for a residential entity comprising 10 traditional houses located in a Moroccan rural area. Various scenarios of an off-grid HRES based on the available power sources are technically and economically examined. HOMER software identifies the optimum configuration of the off-grid taking into account the solar, wind and biomass renewable energy sources. Based on the results and findings, concluding remarks can be outlined as follows;

Meteorological data of the region and the site own resources are considered as inputs to examine the 100% Renewable Energy Scenarios in this area. Based on a detailed techno-economic optimization, it was proved that, for a daily average energy demand of 91.38 kWh and a peak load of 6.44 kW, cost of energy of the optimum configuration (scenario A) is found to be 0.2 \$/kWh. This cost increases from scenario A to scenario F. Therefore, option A is the most cost effective option and chosen as the optimum configuration. As for the option A comprising biomass-wind-PV-Battery, it was demonstrated that the initial investment cost, maintenance cost, NPC and cost of electricity are \$49,524.40, \$4,008, \$123,887, and 0.2 \$/kWh, respectively. These are competitive figures outperforming other studied alternatives.

The proposed hybrid energy system with 100% renewable energy penetration can avoid 26.48 tons of CO<sub>2</sub> emissions annually. The very low quantity of CO<sub>2</sub> emissions can be attributed to the fact that the proposed system does not contain any non-renewable energy source.

As conventional fossil fuel dependent power plants produce huge amount of GHG and CO<sub>2</sub>, the renewable counterparts, which will eventually maximise long-term benefits for the environment and economy, can replace these power plants. Consequently, the proposed hybrid power system has demonstrated an economic viability for feeding rural regions in Morocco with environmentally friendly, renewable based clean sources of energy. This kind of system can be a great competitor to grid-connection especially if the unit prices continue to decrease. Thus, the proposed solutions can provide untapped opportunities for off-grid electricity generation and can be implemented to remedy the situation in African rural zones having abundant renewable energy sources.

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**Table 1.** Estimation of power generation by cows (Hossain and Badr, 2007; Rajbongshi et al., 2017)

<b>Number of animals</b>	<b>Manure production per head (ton/year)</b>	<b>Dry matter content</b>	<b>Organic matter content</b>	<b>Biogas output (m<sup>3</sup>/ton)</b>	<b>Heat energy of biogas (kWh/m<sup>3</sup>)</b>	<b>Estimated power production (kW/day)</b>
27	3.285	0.18	0.86	211.84	3.94	3.03

**Table 2.** Properties of the selected wind turbine

<b>Property</b>	<b>Specification</b>
Brand name	AWS-HC 5.1 kW
Rated power (W)	5100
Rated wind speed (m/s)	11-25
Number of blades	3
Rotor diameter (m)	5.24
Cut in speed (m/s)	2.7-6

**Table 3.** Properties of the selected battery

<b>Properties</b>	<b>Specifications</b>
Nominal voltage	6 VDC
Nominal capacity	167 Ah
Roundtrip efficiency	90 %
Maximum charge current	167 A
Maximum discharge current	500 A
lifespan	15 years

**Table 4.** Information regarding Hybrid power system components

<b>Components</b>	<b>PV</b>	<b>Wind</b>	<b>Biomass</b>	<b>Battery</b>	<b>Converter</b>
<b>Parameters</b>	<b>1 kW</b>	<b>1 kW</b>	<b>Generator</b>	<b>1 Unit</b>	<b>1 kW</b>
			<b>1kW</b>		
Capital cost (\$)	1,600.00	2,155.00	1,600.00	330.00	400.00
Replacement cost (\$)	0.00	0.00	1,250.00	330.00	400.00
O & M cost (\$/year)	15.00	20.00	876.00	10.00	0.00
Life-time, (years)	25	25	2.28	15	15
Efficiency, (%)	-	-	-	90	95
Current type	DC	AC	AC	-	-

**Table 5.** Proposed HRES for application in study site

<b>Proposed HRES</b>	<b>Scenario</b>
PV/Wind/Biomass/Battery	A
PV/Biomass/Battery	B
PV/Wind/Battery	C
PV/Battery	D
Wind/Biomass/Battery	E
Wind/Battery	F

**Table 6.** Comparison of different scenarios based on simulation results.

<b>Scenario</b>	<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>	<b>E</b>	<b>F</b>
<b>PV (kW)</b>	9.11	14.3	46.0	46.7	0	0
<b>Wind AWS</b>	1	0	3	0	3	20
<b>5.1kW</b>						
<b>Biomass (kW)</b>	3	3	0	0	3	0
<b>Battery 1 kWh</b>	53	54	134	235	276	447
<b>Converter kW</b>	4.7	5.26	7.37	8.52	4.07	19.9
<b>COE (\$)</b>	0.200	0.205	0.349	0.411	0.477	0.875
<b>NPC (\$)</b>	123,887	126,595	216,099	253,977	295,353	541,278
<b>O&amp;M (\$)</b>	4,008	4,261	3,397	5,295	8,921	9,179
<b>Capital cost (\$)</b>	49,524.40	47,538	153,073	155,742	192,834	370,980
<b>Production (kWh/year)</b>	36,974	42,278	88,745	77,493	34,851	83,334
<b>excess production (kWh/year)</b>	2,071	7,221	52,605	40,290	253	47,489

**Table 7.** Pollutant emissions corresponding to the optimal configuration

<b>Types of polluting greenhouse gases</b>	<b>Value (kg/year)</b>
Carbon dioxide (CO <sub>2</sub> )	9.58
Carbon monoxide (CO)	0.106
Unburned hydrocarbons	0
Particulate matter	0
Sulfur dioxide (SO <sub>2</sub> )	0
Nitrogen oxides (NO <sub>2</sub> )	0.0664

**Table 8.** Annual electricity production of hybrid system and consumption

<b>Technology</b>	<b>Energy production kWh/year</b>	<b>Energy contribution (%)</b>	<b>Load Type</b>	<b>Energy consumption kWh/year</b>	<b>Contribution (%)</b>
<b>PV</b>	15,106.00	41.00	AC primary load	33,332.00	100.00
<b>Biomass</b>	17,701.00	48.00	DC primary load	0.00	0.00
<b>Wind</b>	4,167.00	11.00	Total	33,332.00	100.00
<b>Total</b>	36,974.00	100.00			



**Table 9.** Summary of various costs related to the PV-Wind-Biomass-Battery hybrid system

<b>Component</b>	<b>Capital (\$)</b>	<b>Replacement (\$)</b>	<b>O&amp;M (\$)</b>	<b>Salvage (\$)</b>	<b>Total (\$)</b>
<b>Battery</b>	17,490.00	12,184.52	9,833.37	-3,191.78	36,316.11
<b>Bio-Generator</b>	4,800.00	19,284.17	33,401.92	-1,023.95	56,462.14
<b>Converter</b>	1,881.64	1,310.85	0.00	-343.38	2,849.11
<b>PV</b>	14,577.76	0.00	2,535.65	0.00	17,113.41
<b>Wind-turbine</b>	10775.00	0.00	371.07	0.00	11146.07
<b>System</b>	49,524.40	32,779.54	46,142.01	-4,559.11	123,886.83

**Table 10.** Summary of DG-Battery system

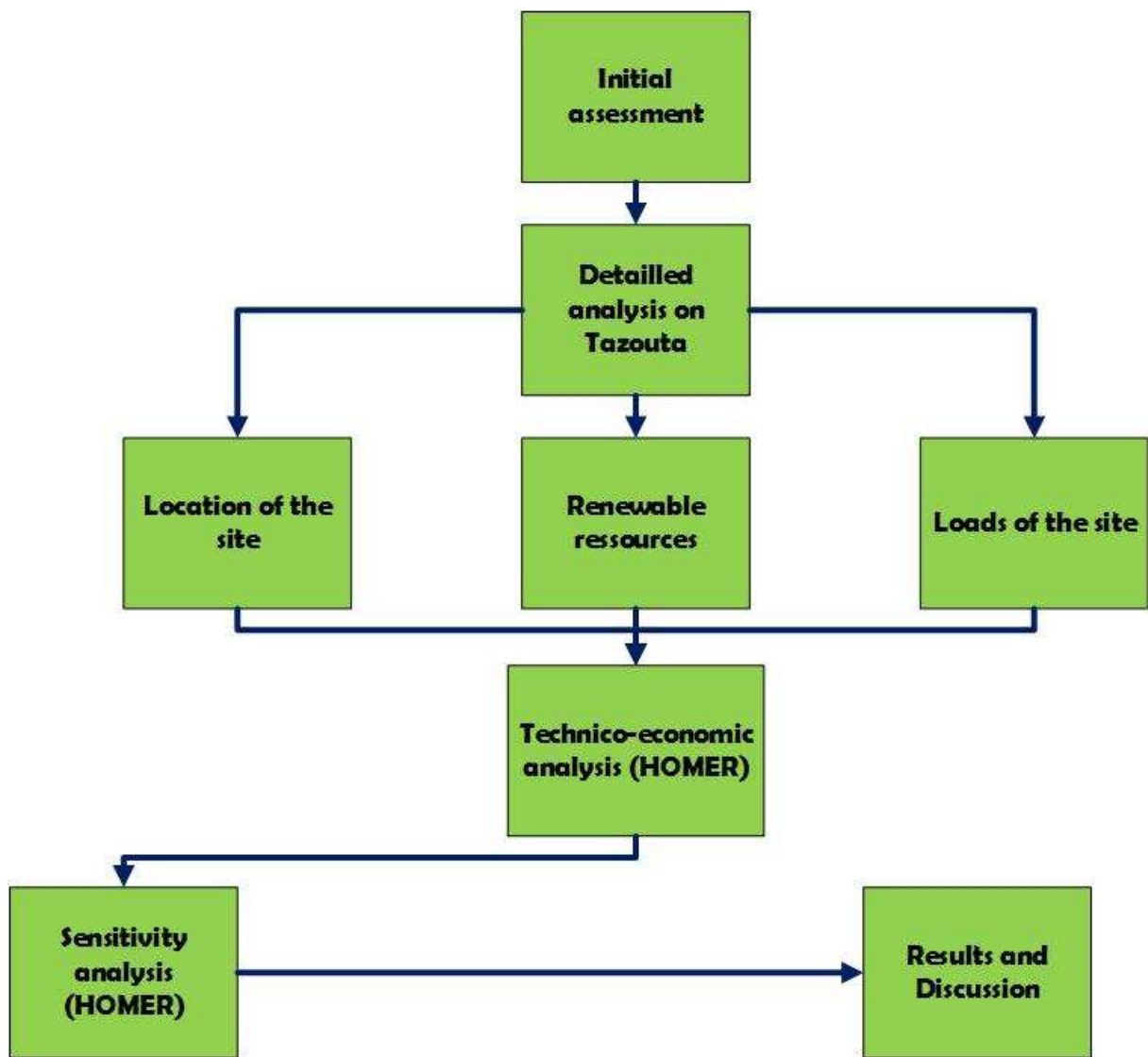
Components/Parameters	Unit	Without introducing a penalty for CO <sub>2</sub> emissions (Scenario 1)	With introducing a penalty for CO <sub>2</sub> emissions (Scenario 2)
DG	kW	7.1	7.1
Converter	kW	3.33	3.33
Battery	Qty	17	17
Net present cost	\$	128,962	230,193
Cost of energy	\$/kWh	0.354	0.372
Operating cost	\$	11,313	11,318
Renewable fraction	%	0	0
Initial capital	\$	9073	9073

**Table 11.** Pollutant emissions corresponding to the DG-Battery system

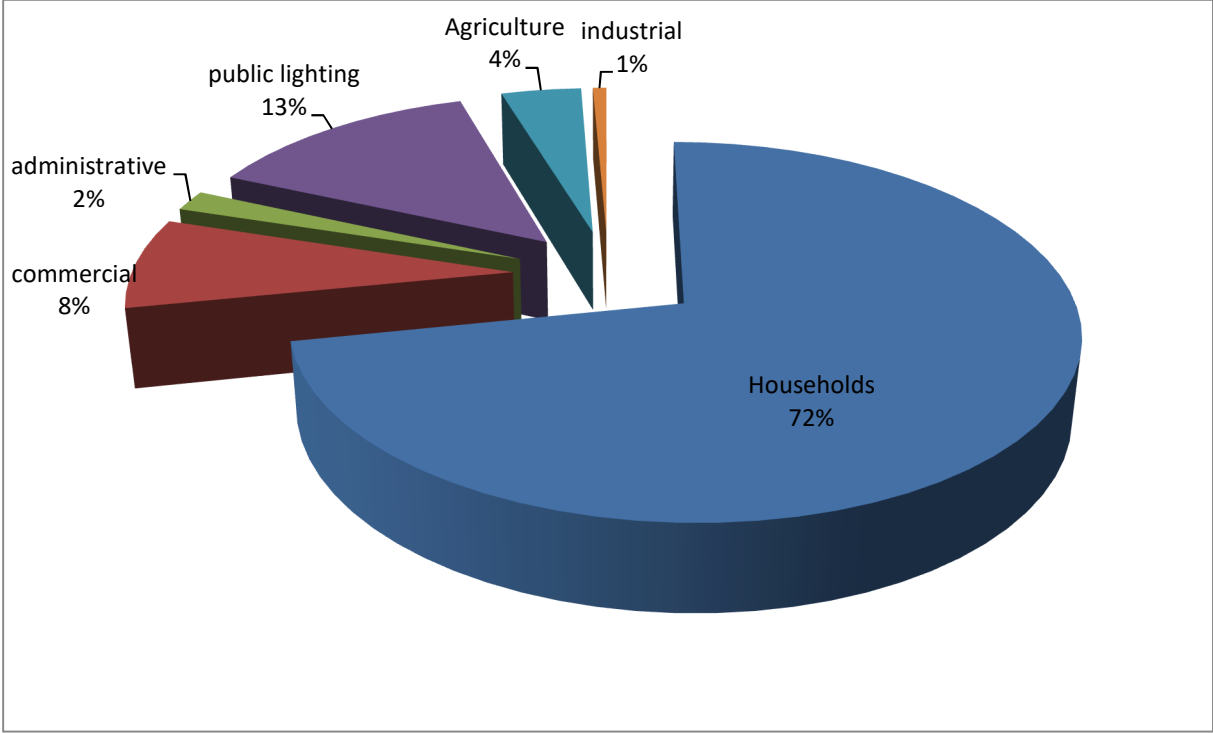
<b>Types of polluting greenhouse gases</b>	<b>Value (kg/year)</b>
Carbon dioxide (CO <sub>2</sub> )	28,824
Carbon monoxide (CO)	182
Unburned hydrocarbons	7.93
Particulate matter	1.1
Sulfur dioxide (SO <sub>2</sub> )	70.6
Nitrogen oxides (NO <sub>2</sub> )	171

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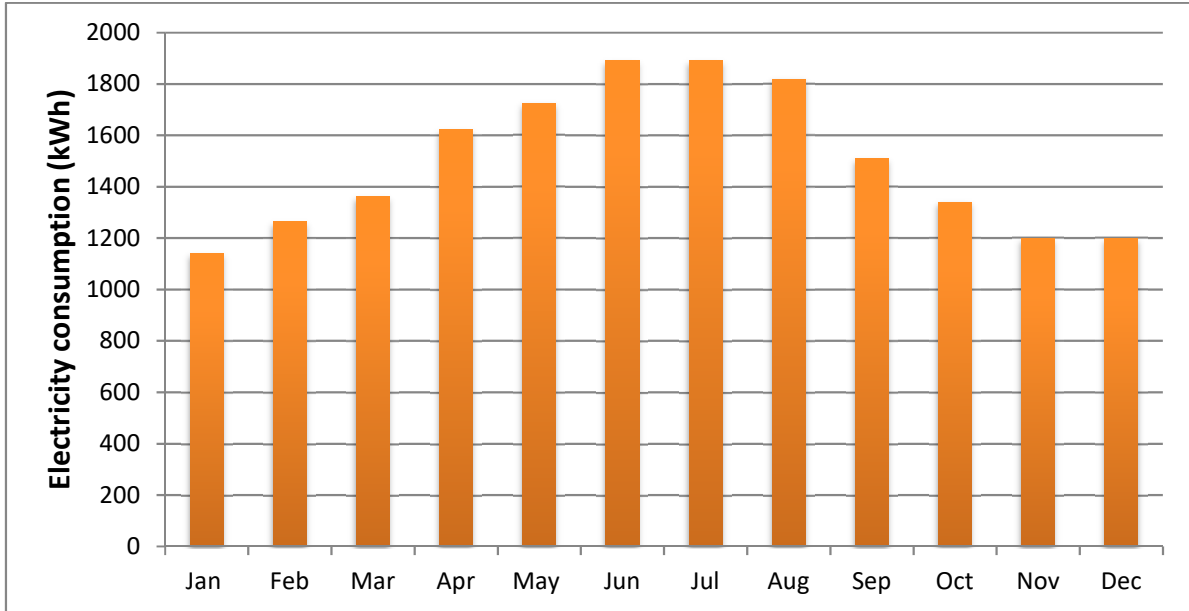
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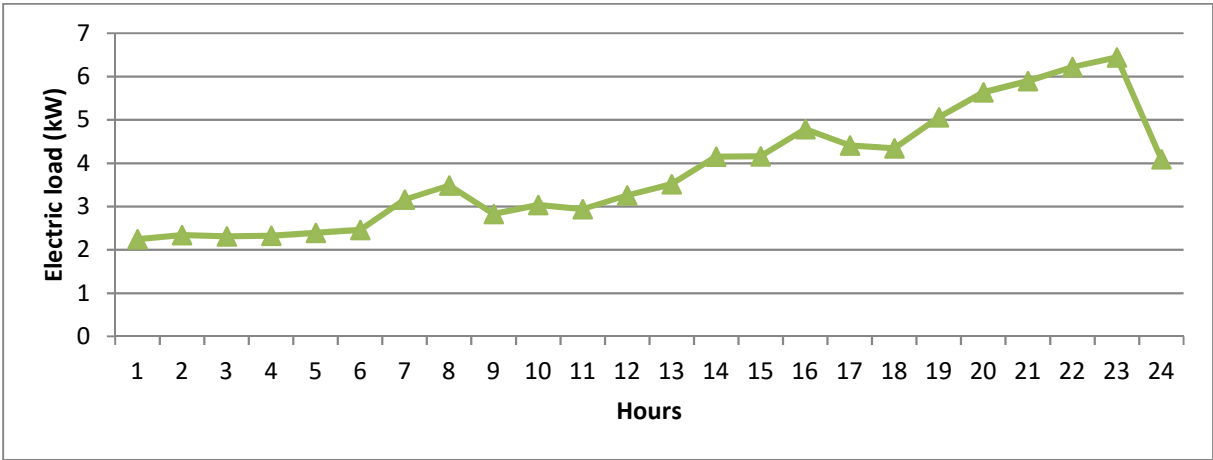
**Fig. 1.** Hybrid power system design methodology



**Fig. 2.** Distribution of electricity consumption by sector

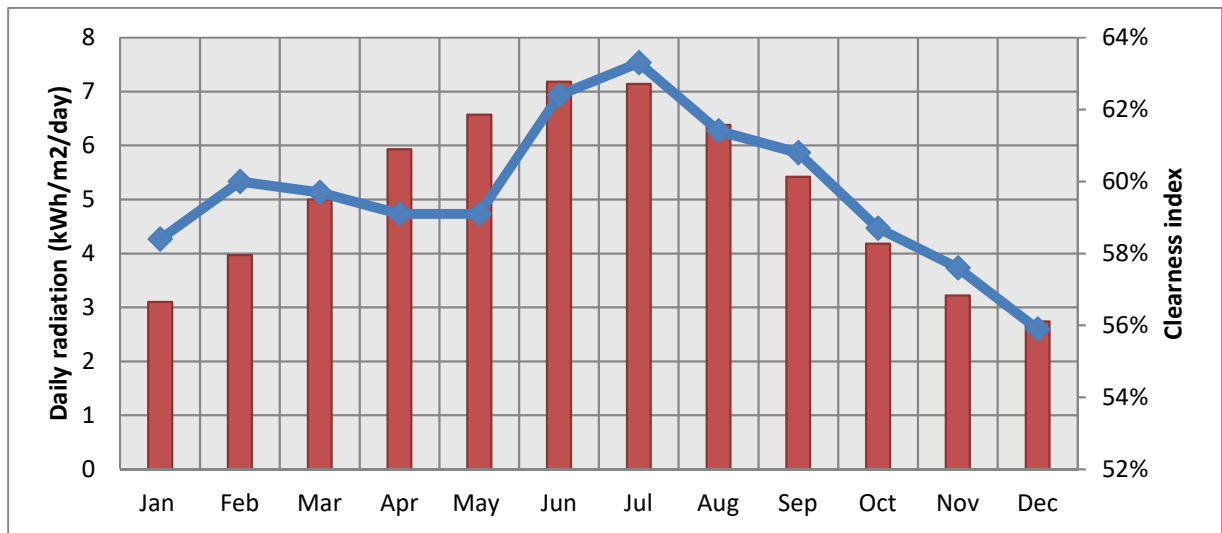


**Fig. 3. Monthly average load of the site**

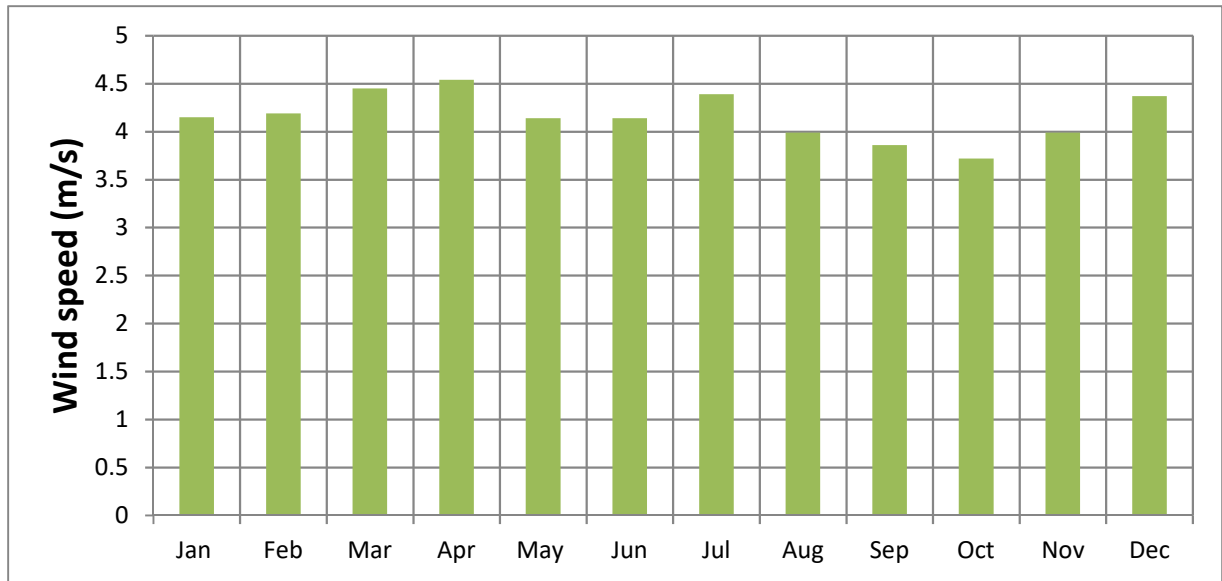


**Fig. 4.** Typical summer day load demand for the site

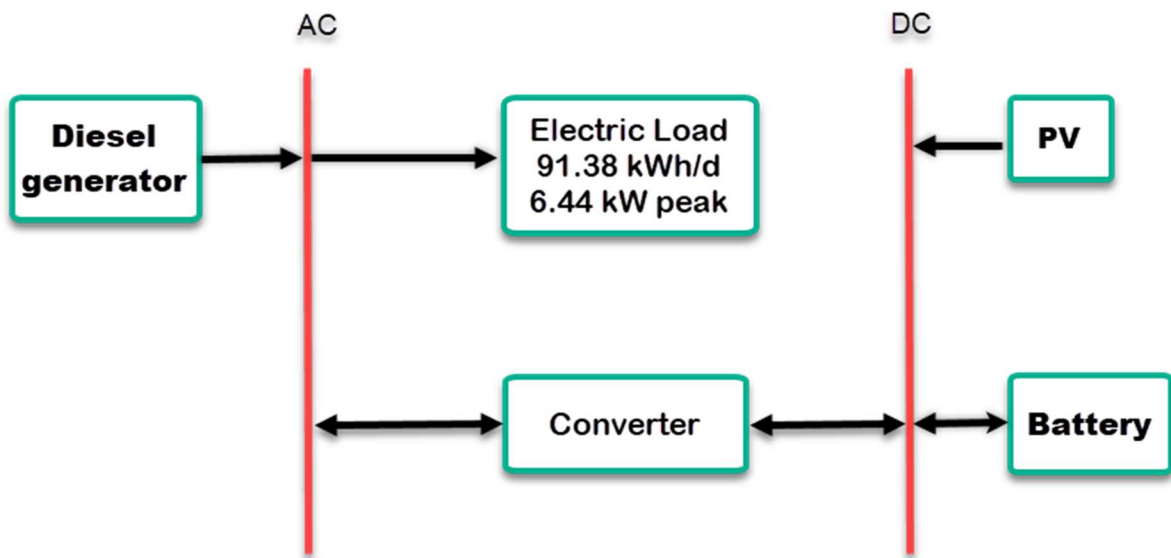




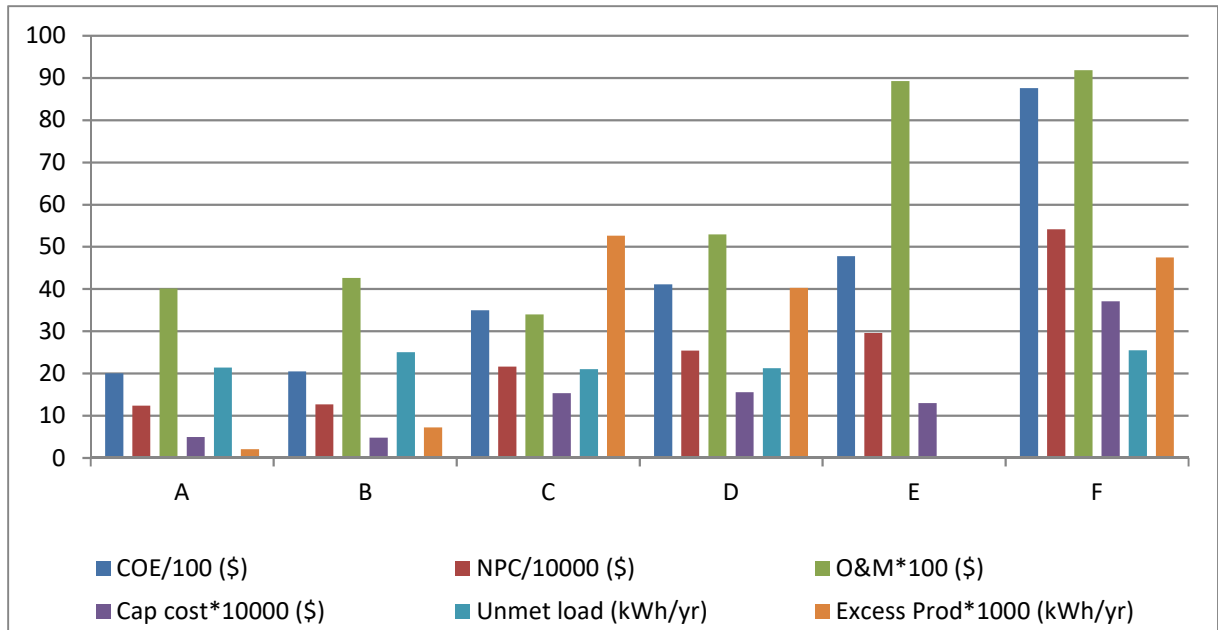
**Fig. 5.** Monthly mean solar radiation and clearness index



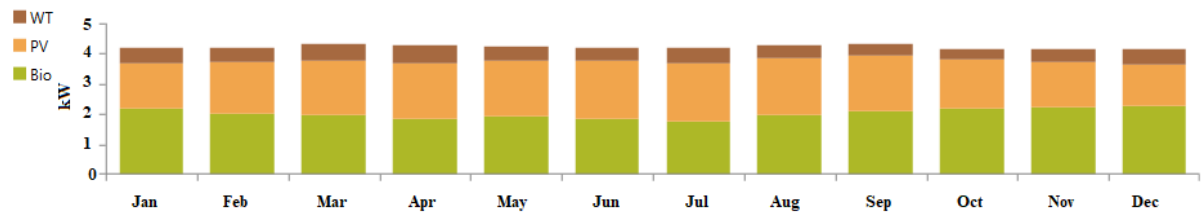
**Fig. 6.** Monthly mean wind speed during the year



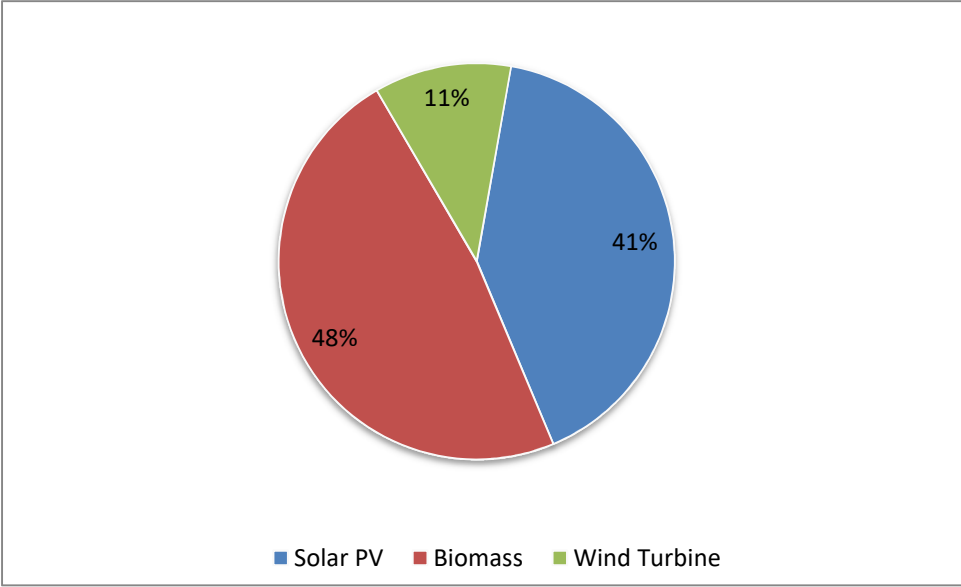
**Fig. 7.** Off-grid configuration of the proposed hybrid power system



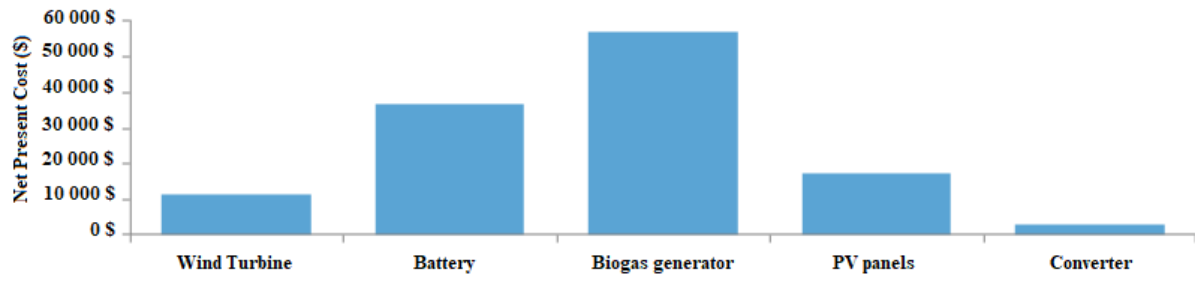
**Fig. 8.** Scenarios performance comparison



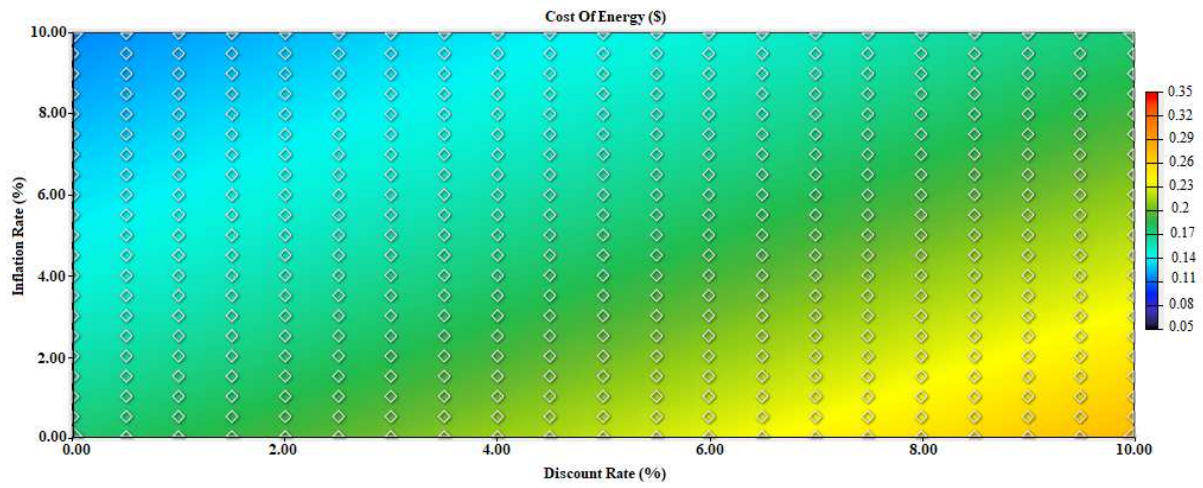
**Fig. 9.** Electrical power generation of scenario A



**Fig. 10.** The share of electricity production (scenario A)

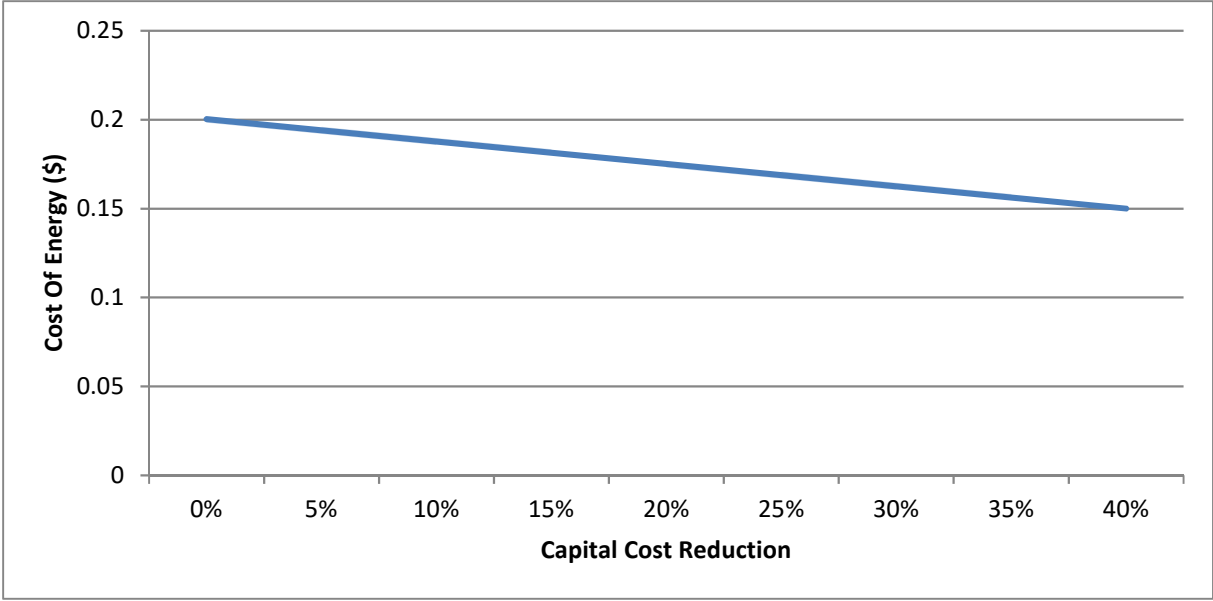


**Fig. 11.** Cash flow summary of each energy components



**Fig. 12.** Effects of discount rate and inflation rate on the COE





**Fig. 13.** Impact of the Capital Cost reduction on COE of the system