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Design and Evaluation of an Island's Hybrid Renewable Energy System in Tunisia

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Abstract— **this paper shows a methodology for optimal sizing of island micro grids in Djerba, Tunisia containing photovoltaic panels, a wind turbine, and a tidal turbine. The battery storage system and a diesel generator are used as compensating energy sources. The process aims to find a configuration within a set of system components that meets the required system reliability requirements.**

The modeling of PV/wind/tidal micro grids is considered as the first step in the optimization of the selection process. This paper aims to study the sizing and optimization of the hybrid power system to supply the load of the studied location in Djerba Island, Tunisia. The objective functions are selected by minimizing the life cycle cost (LCC) and the embodied energy (EE) for a variable probability of loss of power supply (LPSP 0%). MATLAB software is used in all simulations and programming of the micro grid system. Real weather data and a load profile are used to design and evaluate the sizing and optimization results, during the year 2020 to determine the highest component size of a micro grid system.

Keywords—Sizing and optimization system; Life Cycle Cost; Embodied Energy; Probability of Loss of Power Supply.

ABBREVIATIONS

LCC: Life Cycle Cost.

EE: Embodied Energy.

LPSP: Loss of Power Supply Probability.

LPS: Loss of Power Supply.

SOC: State Of Charge.

VPP: Virtual Power Plant.

PV: Photovoltaic.

BOS: Balance of System.

I. INTRODUCTION

Today, the more renewable energy is developing, the more the demand for it is increasing. When the life span of traditional power plants comes to an end, they should be replaced by renewable energy and cleaner technologies. Although renewable energies in electricity should experience an incredible growth in the coming years, it however, compared to other non-renewable energy sources, the participation rate is very low [1]. Moreover, the integration of renewable energy technology into the hybrid power system is necessary, thus improving reliability, power quality, efficiency and reducing fluctuations [2].

In order to use renewable energy sources in an efficient and economic way, every component has to be aggregated and selected. To ensure the least investment and total utilization of the system, we opted for the sizing and optimization process. Therefore, the system can operate under optimal conditions with an appropriate configuration. In such a location, the renewable resources have always been the best alternative source for power generation. The best recognized alternative for power generation is hydropower, wind power, tidal current power and photovoltaic [3].

In isolated areas, it is always hard and uneconomical to produce energy from the grid. Thus, to satisfy the power demand battery storage system and/or diesel generators are usually used.

At present, island power supply mainly depends on diesel generators or the connection with power grid. High cost, poor reliability, environmental pollution and other adverse factors greatly limit the further development of island micro grid [4]. Hybrid renewable energy system is the best highly technological means for clean, green, and continuous island power supply.

Hybrid energy systems configuration presents a higher reliability and lower costs than systems based on only one energy source. Nevertheless, the proper sizing of system components is an indispensable factor for a system's techno-economic feasibility. [5-6].

In the first part of this paper, we describe the modeling of each component of the proposed renewable hybrid energy power system. In second part, however the sizing of each component of the proposed system is defined. The following section is dedicated to develop the objective functions, constraints and the evaluation criteria with the computational methods. Finally, the simulation results are discussed to illustrate the performance of the proposed method, and conclusions are presented in the last section

II. CONCEPT OF THE ISLAND HYBRID ENERGY SYSTEM

The studied system is an economical solution for the island of Djerba in Tunisia. The studied island micro grid is illustrated in Fig. 1. It consists of a photovoltaic unit, wind turbines, tidal turbines as renewable generation sources, and diesel generators and battery storage system as compensating generation source, inverters and controllers.

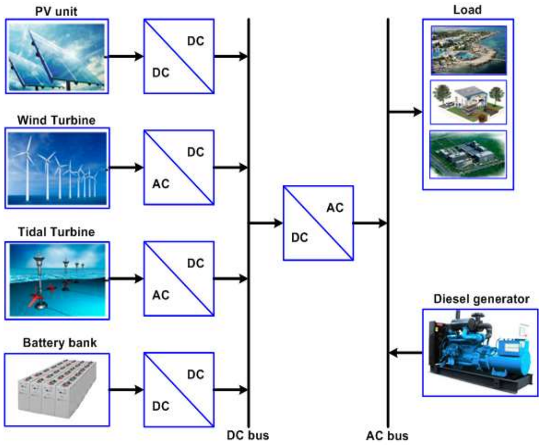


Fig. 1. Island's hybrid renewable energy system structure

III. MODELING OF THE ISLAND'S HYBRID ENERGY SYSTEM

A detailed modeling of each component of the micro grid is presented below.

A. Photovoltaic Unit Model

The generated power of photovoltaic modules is proportional to the semiconductor area exposed to sun light, the surface of photovoltaic modules, ambient temperature, and characteristics of photovoltaic cells under standard industrial solar radiation test conditions [5]. Thus, the generated power P_{pv} can be determined by (1):

$$P_{pv} = N_{pv} \eta_{pv} A_{pv} G_t \tag{1}$$

Among them η_{pv} is the quick efficiency of the photovoltaic module array, N_{pv} presents the photovoltaic group, A_{pv} stands for the location of one module utilized module in the system, and G_t represents the total irradiation.

B. Wind Turbine Model

The output energy obtained from the wind turbines is proportional to the power curve provided by the manufacturer and the roughness of ground region. The power generated by the wind turbine P_{wt} was the result of (2):

$$P_{wt} = \frac{1}{2} N_{wt} \rho_{wt} C_p R_{wt}^2 v_{wt}^3 \tag{2}$$

Where the overall number of wind turbines is N_{wt}, R represents the blade radius, ρ_{wt} represents the density of the air, C_p is the coefficient of power, and v_{wt} stands for the speed of wind. The link between the available power result P_{wt} and the wind speed can be calculated by (3).

$$P_{wt} = \begin{cases} 0 & ; v < v_{cutin}, v > v_{cutout} \\ P_{wt\max} \dfrac{v - v_{cutin}}{v_{rated} - v_{cutin}} & ; v_{cutin} < v < v_{rated} \\ P_{wt\max} & ; v_{rated} \le v \le v_{cutout} \end{cases} \tag{3}$$

C. Tidal Turbine Model

P_t represents the output power of the tidal turbine calculated by (4):

$$P_t = \frac{1}{2} N_t \rho_t C_p \pi R_t^2 v_t^3 \tag{4}$$

Among them, N_t is the number of tidal turbines, ρ_t represents the density of the sea water, R_t is the blade radius of tidal turbines, v_t is the tidal flow speed and C_p represents the coefficient of the power of the turbine approximately (0.35-0.5) in the range [7].

D. Battery Storage Model

The charge and discharge states of the battery are given in equations (5) and (6), which depends in its turn on the previous charge/discharge of the sampling step (t-1).

$$\begin{aligned} E_{bat}(t) &= E_{bat}(t-1)(1-\sigma) \\ &+ \left[\left(E_{pv}(t) + E_{wt}(t) + E_t(t) \right) - \frac{E_L(t)}{\eta_{inv}} \right] \eta_{bat} \end{aligned} \tag{5}$$

The state of discharge of the battery is given by the equation (6):

$$\begin{aligned} E_{bat}(t) &= E_{bat}(t-1)(1-\sigma) \\ &- \left[\frac{E_L}{\eta_{inv}} - \left(E_{pv}(t) + E_{wt}(t) + E_t(t) \right) \right] \end{aligned} \tag{6}$$

For times (t) and $(t-1)$, the power stored in the battery is expressed in $E_{bat}(t)$ and $E_{bat}(t-1)$. The unit is as follows: the self discharge rate per an hour is given by the art. $E_L(t)$ Represents the hourly load required by the electrical equipment. The efficiency parameters of the inverter and the battery energy a storage system η_{inv} and η_{bat}.

$E_{pv}(t)$, $E_{wt}(t)$ and $E_t(t)$ are the energies of each source of the micro grid which are respectively photovoltaic, wind turbines, and tidal turbine. $E_L(t)$ shows the load energy needed hourly, and η_{inv} is the efficiency of the inverter (92% in our case). The constraints of the battery storage presented in (7):

$$E_{bat\min} \le E_{bat} \le E_{bat\max} \tag{7}$$

Where $E_{bat\max}$ and $E_{bat\min}$ represent the maximum and minimum allowed storage energy.

$$E_{bat} = N_{bat} C_{bat} \tag{8}$$

Where N_{bat} is the number of batteries, C_{bat} is the nominal capacity for each battery (Ah).

E. Diesel Generator Model

The diesel generator (DG) acts as an auxiliary power source to compensate the lack of power in the system. Diesel generators must operate at an appropriate power level or it will affect their economy and life span [8]. DG, which depends on fuel consumption and efficacy modeling, is presented in Equation (9) [9].

$$F(t)=aP_{dg}(t)+bP_{gdra} \tag{9}$$

Where the fuel consumption of DG is $F(t)$, $P_{dg}(t)$ represents the actual energy output of DG, $P_{gdra}(t)$ represents the power rating of DG, the values of “a” and “b” are respectively 0.246 L/kWh and 0.0845 L/kWh.

IV. SIZING AND OPTIMIZATION SYSTEM

A. Sizing Of The Island Hybrid System

Sizing of the micro grid is closely linked to the determination of the actual energy used by the load over a time period. The energy must be well determined in order for the sizing to ensure the total energy supply. The formula required to determine the number of each source is:

$$N_{pv}=\frac{P_c}{P_u},\ N_{bat}=\frac{C_{pack}}{C_{element}} \tag{10}$$

For the wind turbines and the tidal it is necessary to calculate the energy consumed:

$$P_{av}=\frac{\sum^{8760}P[kW]}{8760} \tag{11}$$

With P_c its peak power, P_u is unit power, C_{pack} is the capacity of the battery pack in (Ah), $C_{element}$ is the capacity of the battery in (Ah) and P_{av} is the average power. Tables 1 show the design results of the hybrid renewable energy system after the necessary calculations for each element.

B. Formulation Of Optimization Problem

The main purpose of the optimization issue in the studied system is to reduce the investment cost and capital of the microgrid for a lifetime. In this paper, the evaluation criteria such as, reliability requirements (LPSP), Life Cycle Cost (LCC) and Embodied Energy (EE) are selected as objective functions. The optimization objective function of the micro grid island's based on minimum for those evaluation criteria.

C. Loss of Power Supply Probability

Because of the intermittent nature of renewable energy, the reliability of the hybrid power system is a necessary step in the course of the micro grid system. From the beginning to the end, the reliability of the system is represented by LPSP [3]. LPSP presents the probability of the battery state of charge (SOC) at a given time is equal or lower than the minimum $SOC_{\min}$ and the renewable energy production P_{gen} is lower than P_{load}, and the system loss is also considered such that:

$$LPS(t)=P_{load}-\left(P_{gen}+E_{bat}-E_{bat\min}\right) \tag{12}$$

The LPSP equation is presented as a ratio of the missing energies to the all the load demand in a time interval t:

$$LPSP=\frac{\sum_{t=1}LPS(t)}{P_{load}(t)} \tag{13}$$

D. Life Cycle Cost

The VPP LCC system uses the euro (€) as a unit. The life cycle cost of the wind turbine source is realized by adding the cost of the tower, the inverter (changed every 20 years), and the cost of the system balance (BOS). The life cycle cost of the photovoltaic source involves the price of the photovoltaic modules, BOS, inverters, and the devices. Thus, the tidal turbine source is realized by the addition of the cost of the tower, the cost of the inverter, and the BOS (cost of installation, protection, cables and connectors). The life cycle cost of the hybrid system is represented by the Formula (14):

$$LCC(€)=LCC_{pv}+LCC_{wt}+LCC_{t}+LCC_{bat} \tag{14}$$

The life cycle cost (€) equations used in the hybrid electric system (PV-wind-tidal, and battery) are represented as follows [10-11]:

$$LCC_{pv}=875.48A_{pv} \tag{15}$$

$$LCC_{wt}=2594.6A_{wt}+84.158 \tag{16}$$

$$LCC_{t}=2750A_{t}+170 \tag{17}$$

$$LCC_{bat}=17.201\ C_{n}+103.84 \tag{18}$$

Where A_{pv}, A_{wt}, A_t represent successively the area of PV, wind turbine and tidal turbine ,and C_n is the rated capacity.

E. Embodied Energy

The Embodied Energy (EE) is the amount of non-renewable energy used in the life cycle of each VPP component: transportation, manufacturing, origin and propagation. The EE is represented in units of measurement or location. The implied energy is represented via blowing an equation, and the model of the whole energy system is obtained. The embodied PV energy is described EE_{pv} by Equation (19):

$$EE_{pv}=3387A_{pv} \tag{19}$$

Equation (20) is represents the embodied wind turbine energy (EE_{wt}) [7]:

$$EE_{wt}=32.07A_{wt}^{2}+2254.2A_{wt} \tag{20}$$

The embodied tidal turbine energy EE_t is described by Equation (21):

$$EE_{t}=35A_{t}^{2}+3250A_{t} \tag{21}$$

The implied energy (EE_{bat}) of the battery as a function of the rated capacity and shown in the Equation (22):

$$EE_{bat}=60C_{n} \tag{22}$$

Notice that all the life cycle cost estimations are on the basis on a 5% discount rate, a 2% inflation rate, and a 20 year life. The interpolation model is shown in Fig.6. The life cycle cost analysis helps guide designers and select system components. Its analysis and evaluation is a decision support tool [12]. The evolution of EE (implied energy: energy needed to manufacture PV, wind, tidal and battery panels based on the input A_{pv}, A_{wt}, A_t and C_n is shown in Fig.6 respectively. We noticed that EE increases gradually with the area of A_{pv}, A_{wt}, A_t and capacitor C_n.

F. Constraints

The area of each production unit must at all times be within the minimum and maximum range. The system variables, the number of compounds from the photovoltaic source, wind turbines, tidal turbines also batteries must be defined a reasonable maximum value, expressed as follows:

$$\begin{aligned} &0 \le A_{pv} \le A_{pv\max} \\ &0 \le A_{wt} \le A_{wt\max} \\ &0 \le A_t \le A_{t\max} \\ &0 \le C_n \le C_{n\max} \end{aligned} \tag{23}$$

G. Production Unit Restrictions

The output power of each production unit must at all times be within the minimum and maximum range, expressed by the following production unit restrictions:

$$\begin{aligned} &P_{pv\min} \le P_{pv}(t) \le P_{pv\max} \\ &P_{wt\min} \le P_{wt}(t) \le P_{wt\max} \\ &P_{t\min} \le P_t(t) \le P_{t\max} \\ &E_{bat\min} \le E_{bat}(t) \le E_{bat\max} \end{aligned} \tag{24}$$

The power produced by the micro grid must correspond to the load power as presented as follows:

$$P_{gen}(t) = P_{load}(t) \tag{25}$$

The SOC value of the energy storage system is maintained among the least value and the maximum value, which are expressed as follows:

$$\begin{cases} SOC_{\min} \le SOC(t) \le SOC_{\max} \\ SOC_{\min} = (1 - DOD) SOC_{\max} \end{cases} \tag{26}$$

V. CASE STUDY

Djerba is an island in the Mediterranean Sea with an area of 514 km^2 (25 Km by 20 km and a coastline of 150 Km) and located east of Tunisian east coast. The largest island of the North African coast, located in the south east of the Gulf of Gabes that it borders by its eastern coastline, Djerba closes the Gulf of Boughrara to the south.

A. Meteorological Data of the island

Fig.2 shows the curves of irradiance, temperature, wind speed and tidal current speed for 8760 hours by a year 2020 starting from the first of January and ending with 31 December for the year 2020 on the island of Djerba in Tunisia. The meteorological data of the island comes from the data base of the National Aeronautics and Space Administration (NASA). As the observed solar radiation power potential is 244 W/m^2/day, which is sufficient to power the studied location. The average wind speed is 5 m/s. The average temperature is 21°C. The average tidal current speed is 0.9 m/s.

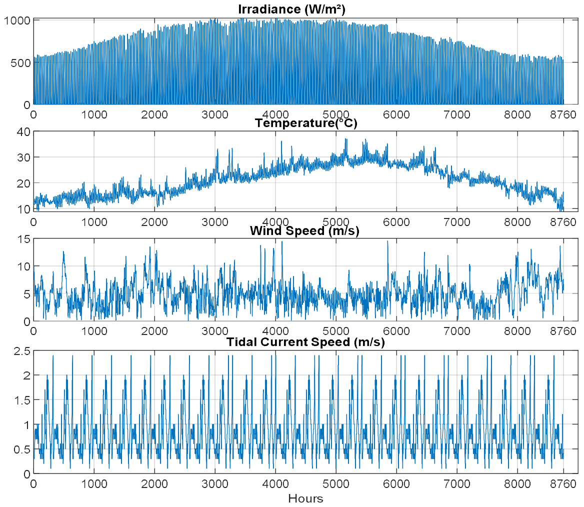


Fig. 2. Data of irradiance (W/m²), Temperature (°C),Wind speed (m/s) and Tidal current speed (m/s).

B. Annual load profile of the island

The proposed strategy is applied to analyze the micro grid of an island in Djerba, Tunisia. The load data are obtained from the HOMER software. The hourly load of the virtual island's electrical system varies from 0.114 to 20.46 kW, and the total load power is 6038 kW. Also, the average generated power of the micro grid system is 17 000 kW. The annual load curves for a typical year based on historical data and generated power are shown in Fig.3.

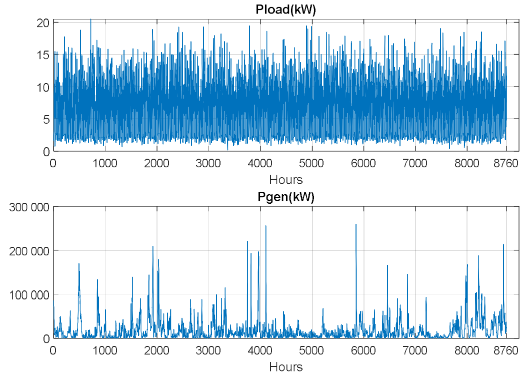


Fig. 3. Result of the island's annual load profile (kW) in 2020, and generated power(kW).

C. Island Hybrid Microgrid Parameters

After the selection components of the electrical energy system, it's important to define the rated power of each source. The photovoltaic unit is based on photovoltaic module with 222 kW power class, wind turbine of 17 000 kW is selected and a tidal current turbine of 172 kW is chosen. The different parameters and the total generated powers of each source of the proposed electrical energy system are summarized in Table.1.

TABLE I. OPTIMAL PARAMETERS OF HYBRID RENEWABLE ENERGY SYSTEM

Sources	**Parameters**	**Generated power**
Photovoltaic	P_{pv}	222 kW
	A_{pv}	140 m²
	N_{pv}	81 panels

Wind Turbine	P_{wt}	18 000 kW
	A_{wt}	315 m^2
	N_{wt}	2 Wind Turbines
Tidal Turbine	P_t	172 kW
	A_t	453 m²
	N_t	1 Tidal Turbine
Battery	SOC	100%
	LPSP	0%
	C_n	2000 Ah
	N_{Bat}	11 Batteries

VI. RESULTS AND DISCUSSION

Evaluation of the hybrid energy system study, MATLAB software is utilized to investigate the system under the real metrological data. To check the equilibrium power in the studied system, Fig. 4 presents the optimal generated power of each source in system after the sizing and optimization methods.

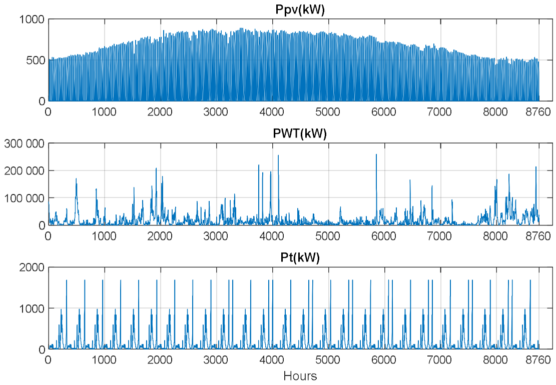


Fig. 4. Power of each source in hybrid energy system for year 2020.

The result illustrated in Fig. 5 is the energy generated by the renewable energy sources: wind turbine power (E_{wt}), source PV (E_{pv}), tidal power (E_t) and, SOC battery and the Loss of Power Supply Probability (LPSP). When the simulation is started, the state of charge is generated via $SOC_{\min} = 20\%$ and $SOC_{\max} = 80\%$. When SOC = $SOC_{\min}$ and $P_{gen} < P_{load}$, consumer satisfaction increases, but when SOC reaches $SOC_{\max}$ and $P_{gen} > P_{load}$, overproduction is evaluated.

On a sunny day, each source of the hybrid electric system generates sufficient energy for the required load and then the battery is charged. Yet, at night, in the absence of the sun is hidden, the wind speed is reduced, while the tidal current speed gets higher, the battery works to match the charging needs. When the battery is charging (SOC = 100%), the LPSP value becomes 0%. These results demonstrate that the micro grid can satisfy the studied location in Djerba Island, Tunisia during all days of the year.

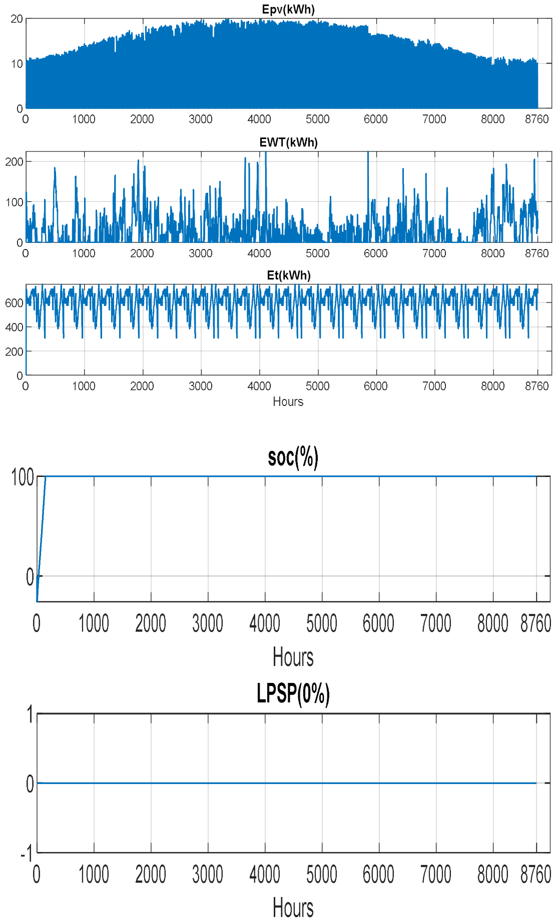
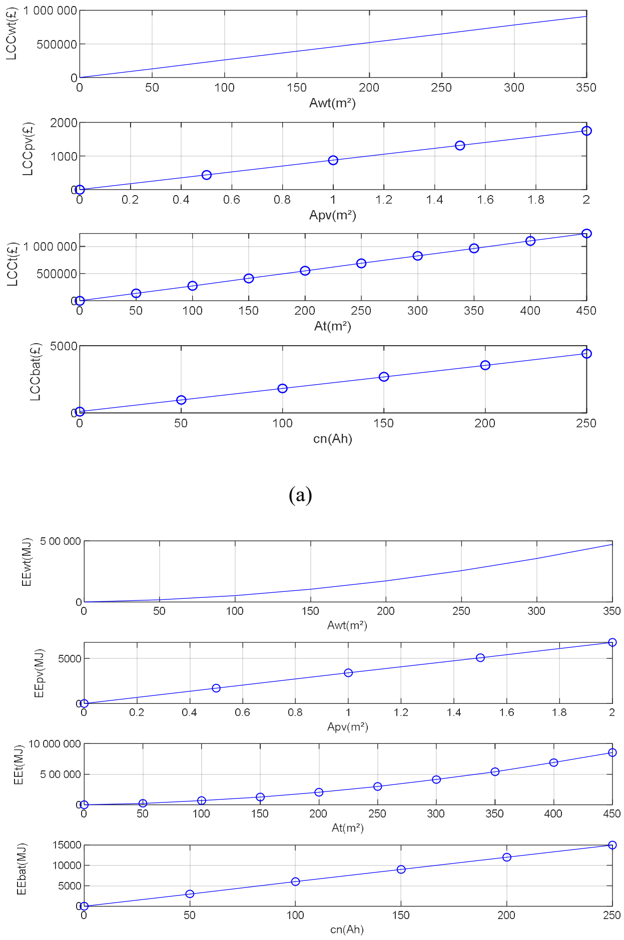


Fig. 5. Optimization results of renewable hybrid energy system

In this paper, the proposed micro grid does not favor energy consumption, when it is used; however, it favors the consumption of the non-renewable energy used to manufacture elements. The result is energy that is called grey energy and is expressed in (MJ). To decrease environmental effect, this energy is modeled then it is used for the design and optimization standard. For solar panels, the embodied energy of 3379 MJ/m^2 is considered. This is the value of a polysilicon solar panel of one square meter.

The calculation is based on the embodied energy of every material and the required energy for the process of the manufacturing. The outcome is shown in Fig.6, which demonstrates a correct estimation of the energy needed for small-sized wind turbines. The same calculations were performed for the tidal turbines. According to the inputs A_{pv}, A_{wt}, A_t also C_n are illustrate in Fig.6 respectively. It can be observed that the increase of EE is accompanied by the increase of areas and battery capacity. These variations are logical because if these surfaces increase, their prices will also increase. For AGM batteries that are selected at the proposed hybrid energy system, the primary energy index is 60 MJ/Ah (20 years). This value assumes that the battery metal recovery rate is 90% and that handling and manufacturing processes are improved by 1% each year.

For LPSP = 0%, the optimal hybrid energy system with the optimal parameters summarized in Table 1. The overall embodied energy EE is 5,033,387 MJ which LCC cost is 1,076,189 €. Finally, this study is important for the studied location in Djerba Island, Tunisia for two reasons one the one hand to decrease the consumption of energy cost by using clean and green the technology and on the other hand because the island depend on the national grid the correlation of the island in all networks and sustainable power supply.



(a)

(b)

Fig. 6. Evaluation criteria of the hybrid energy system: (a) LCC model and (b) EE model.

VII. CONCLUSION

In this paper, an island with a hybrid renewable energy system is established including wind turbines, photovoltaic panels, tidal turbines, battery and diesel, considering the actual green energy sources of the studied location in Djerba Island, Tunisia. MATLAB software is used for the modeling and simulation of the system. The main objective function is to minimize environmental and economic criteria under a given technical criterion: Environmental criteria: EE; Economic criterion: LCC; Technical criterion: LPSP.

The simulation was conducted during the year 2020 under different evaluation criteria. After the simulation of the energy exchange between all system components, the highly efficient system was obtained via the implementation of the LPSP value 0%. Which correlates the higher, EE, LCC, areas (A_{pv} , A_{wt} , A_t) and the storage capacity of the battery (C_n) .

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