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Optimized Hybrid Renewable Energy System for a Baseload Plant

Reda Ragab
Mechanical Power Engineering Dept.
Zagazig University
Zagazig 44519, Egypt
rragab@hotmail.com

Tariq Al Sawy
Mechanical Power Engineering Dept.
Zagazig University
Zagazig 44519, Egypt
tariqalsawy7@gmail.com

Mohamed Hamdi
Mechanical Power Engineering Dept.
Zagazig University
Zagazig 44519, Egypt
mohamedhamdi4474@gmail.com

Hafez A. El Salmawy
Mechanical Power Engineering Dept.
Zagazig University
Zagazig 44519, Egypt
hfsalmawy@gmail.com

***Abstract*—** The objective of this paper is to proof that intermittent renewable supply sources can be integrated to develop a reliable baseload plant, which can generate electricity at a competitive cost to the conventional generation. A methodology has been developed to optimize the design of a hybride plant, which is based on several technologies including; solar PV, wind, hydrogen generation/fuel cells, and batteries to serve as a renewable energy baseload plant. The methodology includes site selection to ensure maximum integration among the intermittent supply sources as well as optimized sizing of both generation and storage technologies. The objective function is for the least Levelized Cost of Energy (LCoE). The system reliability is judged using the Loss of Power Supply Probability (LoPSP) criterion. A MATLAB algorithm has been developed for the initial sizing of the system components, which searches for the optimum solution within the applicability domain. This is followed by HOMER software-based optimization technique for the plant operation. A case study for baseload hybrid plant of a capacity 200 MW is presented. The location of the plant is screened among several sites in Egypt to achieve the best optimum combination of both solar and wind generation considering; resource intensity, site conditions and constraints, as well as integration between solar PV and wind outputs. According to the selected site and according to the developed optimization methodology, the system has a combination of renewable generation/storage capacities of; 87.5% wind and 12.5% solar PV, and storage of 75% fuel cell and 25% battery. This injects energy to the grid with an energy mix of 89 % from direct renewable power sources (solar PV & wind), 8 % from the fuel cell, and 3 % from the battery. This energy mix ensures a steady output baseload of 200 MW throughout the year with zero LoPSP, at a LCoE of 8.61 ¢/kWh. Relaxing the LoPSP constraint to 2.5% resulted in 26.83% reduction in the LCoE to 6.8 ¢/kWh. According to this study, renewable energy generation can be used toward achieving 100% baseload power systems at competitive energy cost to the conventional generation.

Keywords— Hybrid Renewable Energy System (HRES), PV, Wind, Hydrogen, Baseload, HOMER

I. Introduction

The need for the reduction of the greenhouse gases, which is accompanied with an increase in the demand on energy, calls for the use of efficient renewable energy sources. These led to a boom in the demand on renewable energy. One of the major challenges of the renewable energy sources, especially that is generated from wind and solar sources, is their intermittency. This inhibits their applicability to be used for continuous or dispatched power supply. Integrating such intermittent renewable sources with the transmission grid may be a good solution for providing the balancing energy by other conventional plants connected to the grid. This integration has its challenges as it causes instabilities in the grid, if the penetration ratio of renewables become higher [1].

Hybrid renewable energy system (HRES) incorporates the integration and use of two or more renewable power systems. This integration softens the problem of intermittency, yet there will be a need for storage facility. Wide varieties of hybrid energy combinations have been designed and operated to achieve the desired level of system reliability, and to reduce the cost as well as grid stability issues. For example, solar PV/Battery, wind/battery, and solar PV/wind/battery systems have been proposed. A key component in all of these hybrid systems is the energy storage element [2]. The energy storage allows the surplus energy to be stored and reused at higher demands. It can be either thermal, electric, mechanical (i.e. pumped hydro, flywheel, Compressed air), or electro-magnetic. With the introduction of hydrogen as a possible energy carrier, numerous recent hybrid energy systems have included hydrogen systems [3]. The many advantages of hydrogen over fossil fuels explain its various uses and applications. Hydrogen has higher heat content than any other fossil fuel. The possibility of storage for seasonal demand makes it perfect for large scale energy systems. Hydrogen can be generated from renewable sources, and it is environmentally safe fuel. Some of the recent proposed systems include combinations of solar PV / wind turbine/ battery /hydrogen systems [4].

Size optimization is an important step in any HRES design as it provides the balance between the HRES cost and its reliability. Comprehensive survey by [5] nominated size optimization methods as classical, modern and software-based methods. Classical methods build a model for every HRES component and use calculus to find out the optimum size configuration based on cost and/or reliability criteria. These methods may include graphical, numerical, iterative, and stochastic approaches. Modern sizing and optimization methods implement artificial intelligent techniques, which are more accurate, converge faster, and are more suitable for the multi-criteria optimizations; i.e. multi-objective optimizations. Examples of these methods are the genetic algorithm (GA) used by [6]. A recent study by [7] presented a non-linear optimization of hybrid, PV-wind system using pumped hydro storage. The third size optimization approach for HRES includes software-based tools. One of the famous software tools for sizing and optimization of HRES is HOMER Pro [8] used by many researchers like [9], [10]. Sinha and Chandel [11] reviewed the basic features of 19 optimization software tools commonly used in HRES design. The list includes HOMER, RETScreen, iHOGA, TRNSYS, and others. It is worth to mention that HOMER is used in the current study in the final phase of optimization preceded by an iterative MATLAB code for comprehensive and accurate optimization process. In conjunction with sizing, reliability indicators and economic indicators are used to provide the balance between optimized system reliability and its cost. Loss of Power Supply Probability (LoPSP) and Levelized Cost of Energy (LCoE) are both used in the current work.

Renewable baseload (BL) power plant, although technically possible, represents a big financial challenge in the meantime. The intermittency nature of renewable sources, the lack of complementarity between sources (especially solar and wind), added to the prolonged inclement weather conditions in some locations set constraints on the site selection, and raises the CAPEX due to the need for massive storage. Some researchers studied the possibility of using either solar or wind for BL generation, others studied a mix of renewable sources. Solar CSP (Concentrated Solar Power) BL plant is studied and compared with a BL nuclear power plant [12]. They concluded that CSP economically compares to nuclear generation provided that more investment is pumped into the CSP industry to help their prices fall enough by 2030. This is added to the low risk and other externalities that can be gained from the CSP BL renewable plant. Similar conclusion was drawn [13] for a BL wind plant balanced by natural gas combined cycle, or compressed air energy storage. More recent studies [14], [15] concluded that the right mix of RE generation technologies, the complementarity between different renewable sources at specific sites, and demand side management may push renewable sources to collectively provide BL generation capacity

From the previous work reviewed, one can notice the lack of using specialized Wind Resource Assessment (WRA) and PV software tools. This reduces the accuracy of wind and solar power production estimation, and hence, affects the HRES sizing process. In addition, very little work incorporated a clear and detailed, yet simple, site screening mechanism that ensures the complementarity between resources and its effect on storage requirements and HRES sizing. In addition, little updated work is dedicated to the use of renewable sources for **baseload production**, despite the importance of the topic towards more penetration of renewables in existing grid systems.

The current study aims at achieving the least cost of electricity supply from a hybrid renewable energy plant, through adopting an optimization approach, such that it can operate reliably as a baseload plant and achieves a competitive LCoE. For this, it evaluates the potential of combining solar PV, wind, fuel cell, and storage systems to provide steady load from an integrated plant that is fully renewable at a least cost for the supplied energy. A case study of an integrated HRES capable of providing 200 MW is considered, to test the competitiveness of this approach. The plant is grid connected to serve as a BL plant. A storage system is considered to provide load balance to this plant. This includes both fuel cell operated by the Hydrogen produced from the excess renewable energy from the plant, and batteries (Vanadium Rodex Flow Battery, VRFB). The objective is to minimize the cost per kWh supplied through optimum sizing (minimum possible CAPEX) and operation of the plant (minimum possible OPEX). Furthermore, test for additional cost reduction is carried out through adjusting the loss of power supply probability, LoPSP to a certain acceptable predefined value. A collection of industry-standard software products are used in designing the individual components of the HRES. These include NREL SAM, which is used to design and optimize the Solar PV system. WindPro, is used to design and optimize the Wind system. In addition, an algorithm developed in MATLAB is used to identify the optimum sizing of the plant components for a certain site, using a developed iterative technique which has been called Zooming. Finally, HOMER Pro is used for the optimization of the plant operation considering the mix of the supplied energy from different components, such that the lowest cost per kWh is achieved.

II. SITE SELECTION

The site selection is crucial in the HRES design in order to have the lowest energy cost for the proposed plant as this will help in minimizing energy storage needs. A location has both intense solar radiation and high wind speed can achieve the lowest storage cost, providing that solar and wind patterns allows for complementary performance. Using both the Solar Radiation Atlas [16] and the Wind Atlas [17] of Egypt, it is possible to nominate some locations among which an optimum location can be selected based on the previous understanding. The locations nominated for the initial screening process are: Kharga, Ras Ghareb, Saint Paul and Kossier. These locations are shown on Fig. 1

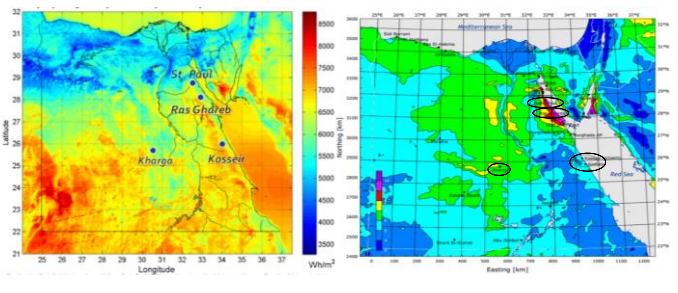

Fig. 1 Solar Radiation Map and Mean wind speed for Egypt with sites circled [16] [17]

Using both WindPro and SAM software and optimizing their output, a test PV and wind plants can be constructed at each of the four sites. The performance and capacity factors of both plants can be obtained at each selected site. Neither Solar PV nor Wind capacity factors alone should be used to select the optimum location for the project, as discussed before. Rather, a Combined Capacity Factor should be used to select the project location. Combined capacity factor (CCF) can be calculated as in ‘Equation (1)’

$$\mathbf{CCF} = \frac{\textbf{Annual combined energy output}}{\textbf{Synchronous Peak power output} * \mathbf{8760}} \qquad (\mathbf{1})$$

The results of the calculations show that Ras Ghareb site has the highest combined capacity factor of around 65%, as shown in Fig. 2.

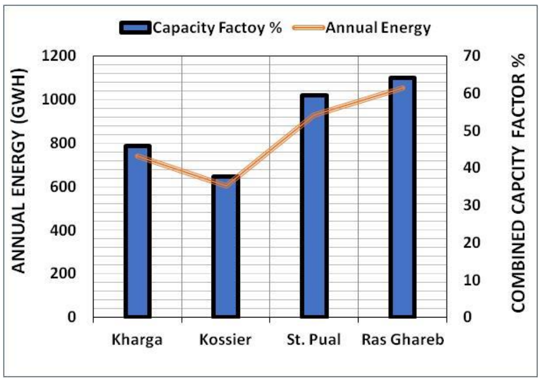

Fig. 2 Combined Wind and Solar Capacity Factor, CCF

Pearson's correlation coefficient "r" is used to quantify the degree of correlation between solar and wind resource. For a hybridized plant of solar PV and wind, sites with small "r" are the perfect sites for this type of plants. Ras Ghareb comes as the second to St. Paul (r_{xy}= 0.256). On conclusion, Ras Ghareb site proves to be the optimum site for the construction of the proposed hybrid system, as it has the highest wind resources, highest **CCF** and good diversity between solar and wind.

III. DETAILED HRES COMPONENTS SIMULATION

A. *Wind System*

Site measurement data are available from a mast located inside the project zone. The mast is about 6 km WSW of the city of Ghareb, and 6 km from the Gulf of Suez in an east-northeasterly direction. Three licensed industry-standard software products were used in wind calculation; namely, WAsP [18], WindPRO [19] , and SAM [20]. All the three software products have the capability of calculating the wind farm performance including array losses using the park wake model. WAsP and WindPro have the advantage of being able to account for the effect of terrain topography and land cover on the performance of the wind farm. On the other hand, SAM has a unique feature of having a parametric simulation tool, in addition to a fully integrated financial model. This feature is useful in selecting the optimum wind turbine module based on the lowest cost of energy, as will be detailed. The combination of the three software products makes the wind calculation model more robust, and reduces any uncertainties.

Three 2MW wind turbine modules with diameters 80, 90, and 100 m, manufactured by Vestas [21], were tested for maximum AEP at a hub height of 80 m. The module with rotor diameter 100 m, V100-2MW-80m, yielded the maximum AEP. This module output is further compared against another module G97-2MW manufactured by Gamesa [22] to account for different technology and expertise. Results shown in Table I indicate that the **V100-2MW 80m** has the lowest energy cost. In addition, the AEP map for the wind farm area is calculated by WAsP, as shown in Fig. 3. The prevailing wind direction is clear in the simulation as well.

Table I Wind farm Calculations

	Scenario I: V100-2MW	**Scenario II: G97-2MW**
Hub height (m)	**80**	**78**
Tip Height (m)	130	126.5
Annual Energy (MWh)	625,133	620,008
LCoE (¢/kWh)	**2.27**	**2.29**

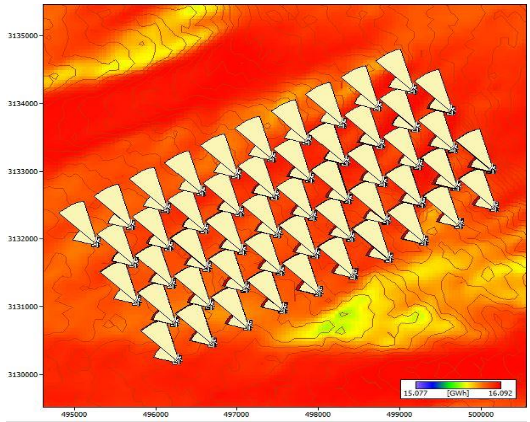

Fig. 3 AEP resource map calculated by WAsP

B. *PV system*

SAM is used to design and optimize the PV system for the selected location. The goal is to select a good set of modules, inverters and their configuration that best suit the site characteristics. Further optimization for the system configuration is carried out in order to get the highest annual energy yield from the solar PV plant in the selected site. Long term weather data file for the site location (Lat 28.311 Long 32.989) is downloaded from the PVGIS tool [23] for the period 2007 – 2016. PV module that best suits the utility-scale project and location is to be nominated and the optimum module is selected based on its nominal power, nominal efficiency, and temperature coefficient. The parametric optimizer at SAM starts with selecting the best module that yields the highest capacity factor followed by optimizing the tracking system and mounting angles. The fully optimized PV system parameters are summarized in Table II.

Table II The fully optimized PV system parameters

Module	Solar City SC330
Inverter	TMEIC: PVH-L3200GR [600V]
DC-AC ratio	1.25
Tracking	1-Axis
Module tilt	34º
Module azimuth	185º
Capacity factor	32.1%

C. *Battery*

The battery considered in the current study is Vanadium Redox Flow Battery (VRFB). It has a unique advantage that; power and energy ratings are independent which makes the stored energy rating is a function of the tank's volume. This independent power and energy ratings makes the VRFB more suitable for scaling up than the well-known Li-ion battery, despite the difference in charge-discharge efficiency. In addition, VRFB has extended life cycle of about 13,000 cycles, along with competitive prices [24] and long discharge time.

D. *Hydrogen Production and Storage*

The surplus energy above the design BL capacity is partially used to produce hydrogen. Water electrolysis needs DC power to split the hydrogen and oxygen into their gaseous phase. The overall efficiency of an electrolyzer can be defined by 'Equation (2)'

$$\eta_{HHV} = \frac{\dot{V}_{H_2} \times HHV}{P_{el}} \qquad (2)$$

Polymer Electrolyte Membrane, PEM method is the technology adopted in the current study for its high energy efficiency and provision of highly compressed and pure hydrogen. Furthermore, it enjoys flexible and dynamic operation and fast starting and loading characteristics. The PEM module selected is the SIEMENS' Silyzer 300 [25]. The produced Hydrogen is stored in tanks for further use in the fuel cell.

E. *Molten Carbonate Fuel Cells*

Molten carbonate fuel cells (MCFCs) are currently being developed for industrial and military applications. MCFCs are high-temperature fuel cells and it work without expensive catalysts or fuel reformers. SureSource 4000™ [26] module is used in the current study. It has a capacity of 3.7 MW/ module and electrical efficiency of 60%.

IV. SOLUTION (SIZING) OPTIMIZATION

The lowest cost per kWh produced can be achieved at certain combination of PV, wind, fuel cells and batteries. In order to find this cost-optimized combination, a hybrid optimization technique combines a developed iterative MATLAB methodology, which is named "zooming algorithm", and a software-based optimization tool, HOMER Pro, is used. The reliability indicator LoPSP and the economic indicator LCoE are both used to achieve the balance between system reliability and cost. A domain containing all possible combinations of the four technologies of the plant: PV, wind, fuel cells and batteries is constructed and discretized to grid points. This domain is constrained by what can be called limiting cases, which include combinations of; wind and fuel cell, wind and batteries, solar PV and fuel cell and solar PV and batteries. After studying all the grid points, the point with the lowest LCoE is marked for further investigation. Another domain is constructed around this point of lowest LCoE to "zoom" at this point and study its surrounding points at smaller steps, seeking for lower LCoE. The domain (grid) is shown schematically in Fig. 4 for two successively searched points A then B.

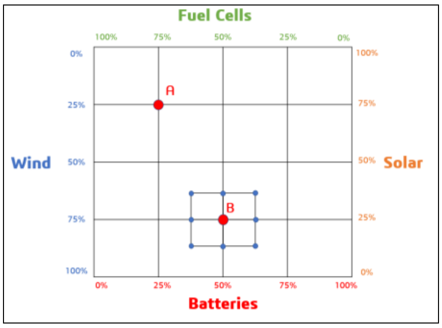

Fig. 4 Optimization Matrix

A MATLAB algorithm is developed to calculate the system composition for each case of the optimization matrix, at a predefined Loss of Power Supply Probability (LoPSP). The output of the algorithm represents a preliminary estimate, which is then refined by HOMER PRO software to develop the optimized combination (solution)

V. CASE STUDY

A case study of 200 MW BL plant is carried out. The plant consists of a hybrid generation facility, which consists of solar PV and wind as well as a storage facility. The storage facility consists of fuel cell and VRFB facilities. The Fuel Cell facility include; electrolysis section of hydrogen generation, Hydrogen storage facility and fuel cell section. Both the electrolysis and the fuel cell sections are equipped with their AC/DC and DC/AC converters. The hydrogen storage facility is equipped with Hydrogen tanks at 40 Bar, necessary piping, gas compression and control. Regarding the Battery section, it consists of battery modules section together with the charging, storage facilities for the electrolyte and control as well as DC/AC converter. Based on a market research [8], [27], [28], the cost estimate and expected life spans for the different plant components are shown in Table III.

Table III Cost estimates for the HRES components

Component	CAPEX ($)	O&M	Life Span
Battery stacks ($/kW)	1590	100	15 y
Electrolyte ($/kWh)	50	0.005	15 y
Fuel Cell ($/kW)	2800	0.01 ($/ h)	50000 hrs
Electrolyzer ($/kW)	1400	20 ($/kW y)	15 y
Hydrogen Tank ($/kg)	60	0	25 y
Converter (kW)	210	0	15 y
Solar Plant	807 ($/kW)	2.1%	25 y
Wind farm ($/kW)	1,024	3.35%	20 y

VI. RESULTS

Considering the defined installed capacities according to the developed MATLAB algorithm for each matrix point, HOMER PRO (HOMER Pro) software is used to simulate the matrix points to find the lowest LCoE based on optimum operation. Schematic diagram of the plant, as represented by HOME PRO software is shown in Fig. 5. The optimized hourly output power for both the wind and solar plants are imported to HOMER PRO from both WindPro and SAM software respectively. Also the required technical data, the average costs of the different technologies and financial parameters re provided. Additional optimization is carried out through HOMER PRO software for the tank size of the VRFB Electrolyte and hydrogen tanks size.

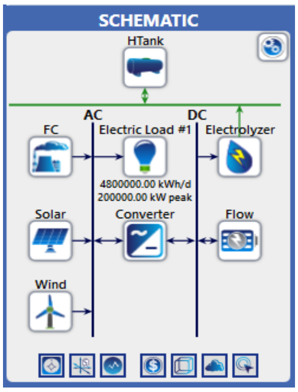

Fig. 5 System Schematic in HOMER

After optimizing the cases in HOMER PRO to obtain the least cost case, the optimum case was found to be at a combination of 87.5%Wind, 12.5% Solar and 25% Batteries, 75% Fuel Cell as underlined in Table IV. This combination has the lowest LCoE (8.61 ¢/kWh) and the lowest CAPEX per kW (7572$/kW). This LCoE of 8.61 (¢/kWh) is in agreement with the cost of baseload electricity reported by Fasihi et al. [14] with slight differences attributed to the assumed financial parameters.

Table IV LCOE (¢/kWh) for the 2nd round of optimization

	Bat 12.5 %	Bat 25%	Bat 37.5 %
	FC 87.5%	FC 75%	FC 62.5 %
62.5 % Wind 37.5 % PV	9.67	8.80	9.25
75% Wind 25% PV	8.61	9.03	9.40
87.5 % Wind 12.5% PV	8.60	<u>8.61</u>	9.70

Table V illustrates the share of every component of the HRES in regard to the percentage share of total energy supplied to the grid and installed capacity (MW). Since this case is calculated for LoPSP approaching zero, the unmet load is only 0.07 % (from the annual energy).

Table V HRES Sizing Results

Technology	Wind	Solar	VRFB	FC
Capacity %	87.5	12.5	25	75
Installed Capacity (MW)	**296**	**73**	86.03	151.7
% Share of Energy supplied to the grid	88.63		2.77	8.6
Tank (kg)	5,000,000			
Electrolyte (kwh)	1,656,699			
LoPSP %	0			
ε	0.07%			

The detailed costs of the HRES are shown in Table 11. As there is a difference in the lifetime of the plant components and the financial analysis is carried out for 25 years, refinance is considered for the short life components. Accordingly the CAPEX of the plant has been calculated based on the Present value. As shown in Table VI, one can figure out the relatively high investment present value (PV) of the CAPEX required for such HRES of installed capacity of 200 MW for baseload application. This may be one of the major barriers precludes the deployment of such systems in power systems. The average cost of 7,572 $/kW is way bigger than that of either solar or wind plants. To well understand the effect of individual system components on the total cost, cost break down chart is presented in Fig. 6. As shown in the figure, the major costs are attributed to the energy storage system. This is confirms the importance of the site selection for this type of application to ensure complementary between solar PV and wind such that minimum storage needs can be guaranteed.

Table VI Optimum case cost data

Total PV ($)	**1,948,016,000**
Operating Cost ($)	33,540,490
System cost ($)	1,514,420,435
Average Cost ($/ kW)	7,572
LCoE (¢/kWh)	8.61

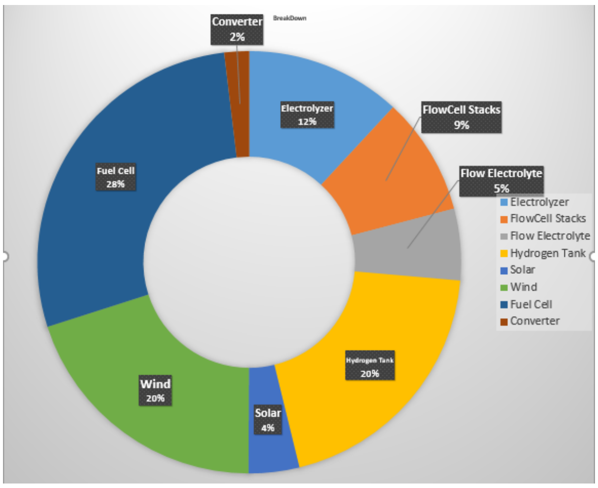

Fig. 6 Cost breakdown at the best case

By relaxing the constraints regarding the LoPSP on the optimized system, a more cost-efficient system can be reached, i.e. lower LCoE. As shown in Fig. 7. If the unmet load was tolerated to be less by 2.5% of the annual energy, the cost will decrease from 8.61 ¢/kWh down to 6.3 ¢/kWh, which represents 26.83% reduction in the cost per kWh supplied to the grid. This LCoE is less than the grid parity in Egypt for NG price based on natural gas price 6 $/MMBTU [29]. Also this cost is less than the cost of the best recent bids for CSP with Storage. It is important to mention that this relaxing can be compensated through operating the fuel cell on Natural gas, as this will only represents 2.5% of the total energy supplied.

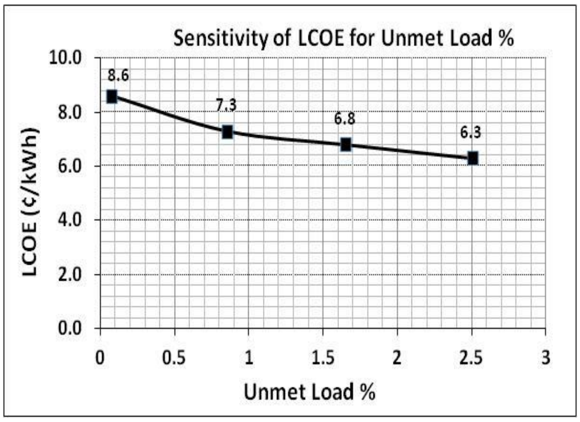

Fig. 7 LCoE change with the unmet load percentage

VII. Conclusions

Using renewable energy systems as baseload units is both technically and financially challenging. Hybridizing renewable energy technologies can represent a cost effective solution to the intermittence of these renewable energy sources, especially the most matured and cost effective technologies like solar PV and wind. Yet, site selection has vital impact on the reliability and cost of the electricity supplied to the grid. This will improve as there is integration between solar and wind, represented by an inverse coupling and high renewable energy resource for the selected site. This reduces the existing financial burden of hybrid renewable energy systems when used as a baseload power plant. In addition, the cost of electricity generation can be further reduced by optimizing the design of both wind and solar PV components. Regarding wind, the highest possible hub height should be considered. This is matched with larger rotor diameter, and suitable matching between the wind scheme in the site and the turbine performance curve. Also the wind plant should be designed in a way to minimize the plant internal losses. Regarding solar PV, in addition to the selection of efficient equipment, one axis tracking is cost effective compared with the two axis tracking system. The currently available professional software products are viable tool to achieve this optimization. Through using the developed optimization algorithm using MATLAB for optimum system sizing, linked to HOMER PRO software for optimum system operation, it is possible to define the least cost for the electricity supplied to the grid from the proposed baseload renewable plant. This approach ensures a balance between optimized system reliability and its cost. This is translated into baseload least electricity cost of 8.61¢/kWh. This cost can be further reduced if the LoPSP is minorly relaxed to 2.5% for the unmet load percentage. The cost achieved is below the cheapest CSP plant with storage as well as the grid parity in Egypt, providing the Natural gas supply is valued at 6 US$/MMBTU . Thus, baseload renewable plants can be optimally sized to provide steady output to the grid with competitive price and high reliability.

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