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Sizing Methodology for Hybrid Solar photovoltaic/Hydrogen System Using Deterministic Balance Method (DBM)-Case Study in Egypt

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Abstract— A technical analysis based on modeling, simulation, optimization and verification was conducted for the design of an off-grid hybrid solar PV/hydrogen system. The main objective is to make sizing optimization of the off-grid system to meet the desired electric load of a residential community in a studied region. Additionally, the goal of this study is to have a 100% renewable fraction penetration in the energy mix resulting in a zero percentage of the greenhouse gas emissions and lowering the cost of energy from power systems and verifying the design concept using SAM (System Advisor Model). The effect of meteorological data inputs for the hybrid off-grid system was investigated in Cairo international Airport zone. The distributed power generation in this paper was using solar PV and Fuel Cell energy systems integrated with electrolyzer and hydrogen tank where the main resource for production is the PV modules so that it satisfies the load demand during the peak sun hours and supplying an excess energy to be stored for the later use of fuel cell to supply community load demand of average 4980 kWhr/day.

Keywords : Solar PV, Fuel Cell, Hydrogen production, Optimization, off-grid

1. Introduction

Nowadays, Software tools have drastically penetrated the engineering fields resulting in a greater dependency on the features the tool they have. In addition, Engineers and Scientists had become much dependent on the analysis and results they got through the usage of different packages of the software applications.

Several software tools were available to evaluate their designs, analyze their performance to find the optimal solution. There were about more than 68 tools available for analyzing the performance of integrated renewable energy systems, out of which 37 tools are most widely used. Some of them are Aeolius, EMPS, Energy Plan, HOMER, Hysim, Hybrid 2, iHOGA, INSEL, RET Screen, SOLSIM, TRNSYS 1.6, etc. [1]. Homer Pro, SAM, Retscreen are the most powerful software programs that can evaluate our system design and obtain accurate results. The methodology they use was a bit challenging to study and to know how our results are calculated in this form. The question still lies on the equations that were being used by the program, the input data and optimization techniques they used to converge for the best optimized results. However, the proposed method was used to size and evaluate the system performance which will be verified using the mentioned software tools after having the same constraints for the fair comparison.

Standalone PV systems are the most popular systems used worldwide especially in the remote areas where there is no access to the electricity grid despite the more recent interest of the market in grid-connected systems. A standalone PV system should provide enough energy to a totally isolated application and maintain its operation in much more reliable performance. The standard configuration of this system is worked out, where the PV generator is connected to the storage battery and then to the load. a PV system must be designed to meet the desired load demand at a high defined level of security.

Firstly, to be mentioned, sizing standalone PV systems is not an easy task due to the random nature of the sun’s radiation at a studied location, the effects of the horizon, the albedo reflection of the surroundings, the orientation of the collecting surface (both azimuth and inclination) and to the unreliable data on the energy demand by the user.

The deterministic balance method is proposed in this paper for sizing optimization of standalone renewable energy systems of a single main source as shown in Figure 1. This paper considers the

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solar-PV as the main energy source, while the energy balance is provided by hydrogen based sub-system rather than the classical battery storage sub-systems. It should be noted that an economic criterion should be combined with represented deterministic balance method for sizing systems with more than one main energy source. For example, in a system with wind and solar PV generators, the selection of sizing of each of them should be based on the energy balance satisfaction and the cost minimization.

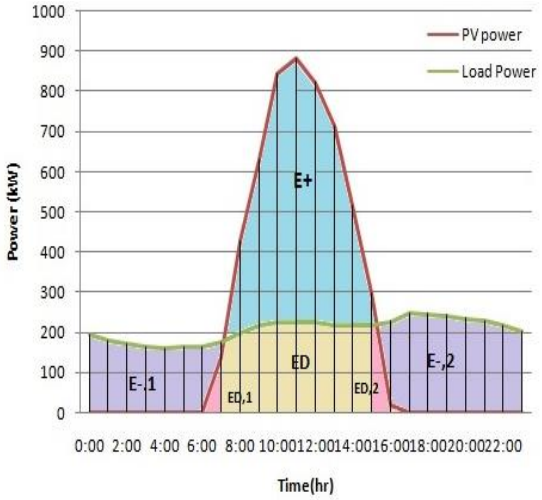

Figure 1. Deterministic balance method

Another example, If the electric load is a summer water pumping and irrigation, there will be a great interest in the energy balance in the summer season only, whereas if the application is a year-time standalone system, the energy balance will be studied for a period of one year. In any of these mentioned cases, the most conservative criteria usually consider for the period of time analyzed, the month having less solar radiation (worst-case design), while another, less conservative approach considers the average monthly radiation value (average design).

Optimizing the hybrid system is the main challenge that determines the successful of each optimization method in the convergence towards the optimal sizing and economical best solution. Once the sizing of each system component was conducted to satisfy all constraints and achieves the best energy production target, the hybrid system would have a higher credit of feasibility and scalability on the site allocation that was carried on. Numerous methods were discussed including meta-heuristic optimization methods, power balance methods and software optimization tools shown in [2], [3], [4]. The proposed method in this paper was started by literature survey based on the systems discussed in [5], [6] as the system architecture and optimization method was the only criteria that the system model could be studied and compared with different methods. System load demand, optimization technique, iteration times and sizing results were the reference which determines the methodology of building the hybrid system and comparing the results obtained by the proposed method of energy balance.

The main point in this paper is to prove the compatibility of the results obtained by the proposed method with other software tools calculations. From then, you will be having a reliable model where you have a detailed overview of each system design issue you could tune to obtain the optimized results.

2. System Description

Setting up a detailed model of off-grid system consisting of PV generators, Fuel cell, electrolyzer and hydrogen storage tank as shown in Figure 2. Considering the meteorological data of Cairo International Airport site as one of data input files for the system model and also having RTS load model as the current load profile for the design and sizing methodology of the system. In addition, using DBM for computing the annual energy production for the system and then reflecting it on the load demand to ensure balanced mode of generation. This method was then used in optimized sizing of each component in the system. From then, the number of PV modules, Fuel Cells, Electrolyzer power and capacity of hydrogen tanks are determined based on the energy balance approach. The hourly electricity and hydrogen balance must be met, either by converting surplus electricity into hydrogen or by converting stored hydrogen into electricity. The hourly simulation is done for the entire year 2018 to size the system components in such a way that there is no curtailment of electricity. Finally, using verification software tools such as Homer and SAM for evaluating the computed results and validating the system performance.

Figure2. System Architecture

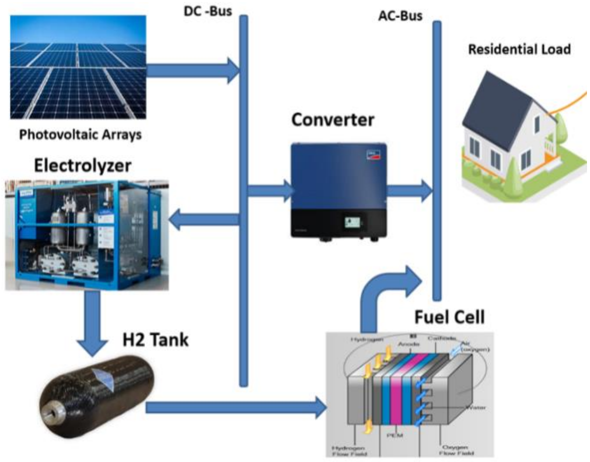

Figure2. System Architecture

The system design model used as an illustrative example for a 100% renewable-based system and is designed in such a way that fulfills the following design requirements:

- The city uses only hydrogen as permanent energy storage and fuel to power all end user requirements [5].
- It uses abundant renewable resources in Egypt: local solar and large-scale wind only [5].
- It is independent of any fossil fuel generators like diesel, natural gas, etc…
- It utilizes the meteorological data at a specific site of Cairo International Airport for evaluating the system energy production.

3. Evaluating A Load Profile for The Community Load

The annual peak load for the test system is 250 kW which will be used as input value for Load model to get the load demand in a time step of 60 minutes. Load model RTS [7] considered to be the most reliable method to get the values of the load profile in areas where you do not have the facilities to measure the energy consumption by the end users existing in the grid. This load model could not be the best method for giving a detailed image of the load profile in Egypt and specifically in the studied site. However, the load profile that was created though this model could be a real case scenario for the system that will be designed to meet this load profile. Even though it may not give the profile that is more expected to be produced by the users' behavior of daily consumption, but it allows the system to experience a real load profile case including the temperature effects as in [8].

The following tables give data on weekly peak loads in per cent of the annual peak load. The load profile was studied during the weekdays and weekends to determine the maximum load demand. From then the system design should meet this load using any of the methods. In this paper, DBM was applied based on the maximum load during the whole year so that the system could be reliable under any conditions and there is no any case of lack of power. To obtain a Complete load profile, there are many procedures and measurements that must be fulfilled so that as if it is a real time case. Thereby, any power system that will be built to satisfy the load demand instantaneously, will be designed smoothly to cover the load for any given period. In applications like supplying power to remote areas, Load profile and Power availability is what comes in the first rank of executing the project. The below data were carried based on a research by the US department of Energy [7] where they predicated an average percentage to be used every hour for acquiring the load profile after determining the Peak power of the Load as an Input.

4. Energy Balance Modes

As discussed previously about the different modes of operation and how they could affect the system design and the load demand-side satisfaction. In this method, calculation will be mainly performed on the three modes as follows: 1) Balanced generation mode. 2) Surplus generation mode.3) Lack of generation mode [9]

a) Balanced generation mode:

$$P_{Gen}(t) = P_L(t) + P_{loses}\ (t) \qquad (1)$$

$$P_{PV}(t) = P_L(t) + P_{loses}\ (t)$$

$$, P_{FC}(t) = P_{ELZ}(t) = 0 \qquad (2)$$

In this mode, the energy provided by the various renewable resources as shown in equations (1,2) is just covering the energy demand and system losses. The load profile is figured out as in section 3 throughout the whole year in a time step of 60 minutes. From then, an excel file is exported indicating the power supplied by each of the PV modules and Fuel cell just to cover the load time for any time in the year. This mode is not executed as the technical point of view is not supporting the critical limits of design. To have a balanced generation mode means that you are critically loading on the available resources of energy and if any other factor affects the process, the system

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would turn into lack of generation mode (which is not acceptable in terms of reliability indices). As a result, the system will be working on the surplus mode that will be discussed briefly in the next section.

b) Surplus generation mode:

$$P_{Elz}(t) = P_{Gen}(t) - P_D(t) \quad (3)$$

$$P_{Elz}(t) = P_{PV}(t) + P_{FC}(t) - P_L(t) - P_{loss}(t) \quad (4)$$

$$P_{Elz}(t) = P_{tank}(t) + P_{h_2,load}(t)$$
$$, P_{FC}(t) = 0 \quad (5)$$

In this mode, the energy provided here is exceeding the demanded load where the excess is being used for hydrogen production for supplying Hydrogen loads (can be converted into electrical and thermal load). The electrolyzer is operated on the DC bus based on the available surplus power and it then delivers it to the hydrogen bus where it meets the hydrogen load and stores the excess in hydrogen tanks.

To supply almost 100% of the required average energy consumption of 150 houses (1,009,673 kW.hr/year) using solar energy and fuel cell. According to the residential profile load curve, the Peak power demand was found to be 250 kW according to the load profile performed by The Electric Power Research Institute (EPRI), So a PV output power of almost 250 kWp which requires 1300 modules (each of 0.32 kWp) with a total installed PV array of 416 kW which is in the range of the limits of the solar PV output. From then the Fuel cell power will balance the required energy which is expected to be working at full rated power during the night hours. According to the energy balance equation, if load following dispatch method was used, then the Fuel cell and PV will be meeting the load demand at the full rated power and the electrolyzer will not have a surplus power to be energized.

However, working in the cycle charging dispatch method will obtain a surplus power sufficient to run the electrolyzer and get energy reserve after fulfilling the load demand.

Manual calculations were performed to ensure that the surplus power reaches a minimum limit of100 kW during the whole day. It was found that the peak load demand was happening from 18:00 P.M till 22:00 P.M and that drives the system to extract much more power from the fuel cell to meet the demand as the PV array is not in operation during this period. When applying the sizing optimization techniques, it was found that this system requires the highest output power limit of the fuel cell and a moderate rated capacity of PV modules as the fuel cell is working the whole day and the maximum output power of PV obtained in a time where there is no high demand for electricity.

c) Lack of generation mode:

$$P_{FC}(t) = P_D(t) - P_{PV}(t) \quad (6)$$

In this mode, the energy provided is not sufficient to meet the demanded load where H2P systems are being critically used to achieve the power balance.

These three modes of operation are being experienced by the system during 24 hours of the day. At the start of the day, PV power capacity is not capable of satisfying the load demand as because of the lower irradiance level. Fuel cell operates in a full capacity as to supply the remaining lack of demand as to satisfy the main goal of this off-grid system and this mode is known as ‘Lack of generation’. During the whole day, PV system is well designed to sustain all energy requirements and produce an excess of energy for the later usage in mode “lack of generation” where you can say that “surplus generation mode” is used to compensate the system in time when mode “lack of generation” happens.

5. Deterministic Balance Method Using Total Energy Production of The System Components

Before applying the Deterministic balance method, it was necessary to determine the detailed model of PV output power, Fuel cell sizing and efficiency, hydrogen tank and its efficiency. To do this, a research was conducted on how to get the exact irradiance profile for the remote area being studied. It was hard to get the exact daily irradiance profile in a time of step of 60 minutes at latitude 30.138, longitude 31.398 (weather station next to Cairo international Airport). On the contrary side, it was easy to determine the day of maximum irradiance throughout the whole year which was on 7th July. During this period of time, Irradiance on the area of Cairo international Airport considered to be at its highest values for the whole 2018. Thanks to the database provided by NASA which facilitated the process of finding the irradiance profile in a specific time for the whole year. However, the problem still exists which is how to get data for the irradiance profile for 24 hr. in a step of 1 hr. METEONORM a German software which contains databases acquired by NASA was able to deliver a detailed report of the daily irradiance profile in the area being studied. Despite the fact that it is limited in information somehow for other remote areas, but It was fitting the studied region to study the irradiance profile in every hour for 8760 days in Cairo. To satisfy the Deterministic balance method, equalizing the net energy produced by the PV (during the sun hours after being consumed through the load) with the Energy needed to cover the time of zero PV output hour (mainly night hours) is mandatory. This net energy will be stored via hydrogen tanks and from then, it will be converted via Fuel Cells to satisfy the whole demand for the day. Using the area under graphs obtained by Trapezium Rule, energy produced by PV and required by the load through Fuel Cells was calculated. Additionally, a discrete optimization as also conducted to determine the optimum number of PV modules required to achieve this balance.

Using the METEONORM Database (version 7.1.3), Monthly Irradiance profile and temperature was conducted as shown in Figures (3 ,4, 5)

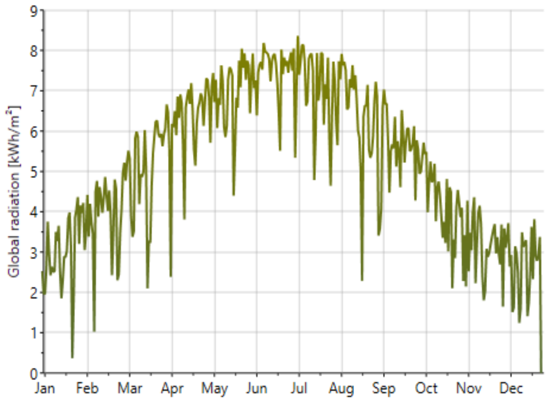

Figure 1. Annual Irradiance Profile in Cairo Airport Zone

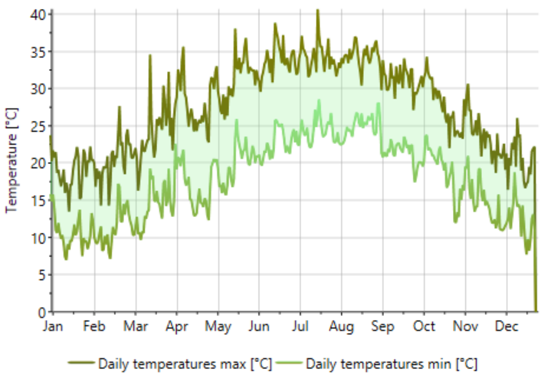

Figure 2.Annual Temperature Profile

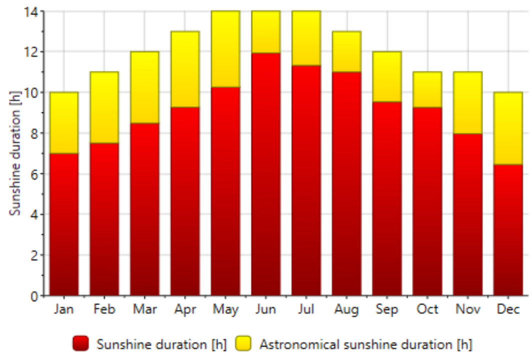

Figure 3. Sun Duration Hours

METEONORM 7.1 Version was used in the analysis phase of computing meteorological data in the location of 30.083 Latitude, 31.283 Longitude at an altitude of 36 m. This location was selected because of the limited available stations that was available in METEONORM database as there was only two locations in Cairo that have a detailed meteorological model. METEONORM database is powerful tool for having a complete irradiance, temperature, wind speed profiles at any time step and during any day of the year. it also offers unique access to the Global Energy Balance Archive Data (GEBA) [10]. The periods 1981-1990 and 1991-2010 are available for solar irradiation on a global scale where It was used for getting the input files of irradiance and temperature 8760 values in a time step of one hour during the whole year. The uncertainty of the data base and the generated typical years is transparently shown directly in the software.

6. Meteorological Data Used During The Study

Date of 31th July was chosen to be the day for selecting the irradiance profile, temperature ranges and sun duration hours. This date was selected as it was obvious form the data collected by NASA Power Data Access Viewer [11] and METEONORM 7 software data base form 1991-2010 that the minimum irradiance and maximum temperature for this region occurs in this time of year. In addition, the load profile in the previous section has indicated that Summer months is having the highest load demand. From then, critical limit of system design was deduced based on powering a load at its maximum demand in a day of the minimum irradiance, maximum temperature. This case represents the worst-case scenario that any

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system could face. If the system was reliably enough capable of supplying the load and producing a surplus power, it could be concluded that this system configuration will be supporting any other scenarios having any other environmental conditions.

7. Methodology for Deterministic balance method

First step of design, it was estimated that 2200 PV modules could satisfy the demanded load and deliver surplus power for the end of the day. This was based on a random guess to start computing values of Energy Production. This initial guess was based on the equation discussed in the deterministic balance methodand it was performed to figure an estimate for the surplus power provided by PV to fully compensate the time of zero PV output power. Equations (1,2) was chosen for evaluating the output PV power taking the irradiance profile of 31st July as mentioned before. The methodology of calculating the energy production by getting area under curves was the main approach that was used during the whole model. There are many ways of calculating area under curves such as trapezium rule, integrating curve functions using Matlab, …etc. Trapezium rule was used in this model for getting the area under curves in a time step of 1 hr as it was difficult to obtain the function of each curve so that it can integrated. Additionally, the accuracy of the trapezium rule was found to be acceptable with the minimum ranges of error. The following terms shown in Figure 1 were used during the system calculations and expressed as follows:

E^+ : Surplus energy supplied by PV arrays
E^- : Total lack of energy which will be supplied by fuel cell and electrolyzer
E^D : Energy demanded by load and supplied by PV arrays
$E^{-,1}$: Lack of energy from 12:00 a.m. till sunrise
$E^{-,2}$: Lack of energy from sunset till 12:00 a.m.
$E^{D,1}$: Energy demanded by load and supplied by PV arrays during sunrise
$E^{D,2}$: Energy demanded by load and supplied by PV arrays during sunset

8. Studying System Design

8.1.Studying the system design on July meteorological data -1st case

After determining the excess energy produced by each one PV module and determining the surplus power by PV. Then calculating the consumed energy by the load supplied by 2200 PV modules as shown in load tables. The optimum number of PV modules needed to sustain the energy balance process through the whole day can be deduced, which can be discussed as a sort of discrete optimization.

Calculations:

$$E^+ = 4306.3\ kWhr$$
$$E^- = E^-(1) + E^-(2) = 2841.5kWhr$$
$$E_D = 2125.5\ kWhr, E_{1,PV} = 1.2626\ kWhr^-$$
$$E^+ is\ approaching\ E^-$$

This calculation based on the assumption that this the maximum values need by the load during night hours as to get the optimum surplus PV power that can cover the load (taking onto consideration the efficiencies of fuel Cell and tank).
It was also noticed that Surplus Energy provided by the PV modules has to exceed the load power during night hours by a certain value. This value is mainly depending on the efficiencies of the fuel cell and hydrogen tank. As a result, higher efficiency system components result in a better sizing optimization result. The equation (7) explains the effect of system components efficiencies on the surplus energy supplied.

$$E^- = E^+ . \eta_{FC} . \eta_{H2,Tank} \quad (7)$$

Back again to the calculations of the previous example,

$$E^-_{Actual} = E^- - E_{D,1} - E_{D.2} = 2348.7763\ kWhr$$

Referring to the equation (7) and taking $\eta_{FC} = 0.82\%. \eta_{H2,Tank} = 0.81\%$
$E^+\ Will\ be\ reduced$

$$E^+ = 4306.3 \times 0.78 \times 0.8 = 2860.244\ kWhr$$

This Value of E^+ is not sufficient to cover the demand load of E^-_{Actual} which is exceeding its generation by almost 800 kWhr. As a result, will increase the PV modules

$$N_{pv} = \frac{(2860.244/(0.81 \times 0.82) + 2125.5}{1.2626} = 5000\ Panels$$

(neglecting the effect of PV modules during first hours of sunrise and sunset)

$$N_{pv} = \frac{(2348.776/(0.81 \times 0.82) + 2125.5}{2.74} = 4480 Panels$$

(if considered the output power of PV during Sunrise and sunset)

In this problem, it was found that the optimum number is 4480 panels which is higher than discussed in our previous Model. This process will continue in the form of iterations until finding the optimum number of PVs which Makes the net surplus power covers the load for every minute during the day. In our case, the optimum number was found after two iterations

8.2. Studying the system design on December meteorological data (minimum irradiance, max temperature and peak load)-2nd Case

December was studied as well as it has critical conditions for the system design: minimum irradiance, peak heating loads and low temperature. This has led to apply DBM for this month as to make sure that the system design is sustaining energy balance for all months. **Calculations:**

$$E^{+} = 4431.3\ kWhr$$

$$E^{-} = E^{-}(1) + E^{-}(2) = 2841.5 kWhr$$

$$E_{D} = 1841.5\ kWhr, E_{1,PV} = 1.2626\ kWhr^{-}$$

Back again to the calculations of the previous example, we will find out:

$$E^{-}_{Actual} = 2348.7763\ kWhr$$

Referring to the equation (2) and taking $\eta_{FC} = 0.82\%. \eta_{H2,Tank} = 0.81\%$

We will get that, $E^{+} Willbereduced$

$$E^{+} = 4431.3 \times 0.82 \times 0.8 = 3013.284\ kWhr$$

This Value of E^{+} is not sufficient to cover the demand load of E^{-}_{Actual} which is exceeding its generation by almost 800 kWhr. As a result, will select increase the PV modules

$$N_{pv} = \frac{(3013.284/(0.81 \times 0.82) + 2841.5}{1.2626} = 5760\ Panels$$

(neglecting the effect of PV modules during first hours of sunrise and sunset)

$$N_{pv} = \frac{(2348.776/(0.81 \times 0.82) + 2125.5}{2.74} = 5400 Panels$$

(if considered the output power of PV during Sunrise and sunset)

In this problem, it was found that the optimum number is 5400 panels which is higher than discussed in our previous Model. This process will continue in the form of iterations until the optimum number of PVs was found which makes the net surplus power covers the load for every minute during the day.

8.3 Energy used by Electrolyzer and Fuel cell for satisfying the load demand

The system is now designed to give an excess power which is almost equal to the energy required by the load during the night hours. Thus, the next step is to identify the sizing procedures of electrolyzer and fuel cell to maintain the required energy demand. for the chosen date of 31st July, the day with minimum irradiance and maximum temperature (worst case scenario for system design) and matching the peak load throughout the whole year. It was found that the load requires 2841.5 kWhr to achieve the balanced mode of energy consumption. Taking hydrogen's higher combustion heat as 0.142 GJul/kg, or 39.44 kWh/kg, the maximum daily Hydrogen production would be 25 kg/ day (neglecting the efficiency of the fuel cell). However, the efficiency of the fuel cell should be considered for the system design as to avoid any mismatching with the load demand. Depending on the type of fuel cell as mentioned in the first chapter of [12], the efficiency of the system could be evaluated to get the energy the load requires instantaneously avoiding any lack of generation. Starting with the excess energy produced by the PV modules which accounts for the efficiencies of both electrolyzer and fuel cell. The energy provided by PV modules is 3000 kWhr to be used by the electrolyzer for producing sufficient hydrogen for later usage by the fuel cell and storing it until operating the fuel cell at times where the energy curve of PV arrays is below the energy load curve. Solid Oxide fuel cell was selected for the system design where it can support

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1 kW - 2 MW and it is more applicable in Large distributed generation areas.

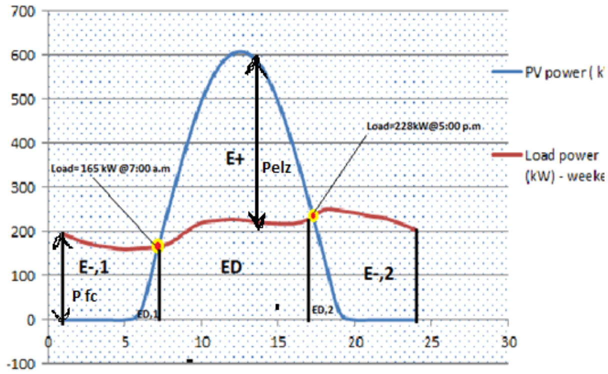

Figure 6.Electrolyzer and Fuel Cell Power Ratings Calculation

As shown in Figure (6), To get the power ratings of the hydrogen system including electrolyzer and fuel cell. The maximum vertical distance between load profile and Photovoltaic energy profile represents the maximum power that the electrolyzer and fuel cell will have to operate to convert this energy into a stored hydrogen by electrolyzer and actual produced energy by the fuel cell in hours of no PV production. As for electrolyzer, the vertical line between load minimum power and PV maximum power is the optimal power rating for the electrolyzer. As for fuel cell, the vertical line between PV minimum power and load maximum power is the optimal power rating for the fuel cell.
Using the load values and PV modules from the tables, the rated power ratings of electrolyzer and fuel cell which are 800 kW and 200 kW respectively.
The mathematical formula of the produced hydrogen from the electrolyzer can be expressed as follows [13]:

Energy required to produce one kilogram of hydrogen =

$$\eta_{Elz} X \frac{H_2 Heating\ Value}{H_2 density} \quad (8)$$

Hydrogen produced in kilograms

$$\frac{P_{Elz}}{Energy\ required\ to\ produce\ one\ kilogram\ of\ hydrogen} \quad (9)$$

The amount of energy generated from Fuel Cell =

$$H_{2\ USED} X \frac{H_2 Heating\ Value}{H_2 density} \quad (10)$$

whereH_2used is the amount of hydrogen input to FC in Kg, H_2heating value is equal to 3.4 kWh/m^3 in the standard condition and H_2density is 0.09 kg/m3. In this work; the used fuel cell is Ballard one. The amount of energy produced from fuel cell is adjusted each hour by controlling the amount of hydrogen released from each single tank. The Hydrogen is kept at a specific pressure as discussed in the theory of glass bottles.

9. PV system losses estimation

Theoretical systems may have 100 % efficiency, but this is not the case when installing a real physical system. A PV array has several factors that prevent PV systems from working at maximum efficiency and reaching their rated output. There are many factors that affect the output of a PV system such as: temperature losses, voltage drop losses, dirt and soil losses, shading losses, mismatch losses, inverter & Transformer losses. The temperature at which the PV module operates has a large effect on its power output and high operating temperatures lead to power losses. The effect of temperature on output varies from module to module and can be calculated using the temperature coefficients provided on the manufacturer's data sheets using the following relations [14]:

$$T_m = 20.4 + 1.2 \times T_a \quad (11)$$
$$T_x = 1 + \alpha(T_m - T_a) \quad (12)$$

where; T_X temperature de-rating factor, α power temperature coefficient for module selected (-0.331% ˚C), Tm is module temperature (˚C), Ta is reference temperature (25˚C), T_a is the average daytime temperature. In this model, it was assumed that AC losses has a fixed value around 7% and Array temperature losses is varying between 5%-11% depending on the temperature monthly profile.

10. Comparing system design with load requirements

The system design was based on the 2nd case of load conditions which is considered to the worst-case scenario that the system could encounter during the whole year. The system was mainly optimized to meet the load demand under any meteorological conditions. Minimum irradiance and Maximum load demand are the critical case that PV/FC system could experience through the 365 days of operation. After calculating the system losses and the overall output energy production for the whole year, a comparison was conducted between the system load and PV/FC system to ensure that load is satisfied during the year and this is illustrated in Figure 8. From then, SAM model [15] will be used for verifying the overall system design. Energy balance based on the hourly simulation, the annual energy balance is defined and presented in Figure 7. The production and energy consumption were investigated in analyzing the annual system behavior. In the October to March period, hydrogen consumption is higher than hydrogen production, and all the hydrogen production comes from solar power. From April to September, hydrogen consumption is lower than hydrogen production due to increasing solar energy resulting from a higher level of irradiance and moderate temperature ranges. For the entire year, all hydrogen from solar surplus electricity goes to hydrogen tank and stored resulting in an approximately 2,000kg of unused hydrogen, except for January and December when approximately no surplus power and all produced energy is consumed by the end users. Those two months considered to be the critical limits for the design of the PV system. As discussed before, this case considered to be the worst-case scenario (minimum irradiance, high load demand) where the system is optimally designed for.

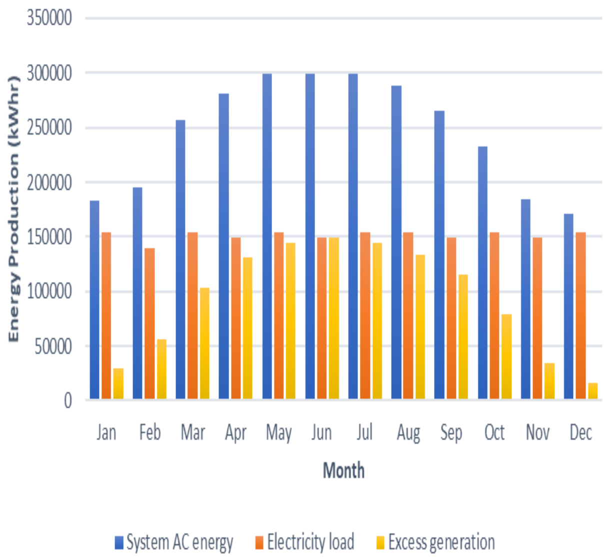

Figure 7. Deterministic balance method satisfying load demand.

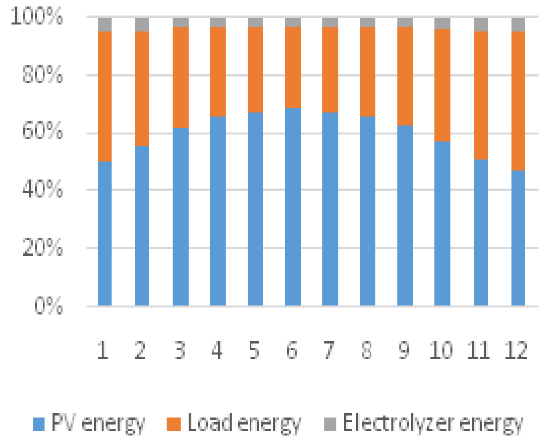

Figure 8. Energy Profile of the proposed system

11. Using SAM (System Advisor Model) Software for Evaluating Energy Production for the whole system

Energy Production throughout the whole year is the critical point for evaluating the system performance results obtained using DBM and other software tools (Homer Pro, PVsyst and PV sol). SAM model was conducted by firstly importing Weather Files using METEONORM platform Which was used before in the Deterministic balance method. This weather file ensured that the input for energy balance model and SAM model are identical and thus preventing any accumulated errors. Secondly, configuring the system design parameters was performed which will be discussed in the next section. Lastly, importing the load that was imported for DBM and then make a detailed comparison between the results of each model. The system consists of 5397 modules of PV array with a configuration of 7 modules per string and 771 parallel strings. These modules are connected to the Load Via 10 inverters with 1.2 DC to AC ratio having a total DC inverter capacity of 1660kWDC and total AC capacity of 1575 kWAC. The results of the total system design are shown in the following Figures (9,10) in terms of the total annual energy production resulting in a monthly report for the energy production for each month that will be used for comparing with the other used methods.

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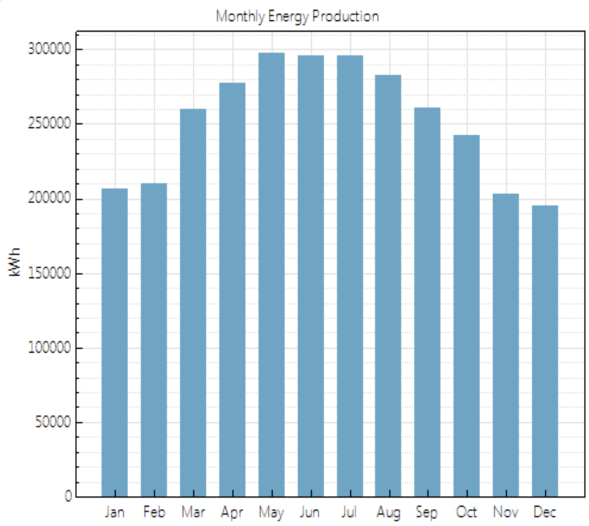

Figure 9.Monthly Energy Production by SAM

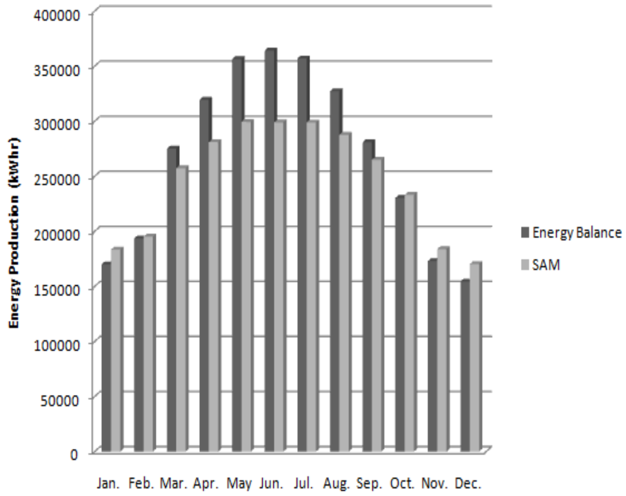

Figure 11.Annual System Energy Production(kWhr) by SAM and Energy Balance

12. Comparison results:

As discussed in the previous sections, the detailed results of each method were elaborated based on the energy production delivered to the system load. From then, A full validation of the Deterministic balance method (DBM) as shown in Figure 11, where there was a slight difference between the average monthly energy production in each model. However, Energy balance model gives an annual energy production of 3201337.657kWhr compared to 2954021kWhr obtained by SAM model having an absolute difference of +7.7% Which is the losses assumed by the software using the same modules with different configurations having a same capacity factor of almost 20% and having the same meteorological data for the studied site.

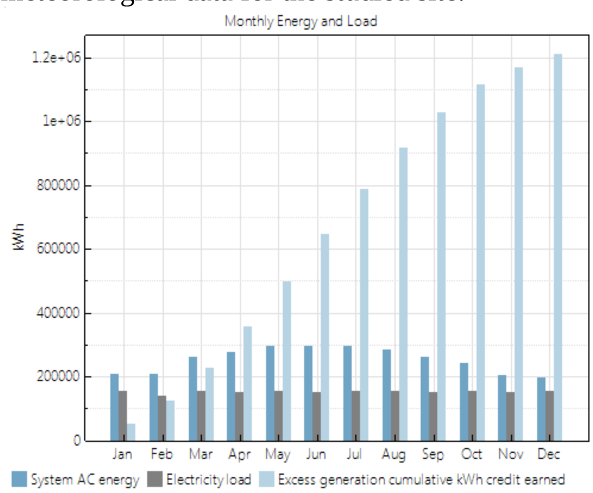

Figure 10. System AC Energy Vs. Load Demand

Although the way of configuration between each PV module was slightly different, this has pushed our model to study the effect of PV arrays connection and how to get a feasible model that could be practically implemented inside our location. Homer Pro Software [16] was also used for verifying the results of annual and energy production and it has already shown a 3,191,291 kWhr which is almost close to the results obtained by the Deterministic balance method.

13. Conclusion:

A new optimized design methodology was used in this paper to design a hybrid off grid power system to meet the electric loads of 250 kW in Cairo International Airport (residential community). The hybrid power system includes two power generators (PV and fuel cell) integrated with electrolyzer for hydrogen production. The results show that the PV/Fuel Cell/Electrolyzer/Inverter power system meets the daily electrical demand of the selected 250 kW in the residential community. A detailed analysis was performed in this study on the proposed standalone hybrid renewable energy system in Cairo international airport with 100% renewable fraction that includes: total energy production and the contributions from the PV and Fuel cell; the energy consumption, AC primary load and the electrolyzer for hydrogen production, the excess power in the system; unmet load. The PV/Fuel Cell off-grid power system integrated with electrolyzer was optimally sized using the DBM method that compares the energy production values of each components and get the best optimal sizing for the system to maintain the energy balance equations. The success of this methodology was evaluated using SAM software which was compared with DBM results. The cost study is another decisive factor to obtain a full comparative analysis of the proposed system and judge the sizing methodologies results.

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