Modelling and Experimental Study on Renewable Energy based Hybrid Systems

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Abstract- In this paper a Renewable Energy Sources (RES) based hybrid system was designed and implemented. It has to cover several electric loads each one corresponds to the annual demands of a typical house, a typical country house and a small company. Experimental process reveals the efficient satisfaction of the desirable electric demands. These scenarios were also simulated by using HOMER software to determine time step results (over 95% load coverage). Moreover, it was found that the served power cannot meet the primary load when simulations take place at HOMER environment. These results are in contradiction with experimental observations that indicate the nearly uninterruptable coverage of the selected annually loads. In order to fill the gap between the real life operation and the simulation process of a hybrid RES project, an Innovative Theoretical Model Simulation (ITMS) based on a mathematical strategy plan, which incorporates the battery bank's State of Charge (SOC), has been developed to accurately predict an autonomous system operation, found in excellent agreement with the experimental results.

Keywords Autonomous systems, Homer, Modelling, Renewable energy, Storage.

Nomenclature

Latin Symbols

DOD	Depth of Discharge (%)
n_{inv}	Efficiency of the DC-AC inverter (%)
n_{Ohm}	Efficiency (%)
P	Power (kW)
SOC	State of Charge (%)
V	Voltage (V)

Subscripts

cap.	Capacity of battery bank
ex.	Excess "green" power
fake	Auxiliary variable for the algorithm
load	Desirable load
rem.	Remaining backup power
ser.	Supplied by the system in each time-step
tot. prod.	Produced by ecofriendly sources

1. Introduction

Several parameters must be taken into account when working on the establishment of a hybrid autonomous Renewable Energy Sources (RES) based system, for the production of electricity that covers a specific desirable load on a daily basis. Hybrid is a system where different technologies are combined to produce electrical energy. Several research studies have already concluded that off-grid hybrid renewable electrical systems can be feasible [1,2], even when their character is not totally eco-friendly, i.e. supported by diesel generators [3-5]. In addition, the final choice of optimal RES combination has to consider the local micro-climate data [6-8].

To assure continuous power supply, independently of the unavoidable variations of the environmental potential, it is necessary to incorporate an intermediate energy storage system into any off-grid RES based power plant. Currently, the most common option for such a buffering is the electrochemical batteries, which (a) are efficient enough to be combined with renewable technologies, (b) have limited initial cost compared to other technologies, (c) provide continuous energy for several hours under predefined constant AC voltage (after converting), (d) are without major safety issues, and (e) do not require a large especially designed room for their installation in small scale building projects [9-12].

Many theoretical studies have been published regarding the design and simulation of hybrid RES based autonomous systems, in order to investigate their feasibility [13,14]. In these studies, several mathematical algorithms have been used to simulate the performance of a potential RES based system in a specific location. The most widely used software package dealing with the simulation of hybrid systems is HOMER [15], which mainly based on a financial optimization process to specify the most optimal scenario in each case study [16]. The basic aim of the presented research study is to propose an Innovative Theoretical Model Simulation (ITMS) based on energy analysis in order to fill the gap between the real life operation and the simulation process of hybrid RES projects.

By HOMER, Dalton [17] showed that the use of diesel generators in small and medium-scale tourist accommodation in remote locations can be replaced by RES based totally eco-friendly technologies with equivalent economic and energy results. An extensive parametric study using HOMER on the electrification of an ordinary house in Canada with an energy consumption of 25kWh/day reveals that the hybrid wind-diesel-battery system feeding the house can be replaced by a totally "green" system with more promising results [18]. Furthermore, various research studies about on-grid systems have been also finalized using HOMER software. This software seems to generate adequate results on energy production and operational performance of several projects [19-22].

Experimentally, it was determined that, during the operation of such a system, the most crucial issues are related to the storage technologies (usually batteries). Thus, during simulations an excessive over-sizing on the power of RES technologies is essential due to the limited capabilities on the accurate prediction of the battery bank's operation offered by existing simulation tools. During the theoretical analysis carried out by HOMER and presented here, it is found that SOC for a battery bank cannot be accurately estimated at each time step. Thus, the design of a new simulation tool (namely, ITMS), based on the accurate prediction of SOC on hourly basis, is necessary. In general, SOC is described through the ratio of the energy input over battery output and can be predicted by measuring the operating voltage during a specific period of the day.

This works intends to prove the viability of a RES-based autonomous system for coverage of typical loads. Actually, the basic aim of this work is not investigated the optimum RES-based system for given load and environmental potential, but to identify if the widely accepted simulation tool HOMER can adequately reproduce the experimental results. Towards this aim, a lab-scale prototype hybrid system has been integrated, including a solar panel, a wind turbine, a battery bank as well as the necessary supplementary staff (controllers, inverter, gauges, etc.). This system has been modelled in HOMER simulation tool as well as in new ITMS environment, for comparison purposes.

2. Materials and Methods

To investigate the feasibility of standalone RES based power plants, a laboratory scale system was designed and established to simulate real-life conditions of electricity "supply & demand". The specific system was built as follows: a Sovello Photovoltaic Panel (PV) at 12V with 205W power at Standard Test Conditions (STC) (i.e. 25 ^{o}C temperature and 1atm pressure) and an Air Breeze Wind Turbine (WT) at 12V with 300W peak power were combined with a storage bank consisting of two EFFECTA 12V/55Ah deep cycle batteries, connected in parallel. Furthermore, an EFFECTA DC-AC inverter (220V/50Hz), which can offer up to 350W continuous power, and a Sunlight controller/charger were also incorporated in the system, as depicted in Fig.1. To finalize the experimental layout, several cables, fuses and gauges were used to indicate voltage and current on specified nodes of the circuit, thus allowing for the calculation of the produced and consumed electricity. The RES devices (PVs and WT) were connected on the inverter through the battery bank, a type of connection not supported by HOMER platform. Exactly the same layout was followed to be modelled such a system through ITMS simulation tool. Moreover the electric power produced by a typical PV and WT were theoretically calculated by using fundamentals physics by using the local environmental potential data [23,24].

Three different loads were designed and selected as presented in "Table 1". These characterize the electricity requirements of a typical four-member family house, a typical country house for the same family and a small company, considered as a single building unit with offices equipped with Air-Conditioning (A/C) systems, lighting devices as well as computers and peripherals. These loads are estimated and downsized in detail elsewhere [25] and are generally valid for the majority of potential applications, therefore adequately representing real life scenarios. The design of the energy production plant followed the same scale-down process, regarding the devices selected. To simulate several different AC loads on an hourly basis, different combinations of twelve light bulbs of different energy consumptions, were selected.

The fluctuations of the electrical load throughout the seasons are due to the operation of devices necessary to cover the resident needs (e.g. A/C systems). The period from September up to May has been considered unique regarding electricity demands, because there are not extreme discrepancies on load requirements during the whole period. Also, the primary load for a small company is increased during a typical weekday of August, as "Table 1" presents, even though the enterprise is closed throughout this period. This has been included to cover unexpected visits of some members in order to finalize projects with deadlines during summer. A similar RES based autonomous system was designed in HOMER using the same operational requirements and covering the same loads as in the experimental process in order to validate the actual time operation. Figure 2 presents the design of the hybrid system on the simulation tool platform for the chosen simulated scenarios.

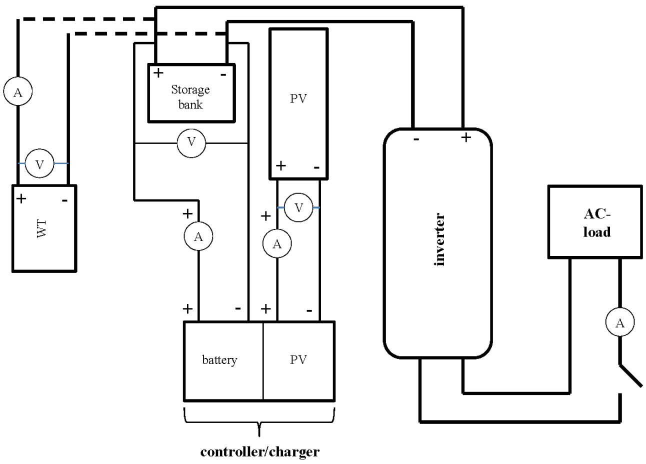

Fig. 1. Schematic circuit diagram of the experimental system.

3. Experimental and Theoretical Process

Initially, three different scenarios have been investigated for several variations of the hourly load coverage, each representing a different real life scenario (Table 1). Real time measurements of voltage and current at the output of the RES devices were taken in five minute intervals. By simply multiplying these two values, the power provided to the system by the environmental sources can be calculated. Thus, the average power offered to the system by RES (i.e. solar and wind energy) can be calculated on an hourly basis. Moreover, excess and unmet load for each scenario can be calculated by knowing the electrical needs on hourly basis, through a typical energy balance. To ensure accurately that results on load coverage for each real life scenario are obtained, all the measurements included in the experimental process were repeated several times during selected days with similar meteorological data.

The meteorological data were collected during the same days throughout the year 2013 in order to adequately represent all possible weather conditions throughout the four seasons. The meteorological data for the specific location of the present project (Agrinio, Western Greece) was provided by local weather stations and have been validated by Hellenic National Meteorological Service. The data recorded

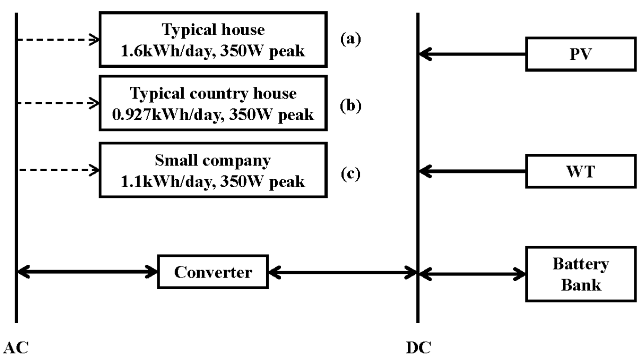

Fig. 2. The three simulated scenarios designed by HOMER.

Table 1. Loads for several typical scenarios during one day [25].

Time (h)	Consumption for September-May (W)						Consumption for June (W)						Consumption for July-August (W)					
	Weekday			Weekend			Weekday			Weekend			Weekday			Weekend		
	*	**	***	*	**	***	*	**	***	*	**	***	*	**	***	*	**	***
00:00-01:00	134	7	3	114	56	3	142	7	3	122	68	3	175	68	3	175	68	3
01:00-02:00	23	7	3	23	45	3	30	7	3	30	56	3	76	56	3	160	56	3
02:00-03:00	21	7	3	15	7	3	30	7	3	23	18	3	76	18	3	152	18	3
03:00-04:00	4	7	3	4	7	3	12	7	3	12	18	3	76	18	3	76	18	3
04:00-05:00	4	7	3	4	7	3	12	7	3	12	18	3	76	18	3	76	18	3
05:00-06:00	4	7	3	4	7	3	12	7	3	12	18	3	76	18	3	76	18	3
06:00-07:00	84	7	3	4	7	3	91	7	3	12	18	3	84	18	3	76	18	3
07:00-08:00	53	7	3	4	7	3	53	7	3	12	18	3	53	18	3	76	18	3
08:00-09:00	3	7	53	4	7	3	3	7	53	12	18	3	3	18	53	76	18	3
09:00-10:00	3	7	53	38	56	53	3	7	53	46	56	53	3	56	53	38	56	3
10:00-11:00	3	7	53	183	90	53	3	7	350	183	90	350	3	90	350	183	90	3
11:00-12:00	3	7	53	84	45	53	3	7	350	84	45	350	3	45	350	84	45	3
12:00-13:00	3	7	53	30	45	53	3	7	350	30	56	350	3	56	350	30	56	3
13:00-14:00	23	7	30	228	339	53	30	7	350	236	350	350	30	350	350	236	350	3
14:00-15:00	23	7	30	114	169	30	30	7	350	122	181	350	30	181	350	122	181	3
15:00-16:00	152	7	53	23	34	30	160	7	350	30	45	350	160	226	3	91	45	3
16:00-17:00	152	7	53	266	34	53	160	7	350	274	45	3	160	169	3	350	45	3
17:00-18:00	114	7	53	38	68	53	122	7	350	46	79	3	122	169	3	137	79	3
18:00-19:00	76	7	53	30	45	3	84	7	53	38	56	3	84	56	3	38	56	3
19:00-20:00	76	7	53	76	113	3	84	7	53	76	124	3	84	124	3	76	124	3
20:00-21:00	76	7	53	76	226	3	84	7	53	76	237	3	84	237	3	76	237	3
21:00-22:00	190	7	53	190	226	3	198	7	53	190	237	3	198	237	3	190	237	3
22:00-23:00	76	7	3	152	56	3	76	7	3	152	68	3	84	68	3	152	68	3
23:00-00:00	114	7	3	53	56	3	114	7	3	53	68	3	122	68	3	53	68	3

*** load for a typical house, ** load for a typical country house, *** load for a small company.**

include the local temperature, wind velocity and solar radiation (global solar radiation on a horizontal surface with a PV tilt of 38^o) as shown in Figs. 3, 4 & 5, respectively. These values were recorded during the experimental process and exactly the same values were chosen for the theoretical approaches by using both simulation tools.

4. Results and Discussion

The experimental process in this research study proves that an established standalone hybrid RES system can adequately cover the electricity requirements for most of cases under hourly basis for different simulated scenarios in the course of a whole year. Experimentally, for the supplied weak environmental energy during winter, the percentage of the uncovered hours during a typical day through the simulated scenarios of a typical house is limited to the 3.33%, as Fig. 6 presents. During the spring and autumn period, the electrical needs can be totally covered, on the contrary to summer days where the worst case reveals due to highest electrical needs (see “Table 1”). This result is attributed to the weekends during the months of July and August, where the system is not capable to supply the appropriate load for the 5.93% of the hours through this period, being out of order by early afternoon.

It seems that summer is the worst season for this specific PV-based system. This behaviour is observed due to fact that the optimization process has to be restricted under both financial and energetic point of view.

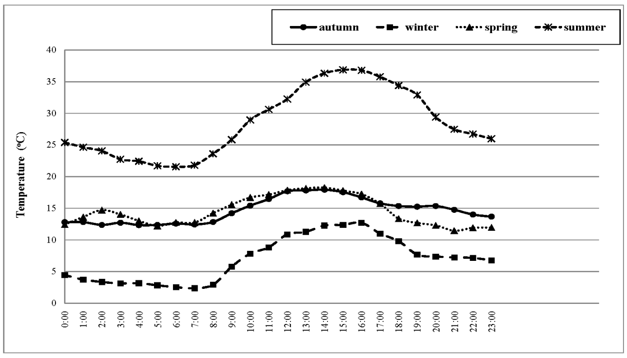

Fig. 3. Average temperature variations during each season (year 2013).

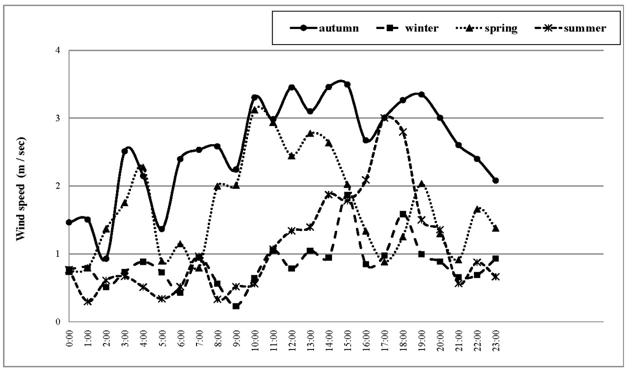

Fig. 4. Average wind speed variation during each season (year 2013).

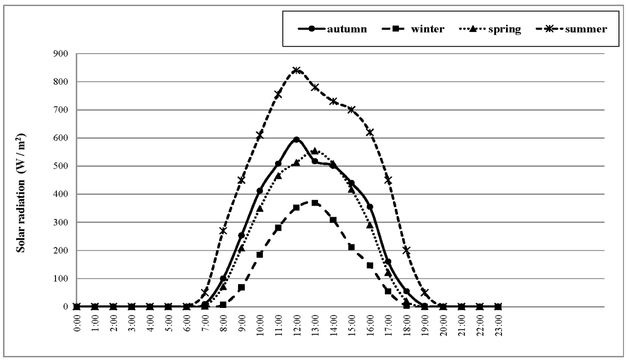

Fig. 5. Average solar radiation during each season (year 2013).

By analysing this, such a system can be characterized as optimized when the power of its established RES devices has been chosen under several financial (limited initial and maintenance costs) and energetic (minimum annual energy waste) restrictions.

The daily simulation process of this worst scenario, as Fig. 7 shows, reveals the high variations of the desirable peak load 0.030kW up to 0.350kW (see "Table 1"), probably due to the operation of an air conditioning unit and this is the main reason for which the RES system fails. The electricity requirements that should be covered for the stable operation are represented by the "primary" load line, the "served" line shows the final load that can be served by the established technologies and the extra energy produced by the "green" equipment is the "excess" line. It must be also underlined that the charge level of the battery is shown on the primary y-axis and the other energy values, as mentioned above, are shown on the secondary y-axis.

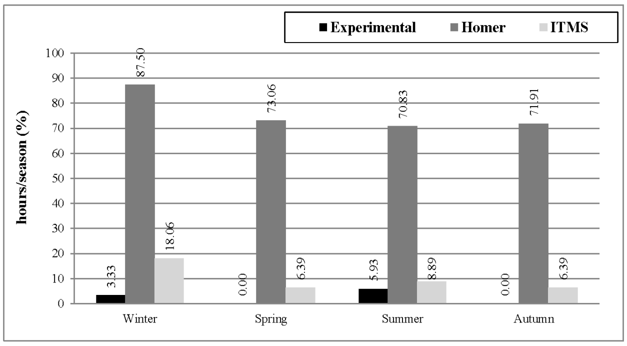

Fig. 6. Rate of the uncovered hours for a typical house and the comparison between Homer & ITMS.

More precisely, the battery bank can theoretically offer 1.320kW to the system but this is not a real time scenario for the operation of the established project. The experimental maximum battery SOC has been determined to an 85%, corresponding to 1.122kW of offered power. This is due to the efficiency of the DC-AC inverter and the internal losses of the electrochemical battery during its operation.

As concern the system simulation through HOMER platform, the operating input values of the RES devices and the local meteorological data are exactly the same as in experimental process. Regarding the load for a typical house scenario (see "Table 1") the theoretical simulation process by HOMER reveals (see Fig. 6) that, the system fails to meet the desirable electric demands for each of the presented season. The coverage of the specific load cannot be satisfied even when the dominated environmental potential is extremely favourable. By analysing the load simulation of a typical house under hourly basis during a typical weekday in June (Fig. 8); it can be clearly seen that the electric demands can

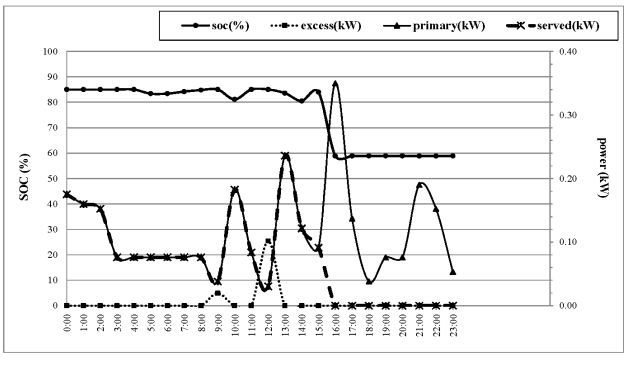

Fig. 7. Real time simulation of a typical house power during a typical July-August weekday.

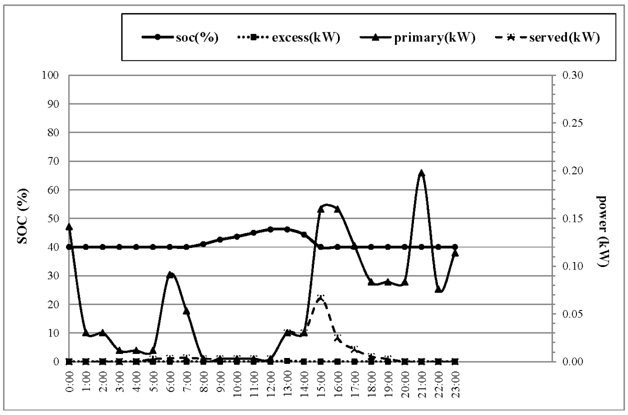

Fig. 8. HOMER simulation of a typical house power during a typical June weekday.

only be obtained for a few hours at the midday hours and the battery SOC remains almost constant at 40%, thus indicating that the battery bank is totally empty and rendering the system out of order. By considering the simulations for each season during a whole year, the same response is also observed, roughly describing the system's operation.

These theoretical simulation results are far from being realistic and various operating parameters should be examined and determined from scratch. Therefore by HOMER, which is the best currently available modelling tool, the desirable power needs seem not to be covered, on the contrary to the experimental observations while considering the typical country house (Fig. 9) and the small company (Fig. 10) load.

Also, HOMER cannot accurately predict the operation of the battery bank, meaning that the capacity of the RES based equipment is insufficient, thus corresponding to its significant over-sizing of the whole system. This indicates that electricity demands of each small scale project cannot be totally covered, even for a single day during a whole year, except for extremely low loads without variations: typical country house during autumn or spring weekdays or typical small company during August weekends (see "Table 1"). This is in contradiction with the real-time data obtained from the already established system, as previously presented here.

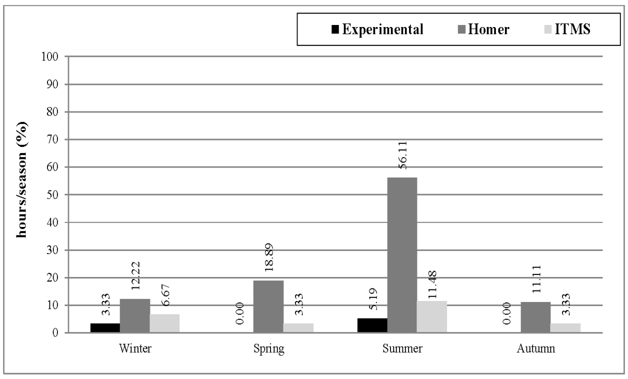

Fig. 9. Rate of the uncovered hours for a typical country house and the comparison between Homer & ITMS.

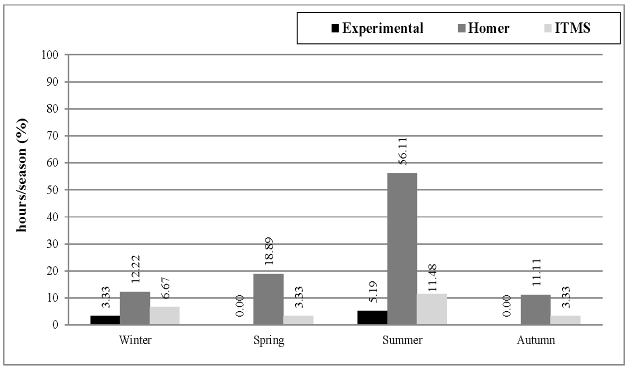

Fig. 10. Rate of the uncovered hours for a small company and the comparison between Homer & ITMS.

By considering the above analysis it is necessary to be implemented an optimization tool, which will offer: a) a more realistic connection among RES devices, b) will be based on an hourly basis simulation process, c) will incorporate parametric analysis on energetic characteristics for each RES device and finally d) its optimization method will be designed on operational system's characteristics, like battery bank's SOC, which has already been proved as one of the most important parameters for a successful simulation process.

Experimentally, SOC appears to vary between 85% and 58% (Fig. 7) and is restricted only by the capacity of the inverter, which cannot operate under 10.5V, even though the battery bank can offer sufficient energy to the system. On the other hand, during HOMER simulations, the SOC value cannot exceed 60% (Fig. 8), which means that the battery bank is almost at the verge of its operational limit and cannot cover the primary load even in combination with RES based technologies. This behaviour can be observed in the majority of the simulated cases, with the exception of low loads, as shown in Fig. 11, which represents the operation of the system during the coverage of the electrical needs of small company throughout a weekend day in August.

As mentioned above, one of the system's crucial parameters is the voltage of the battery bank that indicates SOC and Depth of Discharge (DOD) during batteries operation. This voltage corresponds to the total capacity of the existing storage bank and to the discharge rate when the desirable load is covered. To obtain an accurate correlation between SOC and voltage, it is necessary to investigate how voltage is related to SOC and how the remaining operating capacity of the battery can be predicted through the voltage measured in conjunction with the already consumed electric load during the operational period of a system. Given the voltage at each time-step, estimation for the charge level of a battery bank must also be determined.

The theoretical electric energy hourly offered by the storage bank (batteries) is 1.320kW. When the voltage exceeds 12V, the storage bank is considered fully charged and can provide 85% of the theoretical amount of the stored energy to the established system. This percentage practically represents the discharge efficiency of typical electrochemical batteries.

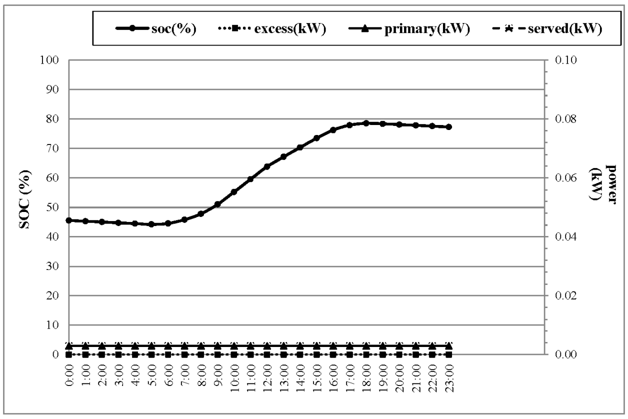

Fig. 11. HOMER simulation of a small company power during a typical August weekend.

Fig. 12 presents the offered energy as a function of voltage. As shown, for voltage values over 12V, the energy is assumed to be constant since the direct current (DC) bus is active up to 12.8-13.2V. When the voltage is lower than 9.5V, the power is approx. 0.530kW, i.e. DOD is at 40% of the theoretical total capacity of the battery bank. Under this DOD value the storage bank could not provide sufficient energy to the system whose demands have to be covered directly by the RES used.

In the range 10.5V to 12V, through the experimental process the offered energy by the specific batteries used in the established system, is approximately fitted by a linear function of the form:

$$P = 0.238\ V - 1.729 \qquad (1)$$

where, P is the power offered by the battery bank and V is the voltage. Above 12V the voltage-energy relation for the specific lead-acid battery bank is linear; indicating that the offered power is constant. Obviously, the coefficients in the above equation are not dimensionless. The values in Eq. 1 stand only for the specific batteries used here and can be easily determined geometrically (see Fig. 12). The slope (0.238) describes the power offered by the battery per unit voltage (kW/V). Although coefficients are unique for each type of batteries, the schematic diagram of the supplied battery power versus battery voltage (see Fig.12) will not dramatically change for lead acid batteries [26] and Eq. (1) can be easily modified to model other backup energy sources based on the same technology.

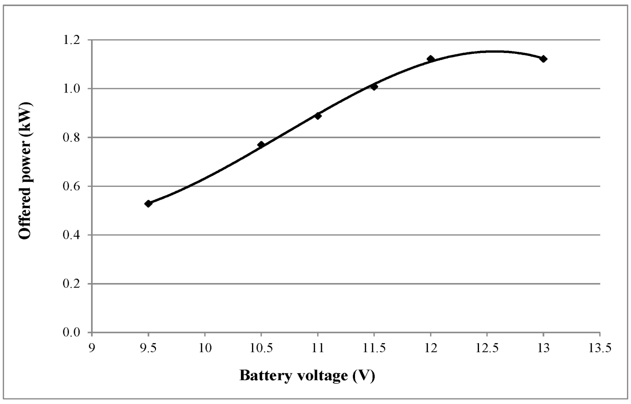

Fig. 12. Power offered from the battery bank as a function of voltage.

5. Design and Validation of an Innovative Theoretical Model Simulation (ITMS)

The above theoretical analysis on the energetic feasibility of standalone RES based systems lead us to design a new software simulation tool that is based on an hourly scale load and daily scale environmental potential. One of the main differences of this new software compared to HOMER, is that the inputs for environmental conditions are the averaged values of a specific hour of a typical day during each season of the year instead of the average values of a whole month. In addition, by correlating SOC with the battery voltage, as previously described, SOC values in each time step are calculated in order to be incorporated in the ITMS tool.

The new theoretical approach proposed here is based on fundamental physics [23, 24] that are widely accepted and have been already applied in several existing software simulation tools. The design of an objective function, which mathematically describes the operation of the electrochemical battery bank and will be based on the energy balance of a simulated RES based project, is considered as essential. This objective function includes all the design and the operational parameters of the system as well as the meteorological data that affect system's efficiency, described as:

$$\begin{aligned} F\left(P_{av.AC}\right) &= n_{inv.}\cdot P_{av.AC} - P_{load} \quad \Leftrightarrow \\ F\left(P_{av.AC}\right) &= n_{inv.}\left[\left(1-n_{Ohm}\right)\cdot P_{tot.prod.} + P_{rem.}\right] - P_{load} \end{aligned} \qquad (2)$$

where P_{load} is the load to be covered, $P_{av.AC}$ is the total power converted through the inverter and available in each time step, $P_{tot.prod.}$ is the primary produced "green" power and n_{inv} and n_{Ohm} is the inverter's efficiency and the Ohmic losses, respectively. Finally, $P_{rem.}$ describes the total available backup power and is directly dependent on Eq. 1 and has to be evaluated at each time step.

Following the circuit applied in the experimental layout (see Fig. 1), where all the DC RES devices supply their power to the storage bank in order to be transformed into AC power via the inverter, the core of the simulation model is the battery bank. Power from RES technologies can easily be calculated whenever the average hourly meteorological data are known. Therefore, the remaining capacity of the battery can be easily calculated by taking into account the coverage of the desirable load for the previous hour when the storage bank has been used to satisfy the demands. ITMS, as already mentioned among other innovations, incorporates the accurate prediction of battery SOC by enabling the Eq. 1 in this theoretical approach. The prediction and the calculation of battery SOC through the remaining backup power $P_{rem.}$ of the system is presented in the flow chart of Fig. 13.

This part of algorithm uses variables describing the physical magnitudes of several input and output power quantities during the simulation process, namely: the desirable load P_{load} which has to be covered, the served power $P_{ser.}$ by the system, the excess power $P_{ex.}$ wasted in the environment, the maximum amount of power $P_{cap.}$ which can be stored in the battery bank, while $P_{tot.prod.}$ and $P_{rem.}$ have been previously defined. It must also be highlighted that all the above parameters are calculated in each time step, thus evaluating the power balance of the hybrid system.

Based on exactly the same environmental conditions and the same equipment, the simulation of the three different projects was performed using the new software (ITMS) and compared to the experimental process. Exactly the same hourly basis desirable loads for the presented scenarios (see "Table 1"), are adequately covered by the power provided, as presented through Fig. 6, 9 & 10, one for each of the chosen scenarios. By comparing all the theoretical and experimental simulations, it can be concluded that the new theoretical simulation approach (ITMS) can adequately achieve the highest percentage of the covered days during all the periods throughout a whole year for each scenario as well as through the experimental process.

The above analysis can specifically reveal that HOMER can adequately simulate the operation of system under real life conditions for a roughly constant electric load (see Fig. 9) and so does ITMS. By increasing the desirable annual load in the same established RES system (see Fig. 6 & 10) HOMER simulations result to discrepancy from reality. This might happen due to the optimization algorithm used by HOMER which is finalized under a financial point of view, not paying significant attention to energy optimization (modelling of the electrochemical battery bank).

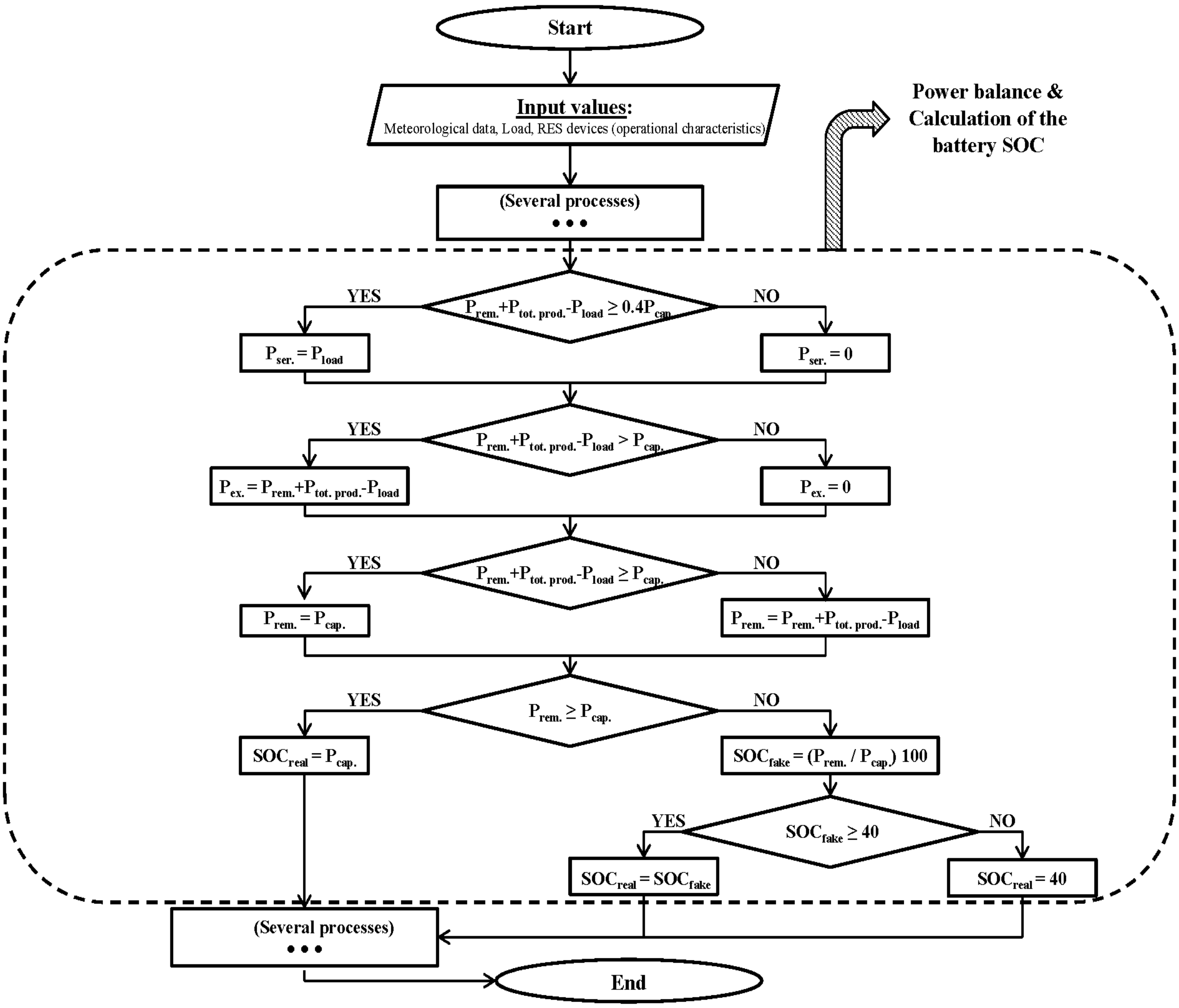

Fig. 13. Flow chart of the system's power balance.

6. Conclusion

Initially, in the present study a laboratory scale off-grid RES based power project was built in Agrinio, Greece to examine the feasibility of such systems under real life conditions. PVs and WT were used as primary energy sources, and a deep cycle battery bank was chosen for intermediate energy buffering. The correlation between SOC and the voltage of the battery bank in each time step was determined in an experimental way in order to be incorporated in a new theoretical simulation tool being therefore an innovative evolution and approach on hybrid systems' modelling.

Three different case studies characterized by different loads were experimentally simulated. The experimental process indicates that the electric load of a typical house can be covered at approx. 97.69% of the 8,640 hours throughout a whole year, which is an impressive result for the feasibility of standalone eco-friendly hybrid systems. Furthermore, the load of a typical country house was also simulated and was proved that approx. the 98.66% of the total hours over a year can be satisfied by RES technologies. Finally, the annual coverage of a small company's (offices) load is also satisfactory, being approx. 95.78%. These quantitative results indicate the influence of the desirable load on the satisfactory coverage: the higher the load, the higher the numbers of hours that the system is out of order.

The same simulations have been also performed theoretically by using both HOMER and ITMS, in order to investigate whether these tools can estimate real life scenarios with acceptable accuracy. ITMS simulations showed that a RES based hybrid system can significantly cover the load of several scenarios, as well as in real life operation, in contradiction to HOMER results that found in disagreement with experimental results. ITMS found 86.4% more efficient than HOMER for loads characterized by high peak power variations (e.g. small company at winter) but this percentage is limited to 5.55% for lower stable loads (e.g. typical country house at winter weekdays). This improvement underlines the different objective functions used by HOMER and ITMS, thus indicating the different focus of each tool: HOMER optimization is under specific financial aspects while ITMS simply implements minimization of power waste and excess electricity.

To conclude, in the present work a new approach on the theoretical modelling was presented and was proven that it can accurately simulate hybrid RES based systems as it happens under real life conditions. This new model is strictly designed on an hourly basis incorporating an innovative code for electrochemical battery bank in order to optimize a system under an energy point of view. Simulation through ITMS provides more realistic results comparing to these by one of most well-known simulation platforms, HOMER. This point is also supported by the fact that the experimental process under real life conditions of such an eco-friendly system gives almost the same results with this new model.

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