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An Optimal Energy Management of Grid-Connected Residential Photovoltaic-Wind-Battery System Under Step-rate and Time-of-Use Tariffs

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Abstract- This paper explores optimization for energy management for a given residential application. The study proposes an approach that can minimize the utilization of the grid for electricity usage in the load and maximize the sale from renewable energy (photovoltaic (PV) and wind turbine (WT)). Besides, the battery storage is permitted to sell the excess power during high price period. A time-of-use (ToU) and step-rate tariffs are incorporated in the model to control the efficiency of the utility grid and also to consider the fluctuation of the electricity price. Therefore, two energy management methodologies are developed to adjust the tariffs for great benefits. Various residential feed-in tariffs (FIT) are implemented in order to reach the potential of cost-saving and earn more cost-benefit. A typical Moroccan house, containing a grid-connected PV-WT-Battery system, is used for study validation. On the one hand, simulation results show that the developed energy management strategies are effective in controlling the power sources optimally. On the other hand, applying the method under a greater FIT, a lesser requirement of battery capacity will be performed as well as a maximum cost saving. Then, the model as a Non-Linear Problem (NLP) is compared with another existing optimization approach to ascertain the effectiveness and validity of the algorithm.

Keywords Optimal energy management, time-of-use tariff, step-rate tariff, feed-in tariff, Non-linear programming, Genetic Algorithm.

1. Introduction

1.1. *Motivations*

In recent years, there is a big trend to use renewable energy sources (RES) in the entire world due to the over-dependence on using fossil fuel which led to its depletion, the increase of electricity cost and energy demand. The latter is expected to increase by 50% and 40% in USA and Europe respectively, also it will be tripled in China [1]. Renewable energy (RE) technologies, including solar PV, WT have gained interest due to their great advantages such as low cost and lower environmental impacts. Further, many developed countries as Germany and Canada [2] apply the RE grid-connected systems and benefit from the excess energy exported to the national grid using attractive FIT for cot effective hybrid system. Nevertheless, in other countries as Morocco, the FIT should be developed in order to minimize the main grid peak load.

North Africa is considered the most producing region of oil and gas in the world, but due to its geographic situation, it has great potential to be a RE powerhouse. Morocco as a country in North Africa, about 93% of its total primary energy consumption comes from coal, oil and natural gas. Indeed, Morocco aims to satisfy its increasing energy demand by exploiting its large renewable energy potential. The target of the government is to reach 42% of RE generation capacity by 2020 and 52% by 2030 [3] focusing mainly on solar and wind sources.

In this regard, Morocco initiates and develops RE technologies which are the major policy incentive [4]. However, due to the intermittent nature of RE, hybridization by exploiting other renewable sources or energy storage systems should be considered [5]. Therefore, several works on study of feasibility, energy management, and techno-economic study for isolated and grid-connected systems have been conducted. Authors in [6], demonstrated that the combination of PV and wind is the best solution for Morocco. In [7], they develop a novel algorithm to solve an optimization problem and reveal the potential of combining RES. Hence, many implemented hybrid systems operated on the battery bank systems in a different electrical system such as residential usage, industrial, and commercial consumption. The actual challenge is to ensure the demand while managing the energy flow optimally by using the appropriate strategy. Besides, the installation of grid-tied/PV/wind systems had found more markets in different sectors. In this vein, most of the existing literature has been conducted on developing energy controllers for isolated and grid-connected systems to reduce the global cost of power and coordinate between the energy demand and supply.

Concerning grid-tied residential PV-WT systems, the optimization is a welcomed strategy taking into consideration electricity tariffs which have an important effect on the economic performance of the hybrid system. The popular electricity purchase tariffs in Morocco are ToU and step-rate tariffs. In terms of policy outlook, they are capable to enhance the energy efficiency of the electricity grid.

1.2. Contribution

Different works on grid-tied systems have developed many energy management strategies for the residential sector. The primary objective of these methods is to minimize the consumption of energy while maximizing energy efficiency. However, there is a gap in reducing energy cost and the interaction between the power generation, power demand, and the grid. Likewise, the profit from managing the surplus energy sold to the main grid. There are two possibilities performed to match the demand, production, and electricity price. Firstly, the sale of excess power to the grid and secondly, the storage of the surplus power to use it when the household demand is high. However, in the first approach, less attractive FITs can result in a less cost-effective hybrid system. In the second approach, the consumer can control the power flow freely between his house and the utility grid (purchase / sell). Further, electricity tariffs have a great impact on the economic performance of RE generation systems and financial benefits for the consumers. Hence, the proposed hybrid system focus on developing optimal energy management to afford a prospect of the reduction of grid energy cost. The system includes PV and wind power systems and the contributions of this study are outlined as follows:

- The developed model permits residential consumers to coordinate the energy flow between production and consumption, and it brings the opportunity for the end-user to export the energy to the provider.
- The strategy aims to lower the energy bought from the main grid when the electricity price is high in the framework of two time-based pricing such as ToU and step-rate tariff. However, most research focus on the ToU program for residential system, therefore, the present study develops a new mathematical formulation of the step-rate tariff which can bring as the ToU significant benefits to the consumer.
- As there is a need of large economic studies of residential applications, there is still a gap in the cost-effectiveness of the hybrid systems connected to the grid that take into consideration the sale of excess energy to the grid and the effect of the battery. Thus, the model is analyzed under a proposed attractive PV and wind FITs, as well as, a speculative performance of the system is discussed under different battery capacity to analyze the impact of the battery and examine the system enhancement. Besides, a comparison between deterministic and stochastic algorithms in order to validate the robustness of the model is performed.

Then, the simulation results reveal that the developed energy management methods schedule the energy flows of the power sources optimally and achieve the maximum profit.

1.3. Structure of the paper

The rest of the paper is organized as follows. Section 2discusses the literature review. Section 3 involves the configuration of the hybrid system and the description of each component. Section 4 describes the suggested energy management strategies under different tariffs and mathematical formulation. The calculation of the optimization problem based on the different algorithms is presented in Section 5. In Section 6, simulations results of a Moroccan case study are discussed and different comparisons are performed to verify the developed strategy. The conclusion and future research are drawn in Section 7.

2. Related Works

In a grid-tied residential hybrid system, the energy efficiency can be enhanced at the POET which contains the following levels: Performance, Operation, Equipment, and Technology [8]. Optimization is considered the widely used strategy for energy efficiency development at the operational stage. Authors in [9] present an energy management method for residential application. The proposed method is a combination between the genetic algorithm (GA) and the rule-based strategy taken into consideration by the authors. The designed methodology aims to perform the residential complex more autonomous by making it less reliant on the utility grid, which is possible by minimizing the power purchased from the grid. In [10], the authors propose a grid-tied PV and wind systems with a double storage system (DSS) containing battery bank, hydropower (PSH), and pumped storage system. In the designed system, the excess renewable energy not absorbed by the PSH is discharged in the batteries and they supply the load that cannot be satisfied by the water turbine. The optimization problem is considered as multi-objective function to reduce the energy imports and the CO2 emissions. In Ref.[11],the study aims to design an efficient fuel cell-battery system for a residential home. A novel power management technique using fuzzy logic is developed, and its robustness is compared and analyzed with other strategies. The results show that the designed hybrid system can operate much easily with a prolonged lifetime. In [12], the work attempts to reduce the operational cost for a residential micro-grid containing PV, WT, battery, and diesel generator. Particle Swarm Optimization (PSO) is the algorithm used to solve the optimization problem and the objective consists of minimizing the total costs of distributed energy resources (DERs) as well as increasing their usage. Authors in [13] propose novel energy management of a Moroccan grid-connected PV/battery trough an optimal management algorithm. The proposed strategy aims to tackle the problem of synchronization between the sources using MATLAB/SIMULINK. The load was powered from the PV generation between sunrise and sundown, the surplus energy will be stored or exported without overtaking a 1000W/hour. Authors in Ref.[14]develop an energy management strategy (EMS)to manage optimally the energy flows and maximize the benefit from the energy exchanged with the grid under ToU tariff. The Fuzzy Inference Systems (FISs) has demonstrated to be effective thanks to the low running time cost. The authors in Ref.[15] implements an EMS under ToU program for a domestic load connected to the grid. The consumers can use energy generated from PV and WT as much as possible to save money on the electricity bill instead of purchasing energy from the main grid. In [16], an optimal control is designed for a micro-grid connected PV/diesel generator system related to industrial and commercial applications. The strategy purposes to reduce the energy used from the grid and the cost of fuel consumption. The calculation of the optimization problem is done using the ‘fmincon’ algorithm. Then, the results show that the system can have a benefit in terms of energy and cost savings. In Ref.[17], a residential PV-Battery Energy Storage Systems connected to the grid is considered. The paper proposes an optimal control strategy under the ToU to achieve peak shaving and reduce the load difference between peak and valley of the grid. To solve the problem, the Particle Swarm Optimization (PSO) algorithm is executed and when the forecast error occurs, the energy exported to the grid, and the exchanged power with the battery will be regulated. Then, the following steps should be re-optimized to keep the optimal control result. The Ref.[18] presents an economic study of grid-connected residential with PV under the actual FIT. The hybrid system is designed and simulated by the software HOMER Grid, and various PV initial costs are tested to examine the feasibility of the system. Authors in [19] implement a home EMS with demand side management (DSM) to enhance the energy efficiency of the grid systems. This model is designed to minimize the peak load and energy cost under price-based tariffs such as ToU and flexible tariffs. The results demonstrate that RES integration in the framework of DSM can achieve a significant reduction in the total electricity cost of the load by minimizing the purchased electricity. The hybrid system considered in the research [20] consists of PV, WT, and battery storage systems. The proposed multi-objective optimization is applied considering the FIT and environmental regulations in Taiwan. The strategy chooses the optimal configuration using the Pareto front sets and achieves a savings of up to 49% and 32% for urban and rural respectively.

However, among the aforementioned research works, there is a gap in the context of the economic performance of the residential hybrid systems by analyzing the impact of the electricity tariffs which bring considerable financial benefits to the end-user. Therefore, this work advances an optimal EMS for a residential PV/WT/battery by examining the effectiveness of the system under TOU, step-rate, and FIT tariffs.

3. Structure of the Hybrid System and Operation Description

3.1. Presentation of the system

The configuration of a grid-connected residential system is shown in Fig.1 and is made up of three principal sub-systems, the PV system, wind system, and the battery storage system. Different converters are required as the converter DC/DC and the bi-directional inverter DC/AC for grid integrative operation. The P_{PV}, P_{WT}, P_{Grid}, P_{ch} and P_{dis} represent respectively, the power flow from PV, WT, utility grid, cherging and discharging of the battery. P_L denotes the power demand by the consumer. If the electricity demand is less than the RE generation, the battery is charged by the surplus power. However, if the load power is above the renewable output, the deficit will be fed by the battery or purchased from the grid in accordance with the operating limits of the battery and electricity price. Some rules of control and schedule are necessary for all sources of the system. As in some countries like China, the residential PV policy is based on the mode “self-consumption first, the excess is sold for the grid” [21].The proposed EMS adopts this but more scheduling rules should be analyzed in the proposed system. Firstly, the priority is given to meet the load from PV and WT power. Secondly, if the renewable power output is larger than the load demand power then the excess will be used for charging the battery or selling to the grid. The benefit from the electricity exported to the utility grid will be defined in the optimization problem.

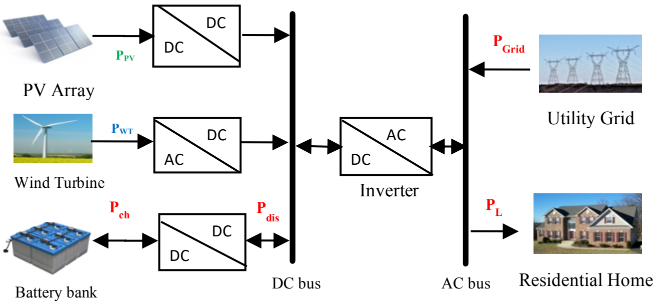

Fig. 1. Schematic diagram of residential grid-tied PV-WT-battery hybrid system.

Thus, when the load demand is greater than the RE generation, the energy storage system (ESS) is established mainly to supply the demand. Nevertheless, the utility grid provides electricity when the household demand cannot be completely met by the REs and the ESS. The battery is also charged by the main grid and discharged to sustain the load demand or to the grid to save electricity cost.

The design of the different power flow is presented in Fig. 2. From the figure the control variables of the system can be identified as follows:

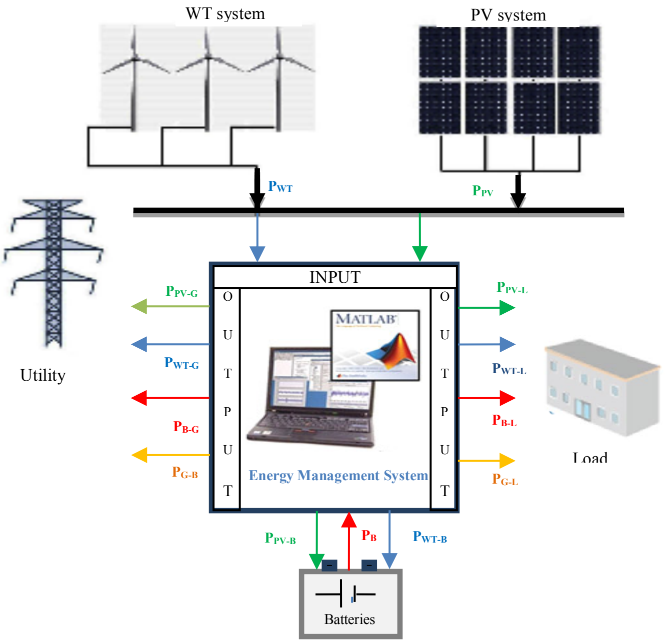

Fig. 2. Power flow of the optimization problem.

-P_{PV-B} and P_{WT-B}: Discharged power from PV and wind to the battery;

-P_{G-B}: Power provided by the main grid to charge the battery;

-P_{G-L}: Power used from the utility grid to feed the load;

-P_{PV-G} and P_{WT-G} are the excess of PV and WT power feed-in into the grid;

- P_{B-G} is the surplus battery power sold to the grid.

The energy management system shown in Fig.2, manages the energy given as input to ensure power balance.

3.2. Photovoltaic system

The output power generated by a PV generator based on the presented model in [22] is calculated as follows:

$$P_{PV} = P_{PV,STC} \times N_{PVs} \times N_{PVp} \times \frac{G_T}{1000} \times [1 - \gamma \times (T_j - 25)] \tag{1}$$

with

$$T_j = T_a + \frac{G_T}{800}(NOCT - 20) \tag{2}$$

where P_{PV} is the output power of the PV generator; $P_{PV,STC}$ is the output of the PV array at the standard test condition (STC) and the maximum power point (MPP); N_{PVs} and N_{PVp} are the number of PV modules in series and parallel respectively; G_T denotes the solar irradiance at STC; T_j is the cell temperature; γ refers to the temperature coefficient of the power; T_a is the ambient air temperature; and $NOCT$ is the nominal operating cell temperature.

3.3. Wind turbine system

The power generated by the wind turbine depends on different parameters as air density, wind speed, and the efficiency of conversion wind energy. The following equation of power law is used to calculate the wind speed at the hub height [23]:

$$\frac{v_h}{v_r} = \left(\frac{h_h}{h_r}\right)^{\alpha} \tag{3}$$

where v_h refers to the wind speed (m/s) at the desired hub height h_h; h_r is the reference height (m); v_r is the wind speed at h_r; and α is the power law exponent ranging.

The generated electric wind power P_E is represented in terms of the wind speed as follows [24]:

$$P_E = \left\{ \begin{array}{c} 0 : if\ "v_f < v"or"v \le v_{ci}" \\ P_{rt} \times \frac{v^3 - v_{ci}^3}{v_{rt}^3 - v_{ci}^3} : if\ "v_{ci} \le v \le v_{rt}" \\ P_{rt} : if\ "v_{rt} \le v \le v_{cf}" \end{array} \right\} \tag{4}$$

where P_{rt} and v_{rt} are referred to the rated power and wind speed respectively; v is the wind speed; v_{ci} and v_{cf} are the cut-in wind speed and the cut-off wind speed. The output power of the WT can be determined as follows [24]:

$$P_{WT} = P_E \times \eta_{WT} \tag{5}$$

where η_{WT} is the combined efficiency of the wind turbine and the generator.

3.4. Battery storage system

The dynamic change of state of charge (SoC) of the battery is determined by the charge and discharge power from PV, WT, grid, and load demand. Therefore, the battery SoC at any given hour will be expressed as a first order difference equation [25]:

Charge:

$$SoC_{(j+1)} = SoC_{(j)} + \frac{\Delta t \times \eta_{ch}}{E_{nom}} \times (P_{ch(j)}) \tag{6}$$

$$SoC_{(j+1)} = SoC_{(j)} + \frac{\Delta t \times \eta_{ch}}{E_{nom}} \times (P_{PV-B(j)} + P_{WT-B(j)} + P_{G-B(j)}) \tag{7}$$

Discharge:

$$SoC_{(j+1)} = SoC_{(j)} - \frac{\Delta t}{E_{nom} \times \eta_{dis}} \times (P_{\mathrm{dis}(j)}) \tag{8}$$

$$SoC_{(j+1)} = SoC_{(j)} + \frac{\Delta t \times \eta_{ch}}{E_{nom}} \times (P_{PV-B(j)} + P_{WT-B(j)} + P_{G-B(j)}) \tag{9}$$

where SoC is the percentage of energy storage; P_{ch} denotes the delivered power for charging the battery; P_{dis} is the power discharged from the battery; η_{dis} and η_{ch} are the battery discharging and charging efficiency respectively; E_{nom} is the battery system nominal energy.

3.5. Utility grid and electricity tariffs

The grid should be able of accepting the excess power, matching the load demand, and charging the battery. As mentioned in this work, the aim is minimizing the net electricity cost by selecting the optimal control of operation that permits to obtain minimum energy from the utility and a maximum benefits from sales. Otherwise, the electricity market is controlled by different prices according to the economic conjunction and the energy policy of the country. In Morocco, the National Office of Electricity and Water (ONEE) is considered as the main power supply utility company and the armed wing of the state able to regulate the production, distribution, and transmission of electricity as well as the purification of wastewater essential to the sustainable development of the country. The electricity tariffs of different sectors such as residential, industrial, and commercial are defined by the Office depending on the season. For domestic use, the applied electricity tariff is described in Table 1 depending on the consumption bands (R).

Table 1. Electricity tariff for Moroccan domestic use [26]

	Consumption range per month (kWh)	**Price (C_r) ($/ kWh)**
R_1	0-100	0.09
R_2	101-200	0.10
R_3	201-300	0.11
R_4	301-500	0.13
R_5	>to 500	0.15

The prices are quoted in Moroccan Dirham (MAD) which is the local currency in Morocco with 1dollar ($) = 9.80551 MAD.As part of the measures performed at the national level, aimed at strengthening energy efficiency, the National Office has set up a new ToU tariff intended for Low Voltage customers (excluding prepayment) for domestic use whose average monthly consumption exceeds 500 kWh. Aiming to peak the evening peak where the cost of the kilowatt-hour is the most expensive, ToU pricing as shown in Fig.3, consists of billing the consumption according to two-hourly shifts at two different rates, a rate for peak hours that last 5 hours and another, cheaper rate for normal hours which last 19 hours a day.

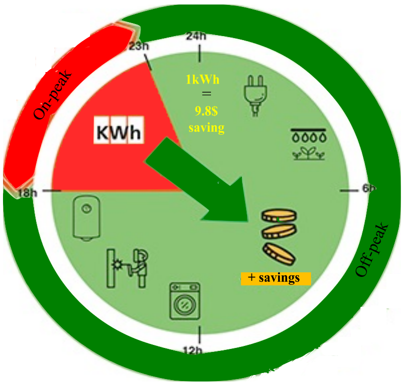

Fig.3. Time-of-use tariff [26].

The value of ToU program estimated for each season is presented in Table 2.

Table 2. Resources data [26]

	Winter		**Summer**	
Period	***On-peak***	***Off-peak***	***On-peak***	***Off-peak***
Hours	17h to 22h	22h to17h	18h to 23h	23h to18h
Price (ρ_j)of the kWh ($)	ρ_P = 0.23	ρ_O = 0.13	ρ_P = 0.23	ρ_O= 0.13

4. Energy Management Strategy and Mathematical Formulation

The optimization framework addressed in this study aims to achieve the optimal control of energy production at sampling time intervals taking into account the operation limits constraints of the hybrid system as well as satisfying the load demand. The flow chart of the proposed EMS is presented in Fig.4and the description of the procedure is outlined as follows. If the PV and WT output power are less than the load demand, the system verifies the SoC of the battery. If battery $SoC^{min}<SoC<SoC^{max}$, the available PV, wind turbine, and the battery powers provide the power to the load. If the load demand overtakes the power supply of the RES and the battery bank, the power needed to compensate the deficit is bought from the main grid. If the $SoC<SoC^{min}$, the load is supplied by the RE and grid power.

If the PV and WT powers exceed the load, the system checks the excess of RE. If there is a surplus of energy, the system verifies again the SoC of the battery. In case of battery $SoC<SoC^{max}$, the excess energy is used to charge the battery or sold to the grid depending on the electricity price. However, if the SoC surpasses the maximum, the available

power fulfills the load and the rest of power is sold to the utility grid.

The developed model aims to minimize the electricity grid expenses of the system by finding the optimal control of the operation. This can allow the system to obtain minimum energy purchased from the grid and a maximum benefit from the power sold to the grid. The electricity tariff is an important parameter in the economical performance of the system; therefore, two tariffs will be implemented in the present study. As mentioned previously, in Morocco, the step-rate and ToU tariffs are the applied program for the residential sector.

In this section, the two tariffs will be analyzed in the proposed strategy.

4.1. Energy management strategy under ToU pricing (EMT)

4.1.1 Objective function

The main purpose includes two objectives. The first part aims to minimize the cost of purchasing energy from the utility grid (charging the battery and supplying the load). The other parts represent the energy sales to the grid from renewable energy and battery under FIT. This multi-objective function can be expressed as:

$$J1 = \sum_{j=1}^{N} \rho_j (P_{G-B(j)} + P_{G-L(j)})\Delta t - \sum_{j=1}^{N} (C_{PV} P_{PV-G(j)} + C_{WT} P_{WT-G(j)})\Delta t - \sum_{j=1}^{N} (\rho_p P_{B-G(j)})\Delta t \tag{10}$$

where ρ_j is the ToU tariff [26], j is the sampling interval, Δt is the sampling time, ρ_p is the peak price period [26], C_{PV} and C_{WT} are the PV and WT FIT respectively [33]. According to the Moroccan Law concerning RE technologies, the authorization of the production of electricity, of renewable origin, by public but also private producers, as well as the possibility of reselling the surplus energy to the grid is in progress. Therefore, in the present paper, it is assumed that the law is applied and the study will focus on the economic analysis under novel attractive tariffs for more cost-effective hybrid residential system.

The daily number of sampling intervals taken into consideration in this case is calculated as:

$$N = \frac{24 \times 60}{\Delta t} \tag{11}$$

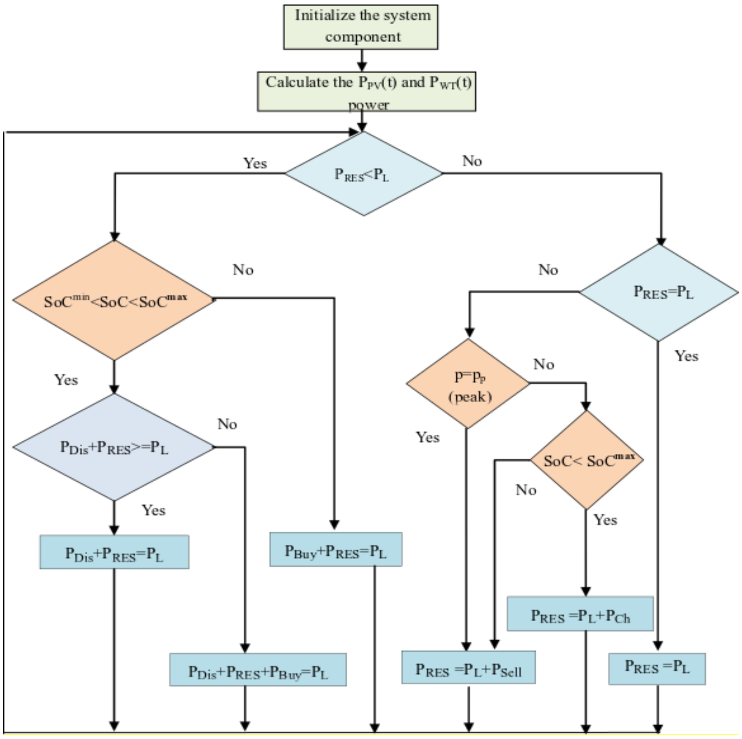

Fig. 4. The operational process of the EMS.

4.1.2. Variable constraints and limits

- *Power balance*

The sum power needed to satisfy the end-user should be given from the sum of PV, WT, the storage system, and the grid at any sampling time (*j*). This can be formulated as follows[27hsan]:

$$P_{PV(j)} + P_{WT(j)} \pm P_{B(j)} \pm P_{G(j)} = P_{L(j)} \tag{12}$$

where $\pm P_B$ is the power generated and received by the battery, $\pm P_G$ is the power purchased and sold to the grid.

- *Constraints*

The sum of power for supplying the load demand, charging the battery, and selling to the grid should be less than the total of renewable power output provided. This is expressed in the following equations:

$$P_{PV-B(j)} + P_{PV-L(j)} + P_{PV-G(j)} \le P_{PV(j)} \tag{13}$$

$$P_{WT-B(j)} + P_{WT-L(j)} + P_{WT-G(j)} \le P_{WT(j)} \tag{14}$$

The grid power should not be imported and exported simultaneously and it can be expressed as follows:

$$(P_{G-B(j)} + P_{G-L(j)}) \times (P_{PV-G(j)} + P_{WT-G(j)} + P_{B-G(j)}) = 0 \tag{15}$$

Additionally, the battery should not be charged and discharged at the same time. This condition can be expressed as follows:

$$(P_{PV-B(j)} + P_{WT-B(j)} + P_{G-B(j)}) \times (P_{B-L(j)} + P_{B-G(j)}) = 0 \tag{16}$$

- *Bounds of the control variables*

For safety reasons, all the power flow must have the upper and lower bounds as formulated in Eq.(17).

$$\begin{cases} 0 \le P_{PV-B(j)} \le P_{PV-B(j)}^{\max} \\ 0 \le P_{PV-L(j)} \le P_{PV-L(j)}^{\max} \\ 0 \le P_{PV-G(j)} \le P_{PV-G(j)}^{\max} \\ 0 \le P_{WT-B(j)} \le P_{WT-B(j)}^{\max} \\ 0 \le P_{WT-L(j)} \le P_{WT-L(j)}^{\max} \\ 0 \le P_{WT-G(j)} \le P_{WT-G(j)}^{\max} \\ 0 \le P_{B-L(j)} \le P_{B-L(j)}^{\max} \\ 0 \le P_{B-G(j)} \le P_{B-G(j)}^{\max} \\ 0 \le P_{G-B(j)} \le P_{G-B(j)}^{\max} \\ 0 \le P_{G-L(j)} \le P_{G-L(j)}^{\max} \end{cases} \tag{17}$$

In order to limit the battery degradation, the SoC of the battery is subject to the following condition:

$$SOC^{\min} \le SOC_{(j)} = SOC_{(0)} + \frac{\Delta t \times \eta_c}{E_{nom}} \times (P_{PV-B(j)} + P_{WT-B(j)} + P_{G-B(j)}) - \frac{\Delta t}{E_{nom}\eta_D} \times (P_{B-L(j)} + P_{B-G(j)}) \le SOC^{\max} \tag{18}$$

The focus of the hybrid system is to make the best decision for short term operation conditions. Therefore, the installation cost of PV and wind power plants is not incorporated in this work since the optimization process is restricted to an analysis of how to control the installed system.

4.2. Energy management strategy under step-rate tariff (EMSR)

4.2.1. Objective function and constraints

The purpose of the optimization problem under the developed step pricing tariff is the same as the ToU tariff. Hence, the objective function is similar to Eq.(10)excluding the cost of the purchased energy from the grid which is developed as follows:

$$(\rho_{r1} \times C_{r1}) + (\rho_{r2} \times C_{r2}) + (\rho_{r3} \times C_{r3}) + (\rho_{r4} \times C_{r4}) \tag{19}$$

whereρ_{r1}, ρ_{r2}, ρ_{r3}, and ρ_{r4}, are the electricity bought from the grid under the corresponding range tariff,C_{r1}, C_{r2} ,C_{r3}, and $C_{r4}$are the step-rate tariff (Table 1).

The monthly upper bounds of the range steps (R) are denoted as R_{M1}, R_{M2}, R_{M3}, and R_{M4}. Therefore, the daily upper bounds p_M are expressed as follows:

$$\begin{cases} p_{M1} = \dfrac{R_{M1}}{30} \\ p_{M2} = \dfrac{R_{M2}}{30} \\ p_{M3} = \dfrac{R_{M3}}{30} \\ p_{M4} = \dfrac{R_{M4}}{30} \end{cases} \tag{20}$$

The total of the daily electricity bought from the grid under step tariff is defined as ρ_S. It is dismantled to the step of tariffs as

If $0 \le \rho_S \le \rho_{M1}$:

$$\begin{cases} p_{r1} = p_S \\ p_{r2} = 0 \\ p_{r3} = 0 \\ p_{r4} = 0 \\ p_{r5} = 0 \end{cases} \tag{21}$$

If $\rho_{M1} \le \rho_S \le \rho_{M2}$:

$$\begin{cases} p_{r1} = p_{M1} \\ p_{r2} = p_S - p_{M1} \\ p_{r3} = 0 \\ p_{r4} = 0 \\ p_{r5} = 0 \end{cases} \tag{22}$$

If $\rho_{M2} \le \rho_S \le \rho_{M3}$:

$$\begin{cases} p_{r1} = p_{M1} \\ p_{r2} = p_{M2} - p_{M1} \\ p_{r3} = p_S - p_{M2} \\ p_{r4} = 0 \\ p_{r5} = 0 \end{cases} \tag{23}$$

If $\rho_{M3} \le \rho_S \le \rho_{M4}$:

$$\begin{cases} p_{r1} = p_{M1} \\ p_{r2} = p_{M2} - p_{M1} \\ p_{r3} = p_{M3} - p_{M2} \\ p_{r4} = p_S - p_{M3} \\ p_{r5} = 0 \end{cases} \tag{24}$$

If $\rho_S \succ \rho_{M4}$:

$$\begin{Bmatrix} p_{r1} = p_{M1} \\ p_{r2} = p_{M2} - p_{M1} \\ p_{r3} = p_{M3} - p_{M2} \\ p_{r4} = p_{M4} - p_{M3} \\ p_{r5} = p_S - p_{M4} \end{Bmatrix} \tag{25}$$

Furthermore, the imported power from the grid will be formulated as follows:

$$\sum_{j=1}^{N} (P_{G-B(j)} + P_{G-L(j)})\Delta t = \rho_{r1} + \rho_{r2} + \rho_{r3} + \rho_{r4} + \rho_{r5} \tag{26}$$

As a result, the daily calculated cost of purchasing energy grid is obtained as:

$$\sum_{j=1}^{N} \rho_j (P_{G-B(j)} + P_{G-L(j)})\Delta t = C_{r1}\rho_{r1} + C_{r2}\rho_{r2} + C_{r3}\rho_{r3} + C_{r4}\rho_{r4} + C_{r5}\rho_{r5} \tag{27}$$

Likewise, the developed EMSR strategy can be reformulated as the EMT strategy except the constraint corresponding to the power bought from the main grid.

Objective function:

$$J1 = \sum_{j=1}^{N} \rho_j (P_{G-B(j)} + P_{G-L(j)})\Delta t - \sum_{j=1}^{N} (C_{PV} P_{PV-G(j)} + C_{WT} P_{WT-G(j)})\Delta t - \sum_{j=1}^{N} (\rho_p P_{B-G(j)})\Delta t \tag{28}$$

subject to:

$$P_{PV(j)} + P_{WT(j)} \pm P_{B(j)} \pm P_{G(j)} = P_{L(j)}$$

$$\rho_{r1} + \rho_{r2} + \rho_{r3} + \rho_{r4} + \rho_{r5} - \sum_{j=1}^{N} (P_{G-B(j)} + P_{G-L(j)})\Delta t = 0$$

$$P_{PV-B(j)} + P_{PV-L(j)} + P_{PV-G(j)} \le P_{PV(j)}$$

$$P_{WT-B(j)} + P_{WT-L(j)} + P_{WT-G(j)} \le P_{WT(j)}$$

$$(P_{G-B(j)} + P_{G-L(j)}) \times (P_{PV-G(j)} + P_{WT-G(j)} + P_{B-G(j)}) = 0$$

$$(P_{PV-B(j)} + P_{WT-B(j)} + P_{G-B(j)}) \times (P_{B-L(j)} + P_{B-G(j)}) = 0$$

$$SOC^{\min} \le SOC_{(j)} = SOC_{(0)} + \frac{\Delta t \times \eta_c}{E_{nom}} \times (P_{PV-B(j)} + P_{WT-B(j)} + P_{G-B(j)}) - \frac{\Delta t}{E_{nom}\eta_D} \times (P_{B-L(j)} + P_{B-G(j)}) \le SOC^{\max}$$

$$\begin{Bmatrix} 0 \le P_{PV-B(j)} \le P_{PV-B(j)}^{\max} \\ 0 \le P_{PV-L(j)} \le P_{PV-L(j)}^{\max} \\ 0 \le P_{PV-G(j)} \le P_{PV-G(j)}^{\max} \\ 0 \le P_{WT-B(j)} \le P_{WT-B(j)}^{\max} \\ 0 \le P_{WT-L(j)} \le P_{WT-L(j)}^{\max} \\ 0 \le P_{WT-G(j)} \le P_{WT-G(j)}^{\max} \\ 0 \le P_{B-L(j)} \le P_{B-L(j)}^{\max} \\ 0 \le P_{B-G(j)} \le P_{B-G(j)}^{\max} \\ 0 \le P_{G-B(j)} \le P_{G-B(j)}^{\max} \\ 0 \le P_{G-L(j)} \le P_{G-L(j)}^{\max} \end{Bmatrix} \tag{29}$$

4.3. Calculation of optimization problem

In this study, two types of optimization algorithms will be used and compared to specify the appropriate one. The algorithms are deterministic and stochastic which are the most methods used recently. The objective function of EMT and EMSR is linear and contains linear and nonlinear constraints with continuous variables. Therefore, this makes the optimization problem to be non linear and solved using *fmincon* solver in Matlab optimization toolbox [28]. *Fmincon* is considered as a deterministic algorithm and characterized by fewer memories and time. Besides, the stochastic algorithm performed for comparison is *GA*.

4.3.1. Fmincon optimization solver

As ‘fmincon’ solver employs the Hessian as the optional input, many ‘fmincon’ algorithms manipulate this type of input such as: interior point, active set. In this study, the interior-point is the algorithm chosen for the ‘fmincon’ solver due to its capacity to resolve the large-scale optimization problems and with a faster convergence [29].

The solver can be formulated as follows [30]:

$$\underset{x}{\text{Min}}/\underset{x}{\text{Max}}\, J(x), subject.to \begin{cases} c(x) \le 0 \\ c_{eq}(x) = 0 \\ Ax \le b \\ A_{eq}x = b_{eq} \\ lb \le x \le ub \end{cases} \tag{30}$$

where *J(x)* represents the objective function; $c(x)$ and $ceq(x)$ are functions that can be nonlinear; A and b denote the coefficients corresponded to inequality constraints; Aeq and beq denote the coefficient of equality constraints.

In this consideration, the major steps of the two proposed EMS are summarized in the flow chart represented in Fig.5.

4.3.2. Genetic algorithm

Based on a natural selection, the GA can solve different optimization problems: the constrained and unconstrained ones. The algorithm frequently changes a population of individual solutions. The GA selects randomly at each step individuals from the actual population to be parents. Then, they are used in order to generate the children for the upcoming generation. During the successive generations, the population "evolves" to the optimal solution. At each step, as observed in Fig.6, the GA uses three principal rules to establish the next generation from the current population [31-32]:

- Selection rules: select the individuals (parents) and involve their genes to the next generation.
- Crossover rules: incorporate two genetic information from the parents to create new children.
- Mutation rules: practice random variations to individual parents to arrange children.

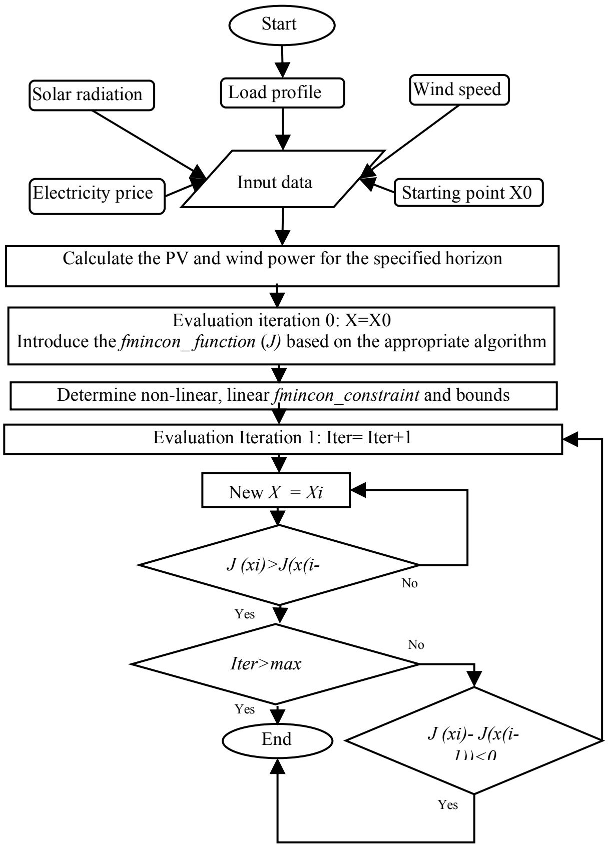

Fig. 5. Flow chart of the FMINCON algorithm.

5. Case Study in Morocco

5.1. Resource and Model parameters

A typical daily load demand profile for a Moroccan grid-connected residential hybrid system is presented in Fig.7(b).The control horizon considered is 24h and the sampling time used is 30 min. Therefore, it follows from Eq.(11) that N=48. The hourly RE data for the selected winter, in Tangier, is shown in Fig.7(a).

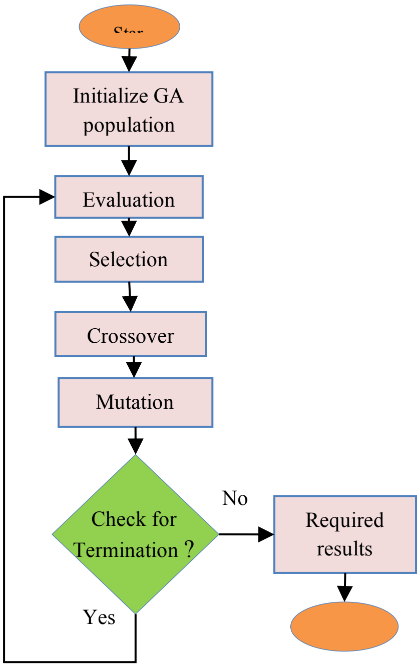

Fig. 6. Genetic Algorithm flowchart.

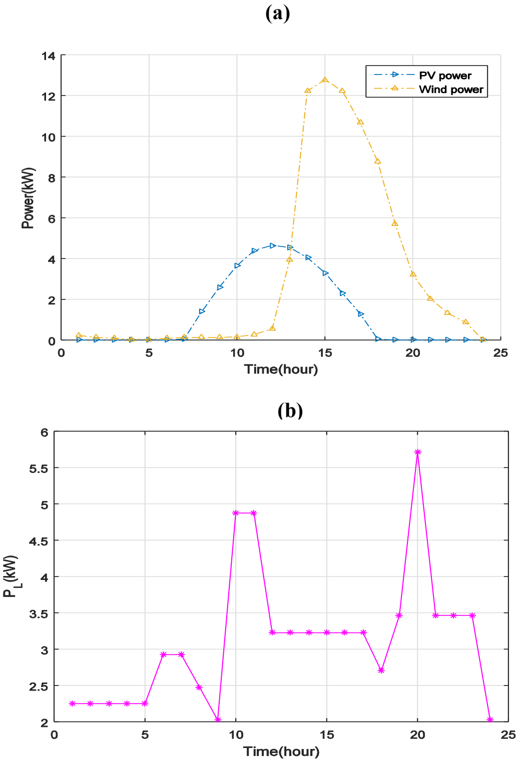
(a)
(b)

Fig. 7. (a): Hourly PV and WT power output of the typical day; (b) :The power demand of the household for 24 h.

Those data have been used as input to the proposed model and the parameters are listed in Table 3.

5.2. Simulation and discussion of results

In this section, the obtained simulation of the managed hybrid system under different tariffs and methods are presented and compared to define the optimal strategy among them. The optimization problem is solved in Matlab using the *fmincon* solver and the discussion of simulation will be performed under two FITs. The first FIT is corresponding to the Moroccan RE tariff [33], and the second one is a FIT that is assumed to be increased and equal to the peak price period (p_p=0.23$/kWh).The baseline cost is defined as the bill paid by the household in the case study before the optimal control intervention whereas the optimal cost is the grid energy cost after optimal control contribution. The bill concerns the grid energy consumed by the load and battery bank. The energy sales are the excess PV, wind, and battery energy fed into the grid depending on the strategy case.

Table 3. Simulation parameters of the hybrid energy system

Parameter	Meaning	Value
SoC_0	Battery initial SoC	90 %
SoC^{max}	Battery maximum SoC	95 %
SoC^{min}	Battery minimum SoC	40 %
η_{Ch}	Battery charging efficiency	85%
η_{dis}	Battery discharging efficiency	95 %
Δt	Sampling time	1h
E_{nom}	Battery nominal capacity	5kWh

The cost saving is calculated as follows:

$$Cost.Saving(\%) = (\frac{Baseline - Optimal.Cost}{Baseline}) \times 100 \qquad (31)$$

5.2.1. Results of the EMT strategy

- Optimization problem under the basic RE FIT

The present strategy is applied for the hybrid residential system under the ToU tariff and the optimization problem is solved using the *fmincon* solver. The figures below present the obtained optimal power flow. From Fig.10, during peak price period, the most surplus of electricity produced from PV and WT is sold to the main electrical grid. This is considered as an efficient way to minimize the electricity purchased from the grid, because of the high electricity price. Opportunely, the availability of PV and WT power is proportionately high. From midday to 18h, the PV and WT output are larger than the household demand, therefore as shown in Fig.8(a and b), the remaining electricity is established in the storage system. During the peak price period from 17h00 to 22h00, as shown in Fig.7(b), there is a peak on the demand and the electricity price is high. Consequently, the electricity is not purchased from the grid and the load is satisfied by the battery storage and the wind power. These can be seen in the Fig.8(c) and Fig.9(e and g). The developed model aims to generate an income at the customer side by maximizing the excess power fed into the grid. Hence, the profit is generated from the WT excess power due to the weakness of the light intensity (Fig.10(a and b)). During off-peak price period from 23h00 to 10h00, only the storage system is used to satisfy the consumer's demand as shown in Fig.8(c).It can be seen from Fig.10, that there is no power sold to the utility due to the low electricity price. While the surplus of power produced from the battery is sold as pointed out inFig.10(c). From 10h00 to17h00, the RES are principally concentrated during this period. Therefore, as shown in Fig.9(f and g), the PV and WT do feed preferentially the house whereas the excess is used for charging the battery within its operational limits (Fig.8(a and b)). It can be witnessed that there is no power bought from the main grid and the excess PV, WT, and battery power is exported to the grid as seen in Fig.10.

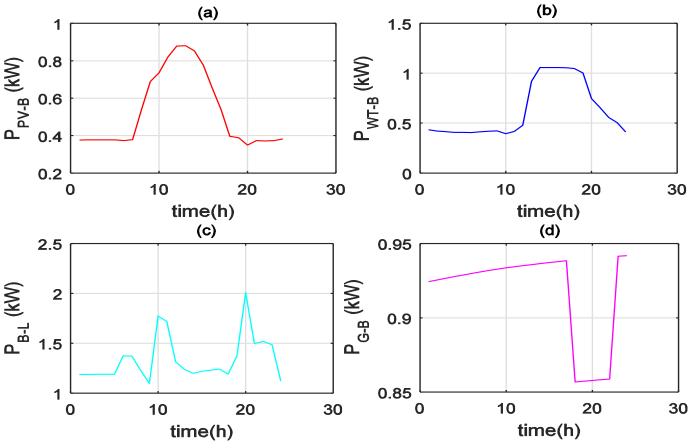

Fig.8. (a)and (b): Discharged power from the PV and WT to the battery; (c): Discharged power from the battery to the load; (d):Imported power from the grid to charge the battery.

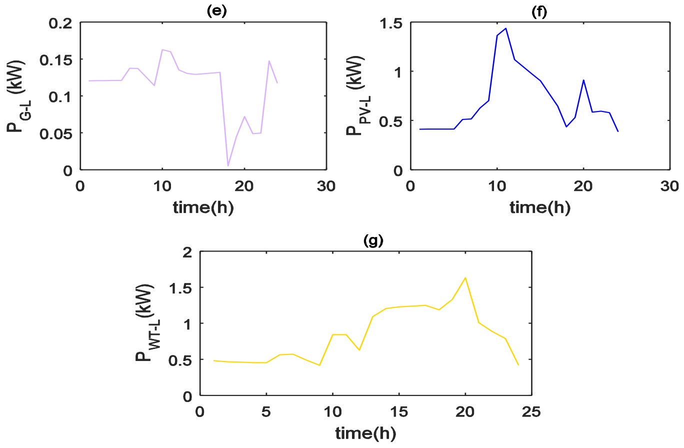

Fig.9. (e) : Discharged battery power from the grid to the load; (f) and (g): Generated power from PV and WT to the load.

- Optimization problem under the proposed RE FIT

In this case, the FIT is increased to be equal to the peak price period (0.23 $/kWh). Comparing to the previous case, it can be noticed that the power produced from PV, WT, and grid for charging the battery is considerably reduced as presented in Fig.11(a, b, and d). The reason is that as the FIT is more attractive, the optimal control aims to sell during the daytime a great amount of energy from PV and WT which is approximately equal to the output generated power. Consequently, a substantial income can be generated as well as an energy cost reduction. This can be illustrated in Fig.13(a and b). Furthermore, Fig.13(c) shows the profile of the storage system injected into the grid which is more increased during high electricity price to benefit from the FIT. Referring to Fig.12(f and g) and Fig.11(c)), the low power purchased from the grid to supply the customer's demand during the peak and off-peak morning periods, is typified by the fact that the load is mainly satisfied by the RE and the battery. Therefore, an attractive FIT means the tendency to sell the maximum energy to the main grid.

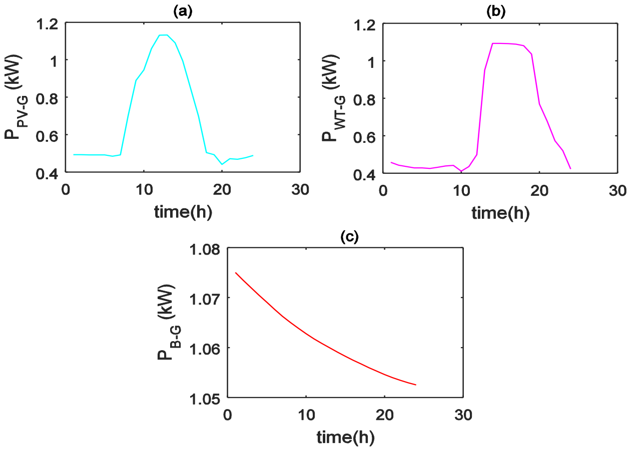

Fig. 10. (a),(b) and (c): Exported power from PV, WT, and battery to the grid respectively.

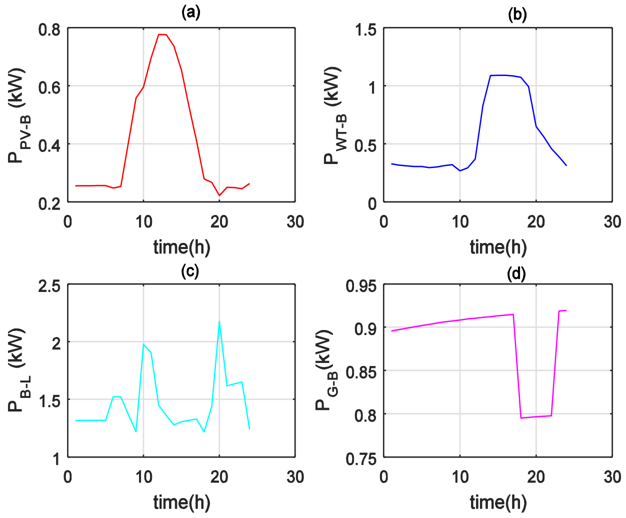

Fig. 11. (a)and (b): Generated PV and WT power to charge the battery; (c):Delivered power from the battery to the load; (d): Purchased power from the utility grid to charge the battery.

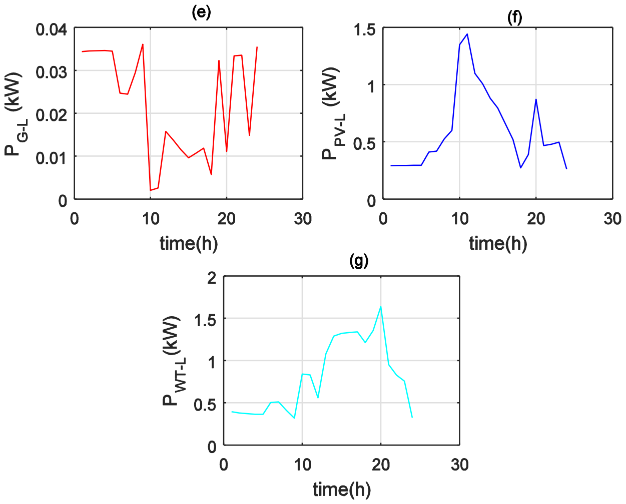

Fig. 12. (e) : Provided battery power from the grid to the household; (f) and (g): PV and WT power for supplying the load respectively.

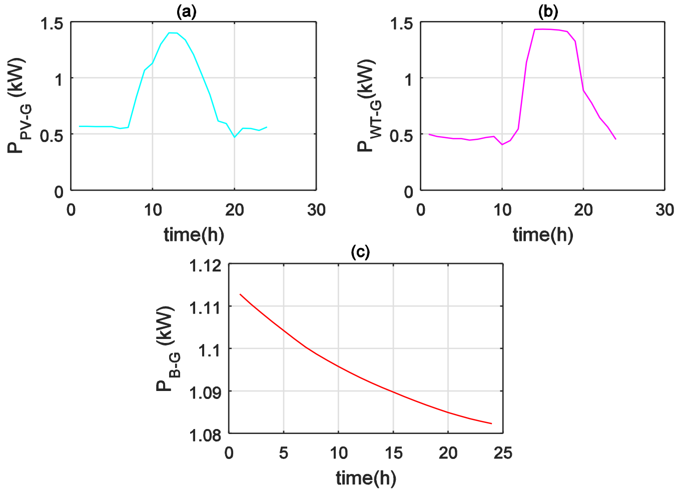

Fig. 13. (a),(b) and (c): PV, WT, and battery generated power to the grid respectively.

- Comparison between the optimal cost and the baseline cost

Table 4 presents the cost saving and sales of the baseline and optimal control under different tariffs. It can be noticed that the increase of the FIT conducts to a high income from sales. Further, EMT provides consumers more benefits to that of the baseline method.

Table 4. Daily baseline and cost savings of the strategies

	Methods	**Baseline Cost ($/day)**	**Optimal Cost ($/day)**	**Sales ($/day)**	**Cost Savings (%)**
EMT method	**EMT (FIT=(C_{PV}, C_{WT})**	11.63	0.0006	3.84	99.99
	EMT (FIT=p_p)	11.63	0.0130	24.79	99.88

5.2.2. Results of the EMSR strategy

- Optimization problem under the basic RE FIT

In this case, the EMS is applied using a developed step-rate tariff and the system parameters are identical to those of the EMT method. The optimization problem is solved as well with *fmincon* in MATLAB and the obtained results are illustrated in the figures below. As the peak demand coincides with the part of the high pricing periods from the utility; this will reach a significant cost of the consumed electricity. Therefore, the wind power and battery are used conjointly to supply the load as shown in Fig.15(f and g) respectively. Figure14(a and b) shows that the battery is being charged by the PV and WT systems while the power imported from the grid to charge the battery and meet the load is minimized (Fig.15(e) and Fig.16(c)). However, the photovoltaic system also contributes to providing the load to a small-time, therefore; the energy storage is used simultaneously to satisfy the demand as illustrated in Fig.14(c) and Fig.15(f) respectively. The excess power which is not used by the load is sold to the grid at a high price period from PV, WT, and battery bank (Fig.16).

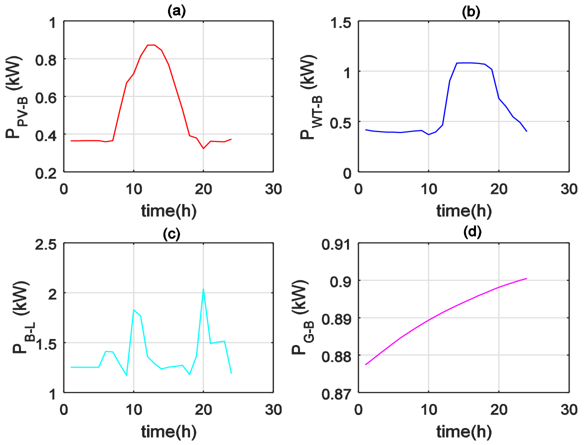

Fig. 14. (a)and (b): Generated PV and WT power to charge the battery; (c):Delivered power from the battery to the load; (d): Purchased power from the utility grid to charge the battery.

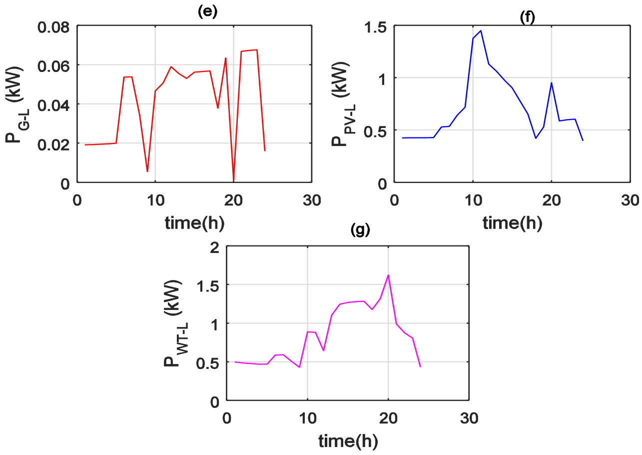

Fig. 15. (e) : Provided battery power from the grid to the household; (f) and (g): PV and WT power for supplying the load respectively.

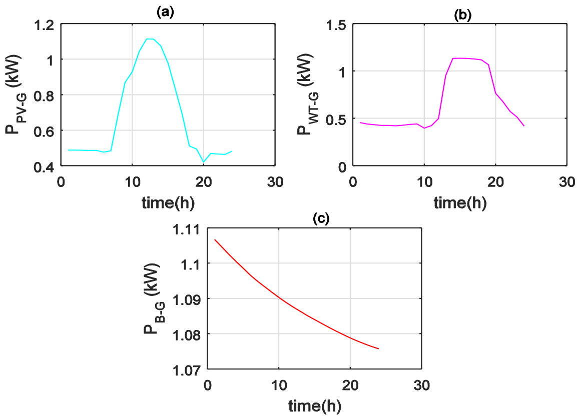

Fig.16. (a),(b) and (c): PV, WT, and battery produced power to the grid respectively.

- Optimization problem under the proposed RE FIT

The energy management is applied with an increased FID to be equal to 0.15 $/kWh and the optimal results are shown in the figures below. It can be seen from Fig.19, during the daytime, the surplus power is exported to the grid to earn more income from RE and battery systems. It can be also observed that the power for charging the battery bank especially from PV is decreased compared to the first case. The cause for this is when the FID is higher, the controller will be prioritizing to sell the excess power to the utility instead of charging the battery or supplying the load. Therefore, as shown in Fig.17(d) and Fig.18(e), the output from the grid to charge the battery and supply the load is reduced.

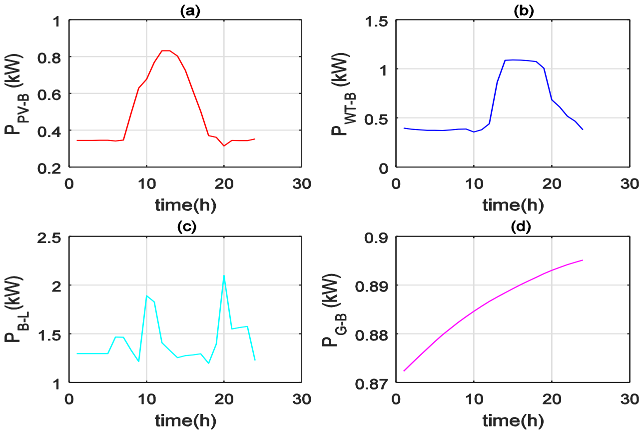

Fig. 17. (a) and (b): Output PV and WT power to charge the battery; (c) :Imported power from the battery to the load; (d): Grid power purchased to charge the battery.

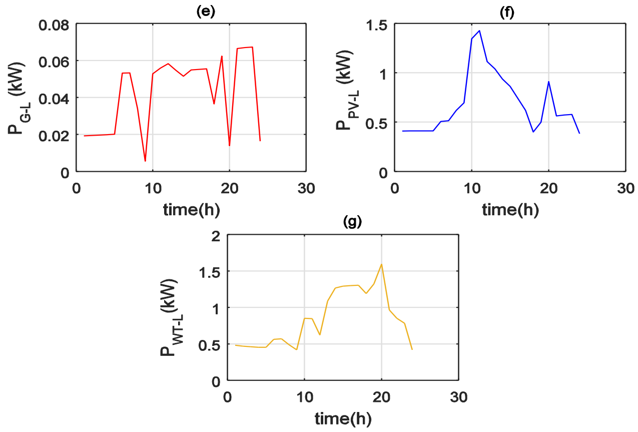

Fig.18. (e): Battery power generated from the grid to meet the load; (f) and (g): Power supply from PV and WT power respectively.

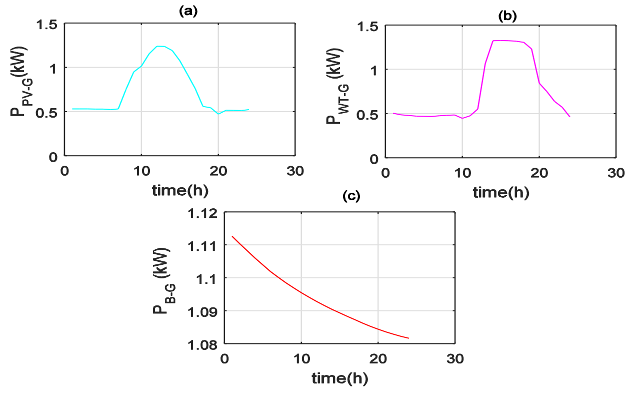

Fig.19. (a),(b) and (c): Exported PV, WT, and battery power to the grid respectively.

- Comparison between the optimal cost and the baseline cost

Again, the baseline method is compared with the optimal EMSR in Table 5. The obtained results demonstrate that even though the energy consumed by the load is identical for all cases, the EMSR strategy increases consumer benefits and cost-savings. Also, it can be noticed that EMSR under attractive FIT has the highest daily income compared to the previous case.

Table 5. Comparison of daily baseline and cost savings

	Methods	**Baseline Cost ($/day)**	**Optimal Cost ($/day)**	**Sales ($/day)**	**Cost Savings (%)**
EMSR method	**FIT=(ρ_{PV}, ρ_{WT})**	11.25	0.0005	4.59	99.99
	FIT=(ρ_N)	11.25	0.0499	14.96	99.55

5.2.3. Impact of the battery

The comparison between EMT and EMSR methods will not be analyzed due to the difference of electricity tariffs for the two approaches. Further, an economic comparison can be performed under different battery capacities as displayed in Table 6.It can be seen from the results that when the capacity of the battery system increased, the cost savings increased and the electricity bill reduced. However, more income is generated for fewer capacities, the reason is that the surplus power will be sold rather than be stored if the constraint of grid failure is not taken into consideration.

Table 6. Optimal energy and cost savings under various battery capacities (EMT strategy)

Battery capacity (B_{max})	**0.75**	**0.85**	**0.95**	**0.98**
Optimal Cost ($/day)	1.3795	1.2636	0.0006	0.0010
Cost Savings (%)	88.1396	14.5683	99.9945	99.9917
Sales ($/day)	14.9946	89.1357	3.8414	2.9024

5.2.4. FMINCON and GA comparison

In order to attain the optimal results of the proposed strategy (EMT case), a comparison between two different methods such as a stochastic and deterministic approach will be performed.

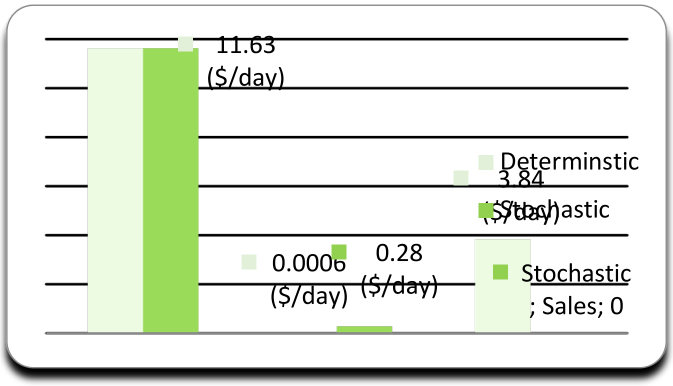

Fig. 20. Daily optimal cost and sales of the two methods.

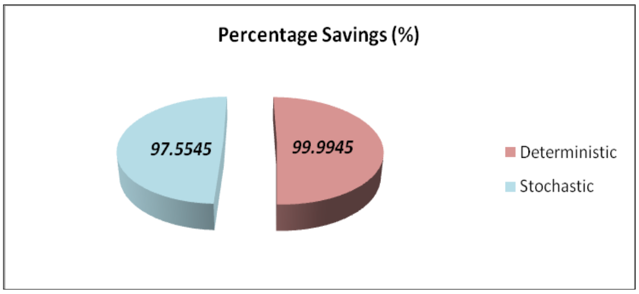

Fig. 21. Cost-saving of the two methods.

Figure 20 and Figure 21 compare the daily economic benefits of the method based on '*FMINCON'* solver and the '*GA'* to indicate the viable approach. It can be concluded that the deterministic algorithm has the best results on the bill after optimization and sales respectively. Consequently, a considerable percentage savings of cost can be achieved with 99.9945%.A comparison of simulation time is conducted to validate the choice of the algorithm. Obviously, as listed in Table 7, the proposed strategy under the 'FMINCON' algorithm has the higher computing speed.

Table 7. Time comparison

Method	FMINCON	GA
Time of simulation	36.51 seconds	100.61 seconds

5. Conclusion

An Optimal EMS is proposed in this paper for a residential grid-connected PV-WT-battery system to utilize renewable energy efficiently and economically. A typical household within the Moroccan network has been identified as a case study for this research. ToU and step-rate tariffs are the most implemented electricity tariffs in Morocco, therefore, two optimal energy management approaches, such as the EMT and EMSR, are proposed. In order to analyze the economic feasibility of the hybrid system, the model is studied under different cases where the FIT is changed. It is observed from the simulation results that the developed strategies reduce the total energy cost to pay to the grid and maximize the use of RE to profit from revenues. Besides, when the FIT increases, the energy and cost savings increase. A statistical comparison with the baseline method is performed and it is revealed that the proposed EMT and EMSR can prove the maximum benefits and satisfy the requirements of the system. The battery capacity affects the saving cost which is efficient merely when the FIT is less attractive. Also, the applied 'FMINCON' solver has been compared with the 'GA' to set-up the model and verify the effectiveness of the algorithm. The results reveal that the deterministic method can improve better management and higher computing speed. Future research work will be focused on the implementation of the proposed energy management strategies with the embedded platform. The parameters and inputs of the model, like PV, WT, load data, electricity tariffs, and other parameters will be downloaded to the appropriate controllers to start the calculation of the optimization problem.

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