A novel decision-making approach based on a decision tree for micro-grid energy management

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ABSTRACT

Environmental challenges such as climate change have accelerated humanity's need for renewable alternative energy sources. For this reason, we propose in this paper a decision-making strategy that allows controlling the flows of energy into a micro-grid (MG) compound of solar energy, batteries, and diesel generator (DG), and connected to the distributed network (DN). Therefore, the power supply to the loads is obtained either from the energy produced by solar sources, from the batteries, from the DN, or from the DG when renewable energy (RE) and batteries are depleted. To make the final decision, we consider four parameters at the same time: the energy produced by solar energy, the requested load, the state of charge of batteries (SoC), and the purchase or sale price. Decision tree (DT) is used to build the energy management strategy to ensure the availability of power on demand by making logical decisions about charging batteries, discharging batteries, buying necessary energy from DN, selling excess energy to DN, and recovering necessary energy from DG. The suggested DT approach is applied to a real MG to minimize the cost-benefit balance, and the comparison analysis demonstrates good results when compared to related works.

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1. INTRODUCTION

In recent years, the environmental problems caused by traditional fossil fuels are becoming more serious. Renewable energy (RE) sources replace fossil ones to provide sustainable and clean energy and protect the atmosphere from the dangers of environmentally degrading nuclear energy [1]. RE has many benefits; it relies on natural resources such as wind, water, and sun, which makes it cost-effective. In addition, it produces clean and green electricity which reduces carbon dioxide emissions and pollution. That is why the production of renewable electrical energy is currently undergoing very significant development [2].

Several free RE sources are increasingly used to generate electricity locally. In particular, photovoltaic (PV) energy is a more promising energy source [3]. It is inexhaustible, practical, non-polluting, and free. However, depending on local weather conditions, this energy is not permanently available and its performance may vary according to unpredictable climatic changes. It is therefore necessary to have a means of compensating for this intermittency so as not to create maladjustment between supply and demand within an installation based on RE like the micro-grid (MG). Storage systems such as batteries and supercapacitors are very necessary. They present the most judicious solution to store the excess electricity produced to later use

[4]. A diesel generator (DG) is also an indispensable component of MG. It offers energy to the electrical loads when the batteries are exhausted.

The combination of several kinds of energy sources is challenging and requires the development of an energy management system (EMS) to ensure the continuous availability of electricity constantly. The integration of new information and communication technologies into the EMS aims to effect a significant transformation in its structure making it more strong to overcome the drawbacks of classical management approaches which are usually ineffective [5]. The decision is a necessary act that allows the EMS to modify its real strategy so as not to make the situation worse. In other words, making a decision lies in the operation of choosing the more appropriate output between several possibilities allowing to provide a satisfactory solution to the problems that may be encountered by the EMS.

In the literature, many works have dealt with the issue of decision-making to optimally control the MG and fulfill the constraints set beforehand for each system. These works have used several approaches such as reinforcement learning method [6], multi-swarm optimization algorithm [7], optimization method [8]-[11], fuzzy logic (FL) [12], [13]. All these works used some internal or external parameters of the MG to make the final decision such as the quantity of energy produced, the state of charge (SoC) of batteries, and the cost of buying or selling the electricity from or to the distributed network (DN). Decision tree (DT) is a decision-making method easy to use, implement, and provides good results. It was widely used in several fields such as medicine [14], traffic control [15], and tourism [16]. In addition, it was used also as a decision-making tool for MG energy management. Different authors have proposed several works based on DT such as [5], [17] and [18]. Amjady and Sharifzadeh [19] presented a new multi-objective decision-making model, including two objective functions of production cost and voltage stability margin, for an optimal power flow problem. The proposed model is applied to several test systems with complex solution spaces and shows its effectiveness by comparing it to several other approaches. Ameur *et al*. [20] uses an intelligent system for optimizing and managing renewable energy systems using multiple agents to manage energy flows between energy resources and storage units. Atia [21] the power management control was done using the fuzzy logic control technique. Zhang [22] presented an energy management strategy using FL and graphical methodology, based on PV and storage systems. Additionally, other works used the fuzzy control strategy based on the status of certain criteria such as loads, renewable energy production, and electricity price to satisfy economic objectives and reduce the balance between cost and profit [23]-[25]. As well, DT was also used in the literature for EMS due to its simplicity of use and implementation. In addition, it provided good decision-making results. But they neglected to consider the cost of buying and selling power, which is seen as a crucial factor that can increase an MG's monthly profit. For this reason, we propose in this paper a DT that allows control of the flows of energy into an MG compound of solar energy, batteries, and diesel generator (DG) connected to the DN. Therefore, the power supply to the loads is obtained either from the energies produced by solar sources, from the batteries, from the DN, or from the DG. This latter is an important component of most MGs because it supports the reliability of electrical loads when RE and batteries are depleted. In addition, the cost of electricity produced by DG can be cheaper than the electricity purchased from the DN especially when the purchase price is very expensive. For all these reasons, we consider four parameters to make the final decision at the same time: the energy produced by solar energy, the requested load, the SoC of batteries, and the purchase or sale price. One decision among five can be made according to the four parameter values above mentioned: Charge batteries, discharge batteries, buy necessary energy from DN, sell excess energy to DN and recover necessary energy from DG. The proposed DT based decision-making method is applied on a real MG and the comparative study shows satisfactory results compared to rules based system (RBS) and a DT that don't take into account neither the electricity price, nor the DG as another component of the adopted MG.

The remainder of this article is organized in the following way. In section 2 we describe the studied MG and its components. We explain the proposed decision-making approach in section 3. The results of the simulation are presented in section 4. Finally, we conclude the paper in section 5.

2. DESCRIPTION OF THE STUDIED MICRO-GRID

The integration of RE and especially the PV installation is a flexible solution that can improve the economy, and become a future supplier of green energy. This section provides a precise description of the studied MG in which we apply the proposed decision-making approach. We will define the different components of the MG as well as their technical information.

2.1. The general architecture of the studied MG

Our study concerns a multi-sources and multi-loads system whose general architecture is shown in Figure 1. This is a hybrid system made up of a combination of several energy sources:

- The PV panels provide clean and green energy. They ensure the production of electrical energy during the hours of sunshine.

- The batteries are used to store excess energy after meeting the energy requirement for later use in the case when the energy produced by the PV field is not sufficient.
- The DN is only used if the energy produced from the PV field and that stored in the batteries are insufficient to meet the demand. The DN is considered an auxiliary source of energy used in the worst case.
- The DG supports the reliability of electrical loads when RE and batteries are depleted. Sometimes, the battery power may be insufficient, but the operation will still require power. To provide instant energy for critical periods we use the internal combustion engine, making it an important component of most MGs.

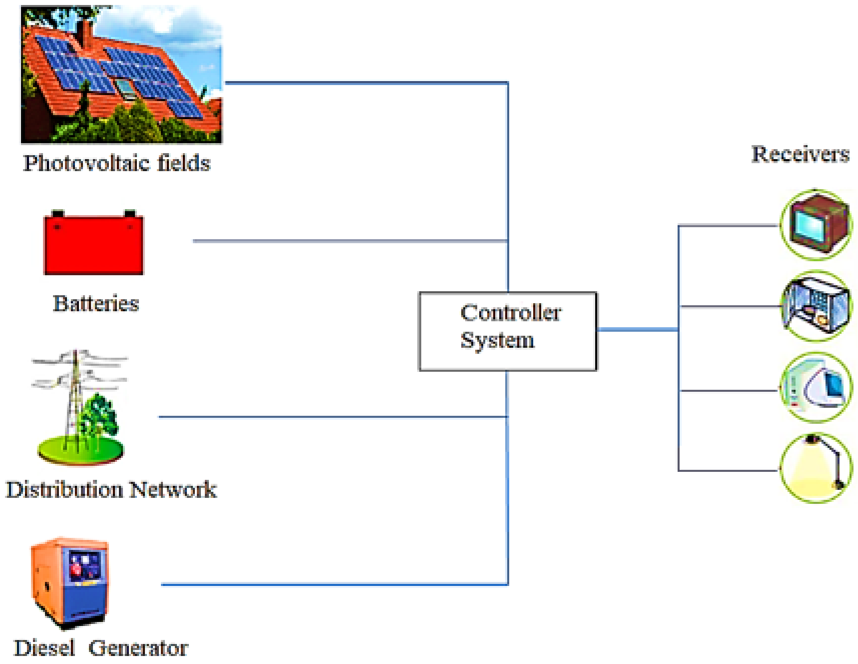

Figure 1. Global diagram of the studied MG

As is remarkable in Figure 1, the controller system is at the heart of our MG. Its specifications are as:
- Protect the battery from excessive charging;
- Protect the battery against deep discharge;
- Allow battery charging with excess energy;
- Automatically manage the energy system production;
- Optimally choose the source that will provide the required power: Batteries, DN, or DG.

2.2. Home electrical devices

We consider the example of a house occupied by a family compound of two persons. A step of estimating solar energy needs is necessary. Indeed, four-light points of 13 W and 12 V are present in the different rooms of the house. A refrigerator with good thermal insulation will be used to store food. This equipment consumes 300 Wh/day. A television and a radio, of power equal to 100 W and 12 W respectively, are used four hours per day. The family owns a 192 W portable computer, used two hours per day.

These elements mentioned above include the essential electrical equipment of the house and are used regularly every day. Other devices are not used daily such as the mobile phone charger, the iron, and the hair dryer. Table 1 gathers all the information needed to conclude the total energy requirement, and to calculate the energy requirement of each electrical appliance, obtain the average consumption spread over time, and define the number of panels required, as shown in (1):

$$Energy\ requirement = Power * Number\ of\ hours\ of\ use\ /\ Voltage \quad (1)$$

Table 1. Summary table of daily consumption

Device	Number (a)	Power in watts (b)	Hours of use per day (c)	Daily consumption a*b*c/12 in AH/day
Lamp	4	13	3	4*13*3/12=13
Refrigerator	1	12,5	24	12,5*24/12=25
Television	1	100	4	100*4/12=33,3
Computer	1	192	2	192*2/12=32
Radio	1	12	4	12*4/12=4

2.3. Sizing of the studied microgrid

The MG components are relatively "standard", and available at a good price/quality ratio. These include in particular:

- 50 Wc-12 V PV modules in polycrystalline silicon with dimensions of 800*630 mm giving a current of 3A and a voltage of 16.5V.
- 220 Ah-12 V “solar” open lead batteries with plates, at 70% discharge, i.e. the depth of discharge is 30%.

We use the following formula to define the number of modules to be used:

$$Energy\ produced\ =\ Number\ of\ modules\ *I\ *R \tag{2}$$

where:
I = Current delivered by a module. In this case, it is equal to 3 Amperes.
R = radiation (in Wh/m².day) / 1000 (in W/m²).

Since the minimum energy to be produced per day is 107.3 AH/day, and since our MG is located in Morocco it has average incident radiation of 5 kWh/m². day, therefore the number of modules required according to equation 2 is Number of modules=107.3/(3A*5000/1000)=7.15. We opt for the use of 7 PV modules.

2.4. Dataset

We apply the proposed EMS on an MG located in Fez city which is characterized by a moderate and summery climate. The temperatures are cool in the morning with the possibility of fog. In the afternoon, temperatures vary between 25 °C and 30 °C. Its average radiation varies between 3,300 and 5,721 Wh/m² as shown in Table 2. Figure 2 illustrates the average monthly solar radiation in Fez city in 2012.

Table 2. Average monthly solar radiation for the city of Fez in 2012 (wh/m²)

January	February	March	April	May	June	July	August	September	October	November	December
3,396	4,348	5,288	5,721	5,620	4,903	4,951	4,970	5,038	4,437	3,508	3,300

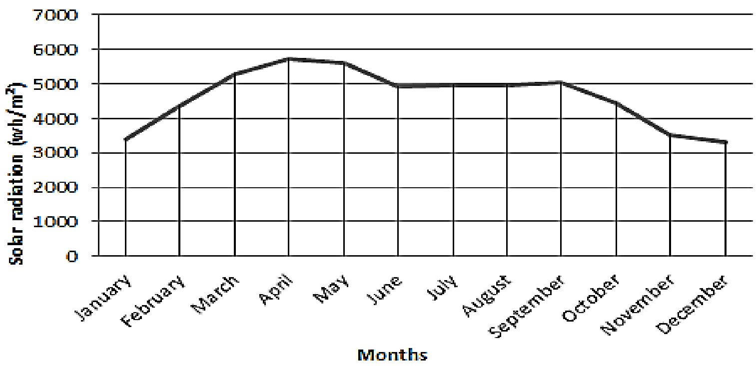

Figure 2. Average monthly solar radiation in Fez city in 2012

3. ADOPTED ENERGY MANAGEMENT SYSTEM

Decision-making is the process of selecting a possible logical choice from several ones, by determining the percentages of effectiveness. This process helps to make informed, reasonable, and more satisfying decisions by organizing relevant information and evaluating alternative solutions. This is the case of an EMS which controls the various operations of MG. Deciding MG consists of choosing the most appropriate action to provide a satisfactory solution to the problems that may be encountered by the EMS. For this, we propose energy management of our MG based on the following four main rules:

- PV energy is mainly used to power the loads.
- The batteries are discharged only to ensure the function of carrying out the charge when the PV energy is not sufficient.
- The batteries are recharged as soon as possible with excess energy from the available source (PV).
- The energy required is taken either from the DN or the DG when the batteries are discharged depending on the purchase price of electricity.

Taking into account the choice of MG with the grid-connected mode, our goal is to predict the decision we need to make at every moment based on the state of loads, REs, batteries, DGs, DN buys, and sell prices. The state of batteries is indicated by the SOC, while the state of loads and renewable energy sources is indicated by the symbol ΔP which is the difference between the energy produced and the energy required. Take in this proposed approach the excessive charge is when the SOC exceeds 70% and the deep discharge is when the SOC is below 30%.

Starting with ΔP. "What is the sign of ΔP?" is a question that we have to solve. There is two answers: negative or positive value, and for each result, it is important to look at the SoC of batteries and the purchase and sale price, which are considered deterministic parameters. If ΔP is positive, the question "Is the SoC less than 30%?" must be answered. If yes, the batteries will be charged. If "Is the SoC between 30% and 70%?" we will consider the price, if it is low we will charge the batteries since we are not going to have an important gain, otherwise, we will sell the excess amount of energy to the DN. If "the SoC is greater than 70%", the batteries cannot be charged, and therefore we will sell the excess energy to the DN.

If ΔP is negative, we must determine whether the SoC is greater or less than 30%. Depending on the answer, we decide whether to discharge the batteries or buy the amount of electricity needed by the DN or use the DGs to recover the energy needed. Below, we will give a detailed description of each decision-making approach separately: the first approach is based on RBS, and the second approach is based on DT.

3.1. Classical decision-making approach

A collection of IF-THEN statements created by an expert is used in the RBS. It is considered a deterministic and classical tool to make decisions. It still has its place in the decision-making tools even if it also has some flaws. The wrong set of rules could produce the wrong result. The system can also start relatively basic before becoming quite complicated as improvements are made. RBS uses regulations created by human specialists. Algorithm 1 describes this reflection of decision base RBS is as shown in:

Algorithm 1: Classical tool to make a decision based on RBS

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We test if the quantity of PV energy produced is greater than the load requested.
        1) If this constraint holds then:
                1.1) If the SOC is less than or equal to 30%, we will charge the batteries
                1.2) If SOC is between 30% and 70% we will test the price.
                 1.2.1) If the price is low we will charge the batteries.
                 1.2.2) If the price is medium, we will sell to DN.
                 1.2.3) If the price is high, we will sell to DN.
                1.3) The surplus of the energy produced is sold having checked if its SOC is
more than 70%.
        2) If this constraint is not verified then:
                2.1) If SOC is less than or equal to 30% we will test the price:
                 2.1.1) If the price is low, we will buy the quantity of energy necessary to
reach the requested load.
                 2.1.2) If the price is medium, we will buy the quantity of energy necessary
to reach the requested load.
         2.1.3) If the price is high, the quantity of energy required is supplemented directly
by the energy of DG.
                2.2) If SOC is between 30% and 70% we will test the price:
                 2.2.1) If the price is low we will buy the necessary energy from DN.
                 2.2.2) If the price is medium, we will discharge the batteries.
                 2.2.3) If the price is high, the quantity of energy required is supplemented
directly by the energy stored in DG.
                2.3) If SOC is greater than 70%, the batteries will be discharged.
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3.2. Decision tree approach

DT is part of the supervised learning methods. It is a probabilistic and tree-based method that extracts rules from a set of pre-classified learning data. In an MG, DTs often consider binary sort data, i.e. true-false, sure-uncertain. The components of the DT are called nodes, they are linked together by hierarchical links. There are three types of nodes: root, internal nodes, and leaf nodes; the root or the father is the node with which one enters the DT, the nodes which have descendants or children are called internal nodes, and the terminal nodes are also called the leaves which have no children.

DT is a decent and handy decision-support tool. It's easy to understand, adding new options to existing trees without any hassle, and easy to link with other decision support tools. Using DT in machine learning has various advantages; it is less expensive to use the tree to predict the data. Data can be used in DT either qualitatively or numerically, and multiple output data allows for problem modeling. It uses a model that makes it easier to understand the results. It is trustworthy because it is testable and quantifiable. Even if source data assumptions are not met, they often lead to accurate results.

The proposed DT for our MG is shown in Figure 3, which explains how to choose the best action based on the available attributes (ΔP, SOC, and buy and sell price). The strongest attribute to be the root is ΔP indicating the state of renewable loads and sources. Then, depending on its value, we examine the SOC and the price attributes which are considered internal nodes in our DT to make an accurate decision among the following ones:

- Charge batteries.
- Discharge batteries.
- Buy necessary energy from DN.
- Sell excess energy to DN.
- Recover necessary energy from DG.

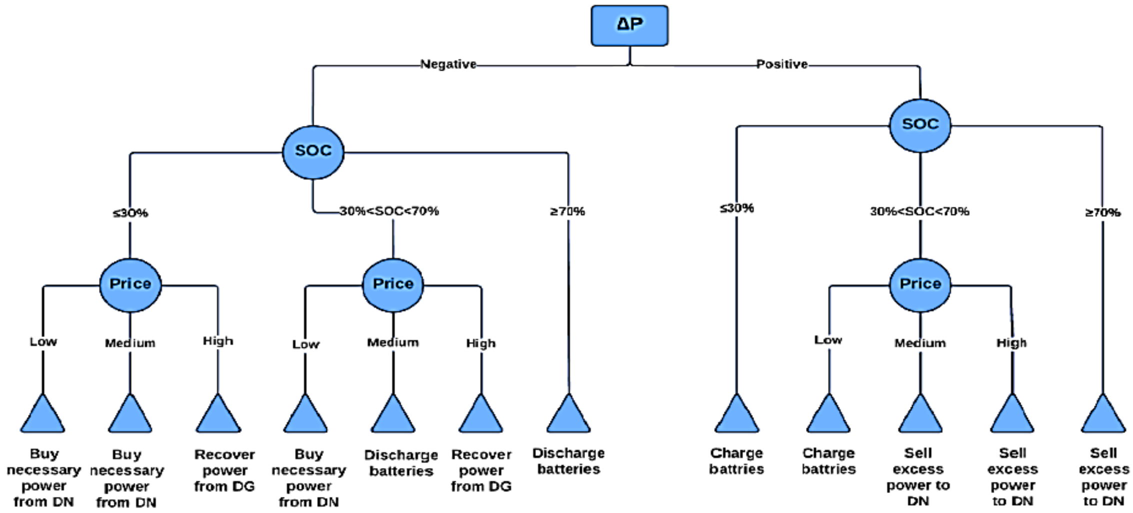

Figure 3. Adopted DT for decision-making

4. RESULTS AND DISCUSSION

In this section, we discuss the performance of the suggested DT using the obtained results. We compare our method with other literature such as RBS [20], and DT [17] which don't take into consideration the price of electricity and the DG as an important component of the MG. Figure 4 presents the simulated daily SOC of batteries for all methods: Classical RBS, classical DT, and the proposed DT method. The maximum charges and the minimum discharges are marked in red on the figure.

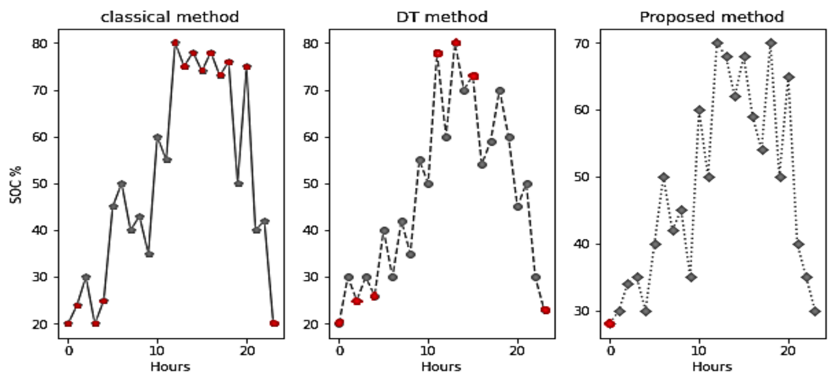

Figure 4. Daily SOC of batteries

In the classic RBS-based approach, over 24 hours, the SOC repeatedly exceeded 70% and was also subjected to multiple deep discharges that damaged the batteries over time. On the other hand, in the DT-based approach, we see that the SOC exceeded 70% three times and was exposed to numerous deep discharges, which harmed the batteries over time compared to our proposed method, the SOC is treated to a single deep discharge and always remains below 70%. To demonstrate that our decision-making technique satisfied the economic goal, a cost-benefit analysis was performed over one month, comparing gains and costs. Figures 5-7 show the benefits and costs. When the two curves are null, it signifies that we have decided whether to charge or discharge the batteries and have not utilized the DN to purchase or sell.

In Figure 5, we followed the classical technique to reach our conclusion, thus we can infer that the costs outweigh the benefits. In Figure 6, we will utilize the decision tree to decide without considering the price of energy or the usage of DG. We may conclude that there are advantages, but the costs outweigh the rewards. In Figure 7, we can conclude that we can earn a financial benefit larger than the expenditure during the test period if we utilize our recommended approach to make the choice.

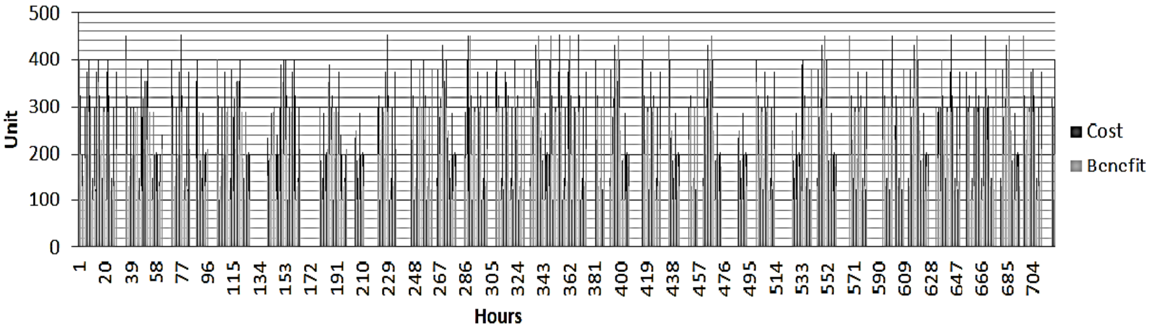

Figure 5. Comparison of costs and benefits for a month using the classical method

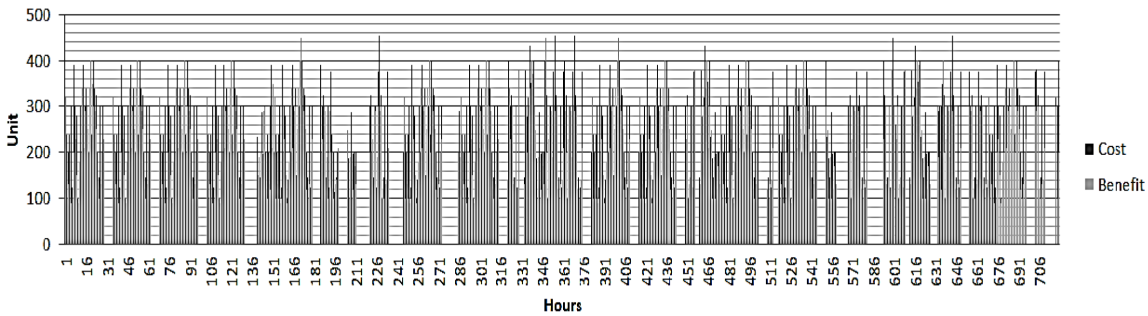

Figure 6. Comparison of costs and benefits for a month using the DT method

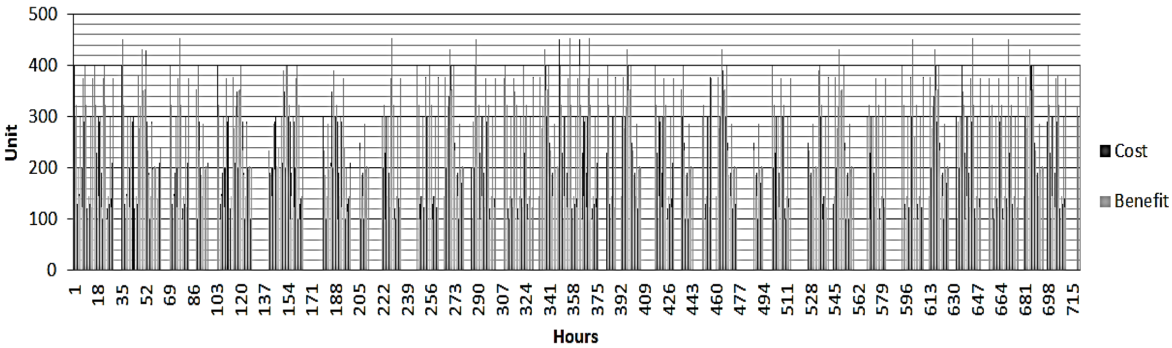

Figure 7. Comparison of costs and benefits for a month using the proposed DT

5. CONCLUSION

In this paper, we have proposed a decision-making method based on DT to regulate the energy flows in an MG composed of solar energy, batteries, DG, and connected to DN. For this reason, the power source for the loads is obtained either from energies produced by solar energy sources, from batteries, DN, or DG when renewable energies and the batteries are exhausted. We have considered the difference between the solar energy produced and the requested load, the SOC of batteries, and the purchase or sale price as parameters to make the final decision which can be: Charge batteries, discharge batteries, buy necessary energy from DN, sell excess energy to DN and recover necessary energy from DG. The proposed DT has taken into consideration the electricity price to maximize the MG profits. The results showed that the suggested decision-making process resulted in no maximum charge for the duration of the trial. Moreover, the comparative analysis proved the performance of the suggested method and demonstrated that the proposed DT provided more ability to make a sensible decision since the benefits always exceeded the expenses. In future work, we think to add more parameters to the DT that will allow us to manage more complicated MG.

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