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Smart Home Energy Management Algorithm Considering Renewables Energies with Storage System and Electric Vehicles

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***Abstract*— The efficient use of the incorporation of photovoltaic generation (PV) an electric vehicle (EV) and solar panel with the home energy management system (HEMS) can play a significant role in improving grid stability and economic benefits of the consumers. To reduce the peak load and electricity bill, a smart appliances control algorithm was proposed for the smart home energy management system (SHEMS) with integration of the renewable energy sources (RES), electric vehicles (EV) and energy storage system (ESS). The proposed algorithm decreases the peak load and electricity bill by shifting starting times of shifted appliances from peak to off-peak periods. Therefore, an energy storage system (ESS) and backup battery storage system (BBSS) are also considered for stable and reliable power system operation. The aim of this is to reduce energy usage and monetary cost with an efficient home energy management scheme (HEMS). In this paper, a cost-efficient power-sharing technique is developed which works based on priorities of appliances operating time.**

***Index Terms*— Smart Home, HEMS, RESs, PV, Electric Vehicle (EV) and ESS**

I. INTRODUCTION

TO reduce energy consumption and carbon emission, several works had proposed various energy management systems [1], [2] for smart grids [3]. The main purpose of EMS is to reduce energy consumption, peak load, and electricity cost is based on shifting the power demand from peak to off-peak hours. In [4], the authors investigated the cost minimization problem in which the electrical appliances allow different levels of delay tolerance. The minimization of energy cost and the maximization of user comfort are the typical optimization problems in recent smart homes [5], [6]. Electricity consumers can manipulate energy consumption to minimize the peak demand while reducing electricity bills [7], [8]. To decrease electricity lost it is important to maintain energy scheduling algorithm for electrical appliances based on the price of the respective time slot.

To fulfil the increasing electricity demand with minimal emissions of greenhouse gases scientists have worked on a generation of energy: renewable energy resources (RESs). Integration of RESs into the grid enhances the stability and reliability of power system. A smart grid has different kinds of operational and operate with smart pieces like smart meters (SM), smart appliances (SA), renewable energy sources, electric energy storage resources etc. The main aspect of SG is the control of power production, transmission and distribution through advanced information and communication technologies (ICTs).

The key factors that make SG superior over traditional grids are: two-way communication advanced metering infrastructure (AMI) and information management units (IMUs). They introduce intelligence, automation and real-time control to power systems. The two-way communication in SG not only keeps the end-users well informed about the varying electricity prices, but also maintenance schedules of the distribution network.

The SG integrates RESs and ESSs and SGs involve the residential and commercial users into demand-side management (DSM). The main objectives of different DSM and DR strategies in SG are the reduction of the electricity cost and minimization of energy consumption in peak hours. To achieve these objectives numerous of algorithms for an efficient HEMS have been proposed, such as integer linear programing (MILP) [9] etc. In this context, we present HEMS which integrate RES, ESS, and EV into the SG system.

The remaining of this paper is organized as follows: section II presents the system description and modeling studied. The proposed home energy management strategy is illustrated in section III. Finally, section IV elaborates the conclusion of this paper.

II. PROPOSED SYSTEM MODEL

This work investigates design of smart grids that targets the reduction of electricity cost for consumers and energy management- make electric grid operation. A Smart Home (SM) equipped with a smart meter along with the energy management controller (EMC), for reliable bi-directional power and information flow between SG and SH. Each consumer has multiple electricity consuming smart appliances with different power ratings and length of operational time (LOT) and is equipped with their own distributable energy generation system (EGS), i.e., micro grid. The micro grid consists of the wind turbine (WT) and solar panel-photo voltaic (PV). The PV and WT produce a quantity of energy depending on weather conditions, which does not always match the load demand. There are two possible scenarios: energy production is insufficient or there is surplus energy generation. These distributed energy generation system are intermittent in nature, therefore, to fulfill the load requirements of costumers, energy storage system (ESS) is also installed i.e., batteries. Energy storage and the main grid allow for the buffering of insufficient or excess power generation. The battery and grid can restore the production/consumption balance by supplying the lack of energy or by absorbing excess energy. In each SH, the consumers put various parameters of all appliances in EMC. EMC is then responsible for the ON/OFF status of all appliances. The proposed optimization model is presented in Fig. 1.

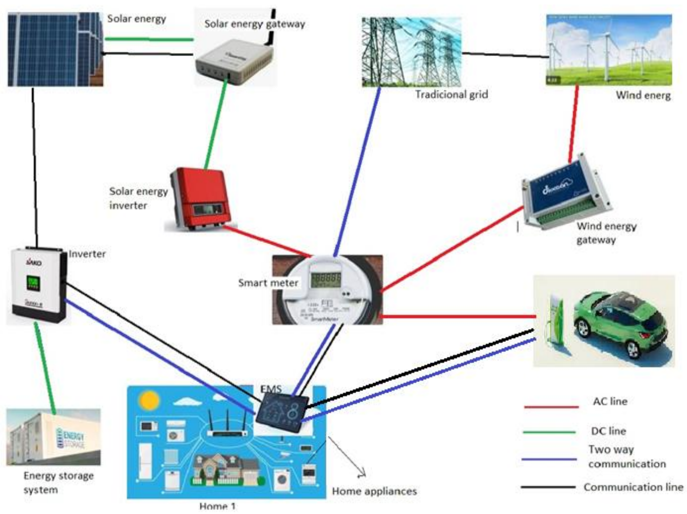
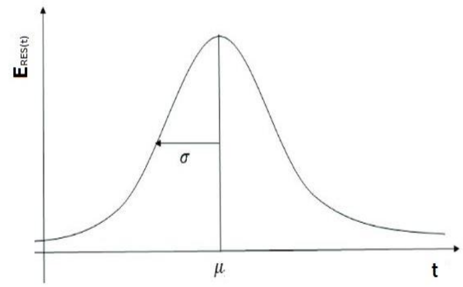


Fig. 1: Proposed system model

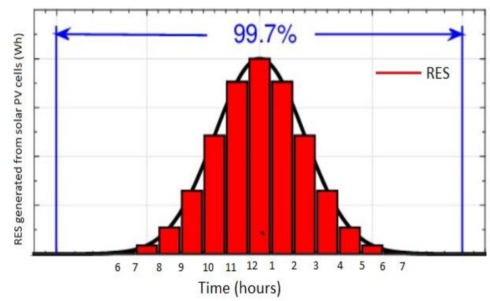
A. RES model

Photovoltaic (PH) cells and wind turbines can be used as local power generators, also known as distributed RES. These RESs can be used for local energy generation, as well as for charging the batteries in BSUs. The generated energy denoted by E_{RES} can be calculated by Gaussian function (1) as follows:

$$E_{RES}(t,\mu,\sigma) = \frac{1}{\sigma\pi\sqrt{2}} e^{\frac{(t-\mu)^2}{2\pi^2}} \quad (1)$$



(a)



(b)

Fig. 2: a) Gaussian function representing the approximate PV cells energy generation (Wh) [10], b) RES Generated energy E_{RES}.

B. Energy Storage Devices: Battery:

The energy stored in the battery depends on their capacity and their state of charge devices, the output power is limited. The SOC is the ratio between the energy contained in the battery and its maximum capacity. There are three parameters that should be taken into account: the rated charging power, plug-in time and state of charge (SOC) battery. The SOC of a battery is assumed to vary between 20% and 100%. The time it takes to fully charge a battery depends on rated charging power, plug-in time and the battery SOC. In this article, battery is assumed to be plugged in when its battery SOC reaches 20% and the battery can be used when $SOC_{B,t} \geq 20\%$. The switch status of B ($S_{B,t}$) at time, intervals can be calculated by the following equation:

$$S_{B,t} = \begin{cases} 0, & SOC_{B,t} = 100\% \\ 1, & SOC_{B,t} < 100\% \\ S_{B,t-1}, & 20\% \leq SOC_{B,t} \leq 100\% \end{cases} \quad (2)$$

Where, $S_{B,t}$ is the device status, $S_{B,t} = 0$, means that the appliance is switched off, $S_{B,t} = 1$, means the appliance is switched on and $SOC_{B,t}$ is the SOC battery in the time interval.

The battery power consumption is in kW, and $P_{B,t}$ at a given time interval can be calculated by:

$P_{B,t}=P_B*S_{B,t}$

Where, P_B is the amount of rated battery power in kW.

C. *Electric vehicle Battery:*

The Battery of Electric vehicle is used to power up the motor of EVs. To model an EV, there are three parameters that should be taken into account; the rated charging power, plug-in time and state of charge (SOC) battery. The SOC of an EV battery is assumed to vary between 20% and 100%. The time it takes to fully charge an EV depends on rated charging power, plug-in time and the battery SOC. In this article, EV is assumed to be plugged in when its battery SOC reaches 20% and the EV battery can be used when $SOC_{EV,t} \geq 20\%$. The switch status of EV ($S_{EV,t}$) at time intervals can be calculated by the following equation:

$$S_{EV,t} = \begin{cases} 0, & SOC_{EV,t} = 100\% \\ 1, & SOC_{CEV,t} < 100\% \\ S_{EV,t-1}, & 20\% \leq SOC_{EV,t} \leq 100\% \end{cases} \quad (3)$$

Where, $S_{EV,t}$ is the device status, $S_{EV,t} = 0$, means that the appliance is switched off, $S_{EV,t} = 1$, means the appliance is switched on and $SOC_{EV,t}$ is the SOC battery in the time interval.

The EV power consumption is in kW, $P_{EV,t}$ at a given time interval can be calculated by:

$P_{EV,t} = P_{EV} * S_{EV,t}$

Where, P_{EV} is the amount of rated EV power in kW

D. *PAR*

The peak to average ratio can be minimized, using EMA, in favor of both the grid and consumer for maintaining demand-supply balance. PAR is the ratio of the peak consumption of the SH and the average consumption of the SH in every interval of time, and can be calculated

$$\mu = \frac{E_{max}}{\frac{1}{T}\sum_{n=1}^{T} E_T} \quad (4)$$

E. *ESS constraints*

To ensure maximum life span (maximum cycles) for the battery, minimum SOC should be defined. On the one hand, the upper limit of the SOC of batteries is defined to 1. On the other hand, batteries have a SOC_{min} set by the manufacturer, indicating that this SOC_{min} level enables batteries to operate.

SOC_s for the ESS battery is limited by a lower limit

F. *User's Comfort in Terms of Waiting Time (τ):*

Presents interval of time when appliance is switched on, and due to the scheduling limitations of the system has to wait to start its operation. As previous have defined the earliest starting time τ_1 and the latest ending time τ_2 of an appliance and τ describes the time interval when an appliance performs its execution. This is presented in Fig. 3.

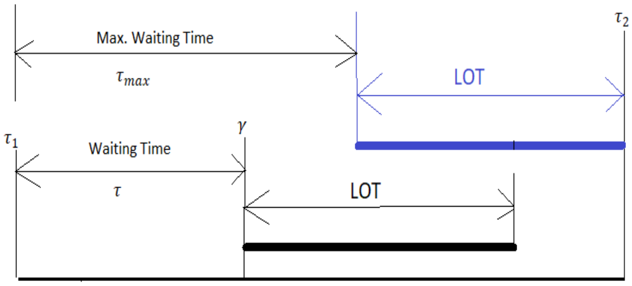


Fig. 3: Starting time, ending time, LOT and waiting time

In this work, we consider 24h for implementation, 1h for each time slot expressed as:

T={t_1, t_2, ………..t_{24}}. Every appliance is connected with the Internet and capable of communication with the energy management controller (EMC). EMC is connected with the Internet via WiFi, which shifts the appliances operation according to the scheduling algorithm. As shown in Fig. 3 the maximum consumer waiting time could be up to τ_{max}.

LOT is defined by all appliances and according this the algorithm will have to start the appliances to complete its operation up to the final time τ_2. For example, if WM has a time span of 10h (from 8:00—18:00) and LOT=2h, this means that our proposed algorithm must start on from 8:00—18:00 to complete its operation of 2h, with a waiting time ranging from 0-8h.

G. *Categorization of Appliances*

We have considered a smart home with multiple home appliances. They are divided into three main categories/classes named shiftable, non-interruptible and base load appliances.

H. *Shiftable Appliances*

Shiftable appliances can be fully managed, and these types of appliances can be shifted or interrupted

In any time, slot keeping in view the minimization of PAR and electricity bill [11]. Shiftable appliances class includes the electrical car, vacuum cleaner, dish washer, washing machine, spin dryer, laptop, cooker hub, microwave oven [12] etc. The energy consumed by all shiftable appliances in the total time interval of 24h with 24 –time slots can be calculated by the equation (5).

$$E_s = \sum_{a_s \in A_s}\left(\sum_{n=1}^{24}(\rho_{s,n} x X_{s,n} x \tau_s\right), \qquad \tau_1 < \tau_s < \tau_2 \quad (5)$$

Where a_s–presents each shiftable appliances,

A_s – is the set of shiftable appliances,

$\rho_{s,n}$ - is the power rating of shiftable appliances

$X_{s,n}$ –is ON(1) and OFF(0) states of the n[th] – shiftable appliances

$$X_{s,n} = \begin{cases} 1, & if\ a_s\ is\ ON \\ 0, & if\ a_s\ is\ OFF \end{cases}$$

τ_s – is the LOT for each shiftable appliance,

τ_1– is the earliest starting time and

τ_2–is the latest ending time of shiftable appliances and $\tau_1 < \tau_s < \tau_2$.

I. Non-Interruptible Appliances

These are those regular appliances A_{ni} that cannot be shifted or interrupted while performing their operations. This type of appliance may not be interrupted when execution starts but shifted to any time slot before starting their execution. Non-interruptible appliances class includes the Washing machine, Dish washer and Spin dryer. This type of appliance may be scheduled between possible earliest starting and possible least ending time. Let $a_{ni} \in A_{ni}$ represent a single appliance from this category. The $\rho_{ni,n}$ presents the power rating of each appliance in this category. Then the total consumed electricity E_{ni} of all Non-interruptible appliances in the total time interval of 24h can be found as in equation 6.

$$E_{ni} = \sum_{a_{ni} \in A_{ni}} (\sum_{n=1}^{24} (\rho_{ni,n} x X_{ni,n} x \tau_{ni}) \qquad \tau_1 < \tau_{ni} < \tau_2 \quad (6)$$

Where,

a_{ni} – presents each Non-Interruptible appliances,

A_{ni} – is the set of Non-Interruptible appliances,

$\rho_{ni,n}$ - is the power rating of Non-Interruptible appliances

$X_{ni,n}$ – is the ON (1) and OFF (0) states of the n[th] – Non-Interruptible appliances

$$X_{ni,n} = \begin{cases} 1, & if\ a_{ni}\ is\ ON \\ 0, & if\ a_{ni}\ is\ OFF \end{cases}$$

τ_{ni} – is the LOT for each Non-Interruptible appliance,

τ_1– is the earliest starting time and

τ_2– is the latest ending time of Non-Interruptible appliances and $\tau_1 < \tau_{ni} < \tau_2$.

J. Base-Load Appliances

Are those regular appliances A_b that cannot be shifted or interrupted while performing their operations. Generally, these appliances considered the main load of any household; these appliances also are non-shiftable and non-interruptible appliances. We consider interior lighting and refrigerators as base load appliances. Let $a_b \in A_b$ represent a single appliance from this category. The $\rho_{b,n}$ presents the power rating of each appliance in this category. Then the total consumed electricity E_b of all base load appliances in the total time interval of 24h can be calculated as in equation 7.

$$E_b = \sum_{a_b \in A_b} (\sum_{n=1}^{24} (\rho_{b,n} x X_{b,n} x \tau_b) \qquad \tau_1 < \tau_b < \tau_2 \quad (7)$$

Where,

a_b – presents each Base-Load appliance,

$\rho_{b,n}$ - is the power rating of Base-Load appliances

$X_{b,n}$ –is ON(1) and OFF(0) states of the n[th] – Base-Load appliances

$$X_{b,n} = \begin{cases} 1, & if\ a_b\ is\ ON \\ 0, & if\ a_b\ is\ OFF \end{cases}$$

τ_b – is the LOT for each Base-Load appliance,

τ_1– is the earliest starting time and

τ_2– is the latest ending time of Base-Load appliances and $\tau_1 < \tau_b < \tau_2$.

Table I: Parameters of home appliances

Appliances Category	Appliance Name	Power Rating (KW/h)	Earliest Starting Time (h)	Ending Time (h)	Time span (τ_2-τ_1)(h)	LOT (h)
Shiftable appliances	Desktop	0.4	18	24	6	3.0
	Laptop	0.1	18	24	6	3.0
	Microwave	1.5	07	10	3	1.0
	V. cleaner	1.6	09	17	8	1.0
	E. vehicle	3.5	18	08	14	3.0
	C. oven	3.5	15	20	5	1.0
	C. hub	3.0	06	10	4	1.0
Non-interrupt. appliances	W. machine	2.2	09	12	3	2.0
	D. washer	1.8	09	17	8	2.0
	Spin dryer	2.5	13	18	5	1.0
Base-load appliances	Int. light.	1.0	16	24	8	8.0
	Refrigerator	0.4	00	24	24	24.0

K. Energy Consumption Mode

The total energy consumption of the house with the smart appliances is given by

$$E_T=E_{ni}+E_s+E_b \quad (8)$$

Where E_{ni} - is the energy consumption of the non-Interruptible appliances, E_s – is the energy consumption of the shifted appliances and E_b is the energy consumption of the base load appliances.

The generated electricity from RES is stored in EES and the EV battery for future use. In ON-peak hours, the smart home uses the electricity from the RES or ESS or EV battery and the excess of the electricity is stored back to the ESS. They use energy from the grid when needed, i.e., when their demand exceeds the RES, generated energy plus the ESS stored energy and plus the energy stored in the EV battery. Their energy consumption is calculated using the following equation:

$$E_{c=E_T-\sum_{n=1}^{24}(E_{RES} \pm E_{ESS} \pm E_{EV})} \quad (9)$$

Where

E_c – is the energy consumption of smart homes.

E_{RES} – is the energy generated in the SH,

E_{ESS} – is the energy stored in the SH.

E_{EV} – is the energy stored in the EV battery.

If E_{ESS} and E_{EV} is the positive, this means that RESs are discharging the batteries and providing energy to the load and if E_{ESS} and E_{EV} is negative, this means that RES charging the battery.

L. The Objective of Energy Management Algorithm With RES And ESS

We consider the following objective for the proposed EMA with RES and ESS:

1) Minimization of the consumers electricity bill
2) Reducing the average waiting time of appliances
3) Minimization of PAR
4) Integration of RES and ESS in the EMA.
5) With these objectives, we can achieve the optimization of energy of all appliances, using different scheduling techniques. If V_T – is the maximum energy capacity in every time slot, then the consumer energy cost can be minimized. Total aggregated energy consumption of home appliances needed to keep within the maximum thresho*ld limit of V_T.*

   $E_T \leq V_T$

   Where E_T is the total energy demand of the consumer.

III. Proposed Schemes

In the smart grid, every smart home is connected with a smart meter, and the smart meter is further connected with an EMC. The smart meter and EMC enable the mutual two-way communication between electricity consumers and the utility. It enables the consumer to perform load shifting from peak to off-peak hours for cost minimization. However, load shifting in off-peak hours may cause the generation of peaks in off-peak hours. This problem is considered an optimization problem; However, our scheme takes into consideration the minimizing of electricity cost and PAR reduction with minimum user waiting time simultaneously. Therefore, the main targets of our work are electricity cost and PAR reduction with minimum user waiting time.

A. Energy management algorithm considering renewable energies resources, energy storage and EV battery storage

The flowchart of the proposed energy management algorithm with RES and EV is presented in Fig. 4. In order to ensure maximum efficiency, the energy of renewable sources is used firstly. Here we define the difference of total consumed energy and total renewable energy (from photovoltaic and wind turbine) as P_T=Pc-(P_{PW}+P_{WT}).

P_C(t) represents the total load of currently working appliances in HEMS system at time t.

P_g(t) represents the power supplied by the main grid at time t. P_r(t) represents the generating power of the RES system at time t. P_i is the working power of the appliance i.

Here the strategy is to minimize energy consumption from the grid. Such, the RES generating power has the highest use priority while the grid power has the lowest use priority. The state of the EV battery depends on the charging/discharging schedule and state of charge (SOC) of the battery.

P_b(t)and P_{EV}(t)are the available output powers of the RES storage system and EV battery, respectively, at time *t*.

In first step, if the generating power P_r(t) of RES system is enough for supporting the requested appliance and all other working appliances at time t, (P_C(t)+P_i), the requested appliance can starts without using energy of storage battery, EV battery and grid; otherwise the energy of the battery is checked.

If the generating power P_r(t) plus the available power of the battery P_b(t) is enough for supporting the requested appliance and all other working appliances at time t (P_C(t)+P_i), the requested appliance can start without using energy from EV battery and grid; otherwise, the energy of the EV battery is required.

If the generating power P_r(t) plus the available power of the RES storage P_b(t) and EV battery P_{EV}(t) is enough for supporting the requested appliance and all other working appliances at time t, (P_C(t)+P_i), the requested appliance can start without using energy from the grid; otherwise, the energy of the grid is required.

The starting time of the requested appliance is determined according to the type of the requested appliance. If the requested appliance is of non-interruptible load type and the power consumption P_g(t)+P_i supplied by the main grid is less than threshold limit of P_t, the requested appliance can start.

When a shifted appliance request for starting at off-peak hours and power consumption, P_g(t)+P_i is larger than threshold limit P_t, the starting of appliances may be shifted for time less than Length of Operational Time (LOT).

When a shifted appliance request for starting at peak hours and power consumption P_g(t)+P_i is larger than threshold limit P_t, and if t>LOT (t- time to off-peak hour) the starting of appliances may be shifted for time t_l=t-LOT, otherwise the appliance can start.

When a HVAC (Heating, Ventilation, and Air Conditioning) requests a turning on, the HVAC can turn on immediately. At peak hours, the HVAC is set to the highest target temperature T_h (for cooling) or in lowest temperature T_l (for heating), in order to reduce the working load. During the off-peak hours, if the power consumption P_g(t)+P_i exceeds the power threshold P_t, the HVAC is set to the higher target temperature T_h (for cooling) $24^oC<T<=T_h$, or to the lowest target temperature T_l (for heating) $T_l <T<24^oC$, in order to provide power constraint.

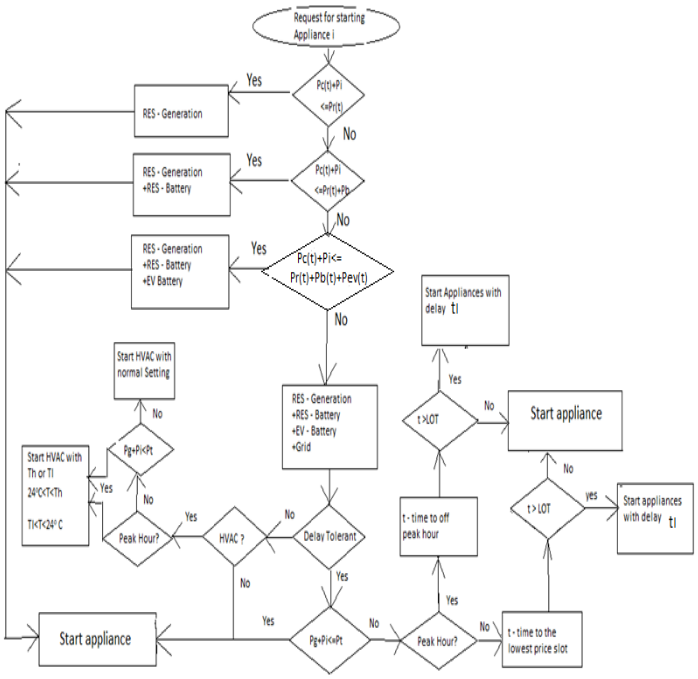


Fig. 4: Flowchart of Energy management Strategy

IV. CONCLUSION AND FUTURE WORK

This paper has presented an optimal algorithm and energy management scheme for a home integrating RES and EV to avoid the peak load, and to reduce the electricity bill. Generation of renewable energy reduces the dependence of the grid. Therefore, the energy bill is reduced, and the use of clean energy is empowered for sustainable development. The use of ESS presents financial interest for homeowners, supports the integration of RER and relieves the main grid during on-peak periods. The proposed scheme reduces the total electricity cost, reduces the PAR reduction factor and achieves a high comfort level of the end-user by minimizing the waiting time of home appliances.

The proposed smart appliance control algorithm significantly decreases the peak load and helps to reduce electric energy cost at home. In this paper, a theoretically detailed description of the algorithm for home energy management is done, where RES is connected.

The practical implementation of the algorithm will be realized in the future since it presents a very complex system, especially the architecture of the control system, which we have chosen for the implementation of the SHEM algorithm, which is also described in this paper. We have closer values of cost reduction after the practical implementation of the algorithm.

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