Dynamic Manager for Electrical Energy Efficiency in Buildings

Gestor Dinámico Inteligente para la Eficiencia Energética en Edificaciones

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ABSTRACT

This paper studies a management model for electrical energy efficiency that allows the integration of several alternatives energy generation sources such as wind, photovoltaic and fuel cell power in order to minimize the power consumption in a building. An intelligent approach is presented to manage the power consumption of appliances. This approach takes into account variables such as temperature, luminance and presence. The integration of several Demand Side Management (DSM) criteria are carried out through dynamic and intelligent selections according to variable performance, customer´s preferences and operation based on comfort or consumption. Likewise, a diagnosis analysis through energy audit is carried out to evaluate electrical appliances proficiency and customer habits. Finally, the design of a fuzzy logic-based manager is presented to select which electrical source and what proportion of energy is needed to satisfy power consumption. According to our experimental results obtained from about 120 several case studies, each of which consists in setting an energy usage during 24 hours with several behavior, energy savings between 27% and 33% can be achieved with the proposed dynamic manager, and is about 5% saver than an individual management criterion.

Keywords: Demand Side Management (DSM), energy audit (EA), energy efficiency, management criteria for electrical energy and alternative energy.

RESUMEN

Este articulo estudia el diseño de un modelo de gestión para la eficiencia de energía eléctrica que permite la integración de diversas fuentes de generación de energía eléctrica como la eólica, fotovoltaica y celda de combustible con el fin de minimizar el consumo de energía eléctrica en una edificación. Se presenta una metodología inteligente para gestionar el consumo de energía eléctrica de los dispositivos eléctricos. Esta propuesta toma en cuenta las siguientes variables exogenas: temperatura, luminarias y presencia. La integración de múltiples criterios de gestión de la demanda de energía (DSM) es llevada a cabo a través de selecciones dinámicas e inteligentes de acuerdo a las preferencias del usuario y la operación basada en confort o consumo. De igual manera, se realiza un diagnóstico a través de un proceso de auditoría energética con el objetivo de evaluar la eficiencia de los dispositivos eléctricos y hábitos de consumo. Finalmente, se presenta el diseño de un gestor basado en lógica difusa para seleccionar la fuente de energía eléctrica y la proporción de la misma requerida para satisfacer la demanda de energía eléctrica. De acuerdo con los resultados experimentales obtenidos en 120 casos de estudio, cada uno de los cuales consistió en establecer un uso de la energía durante 24 horas con diferentes comportamientos, es posible alcanzar ahorros de energía entre 27% y 33% a través del gestor dinámico inteligente, el cual es 5% más ahorrador que un criterio de gestión individual.

Palabras clave: Gestión de la demanda, auditoria energética, eficiencia energética, criterio de gestión para la energía eléctrica y energía alternativa.

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Introduction

In industrialized countries the 40% of the energy is consumed by buildings, where 68% is in the form of electricity (Frank & Goswami, 2007; Huang, 2006; Lior, 2010; Tascikaraoglu, Boynuegri, & Uzunoglu, 2014). Recent research shows that 20%–30% of this energy consumption can be saved through optimized operation and management without changing the structure and hardware configuration of the building energy supply system (A. Di Giorgio, 2012; D. Zhang, N. Shah, 2013; Guan, Xu, & Jia, 2010; N. Gudi, L. Wang, 2012). Likewise, the possibility to achieve higher generation levels without the environmental impact that comes with conventional generation systems has motivated the use of these technologies with renewable sources (Craddock, 2008; M. Sechilariu, B. Wang, 2013; S. Kahrobaee, R.A. Rajabzadeh, S. Leen-Kiat, 2013). However, despite these efforts the world power consumption still growth year in year out (EIA, 2014).

Challenges related to large variability in efficiency strategies based on integration of several criteria as audit energy, demand side management and alternatives energy source remain little explored. Integrating different management approaches offers the possibility of exploiting strengths and compensating their weaknesses when they are used all together. However, this approach requires a model able to operate according to basics

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principles of efficiency from generation and consumption.

In order to overcome related limitations for the management of electrical energy, it is possible combining those activities that involves identification, implementation and verification of improvement plans where the main goal is reducing the consumption of electricity without impacting customer´s comfort (Ravibabu, Praveen, Ch, P, & M, 2009). Therefore, it is important for the adequate management of energy efficiency to include three functional stages: energy audit, efficient management of the electrical appliances and renewable sources. (1) Energy audit provides opportunities for electrical energy saving through identification of bad consumption habits and appliances whose operation and technology cause an excessive level of power consumption (Gomes, Coelho, & Valdez, 2011; Wang & Huang, 2009). (2) Electric energy management allows setting suitable operation points according to exogenous variables (e.g., temperature, luminance, presence, among others) and customer´s preferences adjustment to efficiency policies. (3) The use of alternatives energy sources integrated with a stage of demand management has two advantages: first, the integration of such technologies allows coordinating the operation of individual systems in order to provide suitable energy conditions for all appliances connected to the power grid. Second, the implementation of a management stage provides the possibility to operate the appliance efficiently depending on the need. The management stage involves basic integration knowledge according to principles of efficiency.

Several authors have worked on power consumption saving without impacting the customer's comfort (Frank & Goswami, 2007)(Salehfar, 1999)(Ravibabu et al., 2009). The application of *Demand Side Management* (*DSM)* techniques like *Load Priority* provides suitable management according to customer´s variables. In other cases, those appliances with more consumption during peak demand are identified. Management criteria using computational intelligent techniques provide a reduction of power consumption around 10 to 30 % (Goel, Wu, & Wang, 2010; Matallanas et al., 2012; Ravibabu et al., 2009; Salehfar, 1999).

In this paper, we introduce a framework which it carries out the integration of energy audit, multiple criteria of electrical energy management and alternatives energy sources. A neural network-based criterion has been developed taking into account policies of efficiency and exogenous variables as temperature, presence, luminance, use profile (e.g. computer) and type of activity. Additionally, a fuzzy logic based criterion inspired on differential tariff has been developed. The design of a hybrid manager using several *DSM* and intelligent criteria is proposed, using selection preferences based on priority, comfort or consumption. The selection of each criterion depends on the curve proposed by the dynamic manager (*DM*), which is determined according to the adjustment of efficiency policies in each appliance. Finally, a fuzzy manager for an alternative power station has been designed. This station is composed of three types of energy sources (wind, photovoltaic and fuel cells). These three energy sources are integrated in order to increase system reliability in terms of compliance with the electrical energy demand (S. Kahrobaee, R.A. Rajabzadeh, S. Leen-Kiat, 2013). The meteorological variables provide information to the models used by the *Supply Manager* (*SM*) to establish the amount of power that can be generated by the wind generation (*EGS*), photovoltaic generation (*PGS*) and cell fuel generation systems (*CGS*).

Methodology

Figure I presents a scheme of the proposed management model.

Dynamic Manager

This module shows the recommendations according to the selected management criterion. The *DM* has the possibility of establishing recommendations according to management criterion that fit better to the environment conditions. Energy audit is the basis to estimate power consumption savings. The systematic execution of the audit with the user's role provides an opportunity to identify those appliances that present inefficient operation.

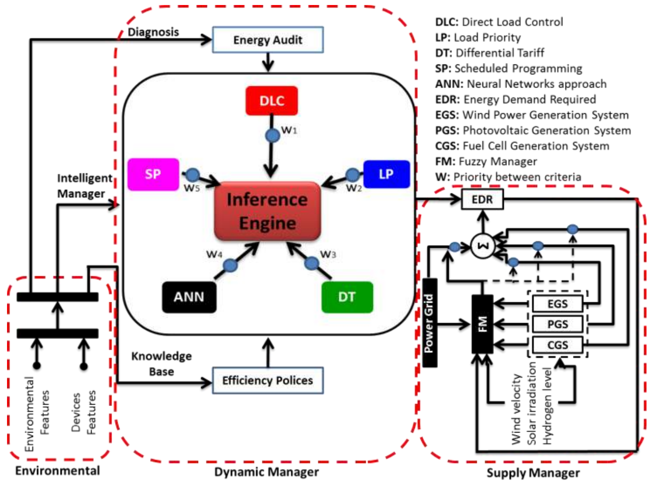

Figure 1. Management Model for Energy Efficiency.

As noticed in Figure I, the dynamic manager has five management criteria: Direct Load Control (*DLC*), Load Priority (*LP*), Scheduled Programming (*SP*), Differential Tariff (*DT*) and Artificial Neural Networks approach (*ANN*). The main objective of the dynamic manager is to propose functional states or a power consumption curve that provides proper operation of the appliance according to the needs of comfort and consumption of electricity (power savings). To achieve this goal, a fuzzy inference engine was implemented for the case of computers, luminaries and televisions. For the air conditioner case, genetic algorithms were used to minimize the proportionality constant (K_U) that indicates the cooling or heating quantity. In computers, lights and televisions the membership functions were designed according to the efficiency guidelines showed in (Gracia, Delgado, Usón, Bribián, & Scarpellini, 2006); for the air conditioner, genetic algorithms were required because it is important to minimize the cooling level without impacting the comfort of the customer. However, due to the appliance operation constraints (e.g., available functional states) it is necessary to select those states that have greater similarity with the proposed *DM*. The states proposed by the *DM* depend on priority and preferences customer selection (individual, priority, comfort or consumption).

An efficient management of air conditioner must guarantee comfortable temperature with less power consumption. The opportunities of savings are related to isolation of the environment and efficiency of the appliance in operation and technology. In this case, only considerations related to operation are used for the design of dynamic manager. The proposed approach seeks modeling the temperature profile in building during 24 hours in function of external temperature ($M(t)$), heat generated within the building ($H(t)$), e.g., luminaries, people and machines and heater or air conditioner ($U(t)$), in order to establish suitable cooling level (K_U) that allows maintaining stable the indoor temperature within the comfort requirements. Equations (1) to (9) are used in the proposed approach (Nagle, Saff, & Snider, 2005).

$$\frac{dT(t)}{dt} = K[M(t) - T(t)] + H(t) + K_U[T_D - T(t)] \quad (1)$$

$$U(t) = K_U[T_D - T(t)] \quad (1)$$

$$Tp(t) = B_2 - B_1F_1(t) + Ce^{(-K_1t)} \quad (2)$$

$$F_1(t) = \frac{\cos(wt)+\left(\frac{w}{K_1}\right)\mathrm{sen}(wt)}{1+\left(\frac{w}{K_1}\right)^2} \quad (3)$$

$$w := \frac{2\pi_o}{24} \quad (4)$$

$$K_1 := K + K_U \quad (5)$$

$$B_1 := \frac{BK}{K_1} \quad (6)$$

$$B_2 = \frac{K_UT_D+KM_0+H_0}{K_1} \quad (8)$$

$$C = T_0 - B_2 + B_1F_1(0) \quad (7)$$

Where,

$M(t)$: Outdoor temperature

$H(t)$: Cooling (heater) rate

$T(t)$: Indoor temperature

K_U: Cooling level

w: Angular frequency of variation.

$\frac{1}{K_1}$: Constant of time with heating and air conditioner.

B_2: Mean temperature in building (daily) without considering the exponential term.

$B_1F_1(t)$: Sinusoidal variation of temperature in building corresponding of outdoor temperature variation.

K: Positive constant, that depends on physical properties of building as amount of doors and windows and type of isolation. For a typical heating and air conditioning, K_U is a little less than 2; for a common building, the constant K is between ½ and ¼ (Nagle et al., 2005).

Equation (3) is the solution of differential equation (1). Function (1) describes the relation between $T(t)$ and K_U. The main idea is optimizing function (10) according to constraints presented in (11 – 13). Function (10) allows evaluating the cooling point required to maintain the indoor temperature within the comfort zone, while function (11) is useful to measure the level of comfort.

$$P_{AC} = f(K_U) \quad (10)$$

$$22ºC \leq T(t) \leq 26ºC \quad (11)$$

$$1.4 \leq K_U \leq 1.48 \quad (12)$$

$$0 \leq P_{AC} \leq P_{ACmax} \quad (13)$$

Furthermore, the proposal seeks to avoid an excessive number of on/off operations on the air conditioning appliance; hence optimization technique is implemented in order to established optimal points of cooling level (K_U) according to temperature deviation of comfort zone. A proportional control is integrated to the thermal model presented in (Nagle et al., 2005) to perform progressive adjustment to the cooling level and thus prevent the appliance from always operating at cooling peaks.

The integration of fuzzy inference engine (for the case of PC, TV and luminaries) and genetic algorithm (for the case of air conditioner) provide operation curves adjusted to the energy efficiency policies. However, the selection of each management criterion depends on customer preferences, e.g., priority list, consumption-based or comfort-based. Hence, the main idea is that *DM* selects the suitable management criterion at each instant time according to these preferences.

Load Priority (LP) (Ravibabu et al., 2009): For this case of study, the air conditioning system was considered as vital[3]. Figure 2 shows an example of application of the load priority criterion for a case study. The results show a reduction in consumption during peak demand.

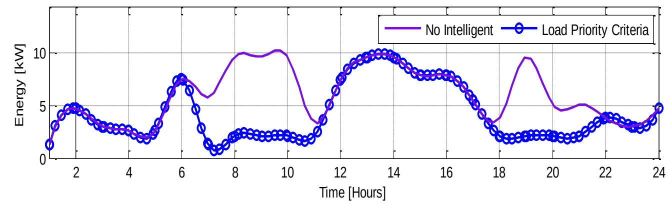

Figure 2. Load priority criteria results

Direct Load Control (DLC) (Goel et al., 2010): The main objective of this proposal is to determine the disconnection time required for saving energy without affecting comfort levels. A detailed analysis of each membership functions is carried out in (Salehfar, 1999).

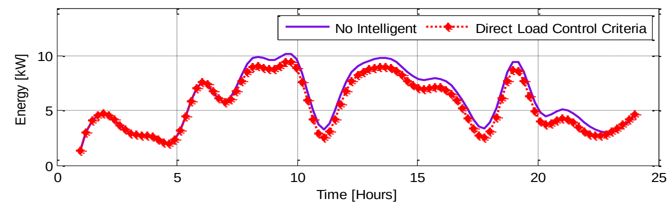

Figure 3. Direct Load Control results

Figure 3 shows an example of application of direct load control criterion for a case study. The results show a reduction in consumption of electricity due to the direct management of the air conditioner.

Differential Tariff (DT): The implementation of this approach were showed in (Christian G. Quintero M.;Jamer R. Jimenez Mares, 2012).

In Figure 4 the power consumption is shown before and after the implementation of the fuzzy system based on the differential tariff criterion.

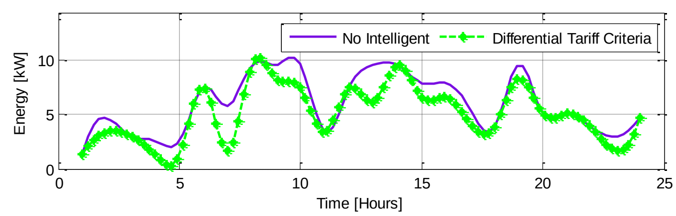

Figure 4. Differential tariff results

Scheduled Programing (SP): This criterion seeks to achieve energy savings based scheduling on and off device at certain instants of the day.

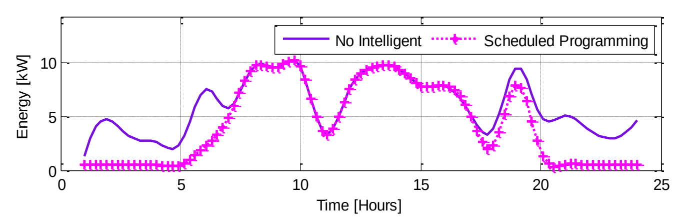

Figure 5. Scheduled programming results

The inputs used for this criterion were presented in (Christian G. Quintero M.;Jamer R. Jimenez Mares, 2012). Figure 5 shows an example of application of scheduled programming in a case of study.

Neural Networks (ANN): The implementation of this approach

[3] They are those appliances selected as relevant by customer.

were showed in (Christian G. Quintero M.;Jamer R. Jimenez Mares, 2012). The proposed architecture has an ANN for each device, given that it can handle independently the loads. The representation of possible situations for each device to control was carried out. For example, PC unoccupied, the system will compare the PC use profile with presence level to determinate if it is necessary carry out any task or not. The obtained data was used to train the neural networks, to obtain a good performance with feed-forward back-propagation network architecture. One hidden layer and sigmoid tangential transfer function were implemented for four ANNs. In this paper, the selection and determination of the number of layers and neurons was adjusted using an iterative algorithm.
Figure 6 shows an example of application of the proposed approach based on neural networks for a case of study. In this case computers, televisions, air conditioner and luminaries have been selected as devices to manage.

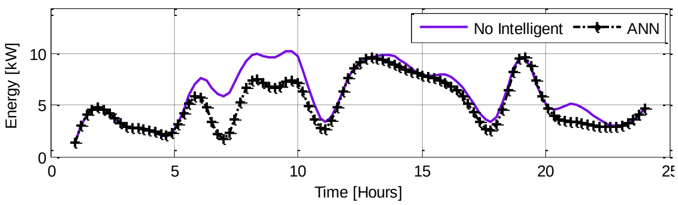

Figure 6. Results of implementation using neural networks

DM based on priority (PMF): It is a non-intelligent approach that seeks to select each criterion according to the priority (w_i) established by the user. However, a threshold was applied in order to consider a possibility of switch to other criterion (immediately lower priority) when the criterion with higher priority does not exceed the threshold set by the user saving.

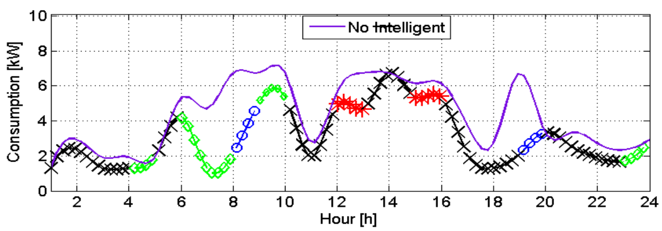

Figure 7. Results of DM based on priority list

Figure 7 shows a case of study where demand management criterion of electric energy using neural networks was selected as the first in priority list followed by differential tariff, load priority, direct load control and scheduled programming, respectively. The criterion colors/markers correspond to the showed in Figure I.
DM based on consumption (DMC): It is an intelligent approach that allows selecting the criterion with greater similarity to the power consumption proposed by dynamic manager. The design of the inference engine of the dynamic manager was performed using genetic algorithms (air conditioner) and fuzzy logic (luminaries, television and computer).

- *Air conditioner:* The genetic algorithm implemented in air conditioner case establishes the cooling factor required to maintain the temperature within the comfort zone. In this proposal the thermal model showed in the methodology was used to evaluate the thermal effect in the environment. The cooling factor was adjusted by genetic algorithm in each instant of time according to variables presented in the methodology. The cooling factor selected by *DM* sets the indoor temperature in comfort zone.
- *Computer:* In this case a fuzzy inference engine was used to present recommendations about efficient operation of computer. The proposed design has four inputs and one output, this considered scheduled activity as new variable.
  - *Inputs*: scheduled activity, presence, PC use profile, time to evaluate the workload.
  - *Output*: proposed states.
- *Luminaries*: The efficient operation of luminaries is associated to some variables presented in (Energía, 2011). Likewise, a fuzzy inference engine was used in the computer case.
  - *Inputs*: *type of activity*, *presence* and *illuminance level*.
  - *Output*: *illuminance level required*.

The efficient operation of television is evaluated only considering the presence level within the environment.

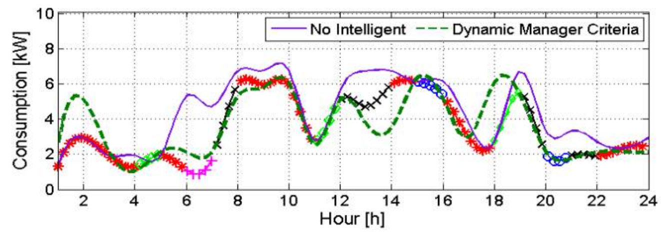

Figure 8. Results of *DM* based on consumption

Figure 8 shows three charts corresponding to power consumption before (solid/purple line) and after (color/marker according to the selected criterion) of application of proposal and, power consumption curve proposed by dynamic manager (red/dotted line).
DM Based on Comfort (DMCF): It is an intelligent approach that allows selecting the criterion with greater similarity to the functional states proposed by dynamic manager. The other characteristics are similar to the presented in the design of *DM* based on consumption.
Figure 9 shows the proposed curve by *DM* based on comfort. In this case, the criterion based on *ANN* were selected more than the others criteria due to consider the environmental characteristics.

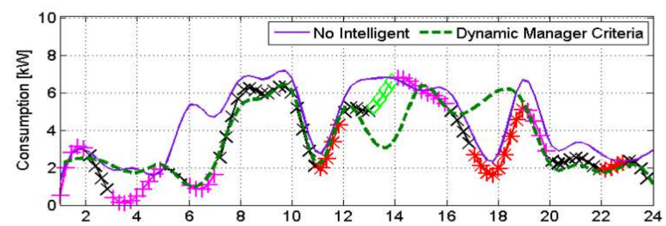

Figure 9. Results of *DM* based on comfort

Supply Manager

This block provides the proper weighting of the energy available in each of the systems of power generation (wind, photovoltaic and fuel cells) (N.C. Batista, R. Melício, J.C.O. Matias, 2013; Z. Guo, W. Zhao, H. Lu, 2012). The energy requirement depends on the input variables related to weather conditions, electricity demand and management criterion selected. The selection of alternative energy sources to be used in integration to an intelligent management system is considered from the development, cost and future of this technology. According to this, it was opted for the selection of power generation from wind speed (wind), solar radiation (photovoltaic) (Romero, 2010) and level of hydrogen (fuel cell) (Colclaser, 1999; Hashem, 2009). The mathematical models were analyzed in (Christian G. Quintero M.;, Ledesma.;, & Mares., 2013).
The inference engine (*SM*) works according to rules "if then" based on expert knowledge gathered from the operation of the proposed generation systems. With the implementation of these rules, the goals are: 1) To fulfill with EDR recommendations, 2) To determine the power required for each subsystem of the alternative power plant based on management scenario selected

and, 3) To allow the power grid supply only in cases where the hybrid alternative energy system cannot meet the *EDR*.

Design of Fuzzy Controller

The implementation of this approach were presented in (Christian G. Quintero M.;Jamer R. Jimenez Mares, 2012).

Experimental Results

In order to reach independence in the experiments, different profiles has been set for power consumption obtained from the functional states of the appliance, which ones have been randomly generated for each experiment. Furthermore, to evaluate the degree of uniformity in the performance of each one of the criteria, an analysis was performed by varying the type of appliance to be managed. Finally, a comparison of distribution of consumption for each one of the management criteria of electric energy demand used in this work was performed.

All appliances that turn off during 10 hours were scheduled. *Load priority* (*LP*) is performed with a fuzzy controller that controls PC, TVs and luminaries without affecting the air conditioning performance. The *LP* management is reached during peak hour. *DLC* is set to control only the air conditioning.

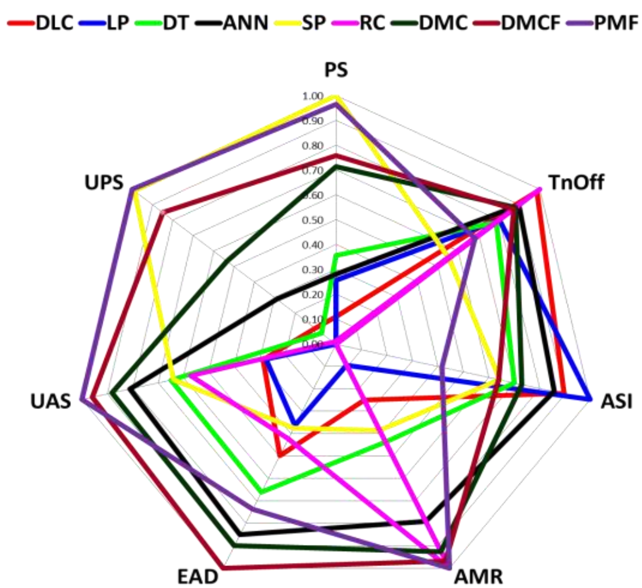

Figure 10. Radar chart to evaluate the management criteria of energy electric demand with the response variables.

The energy supply system of this customer consists of distribution power grid, wind generation system (capacity of 1109 kW), photovoltaic generation system (capacity of 1100 kW) and fuel cells energy (capacity of 940 kW). The test is performed for a typical summer season, a day at the beginning of week (Mallo, 2000), meteorological as wind velocity data and daily solar irradiation from (Craddock, 2008).

Response variable:

Power consumption savings (PS), Time no off (TnOff), Appliance states invariability (ASI), Appliance management regularity (AMR), Environment adaptability (EAD), User adjusted suitability (UAS) and Uniformity (UPS).

Demand Management Evaluation

Figure 10 shows the performance of each one criterion considerate in this proposal. This chart allows easy identification and assessment of each criterion according to the scopes and constraints presented.

The energy audit process is a good complement for the selection of each criterion because it allows reaching power savings near to 33%. In this case was modified the model and characteristics of the appliances to evaluate the response of audit process in terms of power consumption.

Evaluation and Verification SM Operation

In the TableV are shown the studies cases used to evaluate the performance of fuzzy manager for alternatives energy sources.

TABLE V. Studies Cases for the SM

CS	Date	Criteria	WS [km/h]	OT [°C]	FL [%]	WC
Case 1	April 1st, 2014 5:00	Profitability	14.8	25	30	Clear
Case 2	April 1st, 2014 9:00	Reliability	5.6	27	100	Clear
Case 3	April 1st, 2014 9:00	Priority	5.6	27	100	Clear
Case 4	April 1st, 2014 24:00	Percentage	31.5	26	5	Night Clear

CS: Case of study, WS: Wind Speed, OT: Outdoor Temperature, FL: Fuel Level, WC: Weather Conditions

The results of the evaluation of *SM* in the three management scenarios available (cost, reliability and priority of the *EE*, *PE* and *FC*) are carried out. The comparison is performed in a single case and one hour (5, 9, 9 and 24 hours, respectively), under the same environmental conditions, resulting in a level of satisfaction of the identical *EDR*. Table VI presents the satisfaction percentages of active sources according to the conditions hourly weather variables showed in case of study 1.

TABLE VI. Results of Studies Cases for the SM

	Case of study 1		Case of study 2		Case of study 3		Case of study 4	
	% SS	% S	% SS	% S	% SS	% S	% SS	% S
Wind	59.0	59.0	17.3	0.0	17.3	17.3	100.0	50.0
Photovoltaic	26.2	26.2	100.0	100.0	100.0	82.7	28.0	28.0
Fuel Cell	4.6	4.6	100.0	0.0	100.0	0.0	0.8	0.8
Power Grid	100.0	10.2	100.0	0.0	100.0	0.0	100.0	21.2

SS: Satisfaction and S: Supply

This scenario seeks to fulfill with the demand using the most economic subsystem. Currently wind power generation systems are between cost efficiency and more cost effective than *PV* and these than the fuel cell. During profitability management the *EE* is taken as first choice.

In scenario showed in Table VI the manager provides priority to the subsystem that is generating the most power for a specific *EDR*. In this case the *PE* is taken as first choice.

Table VI shows as the power order of each subsystem is indicated by the operator under his own criteria. While in the scenario showed in Table VI, the maximum percentages of operation of each subsystem are assigned by the user. The subsystems set of the plant can supply from 0 to 100% of the power required by the *EDR*.

Conclusions

The results and analysis carried out during this proposal has allowed highlighting the characteristics of each criterion taking into account the response variables discussed in the section of experimental results. However, the main goal in this proposal is reaching power consumption savings without impacting customer´s comfort; hence it's necessary considering the performance of all proposed approach. According to the concept of energy efficiency, this proposal is suitable because allows to reach power saving levels without impacting the comfort of user (e.g., temperature and illuminance).

DM based on priority allows to reach power saving and uniformity level similar to the scheduled program but improving some characteristics as environment adaptability, appliance management regularity, user adjusted suitability and Non off time. *DM* based on consumption presents a suitable behavior in comparison to others criteria proposed by state of art; however, in comparison to the other two proposals (*DM* based on comfort and *DM* based on priority), presents a performance that is less in uniformity, suitability and power saving. *DM* based on comfort provides opportunities of power savings even without the necessity of shut off completely the appliance in a long period of time. Furthermore, some characteristics relevant for the management as environment adaptability, user adjusted suitability and uniformity to diversity appliance are suitable in comparison to other criteria.

Energy sources management scenarios on profitability and reliability show similar results when the goal is guarantee that the most cost effective is also the most reliable. In the reliability case *CGS* was more suitable than *EGS* and *PGS*, while in profitability case the *EGS* was more selected by fuzzy manager due to the low cost of this energy type.

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