FEASIBILITY OF ENERGY STORAGE SYSTEMS TO SAVE COSTS OF SMALL, MEDIUM AND BIG COSTUMERS. USE OF BATTERIES AND ELECTRIC VEHICLES.

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Abstract

Particular household, commercial and industrial customers present an electricity consumption pattern rather fixed. Given this repeated pattern, customers wonder if there is any strategy to follow in order to save money in their electricity bill and connecting batteries to the grid seems to be the most expanded idea. Taking profit of the time-based-pricing of the new electricity rate, energy would be bought during low price periods and stored at the batteries. At high price periods, usually coinciding with peaks periods of consumption, this stored energy would be delivered to the costumer, saving in that way an important amount of energy.

This theoretical idea must be checked in order to guarantee that the initial investment of the installation will be covered. For that reason, a mathematical model that will determine the strategy to follow at each hour of the day and the corresponding savings has been developed.

A wide range of values has been introduced for the different inputs of the model in order to simulate what could be saved in small, medium and big costumers. The obtained results show different conclusions depending on the costumer: although the savings of small consumers represents almost 50% of the usual cost, their consumption is not high enough to overcome the initial investment. For medium and big consumers, if the electric vehicle or nightly rate is contracted, yearly savings going from 750 to 1900 € can be reached depending on the features of the energy storage system: the higher the charging and discharging rates, the higher the savings.

Keywords: batteries – renewable energy – electric vehicles – V2G – V2H – saving - MILP

1. INTRODUCTION

If the typical electricity demand curve of a country such as Spain is observed, two main periods can be differentiated: peaks and valleys. The peak period can reach values 80% higher than those of the valley period and usually it is developed for a low amount of hours each day. For instance, at 8:00 when a big amount of people start working several lights are turned on, the computers are switched on and different industrial machines are started, so the energy consumption increases sharply leading to the so called peaks. On the other hand, during the night very little energy is consumed.

In that way, the actual operation method makes the electricity distribution and transmission networks be oversized in order to support those peaks and this extra cost is charged to the consumers as an investment in the transmission and distribution network, leading to values that can represent even 50% of the costumer's bill.

This situation could be improved just by installing any kind of energy storage system in the distribution network in such a way that demand peaks are covered by the closest storage system to the consumer instead of by a generator placed far away, avoiding in that way oversizing the network between the producer and the consumer to supply these singular high demands.

This solution would lead to high investments, so the government has decided to implement another idea in order to carry out this "peak shaving": a new time-based pricing has been presented. It consists of 14 low cost hours, from 22h to 12h in winter and from 23h to 13h in summer; and 10 high cost hours, from 12h to 22h in winter and from 13h to 23h in summer. This proposal aims the consumer to switch a part of his consumption to the valleys and reducing in that way the amount of energy to be delivered during peak hours. The incentive of having a lower price will be the motor of this trend.

However, it is difficult to change the habits of a person, a family or a company, so one strategy has grown rapidly to get them to remain constant. It consists of installing a storage system in the particular house or company building in order to buy the energy during low price periods and save it at the storage system. During peak hours, part of the demand will be covered by the common grid and the remaining part by the storage system.

The storage system can be a stationary battery, but also an electric vehicle, which besides travelling, will allow us to save energy and money. This practice is commonly known as "Vehicle to Grid, V2G" or "Vehicle to Home, V2H"and is being more and more studied by well-known car manufacturers such as Nissan, with its project LEAF to home; Honda, with its Honda Smart Home project; and Toyota. There are small differences between these two approaches and they can be summarized as follows: V2G systems aims to use the electricity saved in the car as a backup energy supply for electricity grids during high demanding periods, while V2H systems would act as generators do when there are outages, that is, they will allow plug-in vehicle owners to use the energy stored as a temporary home power source.

Moreover, it seems that users will save money not only due to this distribution in the consumption of energy but also due to the contracted power. The electricity bill mainly consists of two terms: energy and power. While the energy term depends explicitly on the consumption, the power term is a fixed term depending on the amount of kW contracted. With the previous strategy, customers could be able to reduce the contracted power as part of the requirements would be covered by the auxiliary system.

2. AIM OF THE STUDY

Although this strategy seems to be suitable for saving costs, they must be quantified and compared to the considerable initial investment that suppose installing a new set of devices such as batteries, rectifiers, inverters and protection devices among others. Because of that, this study aims to elaborate a computer model able to simulate the monthly consumption of different costumers and providing them the most suitable pattern to follow according to the already explained strategy.

Different kind of consumption patterns will be simulated in order to differentiate between small, medium and big costumers.

As a remark, only the savings due to the energy consumption will be calculated, no savings due to the power will be considered.

The feasibility of this idea for the different kind of costumers will be evaluated according to the obtained results.

3. METHODS AND MATERIALS

A fixed storage system will be considered for carrying out this study, so unlike electric vehicles, it will be available 24h a day.

3.1 Mathematical model

The followed approach consists of understanding the issue as an optimization problem at which the cost must be reduced as much as possible provided the demand of the costumer is fulfilled. In particular, it consists of a *Mixed Integer Linear Programming (MILP)* problem. Different constraints will be added to the mathematical model in order to simulate the real behavior of the system.

The set of variables and equations that defines the problem are detailed here below:

Variables:

f_i = Energy extracted from the grid along hour i to charge the battery (kWh).

r_i = Energy extracted from the grid along hour i to supply the consumer (kWh).

b_i =Energy taken from the battery along hour i to supply the consumer (kWh).

s_i = Remaining energy in the battery at the end of hour i (kWh).

Bf_i = Binary variable equal to 1 only if the battery is being charged during hour i.

Bbi = Binary variable equal to 1 only if the battery supplies energy to the costumer during hour i.

Bsi = Binary variable equal to 1 only if the state of charge of the battery is higher than 80%.

With i= 0, 1, 2...,23

Known constants:

C_i = Energy cost at hour i (€/kWh).

D_i = Energy consumption at hour i (kWh).

ε = Small value for solving MILP problems (10^{-7})

M= Big value for solving MILP problems (10^{7})

Cost function:

Min Z = $\sum_{i=0}^{23} C_i \cdot (r_i + f_i)$

Constraints to be fulfilled each hour of the day and month:

$s_{i-1} + f_i - b_i = s_i$ (Eq.1)

$D_i = r_i + b_i$ (Eq.2)

$s_{i+1} - s_i \leq (1 - Bs_i) \cdot v_{charge} + Bs_i \cdot 0.5 \cdot v_{charge}$ (Eq.3)

$Bs_i \cdot 0.8 \cdot cap \leq s_i$ (Eq.4)

$s_i \leq (1 - Bs_i) \cdot 0.79999 \cdot cap + Bs_i \cdot cap$ (Eq.5)

$s_i - s_{i+1} \leq v_{disc}$ (Eq.6)

$0.2 \cdot cap \leq s_i$ (Eq.7)

$Bf_i + Bb_i \leq 1$ (Eq.8)

$\varepsilon \cdot Bb_i \leq b_i \leq M \cdot Bb_i$ (Eq.9)

$\varepsilon \cdot Bf_i \leq f_i \leq M \cdot Bf_i$ (Eq.10)

$b_i \leq s_{i-1}$ (Eq.11)

$s_i \leq cap$ (Eq.12)

$f_i \leq cap$ (Eq.13)

Non-negativity condition:

All the variables ≥ 0.

Eq.1 forces the model to follow the performance of a battery, that is, the existing energy at the beginning of one hour is that existing at the beginning of the previous hour plus that used for charging the battery minus that delivered to the costumer.

Eq.2 forces to fulfill the demand of the consumer at each hour.

The set formed by Eq.3, Eq.4 and Eq.5 allows to reduce the charging rate of the battery once the state of charge is higher than 80%, as it occurs in real batteries.

Eq.6 limits the discharging rate to a selected value and Eq.7 the depth of discharge to 80%.

The set formed by Eq.8, Eq.9 and Eq.10 fix the performance of the binary variables, giving them a unitary value if b_i and f_i are different to zero, a zero value in the contrary case and not allowing both of them to be 1 at the same time.

Eq. 11, Eq.12 and Eq.13 are used to limit the value of S_i and f_i, which will never be higher than the capacity of the battery, and that of b_i, which cannot be higher than the energy already stored.

3.2 Computer model

Once the model is defined, it has been implemented in the mathematical software Matlab 2014a.

Besides the internal code that makes all the suitable calculations, a graphical interface have been included to ease the study to those people not used to this software. This feature allows the user to interact with the program, as some variables are selected by him, being these ones the efficiency of the battery, the efficiency of the full installation (including inverters, converters….) and the charging and discharging rate of the battery. Moreover, it is given the opportunity to evaluate some already saved buildings (their consumption pattern) and new buildings by adding their energy consumption at each hour of each day of the month. This evaluation can be carried out for the three existing rates in the Spanish market:

- **General rate:** approximately constant rate.
- **Nightly rate:** general time-based pricing.
- **Electric vehicle rate:** time-based pricing thought for plug-in vehicle users.

Figure 1 shows the average prices for each rate along a day. To calculate the average the data taken into account goes from 1st February 2014 to 31th August 2014 (applicability period of these new rates).

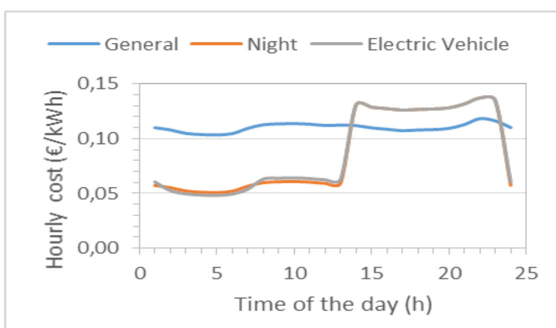

Figure 1. Electricity rates in the Spanish market.

Moreover, the program shows the optimum capacity of the battery that will be installed in order to reduce the cost as much as possible.

3.3 Analysis procedure

Two common values have been given to both efficiencies attending to the literature: 0.9 for the battery and 0.8 for the whole installation.

With regards to the charging and discharging rates an extended range of values has been evaluated to prove the influence of each one.

The analyzed buildings have been divided into three categories according to their monthly consumption: small consumers if this consumption is smaller than 50 kWh, medium consumers if it goes from 50 to 2000 kWh and large consumers if it is higher than 2000 kWh. The analysis has been performed for three different buildings of each category, with a data dispersion lower than 10% between them, and the average results have been studied.

The evolution of the savings with the capacity has been also evaluated for fixed charging and discharging rates.

4. RESULTS

The influence of three different factors on the economical savings has been analyzed to check the field at which we must actuate: the battery capacity, the discharging rate and the charging rate.

4.1 Battery capacity

For analyzing this parameter, three couples of values have been given to the charging and discharging rates for each kind of costumer.

In the case of small consumers, as it can be shown in Figure 2, the general rate allows having yearly savings of 11.82€ in the best case, which means having the highest charging and discharging rates. On the other hand, the nightly and electric vehicle rates show a similar performance allowing having yearly savings of 123.82€ and 129.84€ respectively for the highest charging and discharging rates. The curves described by these two fares can be divided in 3 sections: from 0 to 10 kWh savings increase rapidly (around 9€/kWh), from 10 to 80 kWh they increase slower (around 1.8€/kWh) and from 80 to 100 kWh they remain almost constant, fluctuating around 129€.

The case of medium and big costumers is almost identical, figures 3 and 4. The evolution of the savings with the general rate reaches values of 70 and 72 euros per year if high charging and discharging rates are present. When the nightly or electric vehicle fares are used, and if the charging and discharging rates are high enough, savings increase almost linearly with the available capacity (with higher slope for the higher charging and discharging rates, 15€/kWh). However, if the rates are slow, an increase in the available capacity does not result in higher savings and the curves saturate.

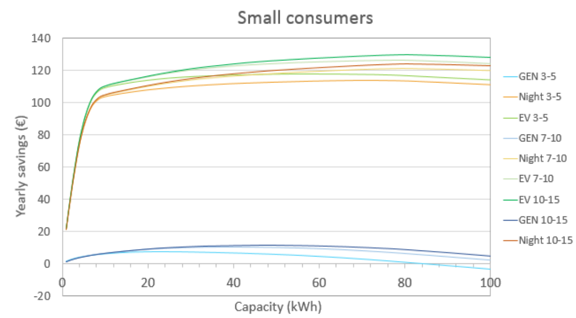

Figure 2. Yearly savings in function of battery capacity for small consumers.

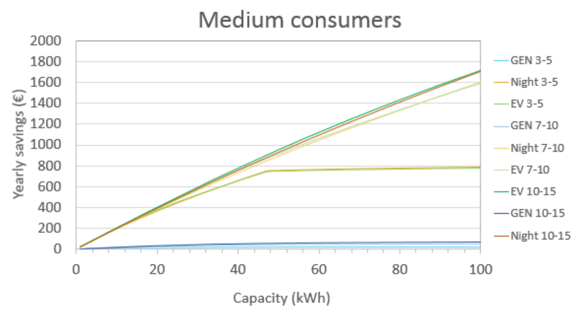

Figure 3. Yearly savings in function of battery capacity for medium consumers.

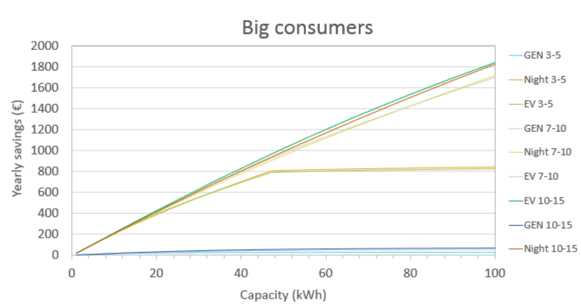

Figure 4. Yearly savings in function of battery capacity for big consumers.

4.2 Discharging rate

This approach has been carried out by fixing the battery capacity to the optimal one for each kind of consumer and the charging rate to 10 kWh/h.

This value is the middle point of the range of study for the discharging rate: from 1 to 20 kWh/h.

In the case of small consumers, as it can be seen on figure 5, the savings are almost independent of the discharging rate. However, for medium and big consumers, the relationship between charging and discharging rate is important to obtain big savings. Figures 6 and 7 show that a higher discharging rate leads to bigger savings, but those are saturated if the charging rate is higher than the discharging one. The increase in the linear part can be quantified as 175 €/kW.

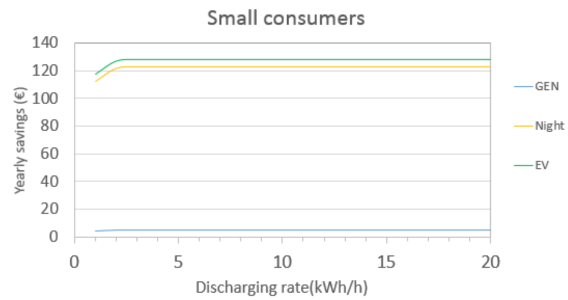

Figure 5. Yearly savings in function of discharging rate for small consumers.

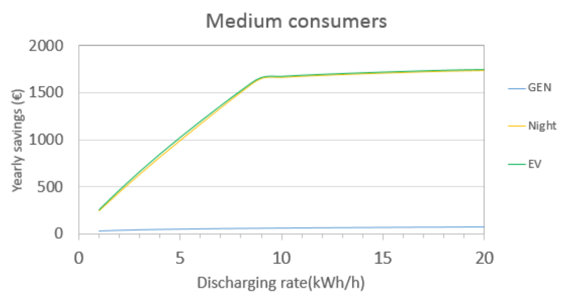

Figure 6. Yearly savings in function of discharging rate for medium consumers.

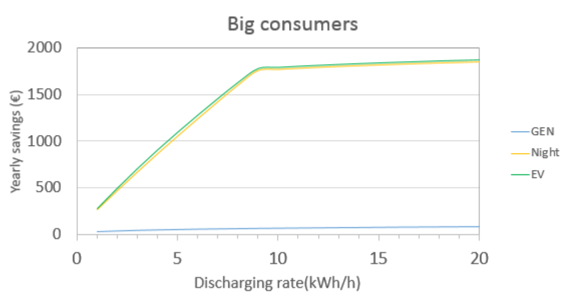

Figure 7. Yearly savings in function of discharging rate for big consumers.

4.3 Charging rate

In order to analyze this parameter, the same procedure as that followed in the previous assignment has been selected but fixing the discharging rate to 10 kWh/h.

The same behavior can be observed, but in that case, the slope in the linear part is around 225 €/kW.

Maximum yearly savings are again very similar, reaching figures of 1740 € and 1965 €, for medium and big consumers respectively, if higher rates are observed.

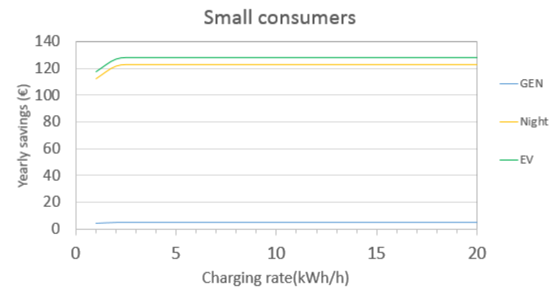

Figure 8. Yearly savings in function of charging rate for small consumers.

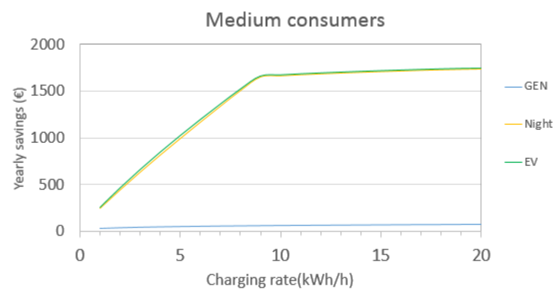

Figure 9. Yearly savings in function of charging rate for medium consumers.

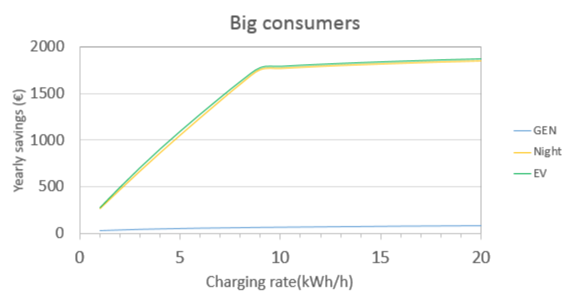

Figure 10. Yearly savings in function of charging rate for big consumers.

5. DISCUSSION

As it was thought, and can be verified in figure 11, the strategy suggested by the software is mainly charging the battery during the valley periods of the night and being an auxiliary source to the network during the peaks.

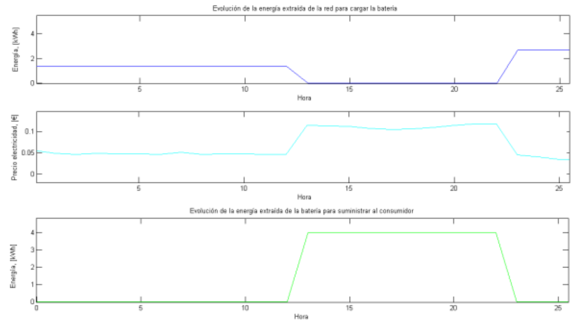

*Figure 10. Daily distribution of the energy **(a)** consumed and **(c)** provided by the battery according to **(b)** the electricity cost.*

Differences between both time-based fares can be quantified as 6% in the worst scenario, so they can be considered as identical when extracting the conclusions of the study. As it is logical, only by contracting the electric vehicle or nightly rate the user will save enough money to be compared to the initial investment in the installation. The general rate leads to yearly savings of 70 € in the best case, which represents 0.01% of the total cost.

By considering the time-based rates, two possibilities are observed.

In the case of small consumers, the consumption is so small that although the savings represent around 50% of the cost, the yearly savings are not enough to overcome the initial investment for the installation. This price can be approximately 10000€, considering all the elements of the installation and the labor, and savings are around 120€ in the best case, so 83 years would be necessary to equalize the investment and this time is considerably higher than the life of the battery.

On the other hand, medium and big consumers can take profit from the exposed strategy, as considerable savings can be obtained. The existing technology will play a very important role in those savings, as the higher the charging and discharging rates the higher the savings. For instance, a charging rate of 3 kW and a discharging rate of 5 kW lead to yearly savings of 765 and 810 € for medium and big consumers respectively. If those rates are increased to 10 and 15 kW respectively, the savings can be quantified as 1720 and 1840 € respectively, values that can overcome the initial investment in the first years and from then, all the money will be real savings.

6. FURTHER RESEARCH

The presented study provides the strategy to follow once the consumption pattern and electricity cost are known. If more data and better equipment were available, it would be very useful to develop a software able to do the same work but predicting the strategy to carry out. As the electricity market decides the prices for each hour of one day the previous day, this prediction of how using the battery could be done just for the next day.

Another aspect to take into account in the future is adding the savings that can be obtained by the reduction of the contracted power.

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