EVALUATION OF LOAD MATCHING AND GRID INTERACTION INDEXES OF A NET PLUS-ENERGY HOUSE IN BRAZIL WITH A HYBRID PV SYSTEM AND DEMAND-SIDE MANAGEMENT

G. Almeida Dávi[a], M. Castillo-Cagigal[a,b], E. Caamaño-Martín[a], J. Solano[a]
[a] Instituto de Energía Solar, Universidad Politécnica de Madrid
[b] ETSI Telecomunicación, Universidad Politécnica de Madrid
Av. Complutense 30, 28040 Madrid, Spain (Tel.: +34 914 533 556/Fax: +34 915 446 341); email:
giovani.almeida@ies-def.upm.es

ABSTRACT: This paper analyzes four scenarios of PV system configuration and proposes an optimized hybrid PV system size in order to improve Load Matching and Grid Interaction (LMGI) indicators, describing the yearly and daily variations of the indexes. A net plus-energy house is modeled in EnergyPlus under humid subtropical and dry tropical climates and electricity flows in the house and with the power grid are based on a high level battery controller simulated with different PV-battery sizes. An economic analysis is presented through two supporting schemes in order to perform analyses of Levelized Cost of Electricity (LCOE), grid parity and system payback time. The results demonstrated the combination of load-shifting demand-side management and small-scale PV-battery capacities provide improvements on building self-consumption and on the effects on the grid. The economic study indicates the building reaches better profitability under current Brazilian net-metering scheme in scenarios without batteries, reducing the payback time and LCOE sensibility analysis indicate the importance in reducing PV costs and to promote financial incentives.
Keywords: Battery storage and control, Load Matching and Grid Interaction (LMGI), Economic analysis

1 INTRODUCTION

In recent years, the ways with which new buildings are being designed have undergone changes, insomuch that introduce new applications of hybrid energy systems. Net plus-energy building (NPEB) is defined as a house that generate at least as much primary energy as the building uses over the course of the year. In this context, the net plus balance means that the annual electrical energy surplus fed-in to the grid is greater than the annual electrical energy imported from the grid. Net-plus energy buildings can reach their full potential in terms of energy conservation and global reduction of greenhouse gas emissions when Load Matching and Grid Interaction (LMGI) issues are taken into account [1]. However, with rapid development of energy technology, LMGI aspects need to be investigated more precisely when involves hybrid PV systems. Load Matching (LM) refers to how the local energy generation compares with the building load by describing the degree of the utilization of on-site PV electricity generation related to the local demand [2] (e.g. the percentage of load covered by on-site generation over a period of time). Grid Interaction (GI) refers to the energy exchange between the building and an energy infrastructure, typically the power grid. (e.g. peak powers delivered to the electricity distribution grid) [2].

In countries where feed-in tariffs (FIT) are applicable, the PV systems owners receive a fixed rate for each kWh fed into the power grid. However, FITs are being phased out in most countries, and PV promotion is switching to self-consumption schemes from a building integration perspective [3]. Recently in Brazil, the Brazilian National Electrical Energy Agency (ANEEL) approved Normative Resolution nº 687/2015 [4], which established an energy compensation system (net metering), whereby the active power injected into the grid by a consumer unit with distributed micro or mini generation offsets the active power consumption. This resolution also assigns the installed PV capacity must be limited to the grid connection capacity.

In this study we analyze the possibilities for the energy provision of a sustainable house using new generation of PV system combined with small-scale energy storage system and Demand-Side Management (DSM), in order to optimize the self-consumption of generated electricity. To this aim, we propose the study of a net plus-energy house prototype developed to the international competition Solar Decathlon Europe 2012, named Ekó House [5], adapted to Brazilian weather conditions through thermal-energetic simulations. Simulations were carried out in different scenarios by combining different storage capacities and the use or not of DSM. The response of different LMGI parameters as well as economic prospects have been analyzed.

2 METHODOLOGY

2.1 Building simulations

Energy modeling of the house was done in EnergyPlus environment (version 8.1). The Energyplus models were based on typical electricity consumption of Brazilian domestic consumers. The analyses were performed for two cities with different solar resource: São Paulo (SP) (Lat. 23.5◦S) and Brasília (Lat. 15.7°S). São Paulo has a humid subtropical climate and Brasília is characterized by tropical climate with dry season in the winter and hot summer [5]. For the studied locations the weather data used for the simulations studies were taken from SWERA database [6]. The HVAC system model consists of a Variable-Air-Volume (VAV) heat pump [5]. In order to reduce HVAC load, the indoor air temperature was kept between 22.5 ºC and 25.5 ºC in summer and from 21 ºC to 23.5 ºC in winter, based on ASHRAE comfort zone [7]. By profiting the high degree of on-site generation allied with low house energy consumption an electrical boiler of 2 kW nominal operating capacity was modeled with nominal thermal efficiency of 90%.

2.2 The demand and its management

Ekó House electricity consumption simulations include typical electrical appliances of a highly electrified house provided with on-site generation: lighting system, cooking appliances, entertainment appliances, HVAC system and electrical boiler. Tab. I resumes annual electricity of the electrical loads considered for the case study. Deferrable loads are appliances that can be displaced along the day and the user or a domotic system can program the time the appliance works, e.g., programmable washing machine. Non-deferrable loads are not controllable appliances that represent instantaneous consumption like lights, fridge and computers [8]. Cooling space and cooking appliances appear to be the principal electricity sources based on energy usage in each location and in São Paulo the consumption of electrical boiler is high due to lower temperatures in the southeast of Brazil.

Demand-side management involves load shifting strategy in order to control the time-of-use of the deferrable loads, preferably to solar periods where the load is compensated by PV electricity and to off-peak periods where the retail electricity price is lower.

Table I: Annual electricity consumption for the test case study.

Load	Consumption (kWh/y)		Share of total (%)	
	Brasília	SP	Brasília	SP
Deferrable				
Clotheswasher	122	122	2.6	2.32
Clothesdryer	150	150	3.2	2.85
Dishwasher	253	253	5.3	4.8
Non-deferrable				
Lights	690	690	14.6	13.1
Cook	1131	1131	23.88	21.45
Fridge	637	637	13.44	12
Boiler/Pump	353	883	8.05	19
Enter. appliances	392	392	8.3	7.45
HVAC	979	898	20.63	17.03
Total	4707	5156	100	100

2.3 Hybrid photovoltaic system and Battery controller

The entire PV array was simulated considering m-Si PV modules and 18.5% efficiency. The PV modules were oriented to the north and the tilt angles were approached to the latitude of each location to maximize annual PV output. The simulated PV generator is expressed by Sandia model [9-11]. Fig. 1 summarizes an electrical diagram of the system with an overview of relevant nomenclature: P_{PV} is the PV generation electricity, P_L is the load consumption electricity, P_{Imp} is the imported electricity from the power grid, P_{Exp} is the exported electricity to the grid (-) and P_{Bat} is the electricity exchanged with the batteries in charge (P_{Char} (+)) or discharge (P_{Disc} (-)).

The installation of a storage system was investigated to optimize the self-consumption and the degree of self-sufficiency of the house. Lead-acid batteries coupled with PV generators have the main advantage to provide higher levels of self-consumption, to reduce the net exported energy and the current issues with PV-grid interaction.

On the second step of the study, simulations were carried out in a high level battery controller. The controller actuates to inject electricity from the storage system to the load when the PV generation is lower than the load consumption or when the Sun goes down, as well as allows to supply the demand during the peak pricing period. As a strategy, the batteries just can be charged with PV energy and the priority is to use energy from the PV system to supply the load as well as the battery State of Charge (SoC) is respected to preserve the battery lifetime. For midcharge (20% ≤ SoC ≤ 95%) the controller performs the self-consumption maximization by no exchanging energy with the grid [8].

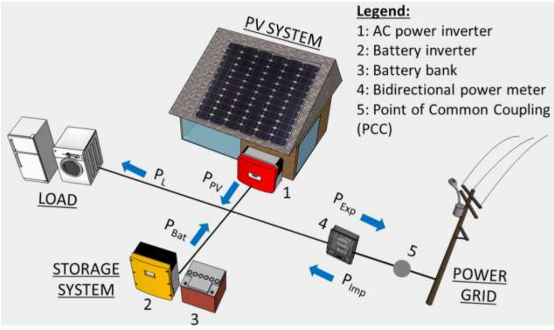


Figure 1: Hybrid PV system topology for residential building under investigation.

2.4 Evaluation equations

The Load Cover Factor, γ_L, defined by [8], represents the percentage of the electrical demand covered by the PV system. A γ_L closer or equal to one the local generation matches the local consumption. The Supply Cover Factor, γ_G, described in [13], is related to the PV-generated electricity that supplied the loads with respect to the total generated electricity. A system operating with γ_G values closer to unit is a system that does not export large amounts of energy to the grid.

$$\gamma_L = \frac{E_{PV\rightarrow L} + E_{Disc}}{E_L} \ (1) \ ; \ \gamma_G = \frac{E_{PV\rightarrow L} + E_{Disc}}{E_L} \ (2)$$

Where $P_{PV\rightarrow L}$ is the electricity produced by the PV system and directly consumed by the load. The Loss of Load Probability (LOLP) represents the fraction of time that the local generation does not cover the building demand [14]. With LOLP analysis it is possible to access the building energy autonomy (A_b) as the fraction of time when 100% of the load can be matched by PV-origin [1].

$$LOLP = \frac{\int_{\tau_1}^{\tau_2} f(t)}{T} \begin{cases} f(t) = 1, \ if \ P_{net} < 0 \\ f(t) = 0, \ if \ P_{net} \geq 0 \end{cases} \ (3)$$

$$A_b = 1 - LOLP \ (4)$$

Where P_{net} is net exported power, T is the evaluation period and τ is the time interval. Grid interaction parameters indicate the magnitude of the power injected or purchased by the building. The capacity factor shows the total energy exchange with the grid divided by the exchange that would have occurred at nominal connection capacity [14]. The capacity factor of imported electricity (CF_{Imp}) and capacity factor of exported electricity (CF_{Exp}) measure the degree of imported and exported electricity with the grid, respectively, normalized with respect to the grid connection capacity (P_{GCC}).

$$CF_{Imp} = \frac{|E_{Imp}|}{P_{GCC} \, . T} \ (5) \ ; \ CF_{Exp} = \frac{|E_{Exp}|}{P_{GCC} \, . T} \ (6)$$

The Dimensioning Rate is defined as the peak power exchange over the connection capacity and in the assumption of "self-consumption" connection mode, we defined DR in terms of imported power (DR_{Imp}) and exported power (DR_{Exp}).

$$DR_{Imp} = \frac{\max(P_{Imp})}{P_{GCC}} \ (7) \ ; \ DR_{Exp} = \frac{\min(P_{Exp})}{P_{GCC}} \ (8)$$

The grid interaction indexes describe the mean grid stress using the standard deviation of the grid interaction over a given period [15]. The grid interaction index of exported electricity ($f_{Grid,Exp}$) gives the ratio of the exported electricity into the grid compared to the maximum value over a year. The grid interaction index of imported electricity ($f_{Grid,Imp}$) indicates the variability of the imported electricity from the grid within a year normalized on the maximum absolute value within an annual cycle. High values of $f_{Grid,Exp}$ means large amount of surplus electricity not profited by the building and high values of $f_{Grid,Imp}$ means the building is strictly depend of the power grid performance.

$$f_{Grid,Imp} = STD\ \frac{P_{Imp}}{max(|\ _{Imp}|)}\Bigg) \quad (9)$$

$$f_{Grid,Exp} = STD\left(\frac{P_{Exp}}{max(|P_{Exp}|)}\right) \quad (10)$$

The Levelized Cost of Electricity (LCOE) is the cost of generating electricity delivered to the load or power grid during hybrid PV system lifetime (n) and covers all system investments and operation and maintenance costs (C) in the k^{th} year. The LCOE is given by Eq. 11, where ρ is the annual discount rate. The investment cost (I) is given by Eq. 12, where I_0 is the initial investment, $C_{inverter}$ and $C_{battery}$ are, respectively, the replacement costs of inverter and batteries.

$$LCOE = \frac{I + \sum_{k=1}^{n} \frac{C_k}{(1+\rho)^k}}{\sum_{t=1}^{T} \frac{(E_{PV} - E_{Exp})_k}{(1+\rho)^k}} \quad (11)$$

$$I = I_o + C_{inverter} + C_{battery} \quad (12)$$

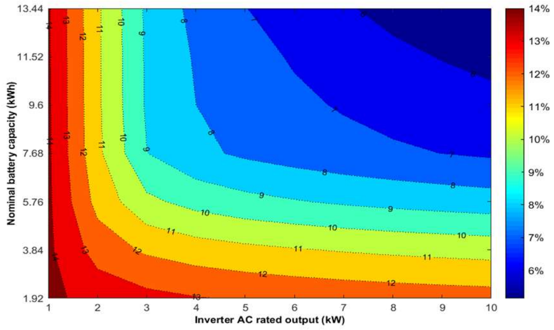
3 RESULTS

The work analysis considers four scenarios as given by Tab. II. The scenarios S1 and S2 do not consider storage system and the scenarios S3 and S4 were simulated with batteries through GridSim [12]. The grid connection capacity (P_{GCC} = 6 kW), not inferior to the PV installed capacity power (P_0), according to Brazilian regulations, was designed according to the maximum annual building demand. It was investigated different scenarios of installed PV output (from 1 to 10 kWac) and battery nominal capacity (C_{Bat}) from 1.92 to 13.44 kWh (40-280 Ah) in order to evaluate an optimized system capacity. The depth of discharge considered in the simulations is 80%.

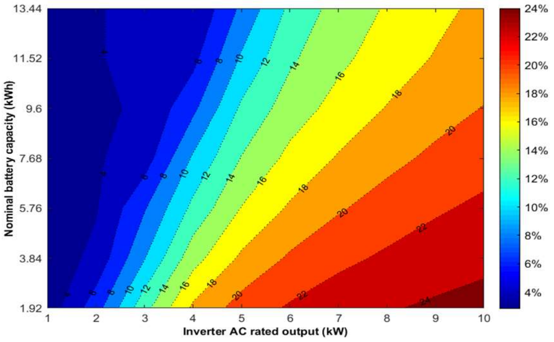
Table II: Building electrical installation scenarios considered in the study.

Scenario	Configuration
S1	PV system (without DSM and storage)
S2	PV system and DSM
S3	PV system and storage
S4	PV system, DSM and storage

A combination of annual simulations results for GI indexes as a function of installed PV output and C_{Bat} variations to São Paulo is summarized in Fig. 2. The results for $f_{Grid,Imp}$ using standard deviation shows that the index declines with increasing PV and storage capacities due to the fact that the building self-sufficiency grows with DSM and storage system strategies. It is important to emphasize that this index describes the fluctuation of the energy exchange with the grid, not the amount of the exchanged electricity [15]. Even in the scenarios of minimum hybrid PV sizes, the maximum imported power fluctuation is just 14% by virtue of the effect of storage in supplying the load leading $f_{Grid,Imp}$ to low and safety margins. On the contrary, the variability of the exported power over the grid grows by increasing the PV size but decreases by increasing the storage capacity. As long as a high PV capacity is combined with a small battery bank, the batteries do not have enough capacity to store sunny days PV surplus over local demand, so that $f_{Grid,Exp}$ can reach up to about 25%. In this sense, smaller PV sizes are more technically effective in the terms of excess of electricity and grid impact, being in the best case $f_{Grid,Exp}$ just 4%.



(a) Grid interaction index of imported electricity ($f_{Grid,Imp}$)



(b) Grid interaction index of exported electricity ($f_{Grid,Exp}$)

Figure 2: Annual mean of grid interaction indexes as function of the inverter size and installed battery capacity in S4.

Figures 3 presents the annual mean ξ_G with inverter AC output deviations. The supply cover factor decreases when the PV size grows, because the P_{PV}-P_L correlation diverges when the PV production grows under a fix consumption pattern. The PV electricity directly consumed by the loads is improved in the scenario S4 with the displacement of deferrable loads to the solar periods and in addition the surplus electricity is profited to match the night-time loads. The optimal PV system size for self-consumption is around 3 kW prior to curve saturation and ξ_G grows from each scenario: 0.27 in S1, 0.36 in S2, 0.55 in S3 and 0.7 in S4. However in the scenarios with storage (S3 and S4) the curves declination is more pronounced and the saturation will occur with highest PV capacities.

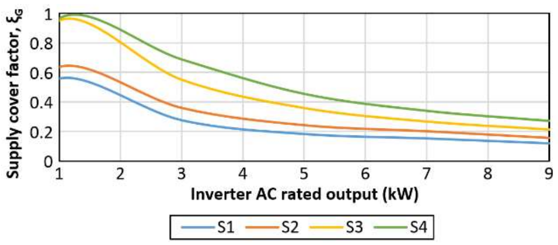


Figure 3: Annual supply cover factor (ξ_G) under different PV system topologies. C_{Bat}: 5.76 kWh.

In order to find the optimal battery bank size that is more efficient for self-consumption Fig. 4 presents variations of C_{Bat} as function of ξ_L. Small-scale battery sizing up to 5.76 kWh (0.5 days of functional autonomy) contributes more for the growth of ξ_L as can be observed in straight line tendency. In the transition between 0.5 and 1 day of autonomy lies a maximum ξ_L and a C_{Bat} higher than 1 day of autonomy should be avoided since contributes less to the growth of ξ_L. By reviewing the previous analyzes, the optimized hybrid PV system corresponding to 3.22 kW_p and 5.76 kWh battery capacity results in a ξ_L of 55%, a ξ_G of 70% and an A_b of around 40%. In this case, the house has a large potential to consume the generated local electricity but it loses in energy autonomy when compared to the larger installed capacities.

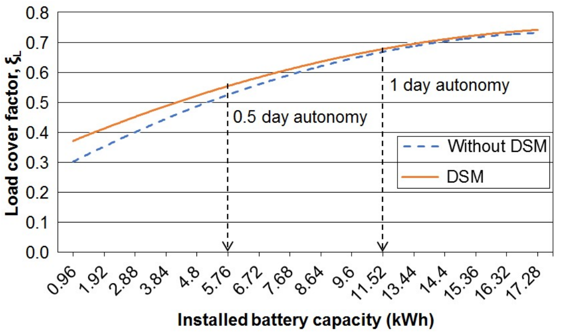


Figure 4: Sizing of battery bank as function of load cover factor in S3 and S4. P_0: 3.22 kW_p.

Figure 5 indicates results of daily electricity flows in the house operating in São Paulo. Without DSM the deferrable loads are allocated when the house occupants get home after work (18:00 h). The PV system charges the battery up to 100% SoC and the battery supplies the load until it reaches the minimum SoC allowed (SoC_{min} = 20%), after which the house extracts electricity from the grid. It is possible to note the convenience to displace deferrable loads to solar periods because the consumption is very low in the afternoon when the PV generation is available. In this sense, from S3 to S4, ξ_G increases 30% while ξ_L increases 20%.

Figure 6 emphasizes monthly variations of ξ_L and ξ_G for the two investigated locations. The monthly daily mean ξ_L ranges from 0.2 to 0.3 in S1 and from 0.25 to 0.35 in S2. With batteries, it was reported major improvements and thus ξ_L ranges from 0.45 to 0.6 in S3 and from 0.47 to 0.67 in the optimized scenario S4. In addition, the application of DSM increases ξ_L and it depends on the amount of "deferrable" loads that are displaced, where the bigger the amount of "deferrable" loads are the higher the parameter is reached [17]. The seasonal variations are more pronounced in winter, where the electricity consumption profile changes due to different temperatures in the country. From May to August less PV energy is produced, the cooling load decreases, the boiler demands electricity before sunset and there are around two hours less of Sun, thus decreasing ξ_L. In Brasília, this effect is not pronounced because it presents better potential of solar energy and even the consumption for DHW is lower than in São Paulo. Otherwise, PV production increases in summer, battery charging potential increases and ξ_L reaches the highest values, up to about 0.7 in São Paulo and 0.6 in Brasília. In São Paulo, ξ_G grows significantly in winter months because the on-site generation gets smaller and the P_{PV}-P_L correlation is optimized, achieving around 0.8 in S4. The same happens in Brasília with the increasing of cooling space consumption in summer, making ξ_G superior than remainder of the year.

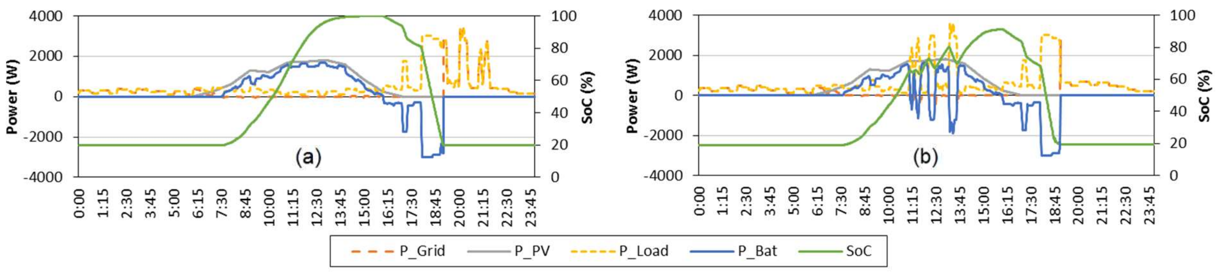


Figure 5: Electricity flows and battery SoC in typical day: (a) Scenario without DSM (S3): ξ_L: 0.54, ξ_G: 0.62, A_b: 0.4. (b) Scenario with DSM (S4): ξ_L: 0.70, ξ_G: 0.90, A_b: 0.37. P_0: 3.22 kW_p. C_{Bat}: 5.76 kWh.

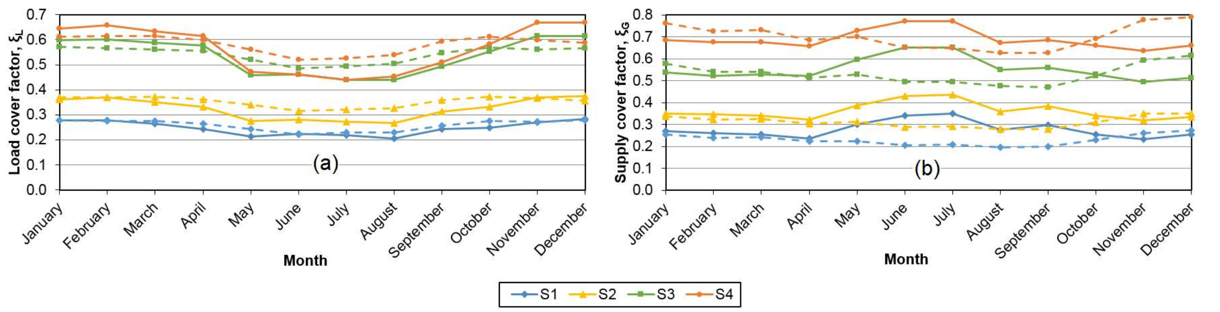


Figure 6: Annual LM indicators. (a) Annual daily mean load cover factor (ξ_L). (b) Annual daily mean supply cover factor (ξ_G). Continuous lines: São Paulo. Dashed lines: Brasília.

The duration curve given by Fig. 7 represents the time duration the building imports or exports electricity, indicating the power levels that electricity exchanges with the grid occur over the year. Positive values mean that electricity is fed into the grid while negative values mean electricity imports from the grid.

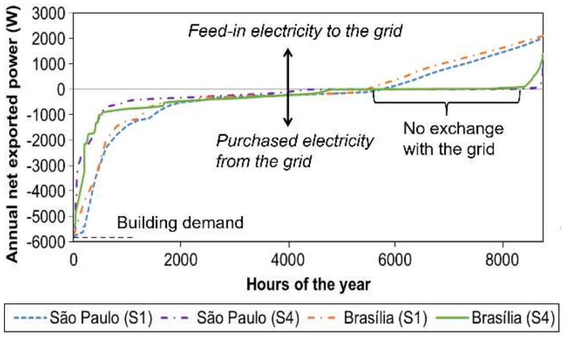


Figure 7: Duration curve for electricity exchanges with the power grid.

The duration of purchased electricity and imported power peaks are reduced with storage in both locations. In a general context, it can be seen the power reduction from 6 kW up to 2 kW implies a lower grid request time if compared to less than 1 kW where the house demands electricity during a larger number of hours. In fact, this power range represents the night-time demand the storage system is not able to supply. As indicated by Fig. 8, there is no exchanges between the building and the grid for a large time interval, representing 35% of the annual period. Similarly, the annual duration of exported electricity is very short in S4 due to the fact the surplus energy not profited by the load is expected to charge the batteries.

Table III highlights the annual results of LMGI indicators calculated for the two studied locations in the scenarios S1 and S4.

Table III: Annual results of LMGI indicators for the studied locations. C_{Bat} of 5.76 kWh (fully charged to discharge, 1h: 4.6 kW), P_0 of 3.22 kW$_p$ and P_{GCC} of 6 kW.

	São Paulo		Brasília	
Scenario	S1	S4	S1	S4
Load Matching indicators				
ξ_L	0.24	0.55	0.25	0.60
ξ_G	0.27	0.68	0.22	0.70
LOLP	0.65	0.60	0.60	0.50
A_b	0.36	0.40	0.40	0.50
Grid interaction indicators				
DR_{Imp}	1.0	0.93	0.95	0.91
DR_{Exp}	0.40	0.30	0.46	0.31
$f_{Grid,Exp}$	25.4%	7.80%	25.5%	7.39%
$f_{Grid,Imp}$	13%	10.23%	13.6%	12.82%
$P_{net} \approx 0$	0.52%	35.42%	0.40%	37.48%
CF_{Imp}	7.60%	5.75%	6.65%	5.60%
CF_{Exp}	6.45%	0.52%	7.80%	0.50%

The results for ξ_L show an increase of 30% from the scenarios S1 to S4 and up to 60% of the load requirements can be met by local generation with respect to the designed system capacity. The supply cover factor (ξ_G) can be increased even more, as it can be deduced when comparing S4 with S1 (40% in São Paulo and 50% in Brasília), showing that up to 70% of the PV electricity is directly profited by the loads. The high annual values of ξ_G for S4 evidence that load and generation profiles are well correlated and the building profits efficiently from locally generated electricity, thus improving the self-consumption capability.

The loss of load probability (LOLP) indicates that around 60% of the time the load is not covered by PV and thus the building must purchase power from the grid. The smallest LOLP occurs for the case S4 in Brasília and then the energy autonomy (A_b) corresponds to 50%, increasing 10% with respect to the scenario without battery. The building energy autonomy constraint is associated to the sizing of the small-scale storage system and the limitation of the PV capacity in order to improve the load matching potential. However, the results evidence that the growth of the hybrid system size improves the energy autonomy.

The results for DR_{Imp} show that the P_{GCC} designed according to the maximum annual electrical demand ensures a safety fraction of an equivalent nominal connection capacity and the grid connection does not exceed the allowed limit. The dimensioned DR_{Exp} in S4 is smaller than the PV system without storage by reason of the designed PV capacity of 3.22 kW$_p$ is far from the designed connection capacity of 6 kW and, in addition, the surplus electricity is used to charge the batteries. Thus, DR_{Exp} is reduced around 10% while the exported power over the grid connection is reduced. The $f_{Grid,Exp}$ indicator is reduced from 25% in S1 to around 8% in S4 mainly due to the capability of the system to reduce grid exchange fluctuations carried out by the battery controller in order to complete daily SoC. The low percentage of the ratio of the imported power metering normalized on the maximum absolute value ($f_{Grid,Imp}$) means an almost constant import instead of high fluctuations, according to energy simulations, and the building does not depend considerably on the power grid performance.

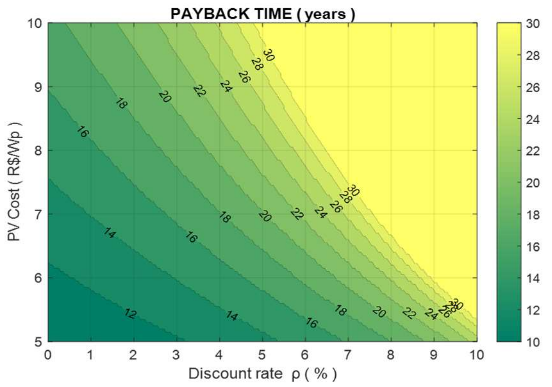
In the scenario S1, the building night-time consumption is strictly dependent of the grid and the purchased electricity can be reduced when the PV generates power. In this sense, the probability of the building acting autonomously from the grid ($P_{net} \approx 0$) is near to zero in the scenario S1 but it increases to 40% due to the use of storage.

The capacity factor suggests about the total energy exchanged with the grid over the year. Through the comparison of normalized imported electricity (CF_{Imp}) it can be concluded that the effect of storing energy decreases the amount of purchased energy and only around 6% of the equivalent energy use of the grid connection is used. The results show the normalized exported electricity (CF_{Exp}) is near zero when applying energy storage by virtue of the efficiency in charging the batteries with PV surplus electricity, and with the displacement of deferrable loads the PV supplies more efficiently the loads, decreasing in effect the amount of feed-in electricity into the grid.

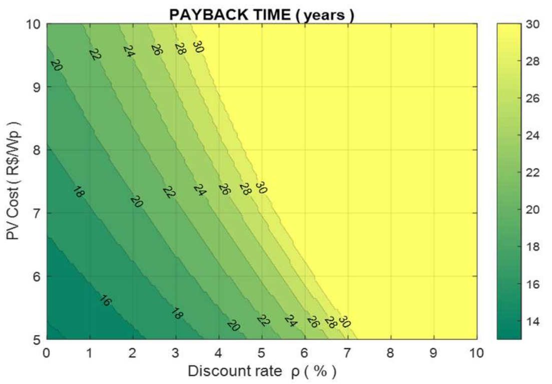
3.5 Levelized Cost of Electricity and payback time

The investigations for the optimized system were performed in scenarios S1 and S4 considering the cost of PV modules, inverter and battery bank obtained from typical Brazilian PV solar system installed at the end of 2015 [18]. Considering added taxes and national taxes the investment cost is 7.24 R$/W$_p$ in S1 (equivalent to 1.80 €/W$_p$) and 9.92 R$/W$_p$ (equivalent to 2.55 €/W$_p$) in S4. The economic analysis were performed considering two supporting schemes: (1) actual Brazilian net-metering in S1, admitting the consumer unit gets credits in amount of active energy for the PV surplus fed into the grid. The credits can be used to compensate the purchased electricity from the grid in a period up to 60 months; (2) no financial compensation for PV excess in S4. It was considered batteries replacement each 10 years and PV generator lifetime of 30 years.

The annual savings obtained by using the energy credits is directly related to the power utility tariffs and the financial incentives. Fig. 8 shows the payback time is shorter for the lowest values of PV cost and discount rate and the higher the credits are, the higher the annual savings will be, leading to shorter return of the investment. Considering the actual investment cost, the payback time is reached from near to 13 years in S1 and from 21 years in S4. By assuming an optimistic financial scenario (i.e. ρ = 4% and PV cost = 6 R$/$W_p$), the payback time can be achieved in 15 years in S1 and similarly in 21 years in S4. The investment is more profitable under Brazilian net-metering scheme (S1), due to the fact the building exports larger amount of electricity into the grid than operating in S4 mode and gets credits from the PV excess, that compensate the energy usage and reduce electricity costs. In S4, for discount rates above 7% the payback approaches or is above the PV generator lifetime, not profitable to invest, according to Fig. 8 (b). The main restriction of this scenario is that the initial investment is higher due to the cost of the storage system, the consumer is not compensated by the night-time purchased electricity that the small-scale storage system is not able to supply and the absence of credits makes the investment less attractive.



(a) Scenario S1 without storage system.



(b) Scenario S4 with storage system.

Figure 8: Payback time perspective as function of discount rate and PV cost deviations for São Paulo.

Figure 9 presents results of LCOE in function of discount rate variations in S4, without compensation for PV excess. As expected, the LCOE is commonly higher in scenarios with battery by virtue of high initial investment when considering costs of battery system and batteries replacement. In consequence, low annual discount rates are requested to the investment to be profitable. By virtue of the low electricity tariff in São Paulo (0.5 R$/kWh), the discount rate must be around 2% for the PV system achieves grid parity. However, a grid-connected PV system without batteries, supported by the Brazilian energy compensation system (net-metering), can achieve grid parity up to 6% discount rate [5], closest to a mature market in Brazil. Despite relatively high irradiation levels, PV LCOE is higher in Brazil than in other countries mainly due to higher installation prices caused by customs duties levied on PV equipment and by the immaturity of the PV market [19].

While in São Paulo PV technology is still far from being competitive against grid tariff, in other Brazilian locations where the electricity tariffs and irradiation levels are relatively higher (i.e. Brasília and Belo Horiz.) grid parity and payback time could be reached sooner [5].

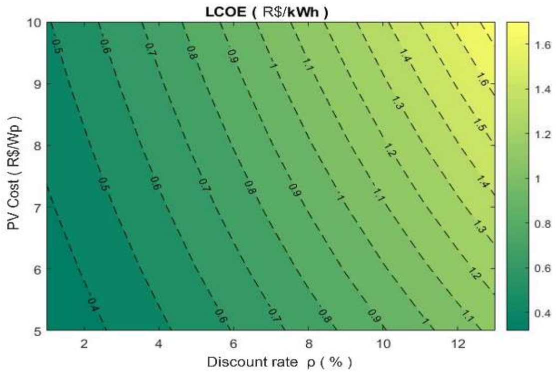


Figure 9: LCOE as function of discount rate and PV cost deviations for São Paulo in the scenario S4.

4. FINAL REMARKS AND CONCLUSIONS

In this paper, simulations results have been established that LMGI indicators present different responses with respect to four scenarios of PV system configuration and the selection of suitable LMGI indicators leads for an important task by reason of strengths and limitations of each one. Furthermore, the study analyzed an optimized PV-battery system, of special interest of building designers and operators. In general, by growing PV-battery capacity, load matching indexes tend to be improved due to the best potential in covering load consumption. However, the degree of self-consumption (ξ_G) decreases when the PV size grows, because the P_{PV}-P_L correlation diverges when growing the PV production. The straight line tendency with respect to battery capacity variations showed that the smaller sizes contribute more to the growth of ξ_L.

In GI terms, graphical representations in carpet plots showed that the ratios of imported-exported electricity into the grid are reduced by increasing storage capacity and the variability of exported power over the grid indicated that small PV sizes are more technically effective when considering PV surplus. It has been shown that curtailment of imported electricity effected with DSM and battery reduces $f_{Grid,Imp}$ to low and safety margins (6-14%), and for the designed system, according to Tab. III, $f_{Grid,Exp}$ is satisfactorily reduced from 25% in

S1 to 8% in S4.

Monthly calculations of ξ_L and ξ_G indicated there are no general rules for load matching by virtue of it depends of decoupled factors (i.e. electricity consumption, PV and ambient temperature). The results showed ξ_L has more potential in Brasília most of the year due to the better solar conditions. However, the house potential in profiting on-site generation is mostly higher in São Paulo winter due to higher consumption combined with lower PV production, which means less excess of PV electricity.

The duration curves in Fig. 8 provided useful information's about PV-grid interaction, indicating the duration of purchased electricity and power peaks over the grid connection are reduced in both locations when applying energy storage. The duration of exported electricity demonstrated to be very short in S4, leading to the reduction of voltage rise associated with reverse power flows, contributing in a positive manner for the grid operation when comparing with larger system capacities.

The application of DSM and storage evidenced increases in the building self-sufficiency and improvements on the grid interaction. The annual results of LMGI indicators showed the LM indexes (ξ_L, ξ_G, LOLP, A_b) presented great improvement from S1 to S4: 30% for ξ_L, 40% for ξ_G and notably 10% for A_b in Brasília. The proposed GI indicators ($f_{Grid,Imp}$, CF_{Imp}, DR_{Imp}) showed slight differences between the two test case scenarios. The results of CF_{Imp} index assigned only around 6% of equivalent energy use of the grid connection was used and this information can be useful for both target groups, building and grid designers. Some indexes were reduced greatly due to the effects of DSM and storage, as expressed by DR_{Exp}, $F_{Grid,Exp}$ and CF_{Exp}. Notably, the normalized exported electricity (CF_{Exp}) decreased near to zero due to system design improvements, and for high penetration situations of renewable energy sources into the grid this condition can be taken into account for a grid design perspective. In terms of the probability that the building acting autonomously of the grid ($P_{net} \approx 0$) it was notified a great increasing of 40%, suitable to guide design process of the next generation of self-sufficient houses.

The study determined under Brazilian net-metering scheme the building reaches better economy by using energy credits generated by PV excess, reducing substantially the electricity costs and the return of investment, but it was denoted the importance of grid tariffs and solar resource to achieve greater profitability. The paper demonstrated the NPEB was set to achieve grid parity with very low discount rates in S4, far from a real market, and highlighted the needs to reduce PV-battery costs and to promote financial incentives in order to achieve shorter payback time.

In conclusion, the parameters proposed in this paper are suitable for analyzing the complexity of NPEB-grid interaction and the implication of hybrid PV on load supplying, aspects of great interest for the development of smart grids and sustainable cities.

5. ACKNOWLEDGEMENTS

G. Dávi wishes to acknowledge the Brazilian National Research Council (CNPQ) for financial support to carry out the studies which led to this article. The authors acknowledge support of the Spanish Ministry of Economy and Competitiveness within the framework of the project "Sistema distribuido de gestión de energía en redes eléctricas inteligentes" (TEC2015-66126-R).

REFERENCES

[1] J. Salom, A.J. Marszal, J. Widén, J. Candanedo, K.B. Lindberg, Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data, Appl. Energy. 136 (2014) 119-131.

[2] J. Salom, J. Widén, J. Candanedo, I. Sartori, K. Voss, A. Marszal, Understanding net zero energy buildings: Evaluation of load matching and grid interaction indicators, in: 12th Conf. of the Building Performance Simulation Association, Sydney (2011).

[3] IEA PVPS Task 1, Trends 2015 in photovoltaic applications, Tech. Rep. 27, International Energy Agency (IEA) (2015).

[4] Agência Nacional de Energia Elétrica (ANEEL), Resolução Aneel nº 687/2015 (2015).

[5] G.A. Dávi, E. Caamaño-Martín, R. Rüther, J. Solano, Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil, Energy Buildings. 120 (2016) 19-29.

[6] SWERA. Solar and Wind Energy Resource Assessment, <http://en.openei.org/apps/swera> (Acessed 2015-10-27).

[7] ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy (2013).

[8] M. Castillo-Cagigal, E. Caamaño-Martín, E. Matallanas, D. Masa-Bote, A. Gutiérrez, F. Monasterio-Huelin, J. Jiménez-Leube, PV self-consumption optimization with storage and Active DSM for the residential sector, Solar Energy. 85 (2011) 2338-2348.

[9] D.L.King, W.E. Boyson, J.A. Kratochvil, Photovoltaic Array Performance Model, Sandia National Laboratories, Albuquerque, NM 87185 (2003).

[10] G. Barker, Predicting Long-Term Performance of Photovoltaic Arrays. Submitted as deliverable for NREL subcontract LAX-1-30480-02 (2003).

[11] EnergyPlus Engineering Reference, Lawrence Berkeley National Lab. Berkely: LBL.

[12] M. Castillo-Cagigal, E. Caamaño-Martín et al, Self-consumption of PV electricity with active demand side management: the GEDELOS-PV system, 25th EU PVSEC Conference Valencia, Spain (2010).

[13] E. Matallanas, J. Solórzano, M. Castillo-Cagigal, et al, Electrical energy balance contest in Solar Decathlon Europe 2012, Energy Buildings. 83 (2014) 36-43.

[14] B. Verbruggen, R. De Coninck, et al, Grid impact indicators for active building simulation, Innovative Smart Grid Technologies (ISGT), IEEE PES (2011) 1-6.

[15] K. Voss, I. Sartori, A. Napolitano, S. Geier, H. Gonzalves, M. Hall, P. Heiselberg, J. Widén, J. Candanedo, E. Musall, B. Karlsson, P. Torcellini, Load matching and grid interaction of net zero energy buildings, Proceedings of EuroSun, Graz, AT (2010).

[16] C.M. Colson, M.H. Nehrir, A review of challenges to real-time power management of microgrids, Power & Energy Society General Meeting. IEEE. 09. (2009) 1-8.

[17] E. Matallanas, M. Castillo-Cagigal et al, Analysis of the self-consumption possibilities in small grid-connected PV systems in Spain. Proceedings of the 26th European Photovoltaic Solar Energy Conference. Munich, Germany. (2011) 4619-4624.

[18] Photon, Photon international GmbH, Germany. November (2015).