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► **To cite this version:**

Nana Kofi Twum-Duah, Manar Amayri, Frédéric Wurtz, Stéphane Ploix. Indicators for Evaluation of Energetic Performance of Net Zero Energy Buildings. 5th IEEE International Smart Cities Conference (ISC2) 2019, Oct 2019, Casablanca, Morocco. pp.136-142, 10.1109/ISC246665.2019.9071782. hal-03713498

HAL Id: hal-03713498

<https://hal.science/hal-03713498>

Submitted on 19 Jul 2022

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Indicators for Evaluation of Energetic Performance of Net Zero Energy Buildings

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Abstract—According to experts, the average temperature of the planet has increased at an unprecedented and alarmingly high rate over the last fifty (50) years. Carbon emissions have been found to be a major catalyst for climate change and the energy sector one of the highest emitters globally. Thus any significant reduction in energy related emissions would have a significant impact on global carbon emissions and consequently global warming. UN-Habitat estimates that approximately 56% of energy produced in most African nations is consumed in buildings. There is a need for energy efficiency and possibly conservation in buildings since they represent the single largest consumer of energy on the continent. Net Zero Energy Buildings (NZEBS), a possible solution for reducing the energy footprint of buildings, represents the evolution of buildings in the near future. The Zero energy concept has a major impact on the design and construction of future buildings. This paper focuses on the review and development of existing Load Match Indicators for zero energy buildings. Four indicators are provided and discussed (i.e. self-consumption, self-production, loss of load probability, and coverage rate indicators). For the purpose of this paper, Predis-MHI (a platform of G2ELab) was used as a case study. Data was collected from the platform's living lab and was used in the calculation and evaluation of these indicators. The results indicate the relevance of each indicator in evaluating the energetic performance of a building and also highlight the practical difficulties faced in evaluating the platform.

Index Terms—NZEBS, Positive Energy Buildings, indicators, building energy performance

I. INTRODUCTION

Energy consumption in all forms has been directly linked to climate change, and globally, buildings (both residential and tertiary) account for a large fraction of energy consumed, e.g., 40% [1] in Europe and 56% in Africa [2]. In line with global climate change mitigation policies, improving the

This work is supported by the French National Research Agency in the framework of the " Investissements d'avenir program (ANR-15-IDEX-02), as well as the COMEPOS Project funded by the ADEME Agency

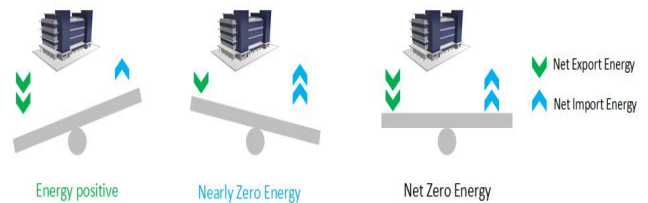


Fig. 1: Building Energy Performance Definitions

Source: Adapted from: [3]

energy performance of buildings will inadvertently yield a significant reduction in carbon emissions.

The Net Zero Energy Building (NZEB) concept (Fig. 1) seeks to deliver buildings which are both energy efficient and have some degree of independence from fossil based energy.

NZEBs as defined by [4] are high performing, highly efficient buildings that use, over the course of a year, renewable technology to produce as much energy as they consume from purchased commercial energy sources. Typically, the energy used in a building must reflect the heating and cooling energy requirements, domestic hot water requirements and other typical energy use.

Indicators typically present raw data, which may otherwise be overwhelming, in a simplified manner, allowing users to quickly and effectively utilize information and in some instances make decisions. Indicators are categorized based on the information they provide and typically for a building they include:

- Technical indicators; which evaluate the energetic performance of a building (Load Match Indicators and Grid Interaction Indicators).
- Usage indicators; which aim to provide information on energy use and waste in a building.

- Comfort indicators; which provide information on the general comfort of building occupants.

All the above mentioned categories of indicators are important in the evaluation of a building, however, for the purpose of this paper the focus was on technical indicators, specifically Load Match Indicators and Grid Interaction Indicators. Section 2 presents a state of the art discussion about indicators and their impact on occupant behaviour related to building energy performance. Section 3 presents the indicators considered for this work. Section 4 presents the source of data used in the work. Section 5 is focused on the results obtained.

II. STATE OF THE ART

The NZEB concept is not a new concept, especially in Europe and North America. The European Union as part of its Energy Performance of Buildings Directive, requires that all new buildings in member states be Nearly Energy Positive by 2020 (Europa). In lieu of this, the Centre Scientifique et Technique du Bâtiment (CSTB), the French building regulator, has since 2012 required that all new buildings meet maximum energy demand of 50kWhpe/m²/year [5].

Similarly, in the US, the passage of the Energy Independence and Security Act of 2007 led to the United States Department of Energy commissioning projects and studies with a goal of achieving the knowledge base and technology for cost effective NZEBs by 2025 [6].

The development of Smart Buildings, has also significantly impacted the development of NZEB as these two concepts are in many ways interconnected, Smart Buildings requiring a higher level of intelligent services added to the core functions of the building.

Several factors contribute to the way and manner in which energy is used in a building. The work of DeSilva [7] identifies 5 key factors which influence energy consumption in a building, these are: climate, building related characteristics (i.e. floor area, shape, construction materials, etc), occupant behavior, building services and systems and the socio economic and legal characteristics of the area in which the building is located. Typically, all these factors can, to a large extent be controlled with the exception of occupants behavior. In reality, buildings by themselves do not consume energy, it is however the occupants (people) that consume the energy [8]. Understanding and effectively being able to influence occupant behavior is key in achieving high energy performance in a building. Janda [8] however, argues that occupant behavior is the least understood and often the most overlooked factor in building energy design. Paone [9] further argues that, both occupant behavior and preferences are important parameters which contribute to the gap between predicted energy performance and the actual energy performance of a building. This crucial parameter, according to Paone [9] is often not considered in both the design and post-occupancy optimization phase of a building's development.

The work of Nguyen [10] shows that by implementing intelligent lighting solutions, it is possible to achieve 58% savings on the energy used by conventional lighting solutions.

Similarly Nguyen [10] estimates that potential savings of between 10% and 40% can be achieved by implementing occupancy based thermal control in buildings.

User behavior is key for the successful implementation of NZEBs, as shown by the works of Nilsson et al. [11], which evaluated the potential impact of continuous feedback on user behavior conducted in Sweden with forty participants. The study involved installing displays in apartments to display in real time the occupants' consumption. The study concluded that occupants who had this display installed recorded no significant energy savings.

A subsequent study carried out in Norway [12], shows similar results. However, in this study the economic status of the households involved was taken into account. The results indicate that more affluent households were already aware of their energy usage and as such feedback displays were quite ineffective. In the case of less affluent homes however these displays yielded positive results.

Lin [13] illustrates the influence of cultural background on occupant's response to feedback. In the study conducted by Lin [13], student dormitories on the campus of Tongji University (constituted of four six-story buildings) were used as a test-bed. Energy meters were installed in these buildings such that the energy consumption for each room in the buildings could be accounted for. In total thirty-nine (39) students, made up of ten (10) Chinese students and twenty-nine (29) international students, participated in the study. The energy consumption of all rooms in the test-bed was however monitored and used for the study, the data from nonparticipating rooms was considered as a control group. Feedback was provided to the thirty-nine (39) participants through a web page, consequently a weekly reminder was sent to the participants over the course of the study which lasted for 13 weeks. The results of the study indicated a 16.7% reduction in the consumption of Chinese students, the results of the international students on the other hand indicated a 23.7% increase in energy consumption. Lin [13] attributes the fact that international students do not pay for their energy consumption as a possible cause of the increase in their energy consumption.

Comparing the works of Lin [13] to those of Westskog [12] and Nilsson et al. [11] it can be concluded that in presenting feedback to end users, a lot of factors need to be taken into account. Key amongst these factors are the cultural and economic background of the occupants. This paper focuses on evaluating Load Match Indicators as defined by [14] which are essential to the development and evaluation of the energy performance of NZEBs.

From the literature studied, it can be concluded that a lot of focus and emphasis has been placed on residential buildings. Tertiary buildings, however, are equally important and hold a large potential for reducing the energy demand associated with buildings. Consequently, this paper focuses on evaluating the energy performance of Predis-MHI, which is housed in a Tertiary building and has the typical load profile of a tertiary building.

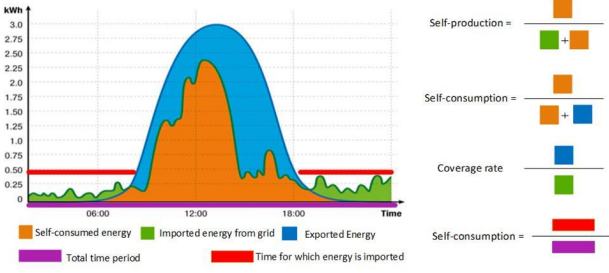


Fig. 2: Definition of Load Match Indicators and Grid Interaction Indicators

III. INDICATORS FOR EVALUATION OF NET ZERO ENERGY BUILDINGS

This section presents relevant indicators which are essential in evaluating the energy performance in NZEBs. This paper considers three Load Match Indicators and one grid interaction indicator as proposed by [14]. In order to effectively analyze the results from evaluating these indicators, four time windows were considered (day, week, month, and year). The main goal of the Load Matching Indicators is to show how the load of the building compares with local energy production. The Grid Interaction Index considered for this work, provides information on how the energy system of the building interacts with the distribution network. The indicators considered for this paper are listed below:

- Load Match Indicators
 - Self-consumption
 - Self-production
 - Coverage rate
- Grid Interaction Index
 - Loss of load probability

A. Self-consumption

This indicator corresponds to the share of on-site renewable electricity production consumed locally within the building, Fig. 2, and is expressed mathematically as [15]:

$$self-consumption = \frac{\int_{\tau_1}^{\tau_2} \min[g(t) - \zeta(t), l(t) + s(t)] dt}{\int_{\tau_1}^{\tau_2} [g(t) - s(t) - \zeta(t)] dt} \quad (1)$$

where:

- $g(t)$ is the onsite production.
- $\zeta(t)$ refers to the energy losses within the system.
- $s(t)$ is the storage energy balance (negative for discharge and positive for charge).
- $l(t)$ building load (demand).
- τ_1 is the start of the evaluation period (first sample)
- τ_2 is the end of the evaluation period (last sample)

It yields a value between zero and one, a zero (0) value implies that no part of the on-site generation is used locally whilst a value of one (1) implies that all the on-site generation is used locally in the building. For European weather conditions (typically France) the values of this indicator are the lowest

during summer and highest during winter (for Photovoltaic (PV) systems).

This phenomenon can be attributed to the high PV yield coupled with relatively low demand during summer and likewise the high rates in winter can be attributed to a low PV yield coupled with a high energy demand in winter.

B. Self-production

The self-production indicator, Fig. 2, provides information on the fraction of the buildings demand which is satisfied by the on-site generation. It is expressed mathematically as [16, eq.6]:

$$self-production = \frac{\int_{\tau_1}^{\tau_2} \min[g(t) - s(t) - \zeta(t), l(t)] dt}{\int_{\tau_1}^{\tau_2} l(t) dt} \quad (2)$$

It ranges between zero and one, where a value of one indicates that the whole load is supplied by the on-site production and a zero value indicates that none of the load is supplied by the on-site production. This indicator peaks in summer and is lowest during the winter for typical European weather conditions.

C. Coverage rate

This indicator provides information about the energy balance of the building (i.e. the extent to which on site production meets the energy demand of the building) over a given time period, Fig. 2. It is expressed as [15]:

$$coverage\ rate = \frac{\sum_i E_{pnren,exp,i,an}}{\sum_i E_{pnren,del,i,an}} \quad (3)$$

where:

- $E_{pnren,del,i,an}$: refers to the quantity of annual energy delivered by the grid to the building, for the energy carrier i , weighted by the conversion factor into primary non-renewable energy (pnren) for energy carrier i .
- $E_{pnren,exp,i,an}$: refers to the quantity of annual energy exported to the grid, for the energy carrier i , weighted by the conversion factor into primary non-renewable energy (pnren) for energy carrier i .

The Formula proposed in equation 3 above utilizes an export/import energy balance. It is however, possible to use a load/ generation energy balance, both energy balances' would yield the same status for the building but ultimately the interpretation of the indicators would change.

The coverage rate indicator has no maximum value, however a value in excess of one indicates that the building is a positive energy building (i.e. generation is in excess of the demand), [15]. A value of one indicates that the building is an NZEB and a value less than one indicates an energy deficit (i.e. energy produced over the evaluation period is less than the energy consumed) .

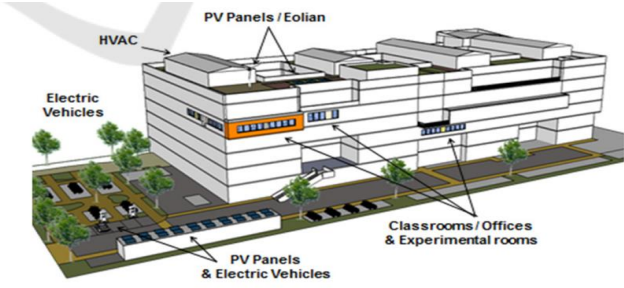


Fig. 3: Predis-MHI living lab production and consumption points within the GreEN-ER Building
Source: Adapted from [18]

D. Loss of load probability

This indicator provides information on the dependence of the building on the grid. It is a probability which indicates the likelihood that the buildings on-site generation will not be able to meet the demand and as such will have to import energy from the grid [17], Fig. 2. It is given as:

$$LOLP = \frac{\int_{\tau_1}^{\tau_2} T dt_{l(t) > (g(t) - s(t) - \zeta(t))}}{\tau_2 - \tau_1} \quad (4)$$

where:

- T : represents the time for which the load is greater than the on-site generation.
- $\tau_2 - \tau_1$: represents the number of samples in the evaluation period.

It has a value between zero and one, where a zero result indicates full autonomy from the grid and a value of one indicates a 100% likelihood of connection to the grid during the evaluation period.

IV. THE PREDIS-MHI PLATFORM

The GreEN-ER building, Fig 3 located in the Presqu'île district of Grenoble, is a smart building designed to house G2ELab and the school of water environment and energy (ENSE³) of the Grenoble Institute of Technology. The building has 6 floors with a floor area of 4500m² per floor, and is expected to have an average occupancy of 2000 people. Many green technologies have been implemented in the building with the goal of optimizing the energy use within the building [18].

Predis MHI (Monitoring Habitat Intelligence) is a platform of the Grenoble Electrical Engineering lab (G2ELab) focused on habitat intelligence (i.e. smart buildings). It acts as a living lab for both academic and research activities and is designed to achieve Net Zero Energy status [18].

The platform has a floor area of 500m² and is composed of offices, lecture rooms, students foyer, Electric vehicle (EV) charging bay and a demonstration lab. The onsite generation is entirely PV with a total installed capacity of 20kWp, no storage is currently incorporated. The data for consumption is made up of lighting, consumption from electrical outlets, consumption from an electric vehicle charging bay and the consumption of the Central Air Treatment of the Platform

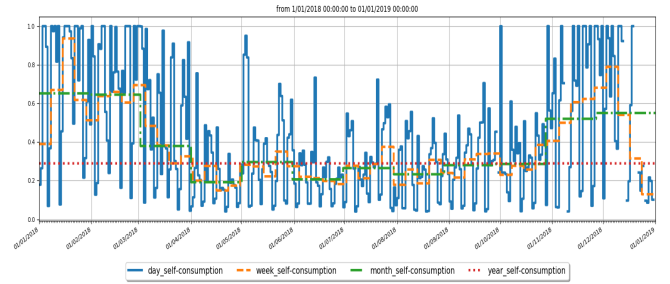


Fig. 4: self-consumption results for Predis-MHI

(constituted of heating consumption, cooling consumption and ventilation consumption). Typically the platform does not use domestic hot water, which is a core component of the energy consumption of buildings as identified by the CSTB [19].

V. RESULTS

For this paper, data for the period 1st January 2018 to 1st January 2019 was considered. Table I shows the consumption and production data as obtained from the Predis-MHI platform. The data has been segregated into the various seasons to draw a baseline for the results obtained in the indicator calculations.

TABLE I: PV Production and consumption of Predis-MHI platform

	Spring	Summer	Autumn	winter	Total
Consumption	2682.6	3036.6	4391.2	3359.3	13546.5
Production	7441.0	8876.9	2568.1	2084.0	21007.8

For the purpose of calculating the indicators, Indicom, an open source tool for the evaluation of energy positive buildings developed as part of the Comepos Project was used.

A. Self-consumption

Based on the available inputs, the results depicted in Fig. 4 were obtained as the self consumption for Predis-MHI. An annual value of 0.28 was obtained, implying that 28% of the energy produced on site was used by Predis-MHI. Consequently, looking at the daily, weekly and monthly curves it can be seen that the self-consumption for Predis-MHI follows the typical self-consumption curve for France (high in winter and low in summer).

B. Self-production

Fig. 5 shows the results obtained for self-production, an annual value of 0.45. This implies that 45% of the demand of Predis-MHI was satisfied by the local PV production, consequently indicating that 55% of the energy requirements of Predis-MHI was imported from the grid. However, due to the relatively low self-consumption obtained, the imported energy will be used to offset the exported energy in the energy balance. Due to the higher consumption and lower PV production during winter, the results are typically lowest in winter and highest in summer.

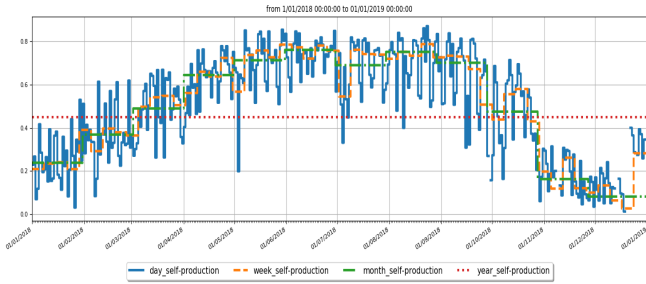


Fig. 5: self-production results for Predis-MHI

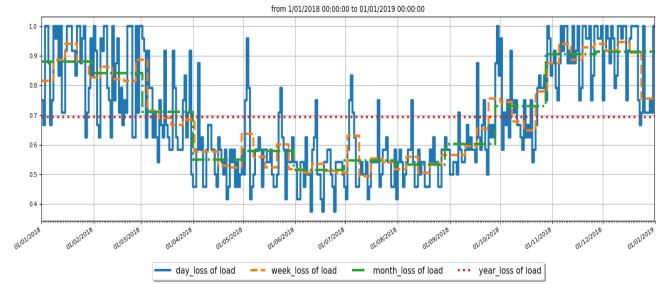


Fig. 7: Loss of load probability results for Predis-MHI

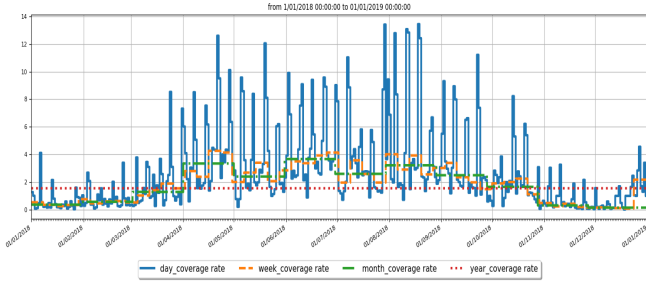


Fig. 6: Coverage rate results for Predis-MHI

C. Coverage rate

The coverage rate is the indicator which actually determines if a building is energy positive, zero energy or nearly zero energy. The coverage rate obtained for Predis-MHI for the period considered was 1.55, Fig. 6. This indicates that Predis-MHI was energy positive. The value of 1.55 indicates that the energy produced on site exceeded the demand of the platform by 55%. Typically during summer days, the coverage rate for Predis-MHI was found to be very high (maximum 13) owing to the long summer days and higher PV production during the period.

D. Loss of load probability

The results for the loss of load probability indicator, Fig. 7, shows that the platform has a high dependence on the grid with an annual value of 0.69. This indicates that there is a high probability that the load cannot be satisfied by the local production irrespective of the fact that the energy produced on site is significantly higher than the demand. This result can be explained by the fact that there is no storage incorporated in the building. It is also noteworthy to remark that the building is a tertiary building and as such the majority of the load is prevalent in the day time. It is therefore not far fetched to assume that in a residential building with no storage the results for this indicator could be worse.

VI. DISCUSSION

The approach in previous works, as depicted in [14], has been focused on computing annual values. This approach whilst useful for regulatory and administrative purposes, is not very useful for the average building occupant. Thus, this study considers a higher resolution when computing the indicators

under study (self-consumption, self-production, coverage rate and loss of load probability). A time windowing algorithm was thus used in the program to allow for calculation of the various indicators for different time steps.

In addition, the self-consumption equation as used in this work (proposed by [15] for the Comepos a project, a French project to realize 25 demonstrator energy positive buildings by 2020) is a modification of the equation proposed by [16] in that the storage is considered as a load and would therefore affect the self consumed energy. Due to the fact that the platform has no storage installed, the effects of this modification are not immediately apparent.

According to [20], typical residential buildings in France should be capable of achieving an annual self-consumption rate between 20% and 50% with no storage, this value should improve to approximately 70% with the addition of storage. Similarly, industrial and tertiary buildings should be capable of achieving an annual self-consumption rate of at least 95%. This is however based on the hypothesis that the energy needs of the building greatly exceed the installed PV capacity, which is not the case with Predis-MHI. Thus considering the results obtained and the referential values provided for residential buildings in France, the self-consumption value of 28% achieved can be considered as a good value, particularly since the loads present in the platform are not very flexible and therefore do not allow for optimization with regards to the PV production.

Since both the self-consumption and self-production provide an indication of how effectively the on-site generation is being utilized by the load, it is imperative to provide this feedback for both building occupant and if available the building manager. The coverage rate, on the other hand, is a direct indication of the energy balance and is also useful feedback for occupants, building managers, and regulatory authorities. The loss of load probability, unlike the other three indicators (self-consumption, self-production and coverage rate), provides information on the interaction of the building with the grid and as such would be more useful for building managers and grid operators. However, the loss of load probability indicator could also be displayed for occupants if used in conjunction with predictive models with a goal to influence user actions in order to achieve higher autonomy from the grid.

For the purpose of evaluating the status of a building

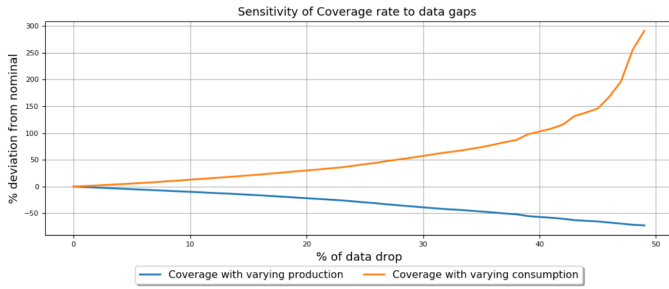


Fig. 8: Sensitivity of Coverage Rate to data gaps

VII. CONCLUSION

This paper evaluated the Load Match Indicators and grid interaction indicators for NZEBs as proposed in the works of [14] and [15]. The data considered for this study was from a tertiary building which was specifically designed to have a high energy performance with an ultimate goal of reducing the carbon footprint of the platform.

The main goal of this paper was to evaluate the relevance and consequently the usefulness of the proposed indicators particularly for building occupants. Both [14] and [15] in their works proposed an evaluation period of one year, which is useful for developing and evaluating regulations. For building managers and building occupants however, the one year evaluation period may not have any significance and will therefore not impact the desired change in behavior that is expected.

(Net Zero Energy, nearly Zero Energy or Energy Positive Building) designed to achieve high energy performance, the coverage rate indicator is the most suitable. However, since it is not very interesting for a building to achieve its target status without self-consuming the energy produced on site, it is also imperative to monitor and possibly optimize the building's self-production and self-consumption. Loss of load probability can be used with robust control algorithms to utilize high consuming devices during the peak production period, thereby improving both the self-consumption and self-production levels of the building.

In terms of their functionality, the self-consumption and self-production indicators are not very easy to understand, especially for the average building occupant. Building designers and regulators will find these indicators more useful than the average occupant. The main constraint being that self-consumption and self-production produce a ratio, it is not clear to a user if the self consumed energy is low with high consumption or the consumption is high with low self consumed energy. Thus, for most building occupants it would be more interesting to have an indicator that would indicate that production is low in relation to the consumption or vice versa.

The addition of storage technology to such a building would lead to higher self-consumption and self-production rates and would also improve the loss of load probability. However, the coverage rate would neither improve nor deteriorate since the higher self-consumption rate achieved by adding storage would imply a lower rate of energy import. Storage would therefore be useful for improving the utilization of the on-site generation, thus, storage would have a positive impact on the self-consumption, self-production and loss of load probability indicators. However, in the case of the coverage rate indicator the effect of storage is non-existent if a load/generation energy balance is considered and negative if an export/import energy balance is considered (equation 3). For the export/import energy balance, it is expected that the coverage rate would be lower with storage due to the round trip efficiency of battery storage technology.

Future works could be done in evaluating the effects of displaying these indicators for building occupants, particularly for the load latch indicators. In addition, a color coding scheme could be incorporated in the evaluating the effects of displaying these indicators as suggested in [21] as an attempt to address the issue of complexity of the indicator for average building occupants.

Since the data was collected using sensors (both physical and virtual), it is possible to have bad measurements (outliers) or periods with no measurements (data gaps). Outliers were treated using data treatment algorithms, data gaps, on the other hand, were left untreated in order to maintain as much as possible the integrity of the data. Data gaps would lead to variations of the indicator in both positive or negative direction depending on which measurement data was lost and the amount of data lost. Considering the coverage rate indicator, a loss of production data is expected to cause a reduction in the resultant coverage rate, whilst a loss of consumption data is expected to cause an increase in the resultant coverage rate, figure 8.

In the case of the grid interaction indicator, possible studies could be carried out considering a PV production prediction model, battery storage, possibly a more flexible load (domestic load) and a robust control algorithm. Such a study could be instrumental in designing low energy and low carbon buildings and could consequently improve grid resilience and reliability (using the micro-grid concept).

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