TASK 40 / ANNEX 52

ANALYSIS OF LOAD MATCH AND GRID INTERACTION INDICATORS IN NET ZERO ENERGY BUILDINGS WITH HIGH-RESOLUTION DATA

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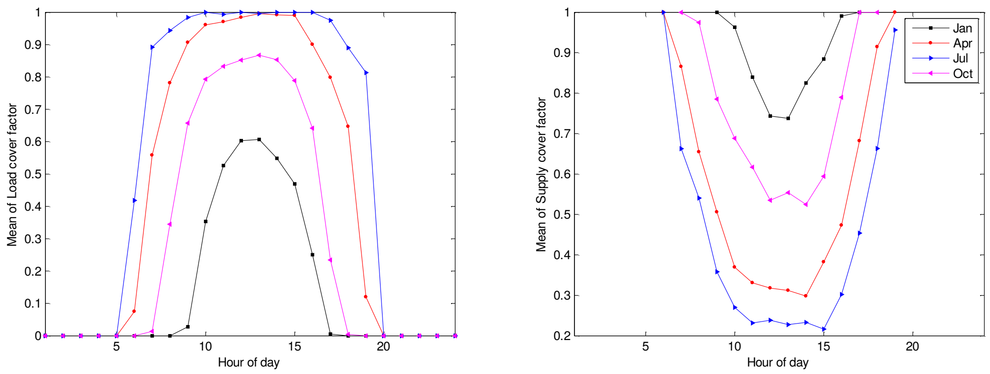
EXECUTIVE SUMMARY

The main objective of this report is to analyze the usefulness and relevance of proposed Load Match and Grid Interaction (LMGI) for Net Zero Energy Buildings (NetZEBs). The methodology is based in the analysis of available high-resolution data (mainly hourly) both from simulated and monitored NetZEBs (Net Zero Energy Buildings) or nZEB (nearly Zero Energy Buildings). The central question is to find a limited set of indicators which provide relevant information to building owners, local grid Distribution System Operators (DSO) when information from building simulations are available at design stage.

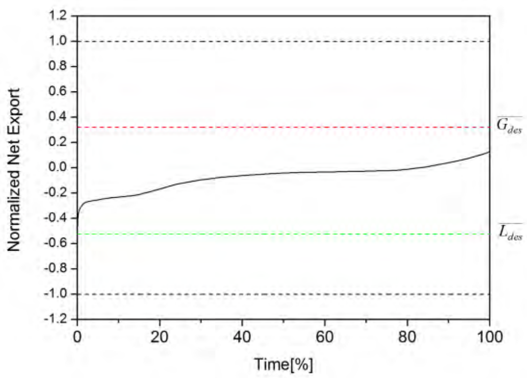
The first two sections of the report introduces why *load matching and grid interaction* are key aspects to be analysed in Net ZEBs together with the fulfilment of the yearly energy balance between on-site generation and buildings load. Buildings will play a significant role as part of a energy system based on *DER – Distributed Energy Resources*. Section two analyses the subject from several perspectives from the operators of national energy grids to the building owners and users. More details and references to previous studies are given when the conditions for the distribution grids are discussed, as the buildings are mostly connected to the medium and low-voltage grid. Analysis led that an accurate analysis will need detailed information of the grid topologies, which in most of the cases is not the case when Net ZEBs are being planned. Also, it is highlighted that grid interaction is an aspect that it should be analysed in the framework of urban planning (at the cluster of buildings level) more than at individual building level.

The third chapter of the report defines the load match and grid interaction indicators that should be computed with the case studies, together with describing the terminology. This is defined in coherence with the framework for Net ZEBs definition established in this current IEA Task. The indicators are computed in sixteen case studies. Seven of them are based on monitored buildings which are individual houses in Nordic countries (Sweden and Denmark), block of flats in Germany and Italy (with a CHP and GSHP with PV systems, respectively) and an office building in Singapore. Monitored data are from a complete year with different details of time resolution (from one minute to one hour). The nine case studies with simulated data uses one-hour time resolution. The simulated case studies covers different climates (from Finland to Spain) and several technologies, although the major part of them combines Heat Pump together with PV as strategy to become zero. A short description of all the case studies is given in section 3 of the report.

Chapter four presents the load match and grid interaction factors computed for all the case studies, with the exception of grid interaction indicators that could not be computed to the lack of the information of the design capacity connection. Results, benefits and drawbacks of the level of information given by each of the indexes has been discussed. Together with the numerical evaluation of the indicators, graphical representation of some indexes is proposed. The advantage of graphical representation is that it condenses a lot of information in a visual form. Graphical representation of load and supply cover factors (left and right, respectively in the next figure) in hourly values give a quite good picture of the correlation between on-site demand and supply of energy. It is possible to illustrate both the daily and seasonal effect, the production pattern of different renewable energy technologies, and applied operation/control strategies.



A new form of graphical representation using normalized load duration curve for net exported energy is proposed in this report. This graphical representation allows to identify the peak values of the net exported energy in a Net ZEB together with the profile of the grid interaction during the whole year knowing the percentage of time when the building is exporting energy. In the same graph, also the relation with the peak load, peak on-site generation and connection capacity are visioned.



The report concludes that load and supply cover factor, together with the loss of load probability are enough indexes to describe the relationship with the on-site generation and the buildings load. Complementary to the annual values, hourly mean monthly values have been demonstrated very useful for describing both the seasonal and daily variations. In the case of grid interaction factors, the indexes which have been demonstrated more useful are the ones that can be extracted from the hourly values of the net exported energy. Generation Multiple is one of useful index which relates the minimum and the maximum peak powers of the net exported energy, which gives additional information if statistical analysis of net exported energy is done and different percentiles are used to analyse the information. Additional indicators as capacity factor or dimensioning rate are indicators which allows to know at which extent a building is using the grid, however it needs knowing the design connection capacity between the building and the low (or medium) voltage grid. It has been demonstrated that in some cases the information of design connection capacity is hard to be known for designers of Net ZEBs, but it can be substituted by a reference or limit value alternatively. Dimensioning rate and Generation Multiple indexes have been demonstrated its usefulness to analyse cluster of Net ZEBs buildings with a limited information of the grip typologies.

Although some aspects needs to be developed in further research (as the extension to indexes to non-all electrical buildings) a selection of load match and grid indicators, together with graphical representation are proposed on the report based on their usefulness and theirs testing in both real monitored and simulated Net ZEBs.

1 INTRODUCTION

A thorough analysis of NZEBs must address the implications of two closely-related, highly dynamic phenomena: the continuous interplay between on-site generation and the building loads, and the resulting import/export interaction with the surrounding energy grid. The term load matching (LM) refers to the degree of agreement or disagreement of the on-site generation with the building load profiles; grid interaction (GI) refers to the energy exchange patterns between a building and the utility grid, and its impact on the overall load of the grid (Figure 1). Collectively, both issues are denominated LMGI.

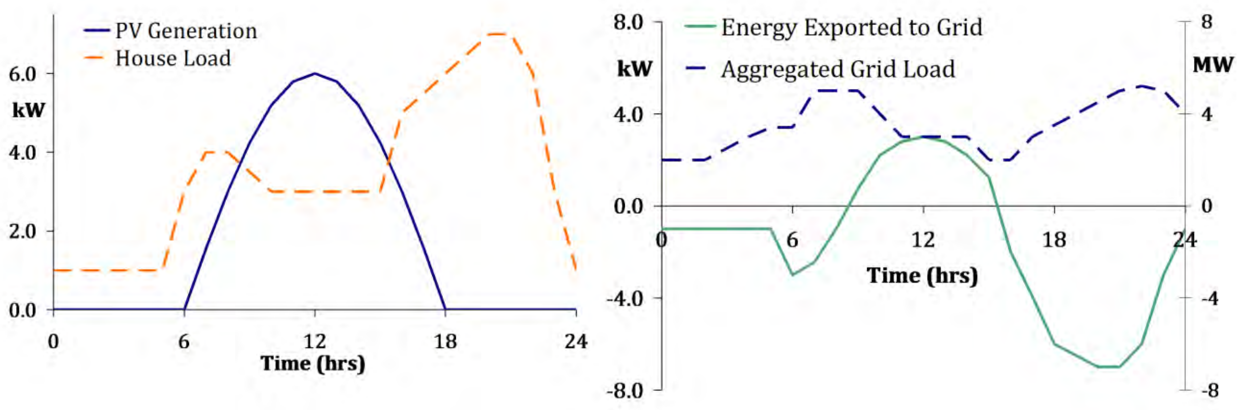


Figure 1. Load matching (left) refers to the relationship between a buildings own generation and load. Grid interaction (right) alludes to the relationship between the energy exported/imported to the grid and the load conditions of the grid itself.

NZEBs have the dual role of being energy producers and consumers ("prosumers"). At all times, Net ZEBs must provide for the needs of their occupants by coordinating on-site generation with energy imports from the utility grid. Considering that NZEBs also export energy to the grid, their relationship with the utility grid is far more complex than that of conventional buildings, which may be seen as passive consumers.

Time is essential in the analysis of LMGI issues. While the design of Net ZEBs has often focused on long-term energy balances, energy exchanges at smaller time scales (monthly, daily, hourly, sub-hourly) are critical. Within a building or within a utility network –as in any energy system– the limiting factor is the maximum power that may be delivered or received. Consequently, even if a building achieves a long-term energy balance between energy generated and consumed, smaller time scales must also be considered. For example, from the utility's point of view, if a Net ZEB is a heavy consumer in winter it will appear to be quite similar to a conventional building, requiring the use of additional generation and transmission capacity. Keeping in mind that the driving concept behind Net ZEBs is the reduction of the environmental impact associated with buildings (e.g., oversized building service systems, intervention of polluting "peaking" power plants, construction of additional generation capacity, etc.), a comprehensive look on NZEBs must address LMGI issues, including quantitative indicators to characterize these issues. This report focuses on load management/grid interaction, in particular in the development, compilation and assessment of appropriate quantitative indicators.

For a long time the issue of the quality of exported energy and how it affects the energy system was out of the scope of Net ZEB concept. Buildings have been largely considered as passive consumers taking energy from the grid or other energy carriers (e.g., fuels) to supply their own needs. Whenever peak load reductions are achieved, it is often not the result of a deliberate effort, but the by-product of energy conservation measures (e.g., adding extra insulation results both in less energy use and smaller peaks). Annual energy use has traditionally been the gauge by which the energy performance of a building is described. Reducing peak loads adds an additional element of complexity to the task of maintaining a comfortable temperature while fulfilling all the other functions required in a building, such as communications, lighting, waste disposal, safety networks.

Another reason for the increasing importance of LMGI is the trend towards a more complex, flexible and dynamic energy system (Figure 2), with more renewable energy systems (both centralized and distributed), energy storage devices, electric vehicles, and smart metering. In this new state of affairs, there will be a continuous, bi-directional exchange of energy and *information* between Smart Buildings and the Smart Grid. Building automation systems (BAS) will do more than provide the building occupants with expected comfort services; they will also make optimal decisions about storing, exporting or importing energy resources depending on expected weather and occupancy patterns, and in response to signals from the grid.

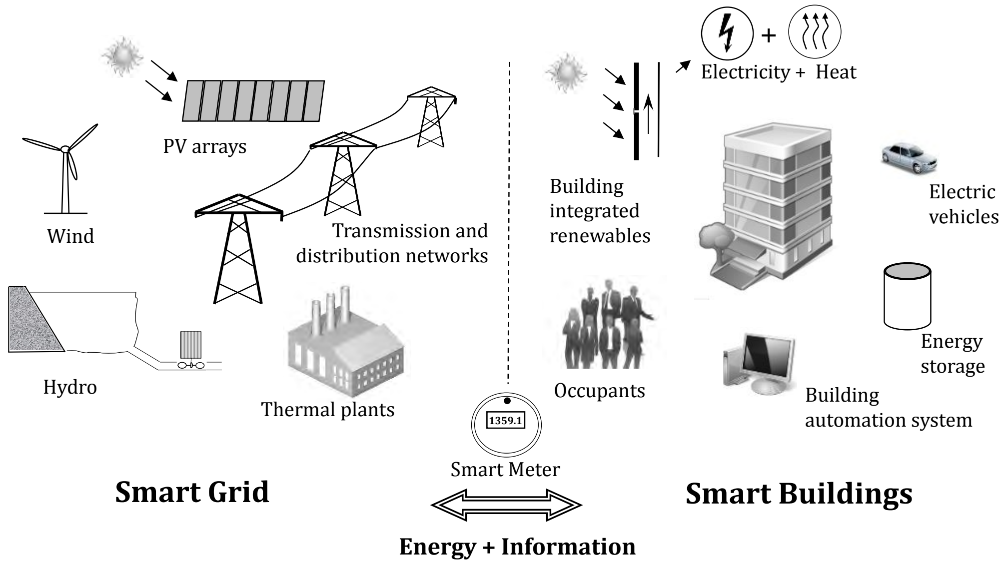


Figure 2. Links between the Smart Grid and Smart Buildings

In [1] the following potential target audiences for LMGI indicators have been identified:

- Building designers and owners
- Community designers and urban planners
- Grid operators at a local distribution level
- Grid operators at a national or regional level
- Policy makers and energy National Regulatory Authorities (NRAs).

2 TECHNICAL FRAMEWORK

In this section, a revision of the technical and economic conditions that can have an impact in the design and operation of NZEB is to be done. The review will be made from several perspectives. Different countries perspectives need to be analysed and compared.

2.1 NATIONAL / REGIONAL ENERGY SYSTEM

Operators of national energy grids (TSO – Transmission System Operator) are familiarized with economic dispatch and planning the operation of generation plants and transmission lines based on expected loads. Aggregated grid indicators at hourly or even higher resolution could help to manage national grids and to increase the penetration of renewables in the electric power system, especially if high daily peak/base load ratios occur.

As NZEB will be part of smarts grids, the question is whether NZEBs require a specific approach about integrating DER (Distributed Energy Resources) and power system balancing. As the penetration of NZEBs would probably be slow and limited in the near future (NZEB vs. nearly-ZEB) the question concerns more the impact of NZEBs in the mid an long term, as is the case of the forecasted role to play EV for some TSO [18]. In any case, high resolution indicators linking NZEBs and national energy systems might be focused on strategic objectives (increasing the penetration of renewables or reducing external energy dependency) and they make sense if seasonal/daily variations need to be taken into account. These seasonal variations and features of the grid could vary from country to country and regionally within one country. Information or indicators for load matching and grid interaction can show whether added load and generation profiles will add to or reduce existing load variations, and thereby what to expect from NZEB expansion in the future. Figure 3 illustrates the difference of aggregated electrical generation profiles in Spain at winter and summer, showing the contribution of DER and wind generation to the total. Figure 4 illustrates the same concept for Sweden, where solar production is very low and the aggregated sum of renewable production is mainly due to wind. It can be appreciated that wind penetration in winter time in Spain can cover more than 30% of the electrical demand, especially at night. In the month of April 2013, power generation from renewable energy sources reached an all-time record representing 54% of production in Spain [27]. Also is clearly appreciated a pronounced seasonal variation in Sweden, and stronger daily fluctuations in load in Spain than in Sweden.

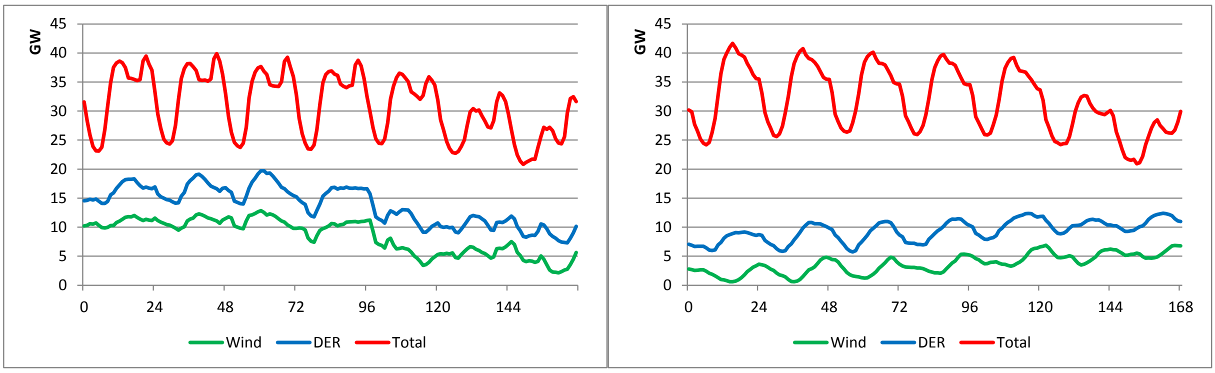


Figure 3. Electrical generation in Spain in winter (February 2010 - left) and summer (July 2010 - right) representative weeks.

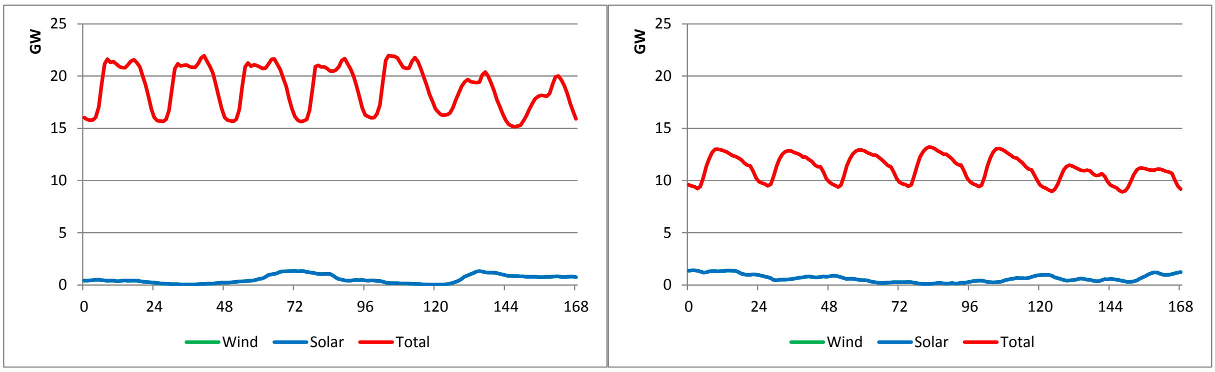


Figure 4. Electrical generation in Sweden in winter (January 2012 - left) and summer (July 2012 - right) representative weeks.

It should be noted, though, that at this level (i.e., national grid) the co-location of the building demand and the on-site generation, which is characteristic for NZEBs, is not as significant as at the local grid level. To balance the power system over a given area, it does not matter if the building loads and generation are located in exactly the same spot or geographically separated.

2.2 ELECTRICITY DISTRIBUTION GRIDS

This section makes a brief summary of the relevant concepts in power distribution and distributed generation necessary to understand the possible impact of NZEBs on distribution systems.

2.2.1 DISTRIBUTION GRID STRUCTURE, OPERATION AND PLANNING

The power system is constructed as a hierarchical arrangement, with a one-way flow of electrical power from a set of large-scale power plants to a large number of individual customers. Voltages are successively transformed to lower levels downstream in the grid. The *distribution grid* covers the lowest voltage levels and is usually divided into two parts, the middle-voltage (MV) grid, spanning 1-36 kV, and the low-voltage (LV) grid, with voltages below 1 kV [7]. Typically, in European grids, the LV voltage is 0.4 kV and the MV voltage is 10 kV. Distribution grids are normally constructed based on radial feeders, with the transformer substation at one end and the last customer at the other, and a number of customers connected along the way. The limiting factor for a distribution feeder is the voltage drop downstream along the feeder, which increases with the total load and the cable impedance.

Distribution system operators (DSOs) are required to keep network voltages within prescribed limits. According to the European standard EN 50160 [16], these are 90% and 110% of nominal voltage, but design limits are typically more narrow [8]. Primary transformer substations connecting the MV grid to the overlying high-voltage grid typically have automated voltage control through on-load tap changers to keep the voltage within bounds, but otherwise the distribution grid normally lacks surveillance and control. Secondary substations between MV and LV grids have manual tap-changer control with a constant turns ratio of the transformer that boosts the voltage to counteract the voltage drop in the MV grid.

When planning a distribution grid, the major factor is the expected peak load on the grid. This determines how large power flows the grid components have to handle. Once the expected load distribution is known, cables and transformers can be dimensioned to avoid overloading and to keep voltages within prescribed limits. It is important to note the effect that load coincidence has on the expected peak powers. For a set of buildings, their respective peak loads may be occurring around the same time but not exactly simultaneously, which effectively reduces the total peak load per customer. A commonly used method to size cables, depending on how many customers are connected, is the Velander method [7], which, in a simple mathematical formula, relates the expected peak power of a certain customer type to the total annual electricity consumption of a group of customers. An example is shown in Figure 5.

This means, as an example, that each customer will contribute less to the capacity requirements of a main feeder connecting one hundred customers than to a single-customer connection downstream in the grid. As long as equipment connecting several customers is sized, load coincidence has to be taken into account. Thus, when grids for NZEBs are designed, or existing grids are adjusted for a conversion of buildings into NZEBs, similar rules of thumb will be useful, both for the load and generation parts.

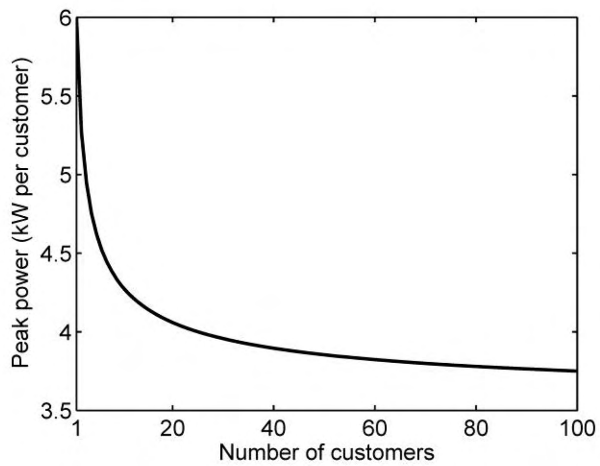


Figure 5. Peak power contribution of customers in a distribution grid as predicted by the Velander method [7]. Evaluated for buildings with heat pumps and an annual electricity demand of 10 MWh.

2.2.2 HOSTING CAPACITY FOR DISTRIBUTED GENERATION

NZEBs are part of the more general concept of *distributed energy resources (DER)*[1], which is most straightforwardly defined as "electric power generation within distribution networks or on the customer side of the network" [9] Integration of DER into power systems is a large and active area of research that has given rise to a vast range of scientific publications. The most important findings are summarized in [8]. Distributed generation may be both beneficial and problematic for the operation of the distribution grid, depending on the penetration level. At modest penetration levels, DER provides benefits such as decreased losses in the local distribution grid and evened-out voltage profiles. For high penetration levels, injected DER power that is not consumed on-site may lead to substantial reverse power flows, increased local losses, overloading of grid components and voltage rise [10]. The impact of DER on grid voltages is outlined in Figure 6. Note that the grid voltage at any point in the grid is affected by the combined power flows to all customers.

[1] Also known as *distributed generation (DG)*

The *hosting capacity* concept has been introduced to describe and analyze the impact of distributed generation on a given distribution system design. In a very broad sense, the hosting capacity is the amount of distributed generation that can be connected to a distribution grid before the performance of the grid, measured by some suitable index, becomes unacceptable [8]. The concept is outlined in Figure 7. The performance index could be network losses, overloading of components, voltage levels or power quality measures. For distributed PV, which is the most common on-site power source for NZEBs, overloading and slow voltage variations are the most important factors [11][12]. Power quality issues, such as harmonic distortions, are normally resolved by PV inverters and fast irradiance fluctuations due to moving clouds over individual PV systems are still slow enough to be just on the verge of giving rise to flicker [8]. For spread-out PV systems, fast irradiance variability is reduced considerably [13] and does not have any impact on flicker-range voltage variations [8].

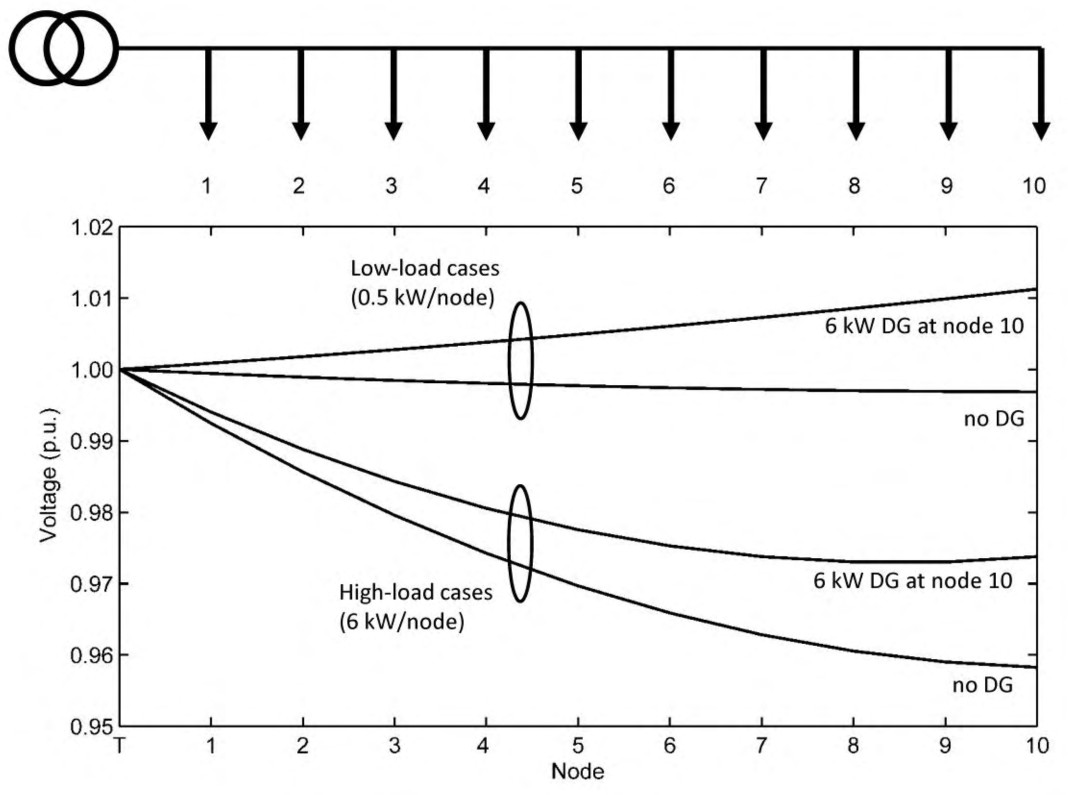


Figure 6. DG impact on voltages along a radial distribution feeder with 10 connected customers and a DG unit at the last node. At high load the voltage drop is reduced and at low load the voltage is raised above nominal. Reproduced from [10].

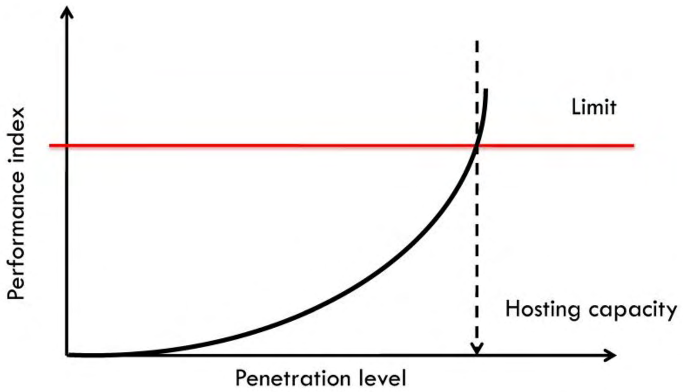


Figure 7. Schematic outline of the hosting capacity concept. The hosting capacity is the penetration level of DER for which the chosen limit in performance is reached.

Two factors in particular may limit the hosting capacity for NZEBs with on-site PV generation within existing distribution grids. First, there is a considerable reduction of the expected peak power demand of an aggregate of buildings due to random coincidence of loads, as predicted by the Velander method, but this is not the case for the total PV generation, since at clear weather all systems will produce their maximum power at the same time. This means that while the marginal capacity that has to be added to supply an increasing number of loads decreases upstream in the grid, the capacity increase due to PV is directly proportional to the total PV capacity. Consequently, for a large number of customers, the load will be much more evenly distributed over time than the PV generation. If the total annual demand and on-site supply are equal, higher grid capacities are required to deal with the PV supply than the demand.

Second, tap-changers in secondary transformer substations are normally used to offset the nominal grid voltage to handle voltage drops. Since voltages in the grid are allowed to vary both above and below the nominal voltage, this allows a larger span of the voltage variations. At low load, connections upstream in the grid are maximally above nominal voltage, and at high load, connections downstream are maximally below nominal, as indicated by Figure 8. The figure also shows how this may limit the amount of PV generation possible to connect. Since the highest peak powers are injected at times of low overall load on the grid, the tap-changer offset could severely limit the allowed voltage variations due to on-site PV.

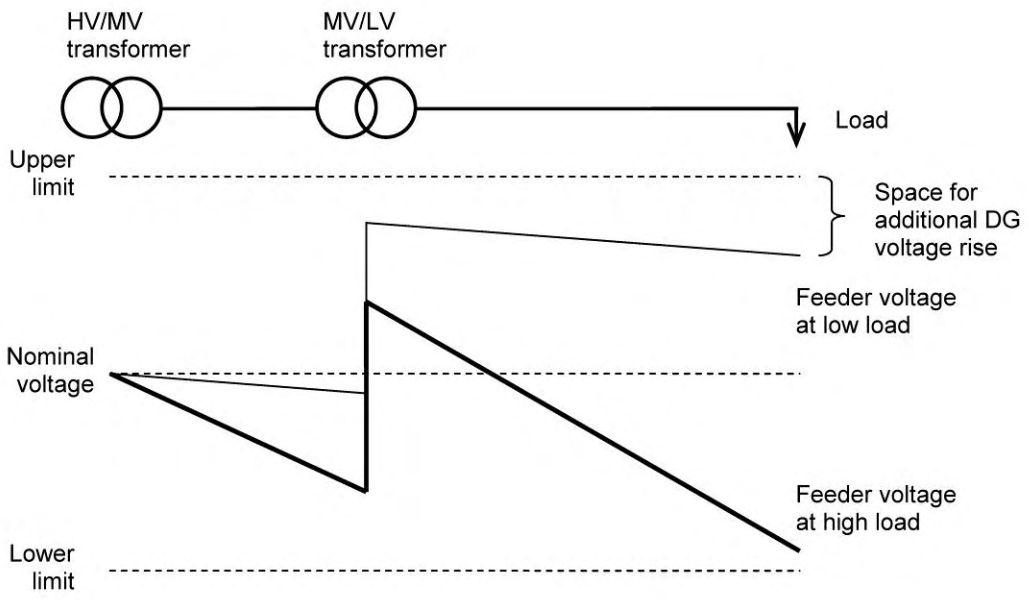


Figure 8. Schematic outline of how tap-changer voltage control limits the hosting capacity for DG.

The hosting capacity for distributed PV depends on the structure, strength, load distribution and operation and control of the individual grid. There are several previous studies taking the above factors into account (see e.g. [10][14]), and all come to varying conclusions about hosting capacities and allowed penetration levels. In general, though, city grids are more robust than suburban or rural grids. For example, in a Swedish simulation study, it was found that representative rural and suburban grids could allow a 60% PV penetration of the annual demand before the allowed voltage was exceeded, while a representative city grid would allow PV penetrations three times higher than the annual demand [11].

The business-as-usual option to increase the hosting capacity of a distribution grid is grid reinforcement, i.e. using cables with lower resistance and reactance. However, these investments could prove costly for the DSO, which is why other options to increase the hosting capacity are currently studied in international research, including altered tap-changer control, reactive power provision by PV inverters, PV power curtailment and increased PV self-consumption by demand response measures or local storage [14]. Studies for Sweden have shown that the former three methods can have a considerable impact on the highest peak injections [11], while the effect of demand-response measures, at least through automated appliance scheduling, is limited [15].

2.2.3 RELEVANT HIGH-RESOLUTION INDICATORS FOR NET ZERO ENERGY BUILDINGS

The above discussion highlights two things. First, planning for urban environments with NZEBs will require distribution grid planners to take both building loads and on-site generation into account; so that the grid can handle both the highest peak demands and the highest injected peak powers. Second, the NZEB design, with a fixed relation between the on-site generation and the building demand, provides planners with limits to the powers that must be handled by the distribution grid, i.e. if the power demand of the building is known, so is the amount of power generated on-site. For a given NZEB, or a set of NZEBs, it should be possible to find a relation between the expected peak demand and the expected peak power generation, which is the information required.

The central physical parameter in the distribution grid interaction is the magnitude of the power (active and reactive) injected or consumed by a group of customers. This will determine the power flow through the grid components and, consequently, currents and voltage levels. Variability is not important *per se*, but variability and coincidence determine which power levels occur and how often. Relevant grid interaction indicators for distribution grid planning should show, or be based on:

- The relation between the expected net peak power demand and the expected net peak power generation for an arbitrary set of typical buildings, both of these in relation to the total annual consumption/generation. With this information, it is possible to choose grid components that can handle all power imports and exports from any group of customers of varying size. Ideally, these should be in the form of rules-of-thumb or formulae similar to the Velander method. Note that load and generation coincidence are crucial for grid design and operation, hence an indicator for the individual building is not sufficient as long as components interconnecting several consumers are considered (which is mostly the case).

- The distribution of power exports and imports above a certain threshold value over a certain period of time (typically a year). This shows how *often* peak powers of a certain magnitude occur. It may be relevant, for example, if curtailment of injected power is required. Instead of dimensioning grids to handle all power exports and imports from buildings, requirements may be put on distributed generators to provide reactive power as grid support, or curtailment of the power output. There could also be requirements on generators to participate in frequency control and time-differentiated tariffs or other incentives could be given to the customers to alter their demand profiles. Quantifying the occurrence of peak powers of a certain magnitude indicates how often problematic levels are achieved with a certain building design and operation.

2.2.4 REQUIRED ELECTRICAL PEAK LOADS FOR LOW-VOLTAGE SUPPLY

As it has been highlighted before the expected peak power demand of one building or cluster of buildings is key information to generate relevant indicators or establish threshold values that indicators can refer to. As example, Table 1, shows the minimum electrical supply requirements in Spain [17].

Table 1.Minimum requirements for electrical supply in buildings in Spain

Type	Minimum Power
Residential, Individual basic level	5 750 W @ 230 V
Residential, Individual high level[2]	9 200 W @ 230 V
Residential, Collective	Simultaneity factor applied to sum of requirements for individual dwellings. (Plus ancilliary spaces)
Office buildiings	100 W/m^2 or 3 450 W/space @ 230 V Simultaneity factor = 1

[2] Residential dwelling with a higl level of electrical needs or with electrical heating/cooling system or with useful surface greater than 160 m^2

2.3 BUILDING DESIGNERS / OWNERS PERSPECTIVE

When evaluating load match and grid interaction, reliable or probable forecasts of the building energy consumption and production on hourly or sub-hourly scale are important. A significant challenge regarding this aspect is the lack of methodologies and standardised tools to make hourly or sub-hourly forecasts based on factors such as the number of occupants or orientation of the PV panels. The existing design approach and building certification programmes are mostly focused on the implementation of energy efficiency measures and hence reduction of energy use [24], and do not usually contain hourly load/generation profiles or, as maximum, contain average profiles.

Economy is often the driving force of the building owners. Thus, when determining or evaluating the building's energy export and import, the economic benefit is determined by the price difference between energy sold to the utility company and energy bought from the utility. These aspects may vary from country to country – and even within each country. As example, in Germany due to policy incentives, consumers receive less for electricity sold to the utility than what they pay for buying electricity from the utility. This makes it beneficial to maximise self-consumption, i.e. minimising export of electricity to the grid. In such a case, households would benefit from having PVs orientated east-west as they will produce electricity in the morning and in the afternoon, following the load profile. In the case of an office building, the PVs might be orientated south as peak load occurs during midday. If an opposite price regime occurs, for example by feed-in tariffs, that makes the price of electricity sold to the grid higher than the price of electricity bought, the orientation of the PV panels should give the maximum production regardless of the shape of the load profile, as the matching is not an important issue. If the spot price of electricity is the only incentive (no subsidies or other policy incentives), the owner may shift load according to the fluctuating electricity price, hour by hour. In both the first and the last case, more flexible demand will make the building more capable of profiting from its onsite production. In these cases, building designers or owners should arrange for making the load and grid interaction as flexible as possible.

3 LMGI INDICATORS

3.1 INTRODUCTION

This section presents quantitative and relevant indicators that can be used to describe Load Matching and Grid Interaction (LMGI) conditions in net-zero or near net-zero energy buildings (Net ZEBs). Load Matching refers to how the local energy generation compares with the building load. Grid Interaction refers to the energy exchange between the building and an energy infrastructure, typically, the power grid. These are independent, but intimately related issues. The main distinction made here is that load matching indicators measure the degree of overlap between generation and load profiles (e.g. the percentage of load covered by on-site generation over a period of time) whereas grid interaction indicators take aspects of the unmatched parts of generation or load profiles into account (e.g. peak powers delivered to the electricity distribution grid).

A comprehensive revision of LMGI indicators are given in [1] together with some proposals for alternative indicators. These indicators have been used to evaluate NZEB test cases [1][6][21], while some other indicators are also proposed in the literature [5][20][23]. The indicators selected and described in this section will be evaluated in the following sections through case studies.

3.2 TERMINOLOGY

The sketch depicted in Figure 9 provides an overview of relevant terminology addressing the energy use in buildings and the connection between buildings and the power grid.

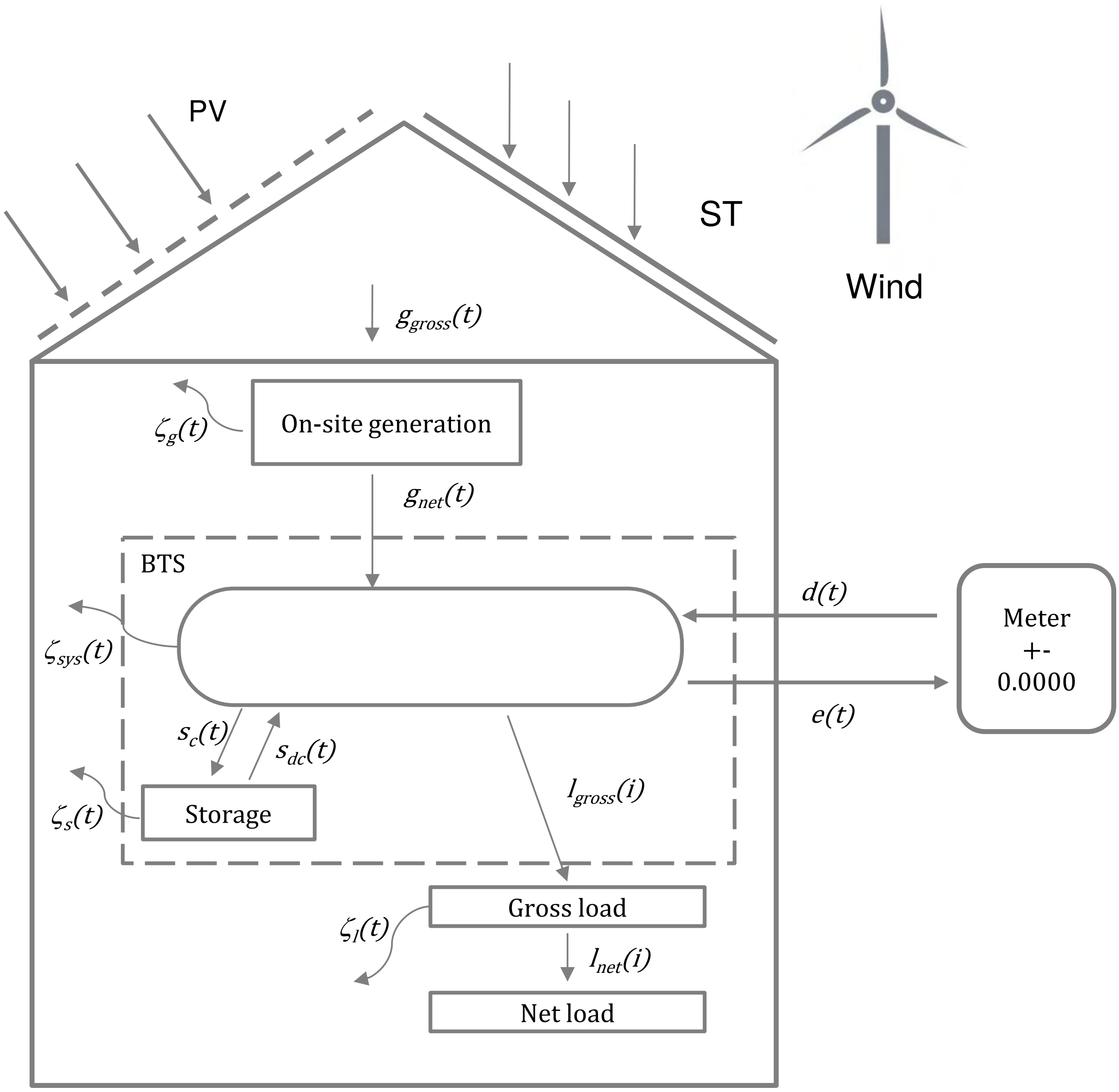


Figure 9. Schematic view of the energy flows in a Net ZEB

Nomenclature

t	*time*	
e, E	*exported energy*	
d, D	*delivered energy*	
ne	*net exported energy*	
g, G	*on-site generation*	
	g_{net}	*net on-site generation*
	g_{gross}	*gross on-site generation*
	$\bar{g}$	*average on-site generation*
s_c	*charging storage energy*	
s_{dc}	*discharging storage energy*	
S	*storage energy balance*	
U_s	*Internal storage energy*	
T	*evaluation period*	
τ_1	*start of the evaluation period*	
τ_2	*end of the evaluation period*	
w	*weighting factor*	
l, L	*load*	
	l_{net}	*net load*
	l_{gross}	*gross load*
	$\bar{l}$	*average load*
ζ	*energy losses*	
	ζ_g	*generation energy losses*
	ζ_s	*storage energy losses*
	ζ_{sys}	*Building technical systems energy losses (excluding storage)*
	ζ_l	*Load energy losses (e.g.: distribution losses)*
BTS	*Building Technical Systems*	
E_{des}	*Designed/required connection capacity*	

Subindex

i	*energy carrier*
d	*delivered*
e	*exported*
b	*building*

The core principle for Net ZEBs is the balance between the weighted demand and weighted supply [2], which are described in Eq. 1, based on delivered and exported energy quantities, where *i* stands for energy carrier.

$$\sum_i \int_{\tau_1}^{\tau_2} e_i(t) \cdot w_{e,i}(t) \cdot dt - \sum_i \int_{\tau_1}^{\tau_2} d_i(t) \cdot w_{d,i}(t) \cdot dt = E - D \geq 0$$

Eq. 1

A general energy balance in the building is represented with Eq. 2

$$g_{net}(t) + d(t) = l_{net}(t) + \zeta_l(t) + \zeta_s(t) + \zeta_{sys}(t) + e(t) + \frac{dU_s}{dt}$$

Eq. 2

where

$$g_{gross}(t) = g_{net}(t) + \zeta_g(t)$$ *Eq. 3*

$$s_c(t) = s_{dc}(t) + \zeta_s(t) + \frac{dU_s}{dt}$$ *Eq. 4*

$$S(t) = s_c(t) - s_{dc}(t) = \zeta_s(t) + \frac{dU_s}{dt}$$ *Eq. 5*

$$l_{gross}(t) = l_{net}(t) + \zeta_l(t)$$ *Eq. 6*

If we integrate over time between τ_1 and τ_2 (the evaluation period), then we have

$$\int_{\tau_1}^{\tau_2} g_{net}(t) + \int_{\tau_1}^{\tau_2} d(t) = \int_{\tau_1}^{\tau_2} l_{gross}(t) + \int_{\tau_1}^{\tau_2} \zeta_{sys}(t) + \int_{\tau_1}^{\tau_2} e(t) + \int_{\tau_1}^{\tau_2} S(t)$$

Eq. 7

$$\int_{\tau_1}^{\tau_2} g_{net}(t) + \int_{\tau_1}^{\tau_2} d(t) = \int_{\tau_1}^{\tau_2} l_{gross}(t) + \int_{\tau_1}^{\tau_2} \zeta_{sys}(t) + \int_{\tau_1}^{\tau_2} e(t) + \int_{\tau_1}^{\tau_2} \zeta_s(t) + \Delta U_s$$

Eq. 8

If we consider that over the evaluation period, $\Delta U_s \cong 0$, then:

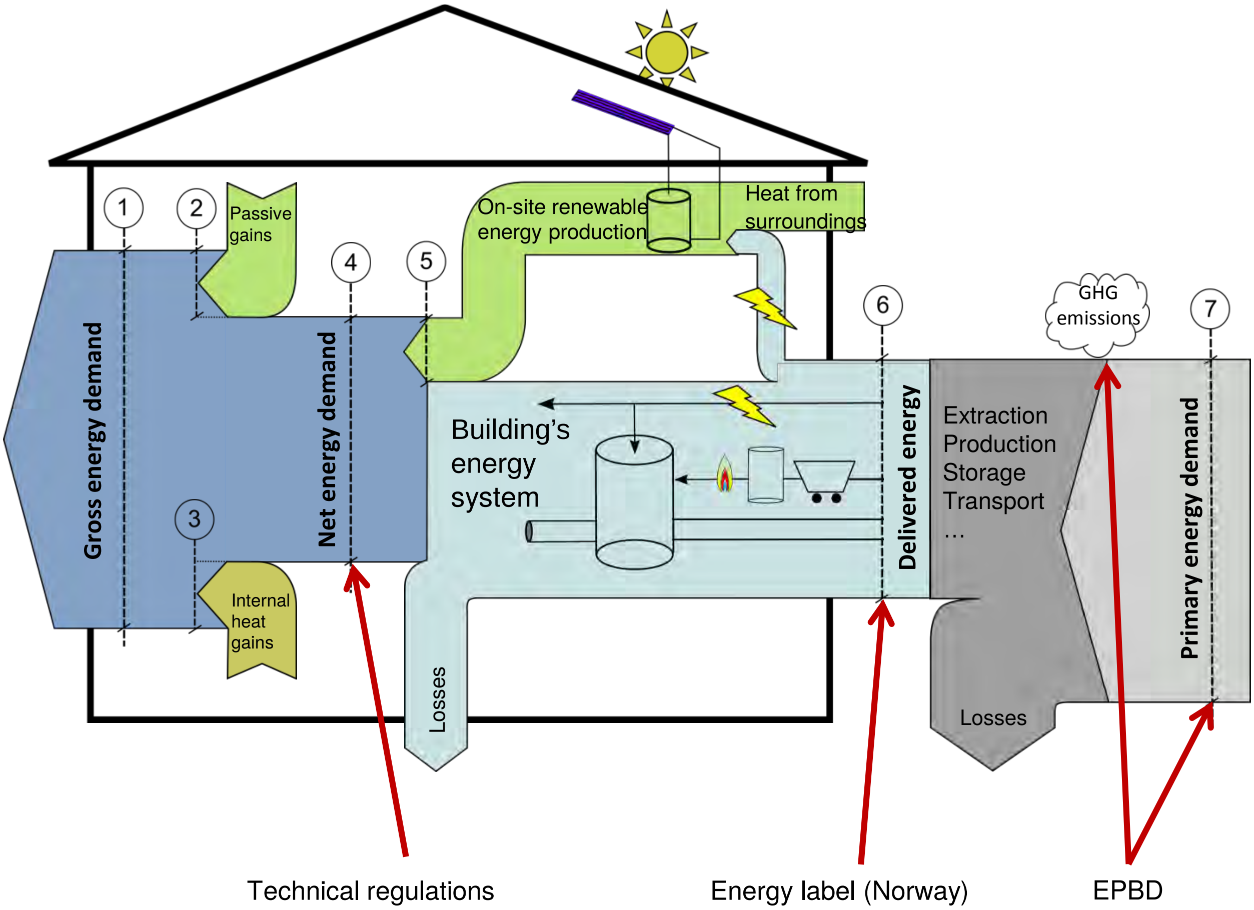
$$\int_{\tau_1}^{\tau_2} g_{net}(t) + \int_{\tau_1}^{\tau_2} d(t) = \int_{\tau_1}^{\tau_2} l_{net}(t) + \int_{\tau_1}^{\tau_2} \zeta(t) + \int_{\tau_1}^{\tau_2} e(t)$$

Eq. 9

Net exported energy is defined as:

$$ne(t) = e(t) - d(t)$$ *Eq. 10*

A graphical presentation using Sankey diagrams could help to understand the energy flows and the energy balance. An example for a Norway case is presented here.



Ref: Rasmus Z. Høseggen, Ph.D. Associate Professor II, NTNU and Senior advicer, Evotek

Figure 10. Schematic illustration in form of a Sankey Diagram for a NZEB [21]

3.3 LOAD MATCH INDICATORS

Load match indexes intend to describe the degree of the utilisation of on-site energy generation related to the local energy demand.

3.3.1 LOAD MATCH INDEX

The first proposed index was the load match index [22], defined as the average value over an evaluation period of how the on-site generation covers the energy load. The load match index intends to describe the matching degree between on-site energy generation and the building load. As higher the index is, better the coincidence between the load and the onsite generation.

The formulas describing the load match index vary from very general ones [2,22], which do not specify if storage and losses of energy are included, to very clear definitions [1, 6].

$$f_{load} = \frac{1}{N} \cdot \sum_{year} min\left[1, \frac{g(t)}{l(t)}\right]$$ *Eq. 11 [2]*

$$f_{load} = \overline{min\left[1, \frac{g(t) - S(t) - \zeta(t)}{l(t)}\right]} = \frac{\sum_{\tau_1}^{\tau_2} min\left[1, \frac{g(t) - S(t) - \zeta(t)}{l(t)}\right]}{N}$$

Eq. 12 [1]

where N is the number of samples in the evaluation period, from τ_1 to τ_2. In case that hourly resolution data are used and the evaluation period is a complete year, the number of samples is 8760.

In this study the most detailed formula is used, which indicates that storage as well as losses of energy should be included in the load match index calculation.

3.3.2 LOAD COVER FACTOR AND SUPPLY COVER FACTOR

Load cover factor is also described in [1] and represents the percentage of the electrical demand covered by on-site electricity generation and is defined as

$$\gamma_{load} = \frac{\int_{\tau_1}^{\tau_2} min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} l(t)dt}$$

Eq. 13

Then a complementary index, the supply cover factor, can be defined representing the percentage of the on-site generation that is used by the building. Mathematically, it could be defined as:

$$\gamma_{supply} = \frac{\int_{\tau_1}^{\tau_2} min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} [g(t) - S(t) - \zeta(t)]dt}$$

Eq. 14

or as in equation Eq. 15, if storage and system losses are not substracted from the on-site generated energy.

$$\gamma_{supply} = \frac{\int_{\tau_1}^{\tau_2} min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} g(t)dt}$$

Eq. 15

In [20], two factors are computed. The REF – Renewable Energy Factor (very similar to the load cover factor load) and the REM – Renewable Energy Matching (similar to the supply cover factor).

$$REF = \frac{\int_{\tau_1}^{\tau_2} min[g(t) - S(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} l(t)dt}$$

Eq. 16

$$REM = \frac{\int_{\tau_1}^{\tau_2} min[g(t) - S(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} g(t)dt}$$

Eq. 17

In [5], the demand cover factor (or self-generation) for all-electric buildings is defined as:

$$\gamma_D = \frac{\int_{\tau_1}^{\tau_2} min[P_D, P_S]dt}{\int_{\tau_1}^{\tau_2} P_D dt}$$

Eq. 18

Where P_S is the local power supply and P_D the local PV power demand. The term $min[P_D, P_S]$ represents the part of the power demand instantaneously covered by the local PV power supply or the part of the power supply covered by the power demand. Also, in [5], the supply cover factor (or self-consumption) for all-electric buildings is defined as:

$$\gamma_S = \frac{\int_{\tau_1}^{\tau_2} min[P_D, P_S]dt}{\int_{\tau_1}^{\tau_2} P_S dt}$$

Eq. 19

Table 2 shows the equivalence between the load and supply cover factors and other nomenclatures for the load match indexes in the literature.

Table 2. Equivalence of cover factors in the literature

Load Cover factor γ_{load}	Renewable Energy Factor *REF*	Demand cover factor (self-generation) γ_D	
Supply cover factor γ_{supply}	Renewable Energy Matching *REM*	Supply cover factor (self-consumption) γ_S	
[1]	[20]	[5]	**Literature references**

A conceptual item related with the computation of the cover factors (and thus related with the computation of share of renewables in a building) is the treatment of losses. In the nomenclature, we have distinguished between:

- Storage losses
- Building technical systems losses (excluding, storage losses)
- Load losses (for example, distribution losses)

In Eq. 13, Eq. 14 and Eq. 15, the sum of the storage losses and the variation of internal energy in the storage sub-system (S(t)) and the system losses ($\zeta(t)$) are substracted from the on-site generation. In [1], system losses are substracted from on-site generation In [21], storage losses and distribution losses are distinguished. Although is not completely clear, it seems that only storage losses (difference between charging and discharging storage system) is substracted from on-site generation to compute the load match factor In [6], same computation as in [1] is used.

In [20], two factor are computed. The REF – Renewable Energy Factor (very similar to the load cover factor load) and the REM – Renewable Energy Matching (similar to the supply cover factor). Although losses are considered in the balance, they are not substracted to the on-site generation to compute REF or added to the load to compute REM. ES(t) and HS(t) in [20] represents storage balance in the battery (ES) and in the solar tank of the system (HS) (then charging minus discharging). In [5], where Eq. 18 and Eq. 19 are defined, no electrical storage system is considered in the model and a water storage tank is considered as part of the thermal building system model. The model only includes BIPV as renewable generation system and is connected to the electrical grid.

3.3.3 DIFFERENCE BETWEEN LOAD COVER FACTOR AND LOAD MATCH INDEX

The two factors can be defined either in the continuous domain, i.e. using integral notation ($\int$), or in the discrete domain, i.e. using the summation notation ($\sum$). In literature the load cover factor, γ_{load} is presented with the integral notation [1][5] while the load match factor, f_{load}, is presented with the summation notation [2]. For the sake of comparability they are both presented here in the integral notation, given that the considerations developed below would hold true also for the summation notation.

The two factors are meant to express the same thing, i.e. the share of the load (energy demand) that is covered by the on-site generation (energy supply) for a specific energy carrier. Nevertheless the two factors are not identical, since their mathematical definition is different, as shown in the following table. The factors are first defined as found in literature, but using integral notation for both of them and using the same nomenclature. Thereafter the two factors are further manipulated in order to write them in a comparable fashion and highlight the difference.

load cover factor, γ_{load}	load match index, f_{load}
$\gamma_{load} = \frac{\int_{\tau_1}^{\tau_2} min[g(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} l(t)dt}$	$f_{load} = \frac{1}{T}\int_{\tau_1}^{\tau_2} min\left(1, \frac{g(t)}{l(t)}\right) dt =$
$= \frac{1}{L}\int_{\tau_1}^{\tau_2} min[g(t), l(t)]dt$	$= \frac{1}{T}\int_{\tau_1}^{\tau_2} min\left(\frac{l(t)}{l(t)}, \frac{g(t)}{l(t)}\right) dt =$
$= \frac{1}{T\bar{l}}\int_{\tau_1}^{\tau_2} min[g(t), l(t)]dt$	$= \frac{1}{T}\int_{\tau_1}^{\tau_2} \frac{1}{l(t)} min[g(t), l(t)]dt$
$= \frac{1}{T}\int_{\tau_1}^{\tau_2} \frac{1}{\bar{l}} min[g(t), l(t)]dt$	

It should be noticed the difference inside the integral sign: while the load cover factor γ_{load} has $1/\bar{l}$, which is a constant quantity, the load match factor f_{load} has $1/l\,(t)$, which is a quantity varying with time. This causes a numerical difference between the two indicators, which in most cases may be expected to be small but is nevertheless a difference.

It may be argued that γ_{load} has a somehow more intuitive definition, being the ratio between two quantities. Furthermore, a closer look shows that actually γ_{load} beholds a mathematical property that f_{load} does not have, as shown below. With starting point from the last form of γ_{load} equation form the previous table it can be seen that:

$$\gamma_{load} = \frac{1}{\bar{l}} \cdot \frac{1}{T}\int_{\tau_1}^{\tau_2} min[g(t), l(t)]dt = \frac{\bar{x}}{\bar{l}}$$

Eq. 20

if we define $\bar{x}$ = average x, where:

$$x = min[l(t), g(t)]$$

Therefore γ_{load} represents the arithmetic average between two quantities. The same cannot be said for f_{load} since it contains inside the integral the time dependent term $1/l(t)$. This gives to the load cover factor γ_{load} a somewhat more elegant mathematical formulation than the load match factor f_{load}.

Finally, as discussed in [5] and in the previous sub-chapter 3.3.2, the load cover factor γ_{load} may be used in combination with the supply cover factor γ_{supply}, which is defined in a symmetrical way as the share of the on-site generation (energy supply) that is covered by the load (energy demand). The two cover factors γ_{load} and γ_{supply} would have the same numerical value when the balance for the energy carrier is exactly zero in the observed period, while it would differ for nearly zero or plus balances. An attempt to create a similar symmetrical factor of f_{load} would fail to reproduce the same behaviour – i.e. having the same numerical value when balance is exactly zero – for the reasons explained above.

In conclusions, although the two indicators appear similar, the load cover factor is to be preferred for the reasons explained here and it is proposed to be used instead of the load match index. The rest of this report will therefore address the load cover factor γ_{load} and disregard the load match index f_{load}.

3.3.4 LOSS OF LOAD PROBABILITY

The loss of load probability (LOLP) can be defined as the percentage of time that the local generation does not cover the building demand, and thus how often energy must be supplied by the grid. This index could be useful to evaluate different load control strategies in a building.

$$LOLP_b = \frac{\int_{\tau_1}^{\tau_2} dt_{\,l(t)>(g(t)-S(t)-\zeta(t))}}{\tau_2 - \tau_1}$$

Eq. 21

An equivalent method to define this indicator based on exported/delivered energy is:

$$LOLP_b = \frac{\int_{\tau_1}^{\tau_2} dt_{\,ne(t)<0}}{T}$$

Eq. 22

3.4 GRID INTERACTION FACTORS

Grid interaction factors can be computed using actual power values or can be presented using normalized values. As the objective of computing grid interaction factor is to measure how the utilisation of the grid connection is in relation to the building or a cluster of buildings, **we propose to use the design connection capacity as normalizing quantity**.

The nominal grid connection capacity is denoted by E_{des}

3.4.1 PEAK POWER GENERATION/EXPORTED

This indicator represents the normalized peak value of the on-site generation or exported energy.

$$\overline{G_{des}} = \frac{G_{des}}{E_{des}} = \frac{max[g(t)]}{E_{des}} \qquad \text{Eq. 23}$$

$$\overline{G_{des}} = \frac{G_{des}}{E_{des}} = \frac{max[e(t)]}{E_{des}} \qquad \text{Eq. 24}$$

3.4.2 PEAK POWER LOAD/DELIVERED

The normalized peak power of the load or delivered energy is represented by the following equations.

$$\overline{L_{des}} = \frac{L_{des}}{E_{des}} = \frac{max[l(t)]}{E_{des}} \qquad \text{Eq. 25}$$

$$\overline{L_{des}} = \frac{L_{des}}{E_{des}} = \frac{max[d(t)]}{E_{des}} \qquad \text{Eq. 26}$$

3.4.3 GENERATION MULTILPLE

The *generation multiple* relates the size of the generation system with the design capacity load. It is expressed as the ratio between generation/load peak powers or exported/delivered peak powers.

$$GM = \frac{G_{des}}{L_{des}} \qquad \text{Eq. 27}$$

$$GM_{(g/l)} = \frac{G_{des}}{L_{des}} = \frac{max[g(t)]}{max[l(t)]} \qquad \text{Eq. 28}$$

$$GM_{(e/d)} = \frac{G_{des}}{L_{des}} = \frac{max[e(t)]}{max[d(t)]} \qquad \text{Eq. 29}$$

3.4.4 DESIGN RANGE

The design range is defined as the amplitude between the generation/load or the exported/delivered energy values.

$$A_{des} = G_{des} - L_{des} \qquad \text{Eq. 30}$$

3.4.5 NET EXPORTED VALUES AND RANGES

Defining the normalized variable for the net exported energy as:

$$\overline{ne(t)} = \frac{ne(t)}{E_{des}} \qquad \text{Eq. 31}$$

The maximum and minimum peak power can be defined as:

$$\overline{ne_{max}} = max\left[\overline{ne(t)}\right] \qquad \text{Eq. 32}$$

$$\overline{ne_{min}} = min\left[\overline{ne(t)}\right] \qquad \text{Eq. 33}$$

Having the possibility to statistically analyse net export values, the following values can be computed

$$GM_{ne,100/0} = \frac{|ne_{max}|}{|ne_{min}|};\ GM_{ne,99/1} = \frac{|ne(t)_{99\%}|}{|ne(t)_{1\%}|};$$

$$GM_{ne,95/5} = \frac{|ne(t)_{95\%}|}{|ne(t)_{5\%}|};\ GM_{ne,75/25} = \frac{|ne(t)_{75\%}|}{|ne(t)_{25\%}|}$$

$$A_{ne,100/0} = ne_{max} - ne_{min}; A_{ne,99/1} = ne_{99\%} - ne_{1\%}$$

$$A_{ne,95/5} = ne_{95\%} - ne_{5\%}; A_{ne,75/25} = ne_{75\%} - ne_{25\%}$$

3.4.6 CAPACITY FACTOR

The capacity factor shows the total energy exchange with the grid divided by the exchange that would have occurred at nominal connection capacity, i.e, a measure of the utilisation of the grid connection.

$$CF_{b,E} = \frac{\int_{\tau_1}^{\tau_2} |ne(t)| dt}{E_{des} \cdot T} \qquad \text{Eq. 34}$$

We discard to use the alternative capacity factor defined in [1] which indicates the path of the energy exchange with the grid. Although, it makes sense for instantaneous values or short periods of time, the annual value for a NZEB with the definition in [1] will be always equal to 0.

3.4.7 DIMESIONING RATE

The dimensioning rate is the maximum absolute value of the net exported energy and thus it will coincide with $\overline{ne_{max}}$ or $\overline{ne_{min}}$

$$DR = \frac{max[|ne(t)|]}{E_{des}} \qquad \text{Eq. 35}$$

The sketch in Figure 11 intends to show the main values expressed in the equations above.

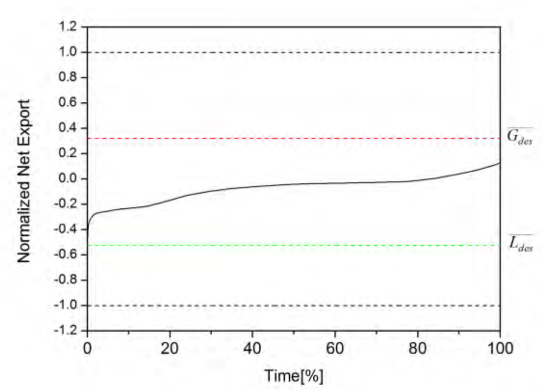


Figure 11.Example of load duration curve for normalized net exported electricity. Also the values of $\overline{G_{des}}$ and $\overline{L_{des}}$ are shown in the graph (horizontal red and green dashed lines) together with the normalized value of E_{des} (+1 and -1).

3.4.8 CONNECTION CAPACITY CREDIT

The connection capacity credit, or power reduction potential originally defined in [23], can be defined as the percentage of grid connection capacity that could be saved compared to a reference case. It can be reformulated as

$$E_c = 1 - \frac{DR}{DR_{ref}} \qquad \text{Eq. 36}$$

Positive values of the index indicates a saving potential with respect to the reference case, and negative values means there is a need to increase the grid connection.

On the other hand, taking the connection capacity as reference, it will be possible to identify the power reduction potential

$$E_{c,des} = 1 - DR \qquad \textit{Eq. 37}$$

On the contrary, if the reference case is the a building with no on-site generation, the following equation can be defined, to characterize the power reduction potential

$$E_{c,ref(G=0)} = 1 - \frac{DR}{L_{des}} \qquad \textit{Eq. 38}$$

3.4.9 PEAKS ABOVE CERTAIN LIMIT

The peaks above certain limit value indicate the part of analysed period that net export energy exceeds a certain barrier. The generic formulation is:

$$E_{>E_{lim}} = \frac{\int_{\tau_1}^{\tau_2} dt_{|ne(t)|>E_{lim}}}{T} \qquad \textit{Eq. 39}$$

Considering that the grid connection capacity should never be exceeded, in case that the aim is to limit the grid connection capacity the limit value should be the capacity that is aimed at. Other suggested value could be a certain value which is a turning point for which contracting or grid connection rules are to be fulfilled in relation to connection to the local grid distribution.

3.5 OTHERS GRID INTERACTION INDICATORS

3.5.1 NO GRID INTERATION PROBABILITY

This index means the probability that the building is acting autonomously of the grid. In that case, the entire load is covered by the direct use of renewable energy or by the stored energy

$$P_{E\approx 0} = \frac{\int_{\tau_1}^{\tau_2} dt_{|\overline{ne(t)}|<0.001}}{T} \qquad \textit{Eq. 40}$$

3.5.2 GRID INTERACTON INDEX

The grid interaction index indicates the variability of the exchanged energy between the building and the grid within a year normalized on the maximum absolute value.

$$f_{grid} = STD\left(\frac{ne(t)}{max(|ne(t)|)}\right) \qquad \text{Eq. 41}$$

3.5.3 GRID CITIZENSHIP TOOL

The aim of this tool is to qualitatively estimate the way that an interconnected component e.g. an energy producing building or a microgrid of such buildings, interacts with a greater power system, e.g. low-voltage power grid. It consists of the following factors: component ratio (CR) – describes the proportion between on-site generation and load; storage ratio (SR) – gives a qualitative indication of how well on-site generation is supported by on-site storage; intermittency ratio (IR) – indicates how reliable the component is at supplying energy. CR and SR factors are between -1 and 1, and IR varies from 0 to 1.

$$CR = \frac{G_{des}-L_{des}}{G_{des}+L_{des}} \qquad \text{Eq. 42}$$

$$SR = \frac{G_{des}-S_{des}}{G_{des}+S_{des}} \qquad \text{Eq. 43}$$

$$IR = \frac{G_{daily\ avg}+S_{des}}{G_{des}+S_{des}} \qquad \text{Eq. 44}$$

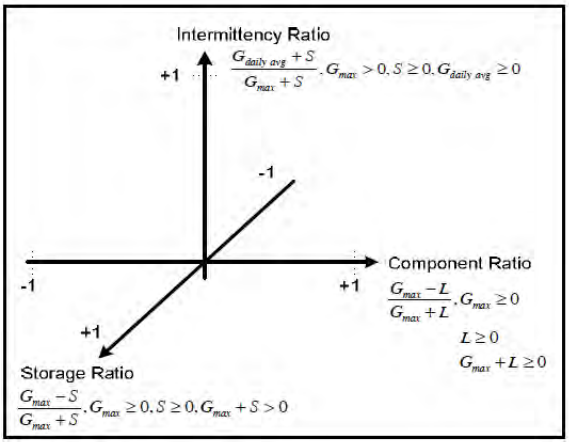


Figure 12.Qualitative tool for judging microgrid “grid citizenship”. From [26].

3.5.4 EQUIVALENT HOURS OF STORAGE

The *equivalent hours of storage* corresponds to the storage capacity expressed in hours. The physical capacity is the number of hours of storage multiplied by the power design load. This index should be explored as potential indicator of flexibility in buildings with storage system.

$$N_{h\_S} = \frac{S_{des}}{L_{des}} \qquad \text{Eq. 45}$$

4 CASE STUDIES

4.1 MONITORED BUILDINGS

The monitored data are available for six buildings, which represent different building topologies and renewable energy technologies. Table 3 gives an overview of seven case studies which are identified using the notation MB, *for monitored buildings*. Not all six buildings are fulfilling the zero energy standard. This is the case of MB5: two set of data are available for this multifamily house in Italy (2009 and 2011) being the data of year 2011 closer than the zero balance due to a reduction of loads and greater energy generated from the PV system. MB1 which is a house in Denmark and MB6 which is a refurbished building in Germany where a CHP system was installed are nearly ZEB.

Table 3.Overwiew of the case studies: Monitored Buildings

Case study	Country	Building type	Technologies	Energy infrastructure	Resolution Time
MB1	Denmark	Single family house	Photovoltaic / Heat pump + Solar Thermal	Electricity grid	1 hour
MB2	Denmark	Single family house	Photovoltaic / Heat pump + Solar Thermal	Electricity grid	1 hour
MB3	Denmark	Single family house	Photovoltaic + Solar Thermal / Heat pump	Electricity grid	12 min
MB4	Singapore	Office	Photovoltaic / Electric driven chillers	Electricity grid	1 hour (year)
MB5	Italy	Multi- family house	Photovoltaic + Solar Thermal /Heat pump / Cooking system with metane	Electricity grid & metane	1 hour
MB6	Germany	Multi- family house	Gas driven CHP, additional condensing boiler, water storage, smart control	Electricity & gas grid	5 min
MB7	Sweden	Single family house	Photovoltaic + Solar thermal / Heat Pump	Electricity grid	1 min

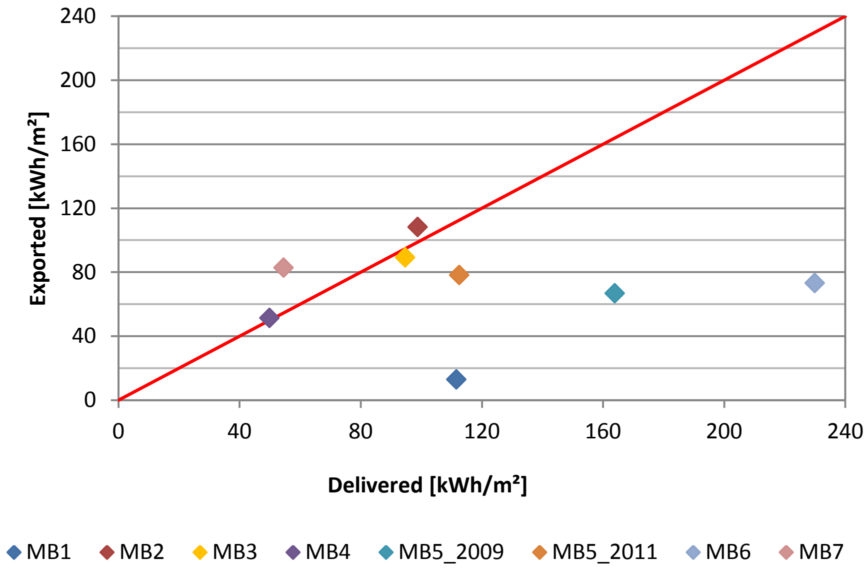


Figure 13. ZEB status exported v. delivered for the monitored buildings. Figures are in kW·h/m² (Primary Energy)

4.1.1 MB1 AND MB2- FLAMINGO HOUSE - DENMARK

The Flamingo house is a single family house in Denmark, with a gross floor area of 166 m living space. The house was built in 2008 and is occupied by a family: two adults and two children.

The annual space heating demand is calculated to be 18 kWh/m. The energy system is composed by 16 m2 of PV panels (2 kW_p), 8 m of thermal solar collectors for domestic hot water and space heating and a 5 kW ground coupled heat pump for both domestic hot water and space heating. More details may be found on: www.flamingohuset.dk (unfortunately only in Danish).

Measurements are available for more than one year since February 2009, in 1-hour resolution. For the analysis in that report data corresponding to the year 2012 has been selected (MB1). The Flamingo house is not a NetZEB. Then, a variation of the MB1 case has been generated artificially with the hypothesis of increasing the PV capacity by a factor of 4.5, which is identified as the MB2 case study.

Table 4.Features of the MB1 and MB2 case studies. The Flamingo house

Characteristic	Value
Installed PV capacity – MB1	2.0 kWp
Installed PV capacity – MB2	10.0 kWp
Installed PV area – MB1	16 m^2
Solar thermal area	8 m^2
Building area	166 m^2
Design connection capacity	10 kW[3]
Thermal storage capacity/volume	300 litres
Electrical storage capacity	-

[3] 25 A / 400 V = 10 kW

4.1.2 MB3 - ENERGY FLEX HOUSE - DENMARK

EnergyFlexHouse® consists of two, two-storied, single-family houses in Denmark, with a total heated gross area of 216 m each. The two buildings are in principle identical, but while the one building acts as a technical laboratory (Energy-FlexLab), the other is occupied by typical families who test the energy services (EnergyFlexFamily). The houses are built so they are better than the Low E class 1 defined in the former Danish Building Code from 2008. The annual energy demand for space heating, ventilation, DHW and building-related electricity (not including energy for the household) amounts to less than 30 kWh/m. With the PV production, EnergyFlexFamily is energy neutral over the year including the demand for electricity of the household and an electric vehicle. The heating system consists of two heat pumps and a solar heating system. One of the heat pumps produces space heating via the floor heating system. The other heat pump is located in series with the passive heat exchanger of the ventilation system. This heat pump both preheats fresh air and DHW. The solar heating system preheats primarily DHW but may also deliver space heating. The efficiency of the passive heat exchanger is around 85%.

The layout of the two houses is similar to the layout of many Danish single-family houses, although reversed concerning the use of the two floors. The buildings were put into operation during the autumn of 2009. Analyzed data corresponds to year 2010 which has been recorded with a 12 minutes resolution and do not include EV consumption.

Table 5.Features of the MB3 case study. The EnergyFlex house.

Characteristic	Value
Installed PV capacity	10.6 kWp
Installed PV area	60 m^2
Solar thermal area	4.8 m^2
Building area	216 m^2
Design connection capacity	25.2 kW[4]
Thermal storage capacity/volume	180 litres
Electrical storage capacity	-

[4] 63 A / 400 V = 25.2 kW

4.1.3 MB4 - ZEB @ BCA ACADEMY - SINGAPORE.

ZEB @ BCA Academy is a non-residential-Educational building, with PV generation, located in Singapore. This building is operating since 2009, with a 4.500 m^2 of net floor area and 2.018 m^2 of conditioning area. The ZEB project is intended as a functioning demonstration in the efficient use of energy in a building through both passive and active means for which a section of the existing BCA Academy has been converted for this purpose. Glazing, lightweight wall systems, shading devices, light shelves and green walls are incorporated into the west facade. Some rooms at the ground level have ducting of natural light for illumination. Light tubes are also installed to direct light into the interior of an office environment. The roofs are covered with solar PV panels to generate sufficient electrical energy to be self-sustaining, and certain part of the roof incorporates a ventilation stack to test the effect of convection air movement within a naturally ventilated environment.

Table 6.Features of the MB4 case study – ZEB @ BCA Singapore

Characteristic	Value
Installed PV capacity	190 kWp
Installed PV area	1 540 m^2
Building area	4500 m^2
Design connection capacity	200 kW
Electrical storage capacity	-

4.1.4 MB5 - Leaf House - Italy

Leaf House is a technologically innovative muti-family house: its characteristics of cheapness, simplicity, efficiency and silence combine and integrate to create a house made for the environment. Leaf House is a clean energy laboratory, a place to be studied and visited, awakening and educating people to future. Leaf House is an example of saving and respect; it is a house composed of six flats, a real house where real people live. The average electric consumption per family in Ancona area corresponds to about 2100 kWh/year. With all the precautions used in the Leaf House, the electric consumption should not exceed the 1.500 kWh/year. All consumptions are monitored and just after the first year of use it will be possible

to have more reliable data. The house is provided with a geothermal heat pump and thetechnical systems are completed by a solar thermal collectors field and a photovolatic system. The electric consumptions including the air-conditioning and the heating system ones are covered by the photovoltaic plant integrated in the building cover. Real monitored data are available with 1 hour time resolution. Two set of data are analysed in this report corresponding to year 2009 and 2011.

Table 7.Features of the MB5 case study – The Leaf house

Characteristic	Value
Installed PV capacity	20.0 kWp
Installed PV area	150 m^2
Solar thermal area	19 m^2
Building area	480 m^2
Design connection capacity	50 kW
Thermal storage capacity/volume	1000 litres
Electrical Storage capacity	-

4.1.5 MB6 – CHP WUPPERTAL- GERMANY

A combined heat and power unit (CHP) with smart control was integrated in the heat supply of a typical multifamily building in Wuppertal, dated from early 1900 [31]. Buildings of this type are characteristic for many cities in Germany and form the appearance of old town quarters with complete perimeter block developments. Due to heritage for the historical facades, thermal insulation measures are limited and expensive. The original heat supply was a central natural gas boiler for space heating by radiators combined with electric heaters for DHW in the individual apartments. The measured gas consumptions achieved 145 kWh/m·y before the modification of the heating system. With a research project supported by the foundation "Zukunft NRW" the building was equipped with a central CHP unit using natural gas and assisted by a condensing boiler for peak heat loads. The DHW water supply was combined with the central heating system to generate an additional, all year round heat load. To allow flexibility in operation times and cycles of the CHP a 2 m water tank acts as thermal buffer together with the very high thermal mass of the building structure. The experimental control system is based on a cost optimization function and a prediction algorithm for the thermal and electric load of the building. In practice the CHP unit was very flexible operated with respect to the power needs without neglecting coverage of the heat demand. Almost no use of the gas boiler was recorded (only Jan/Feb). The total gas consumption in 2011 was measured to 171 kWh/m/y combined with 61 kWh/m of electricity generation, of which 28 kWh/m/y were supplied to the grid and the other 33 consumed in the households.

Table 8.Features of the MB6 case study - CHP Wuppertal - Germany case study

Characteristic	Value
Installed CHP power	5.5 kW
Installed CHP heat	14.8 kW_t
Installed gas burner capacity	14.0 kW_t
Building area (heated)	465 m^2
Number of occupants	12 persons
Design connection capacity	80 kW[5]
Thermal storage capacity/volume	2000 litres + 300 litres (DHW)
Electrical storage capacity	-

[5] 80 kW is the reference value for the case of electric supply for DHW; 40 kW in case that DHW is supplied by othar energy carriers / systems (CHP, gas burner, etc.). We take 80 kW as the reference value for the connection capacity.

4.1.6 MB7 – FINNÁNGEN HOUSE - SWEDEN

The Finnängen house is the first renovated plus-energy house in Sweden. Finnängen was built in 1976 (Myresjöhus). The building has a wooden structure with brick decoration. Due to moisture risk in the cellar wall (concrete with wooden beams just inside) the owners decided to renovate the house in 2010 and add an extension. The walls were clad with air-tightness layer, external insulation and plaster. The roof tiles were exchanged to steel roof, photovoltaic and solar-thermal. The building envelope can now be classified as a passive-house according to the FEBY criteria (air-tightness 0,13 ACH, U-value roof 0,07 W/m2K wall 0,10 W/m2K, new ground 0,12 W/m2K), except for the old house ground that was not refurbished. Space heating is supplied through hydronic floor heating and radiator system which is heated by solar thermal and horizontal ground source heat pump system. In 2011 the house used 7202 kWh (28,6 kWh/m2) totally, out of which ~3000 kWh (12 kWh/m2) is used in the heat pump, ~1000 (4 kWh/m2) is used for ventilation and heating circulation. The remaining ~3000 kWh (12 kWh/m2) is household electricity. The power supply through the photovoltaic system was 8356 kWh in 2011, thus a surplus of 1154 kWh. Monitored data from the building has been recorded with 1 minute time resolution and the analyzed data corresponds to the year 2011.

Table 9.Features of the MB7 case study – The Finnängen house

Characteristic	Value
Installed PV capacity	10.0 kWp
Installed PV area	68 m^2
Solar thermal area	11.8 m^2
Building area	252 m2
Design connection capacity	17 kW
Thermal storage capacity/volume	750 litres
Electrical Storage capacity	-

4.2 SIMULATED BUILDINGS

The simulated data are available for nine case studies, which represent different building topologies and renewable energy technologies, see Table 10, which are identified using the notation SB, for simulated buildings. They are designed to fulfil the zero energy standard. However, when looking on the annual balance between consumption and production or imported and feed-in energy, five buildings are plus energy houses, and three are nearly zero houses, see Figure 14 and Figure 15.

Table 10. Overview of the case studies: Simulated Buildings

Case study	Country	Building type	Technologies	Energy infrastructure
SB1	Denmark	Single family house	Photovoltaic / Heat pump	Electricity grid
SB2	Denmark	Single family house	Photovoltaic / Heat pump	Electricity grid
SB3	Germany/ Spain	Single family house	Photovoltaic	Electricity grid
SB4	Germany/ Spain	Single family house	Photovoltaic / battery	Electricity grid
SB5	Finland	Single family house	Micro wood pallets CHP	Electricity grid
SB6	Norway	Multi-family house	Photovoltaic / Heat pump	Electricity grid
SB7	Spain	Multi-family house	Photovoltaic	Electricity grid
SB8	Sweden	Multi-family house	Photovoltaic / Solar thermal collectors	Electricity grid + District heating
SB9	Sweden	Multi-family house	Photovoltaic / Solar thermal collectors / battery	Electricity grid + District heating

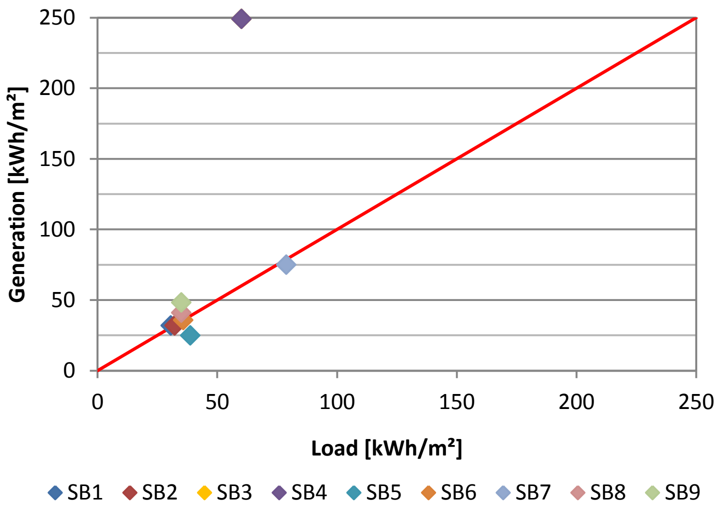


Figure 14. ZEB status generation vs. load

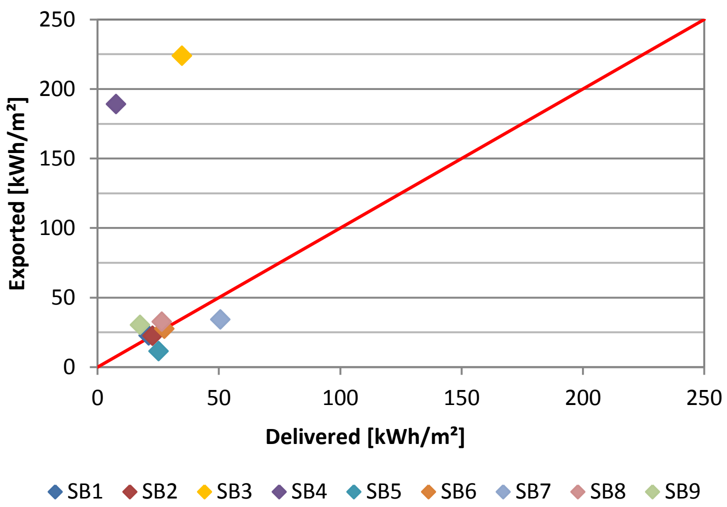
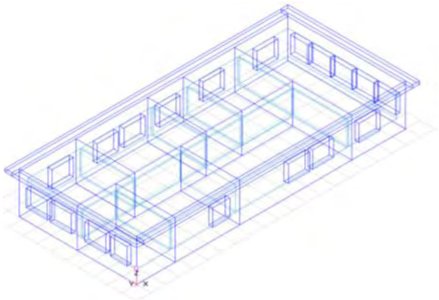


Figure 15. ZEB status exported vs. delivered energy

4.2.1 SB1 AND SB2 - DENMARK

The case study is a single family house located in Aarhus city in the northern part of Denmark. The building is 157m^2 with the main facades towards north and south. The energy supply system consists of the PV models, placed on the roof, and a ground source heat pump. The building is designed to be connected to the local power grid distribution system. The characteristics of the building are presented in and Table 11. Moreover, the main difference between the two Danish case studies is COP of the heat pump. It varies during the year between 3 and 4 or 2 and 3, for the first and second case study, respectively.

Table 11. Characteristics of the SB1 and SB2 case study



Characteristic	Value
Installed PV capacity	5,53 kWp
Installed PV area	44,3 m^2
Design connection capacity	n/a
Electrical storage system	-

4.2.2 SB3 AND SB4 - GERMANY

The case study is a "House for Europe", the Bergische Universität Wuppertal house participating in the Solar Decathlon Europe competition in 2010. The building is 50 m^2, it uses solar energy as the only energy source, and is equipped with technologies that permit maximum energy efficiency. PV generator systems on the roof and the south façade contribute, respectively, with about 6.4 and 3.8 kWp of installed capacity. The system is equipped with a 6 kW·h battery, enabling different modes of operation (grid connected, battery-buffered and occasionally stand-alone). SB3 set of simulated data corresponds to a system without storage. SB4 data set corresponds to a system with battery, where the battery use is optimized to preferably match the electricity demand of the house with its own solar energy generation.

Table 12. Features of the SB3 and SB4 case study

Source Peter Keil

Characteristic	Value
Installed PV capacity	10.2 kWp
Installed PV area	70 m^2
Design load capacity	15 kW
Design connection capacity	15 kW
Storage capacity (full charge to discharge in 1h)	2.91 kW
Storage capacity	6 kWh

4.2.3 SB5 – FINLAND

The house is located in Helsinki, Finland (60.2°N, 24.9°E). It is one-story house with floor area of 150 m2. The height of the first floor is 2.5 m, covered by a ventilated attic space that is not considered a heating space. The total glazing area is 21 m^2, which corresponds to 16% of the heated floor area. External solar shading is considered as solar protection for all windows. Additionally, a window opening strategy is used by considering 0.375 m^2 (1.5m height and 0.25m width) of each window is airing and has a possibility to open to avoid overheating during summer. Therefore, there is no need for cooling systems. The indoor air temperature is set at 21 ºC. All rooms in the house are heated by water radiators. The profiles of occupancy, DHW, lighting, and household appliances are compiled based on a detailed measured hourly profile of the RET project conducted by VTT in 2005 [32]. The house is simulated by Trnsys 17 software [33]. A 1.38 kW_e wood pellet Stirling engine (WP-SE) is the standalone biomass-based micro CHP.

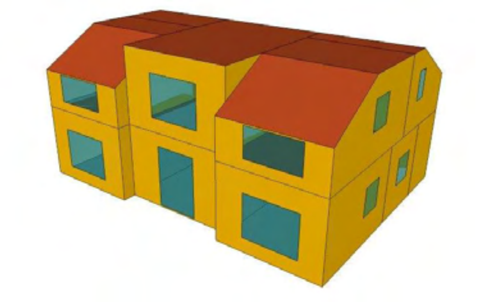
Table 13. Characteristics of the SB5 case study

Characteristic	Value
Installed CHP capacity	1,38 kW
Design connection capacity	n/a
Electrical storage capacity	-
Thermal storage capacity/volume	n/a

4.2.4 SB6 - NORWAY

The case study considers a cluster of 200 similar detached single-family houses. The basic segment of the study is a theoretical single-family house having an area of 160 m^2 and located in Oslo climate. The thermal properties of building envelop are adjusted to conform to the Norwegian passive house requirements. The heating needs of the house are fulfilled using a combination of an air-to-water heat pump and a solar thermal collector. Thermal collector covers most of the DHW needs during summer while heat pump covers the heating needs for both SH and DHW during the heating period. All the houses in the cluster are considered to have similar architectural characteristics and orientations, however, different number of occupants and appliance ownerships. The households' composition is adapted to represent the Norwegian national average whereas photovoltaic is designed to meet the average electrical consumption of all the 200 households in the cluster. The energetic performance of the heating systems is computed by simulating all the houses using stochastic occupant internal gains. This leads to annual seasonal performance factor of the heating systems vary between 3 to 5.5 (taking solar collector into account) for the different houses.

Table 14. Characteristics of the SB6 case study

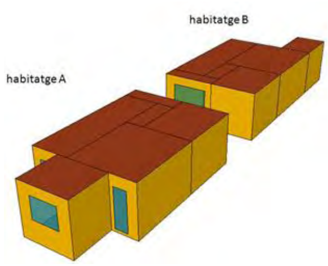


Characteristic	Value
Installed PV capacity	5,5 kWp
Installed PV area	50 m^2
Design connection capacity	n/a
Thermal storage capacity/volume	n/a
Electrical storage capacity	n/a

4.2.5 SB7 – SPAIN

The case study consists in a typical multifamily house from the latest 60's composed by 10 individual flats with an average useful surface of 55 m^2 per flat. The building is located in a high dense block typical in the metropolitan area of Barcelona. The case study considers retrofit options based on adding insulation to the facades and the roof, improving quality of the windows, both frame and glazing systems, and considering appropriate fixed and shading devices to prevent overheating. The building is considered to be provided by a solar thermal system to cover part of the DHW needs and a reversible heat pump for the heating and cooling loads. The roof is covered by a PV system of 37 kW_p.

Table 15. Characteristics of the SB7 case study

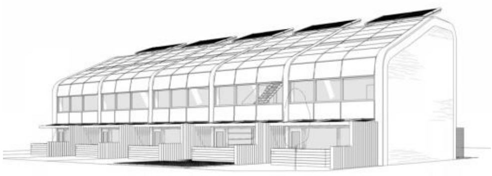


Characteristic	Value
Installed PV capacity	38 kWp
Installed PV area	400 m^2
Installed solar thermal area	22 m^2
Design connection capacity	44 kW
Thermal storage capacity/volume	1500 litres
Electrical Storage capacity	-

4.2.6 SB8 AND SB9 - SWEDEN

The Swedish building is designed as a terraced house with five dwellings. Each dwelling has a conditioned area of 138 m2. The building, situated in the city of Malmö in the south of Sweden, is designed to be connected to the electricity grid and district heating network. A large roof and facade towards south-southwest are equipped with PV modules. On the top of the roof, which is horizontal, solar thermal collectors are mounted. A battery for storing electricity is installed, but the building also relies on the grid as a battery, both for heat and electricity and will therefore export energy when the building's system generates a surplus which cannot be stored and import energy when the building's system does not produce the quantities of energy required. The energy performance of the building is investigated based on hourly data generated by simulations, using VIP Energy (http://www.strusoft.com/products/vip-energy).

Table 16. Characteristics of theSB8 and SB9 case study



Characteristic	Value
Installed PV capacity	34 / 37 kW_p
Installed PV area	265 m^2
Design load capacity, heating	16 kW
Design load capacity, electricity	5 kW
Design connection capacity	37 / 44 kW
Storage capacity(full charge to discharge in 1h)	5 kW
Storage capacity	25 kWh

5 RESULTS AND DISCUSSION

5.1 OVERVIEW OF ENERGY BALANCE

An overview of the annual values for the main yearly quantities in the energy balances (generation, load and net exported) are presented in the following graphs, together with the monthly pattern of the net exported electricity.

A statistical representation of each quantity is presented. In the case of yearly graphs, each notched box represents the percentile 10, 25 (or lower quartile), 50 (the median), 75 (or upper quartile) and percentile 90. Whiskers extending from the box represent the percentil 5% and 95%, bottom and up respectively. Small cross represents percentile 1% and 99% and mininum and maximum values of the distribution are depicted by a solid square. Small square inside the each box indicates the mean value. (see example in Figure 16).

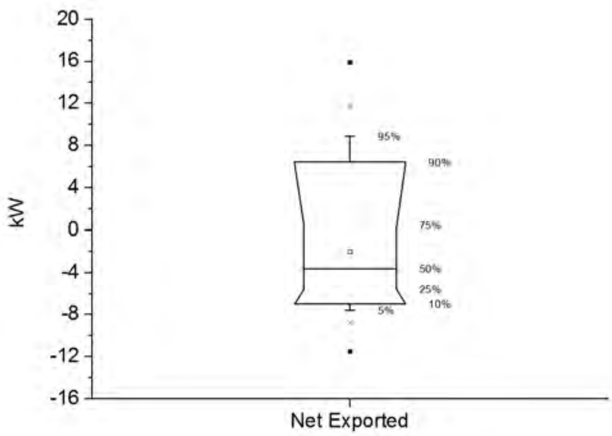


Figure 16. Sketch of the statistical values represented in yearly graphs.

In the case of the monthly graphs, for each box, the bottom horizontal line indicates percentil 10%, then the lower quartile, the median (horizontal line), the upper quartile and the upper horizontal line represents the percentil 90%, respectively. Small box inside the each box indicates the mean value. Whiskers extending from the box represent the minimum and maximum values of the distribution.

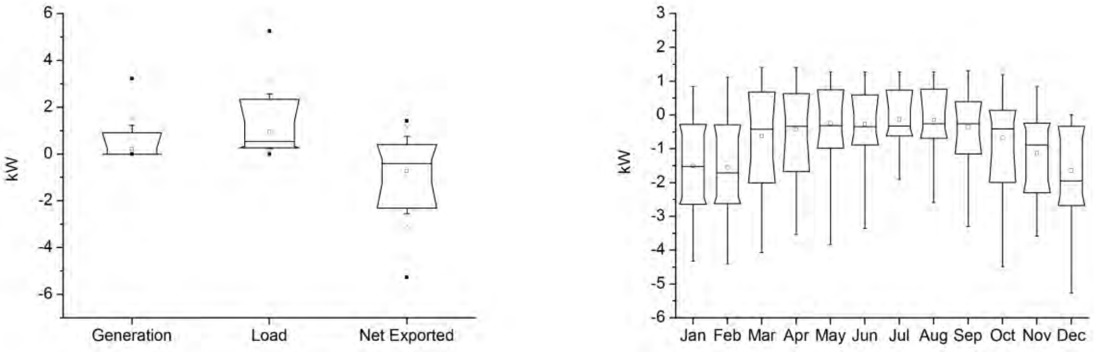


*Figure 17. **Case study MB1.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

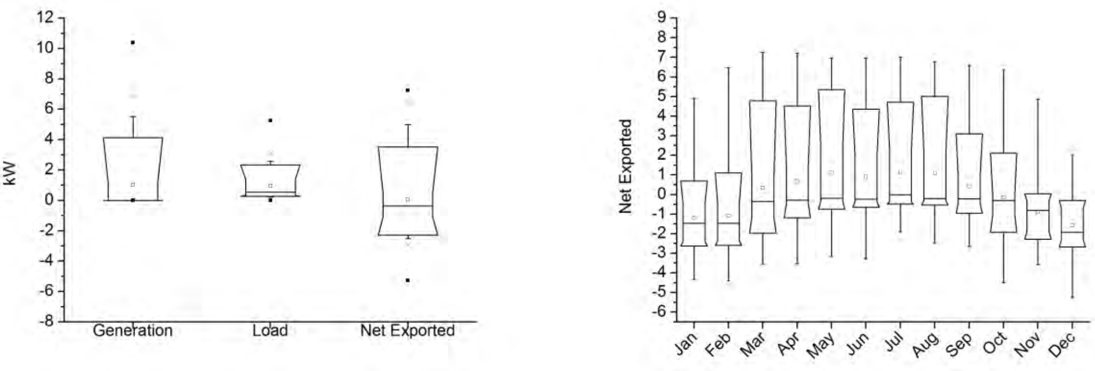


*Figure 18. **Case study MB2.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

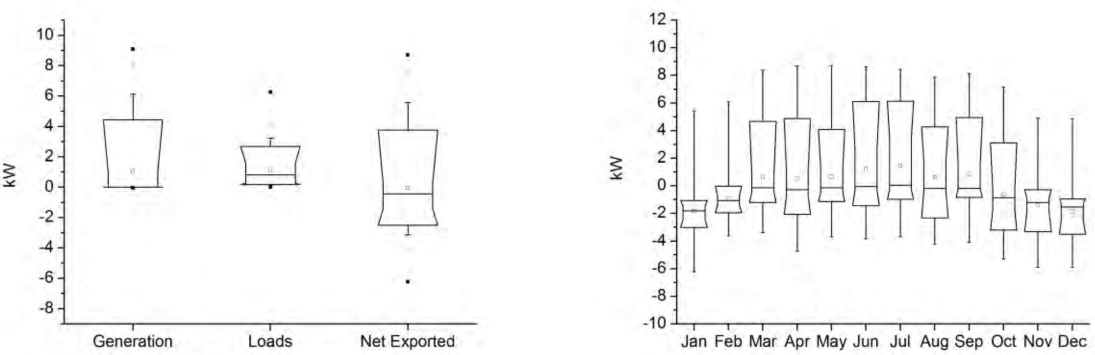


*Figure 19. **Case study MB3.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

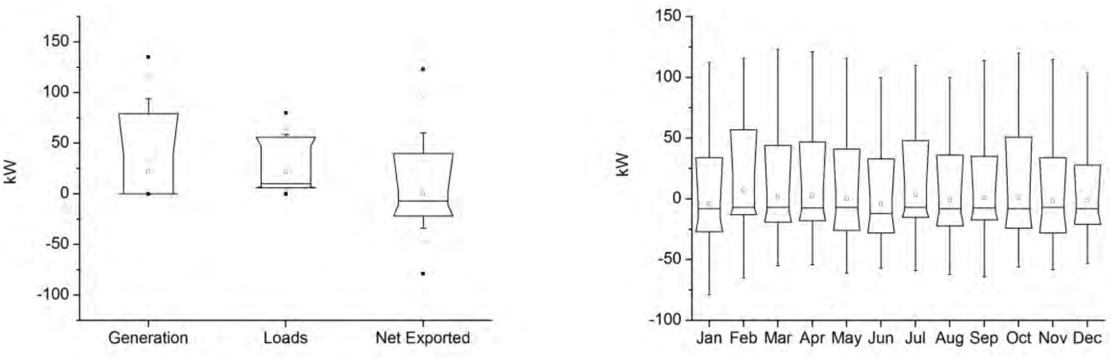


*Figure 20. **Case study MB4.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

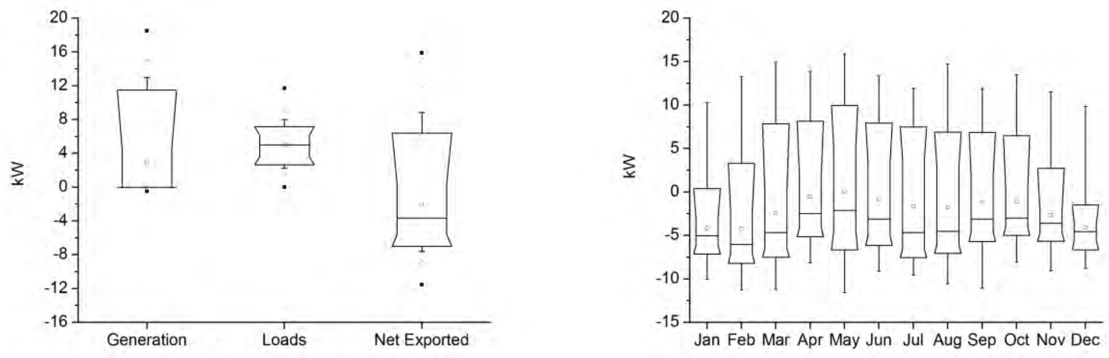


*Figure 21. **Case study MB5, year 2009.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

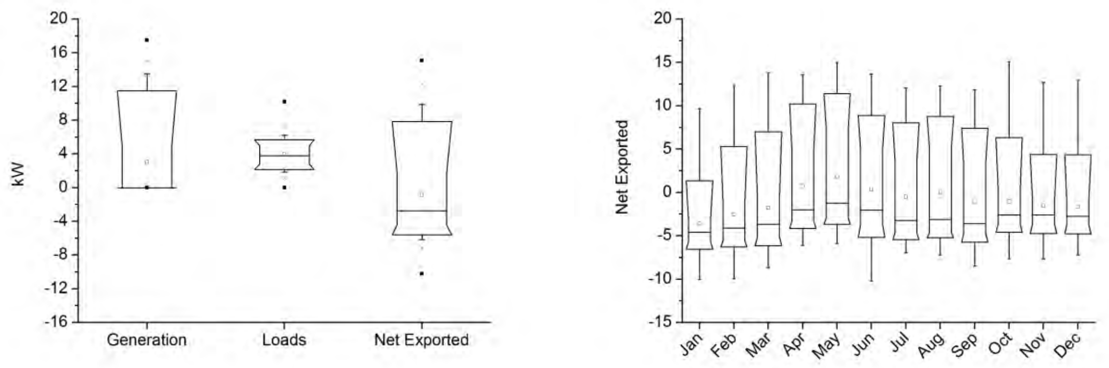


*Figure 22. **Case study MB5, year 2011.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

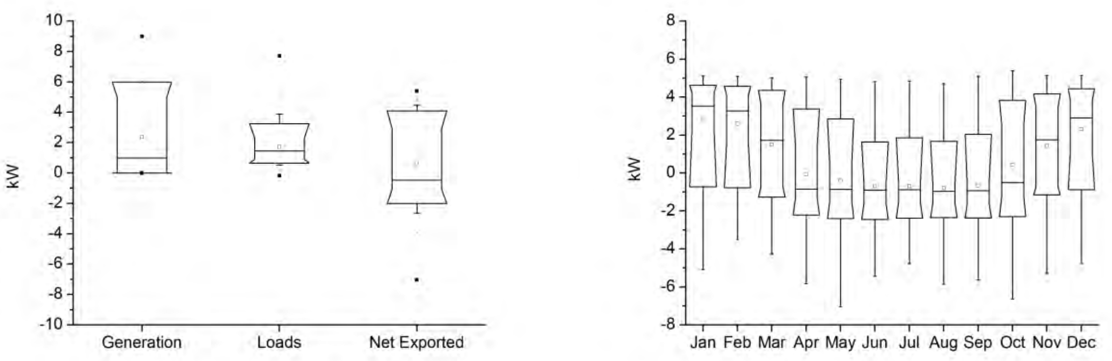


*Figure 23. **Case study MB6.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

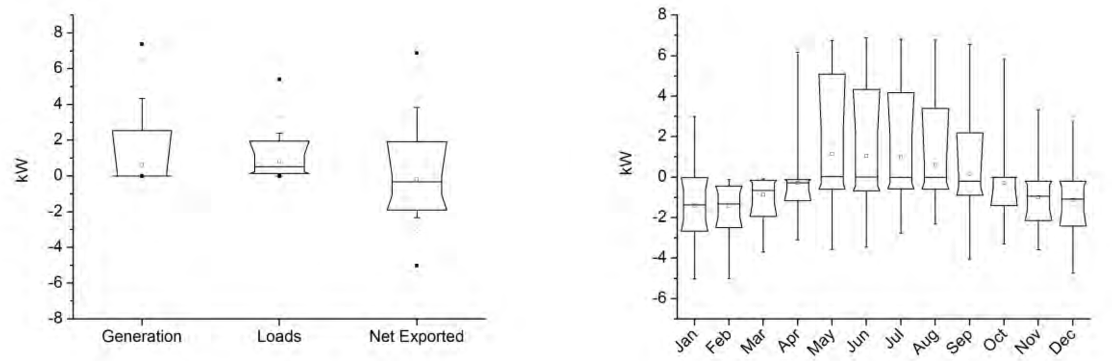


*Figure 24. **Case study MB7.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

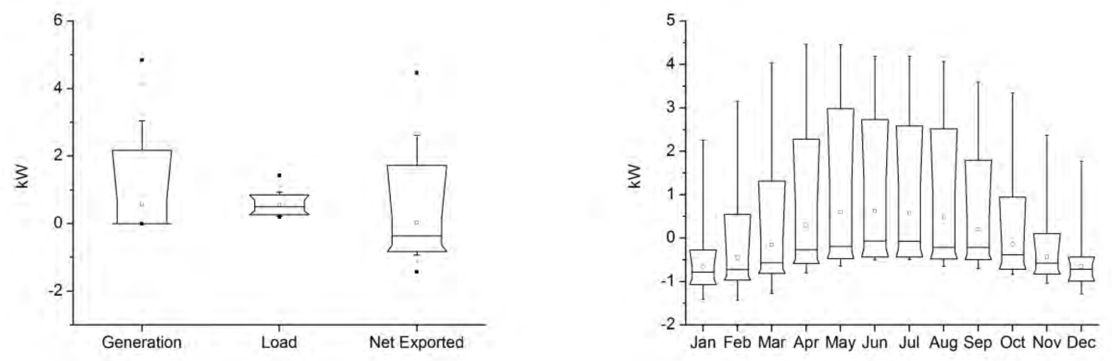


*Figure 25. **Case study SB1.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

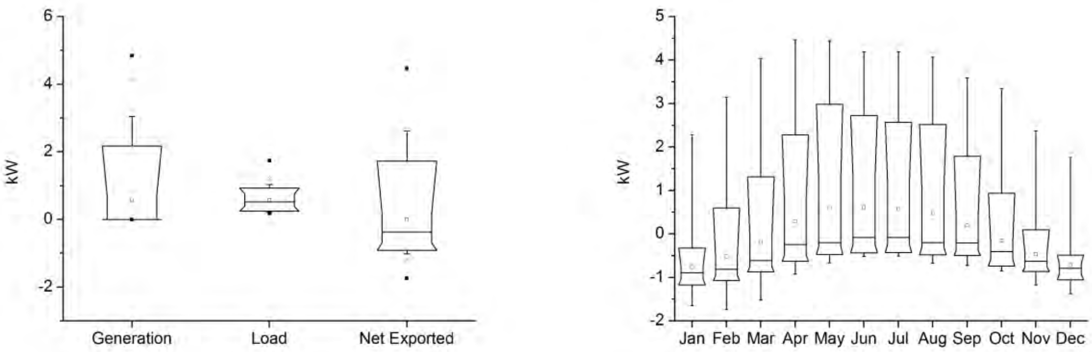


*Figure 26. **Case study SB2.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

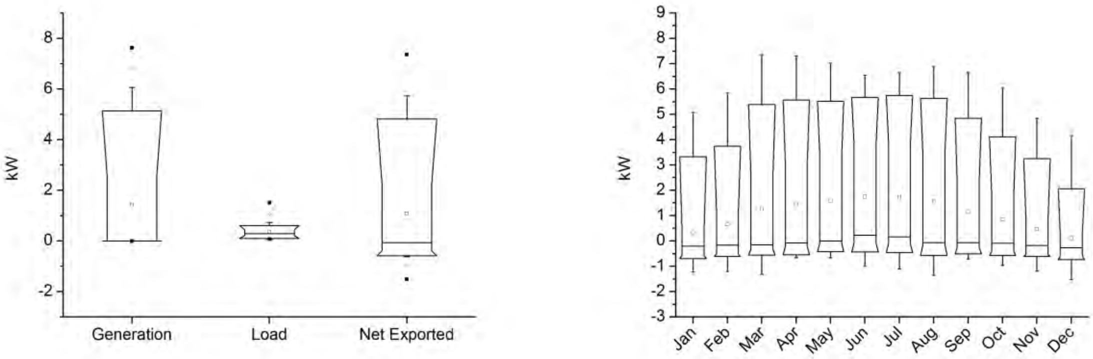


*Figure 27. **Case study SB3.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

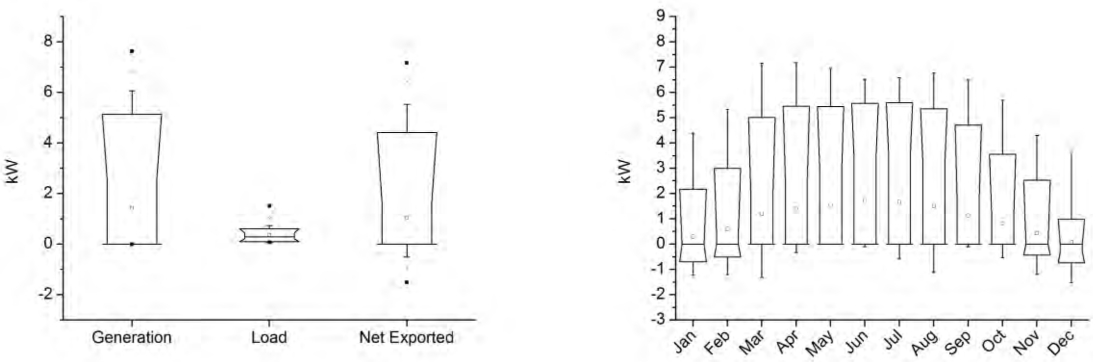


*Figure 28. **Case study SB4.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

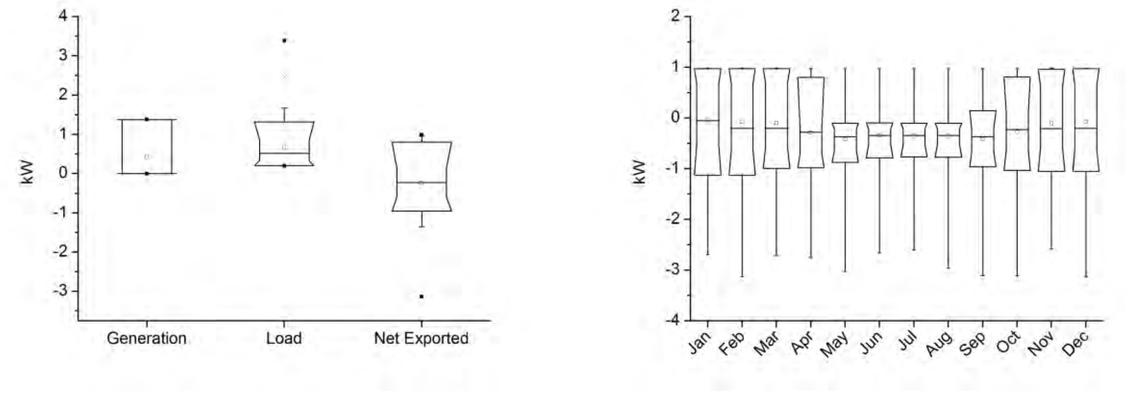


*Figure 29. **Case study SB5.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

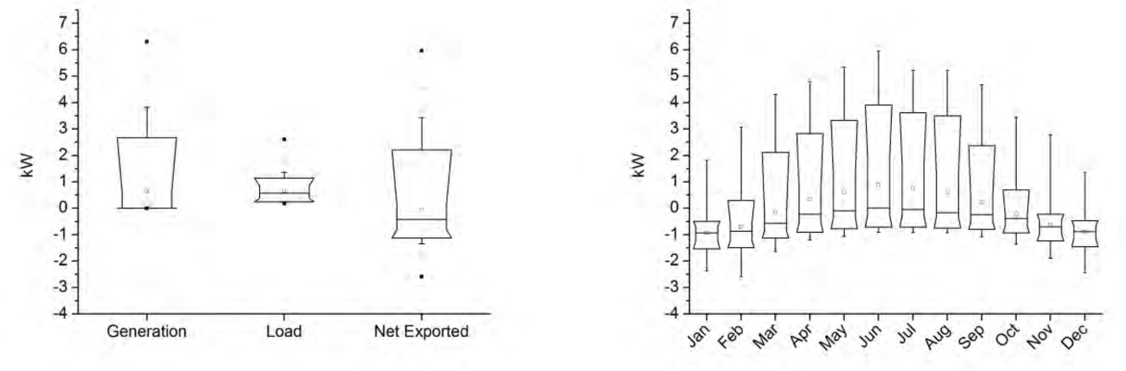


*Figure 30. **Case study SB6.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

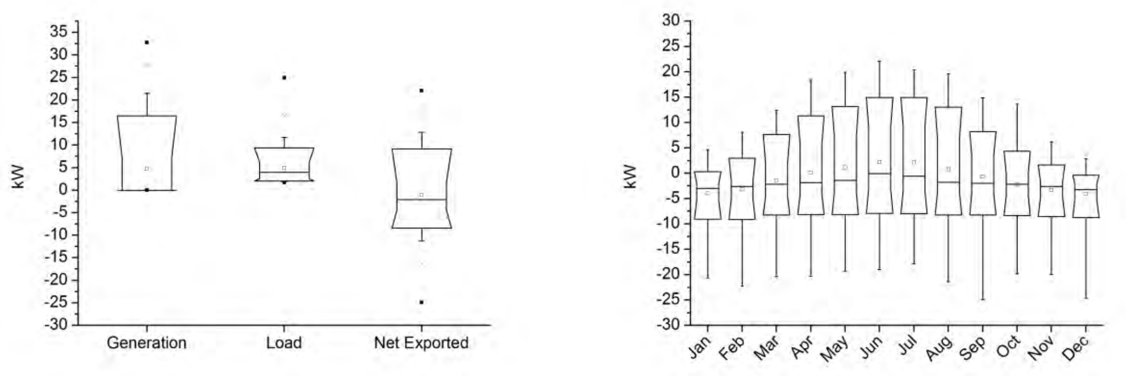


*Figure 31. **Case study SB7.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

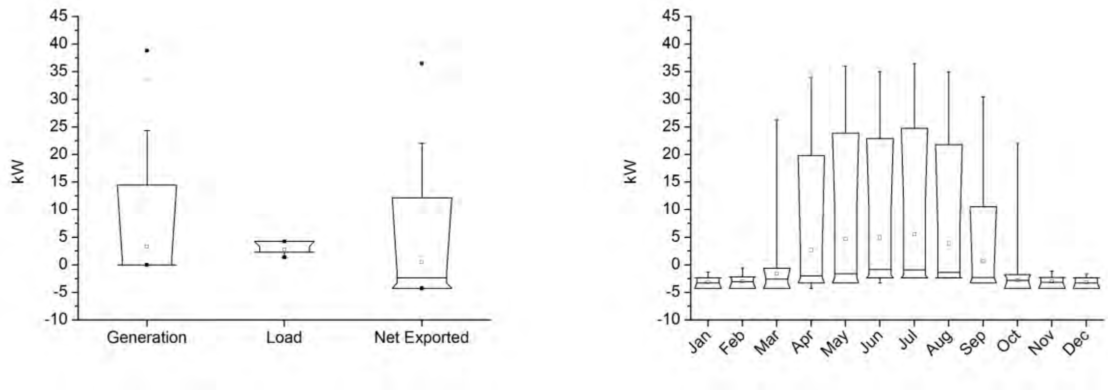


Figure 32*. **Case study SB8.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

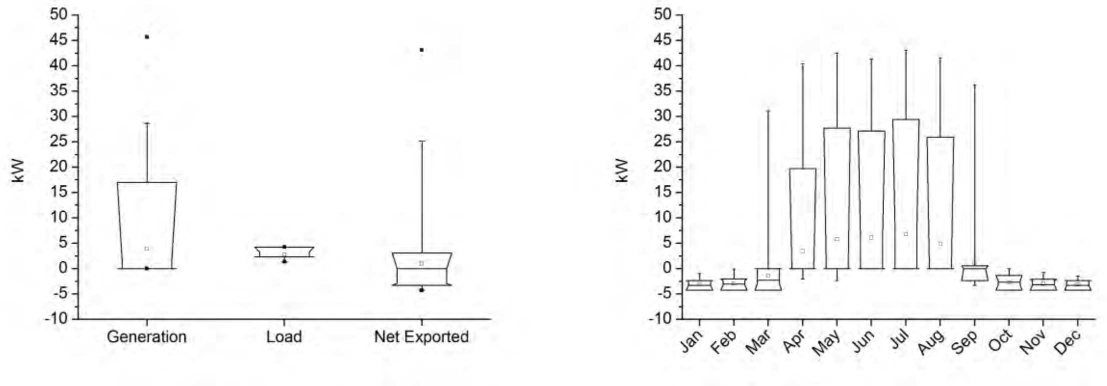


Figure 33*. **Case study SB9.** Generation, load and net exported energy values (left) and monthy generation of the net exported electricity (right) in kW.*

The graphs presented above gives a clear picture of the main magnitudes (generation, load and net exported energy) and also the seasonal differences between months. All buildings whichs bases their strategy on using PV, as method for compensating the energy balance, exports more energy in summer months, except case MB4 which shows only slight differences between months due to the climate. Buildings equipped with CHP (MB6 and SB5) shows a complete different trend, exporting more energy in winter times. The graphs help to appreciate the differences between peak values (maximum and minimum) with percentiles. In most of the cases differences between peak net exported power and percentil 90% is significant and also for negative values (delivered energy). Usually trends of the peak values follows similar seasonal trends as the balance, although in the case of monitored data monthly variations of peak values are minor and more stochastic distributed. One possible explanation could be the influence of stochastic load in real data while daily profiles with minor or even none seasonal variation for different months are used in the simulation programs.

5.2 LOAD MATCHING FACTORS

As presented in chapter 3 the load matching (LM) factors describe the degree of matching of on-site energy generation to local energy demand, and thus they can also indicate the building's expected interaction with the energy infrastructure, i.e. the amount of imported and exported energy. In this section, the results of these factors for both monitored and simulated test cases are presented and discussed. In Table 17 and Table 18, the annual values for the load cover factor (γ_{load}) and the supply cover factor (γ_{supply}) are presented together with the loss of load probability ($LOLP_b$), for monitored and simulated case studies.

Mean hourly values of load and supply cover factors averaged over four months, which are chosen to represent different seasons, are shown for each case study from Figure 34 to Figure 50. Lack of values for γ_{supply} indicates periods with no on-site generation, correspondingly in these periods γ_{load} equals zero.

Table 17. Annual cover factors and loss of load probability for monitored case studies.

	MB1	MB2	MB3	MB4	$MB5_{2009}$	$MB5_{2011}$	MB6	MB7
γ_{load}	0.140	0.239	0.206	0.582	0.306	0.326	0.585	0.179
γ_{supply}	0.588	0.222	0.216	0.575	0.519	0.420	0.427	0.236
$LOLP_b$	0.829	0.701	0.717	0.734	0.742	0.703	0.522	0.715

Table 18. Annual cover factors and loss of load probability for simulated case studies.

	SB1	SB2	SB3	SB4	SB5	SB6	SB7	SB8	SB9
γ_{load}	0.309	0.296	0.422	0.872	0.376	0.246	0.358	0.241	0.476
γ_{supply}	0.295	0.297	0.102	0.217	0.585	0.246	0.453	0.205	0.358
$LOLP_b$	0.716	0.717	0.576	0.205	0.735	0.728	0.694	0.827	0.863

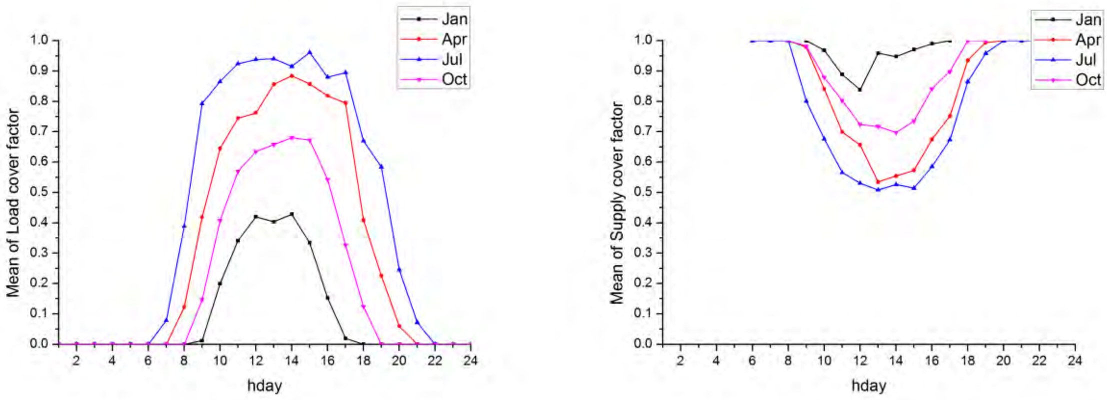


Figure 34. ***Case study MB1.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

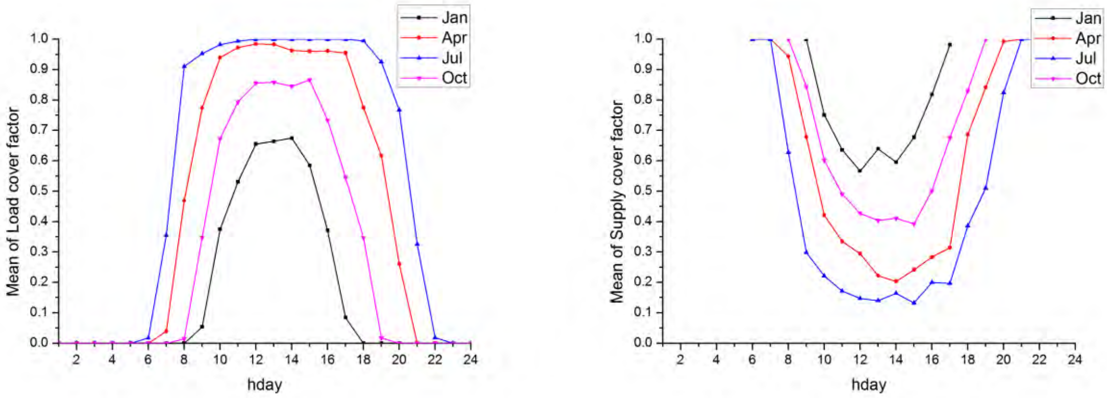


Figure 35. ***Case study MB2.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

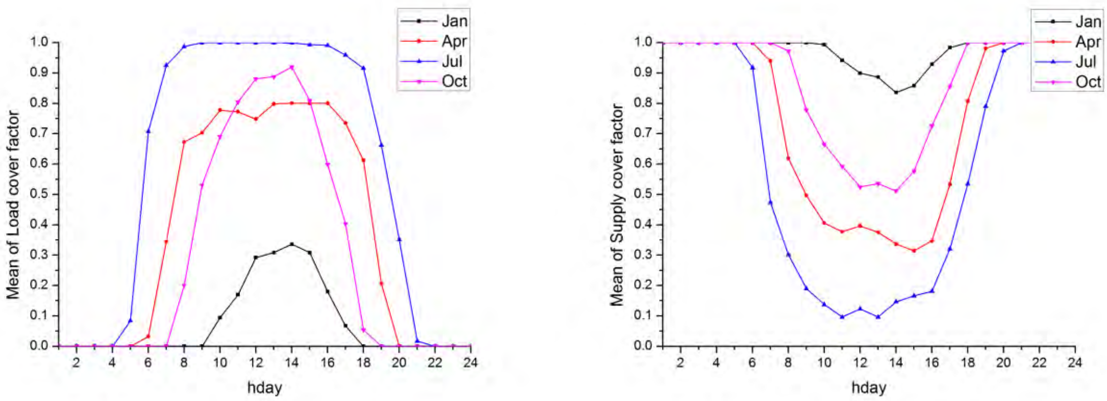


Figure 36. ***Case study MB3.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

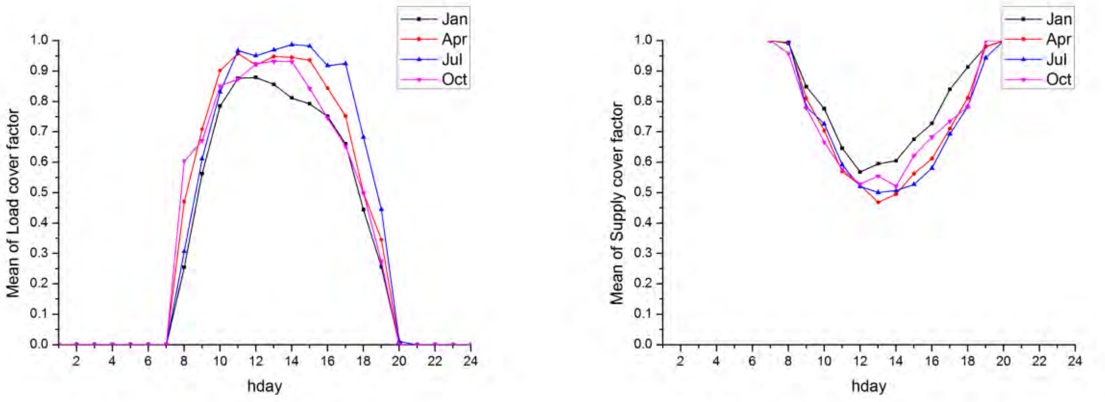


*Figure 37. **Case study MB4.** Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

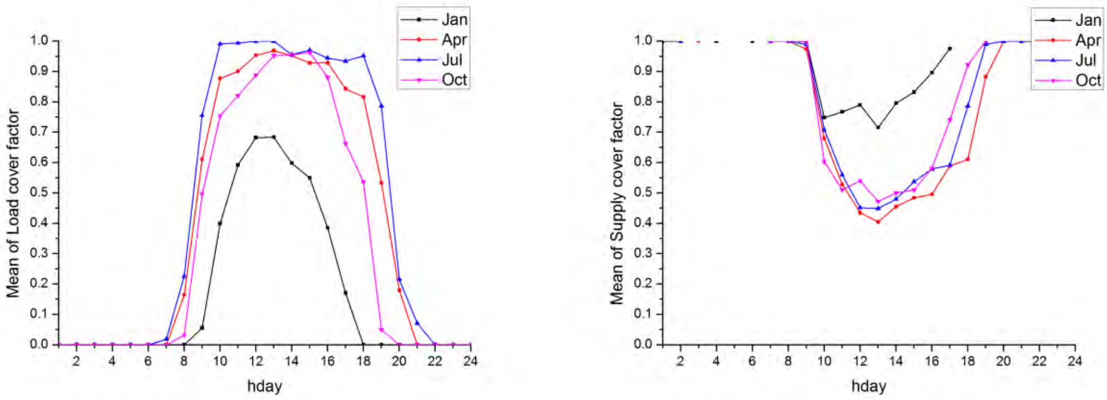


*Figure 38. **Case study MB5. Year 2009.** Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

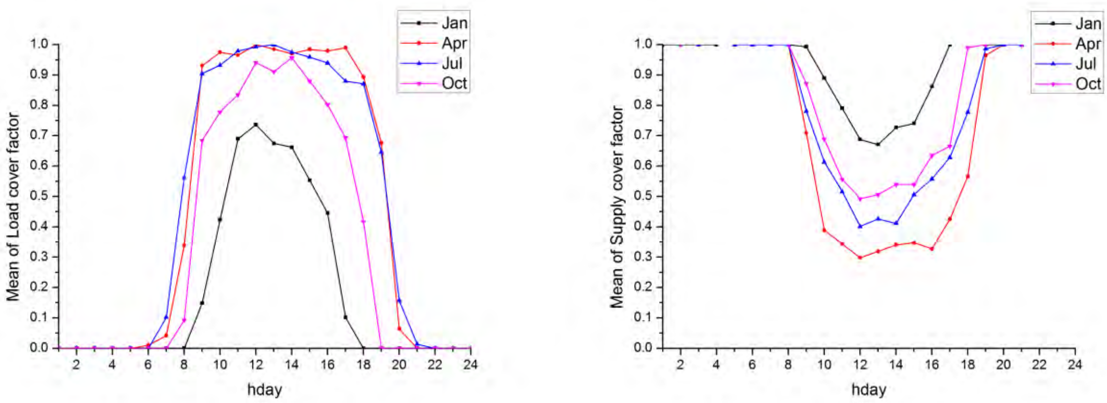


*Figure 39. **Case study MB5. Year 2011.** Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

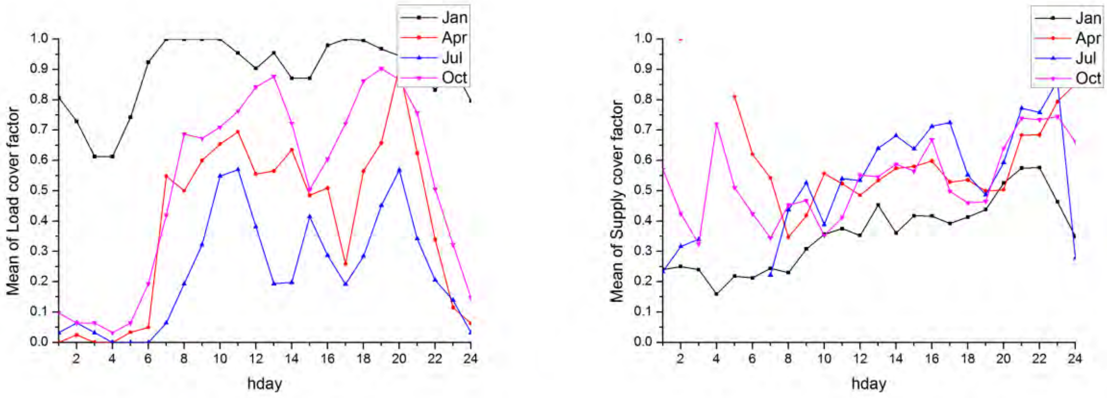


Figure 40. ***Case study MB6.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

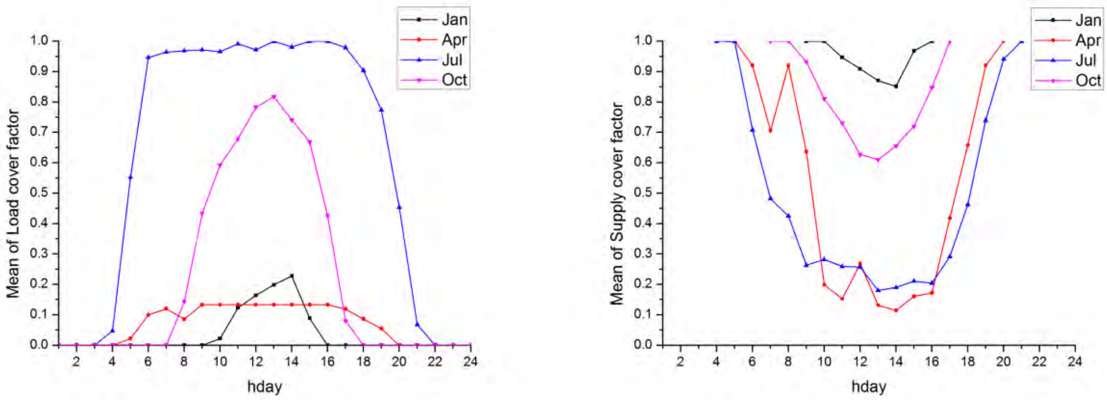


Figure 41. ***Case study MB7.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

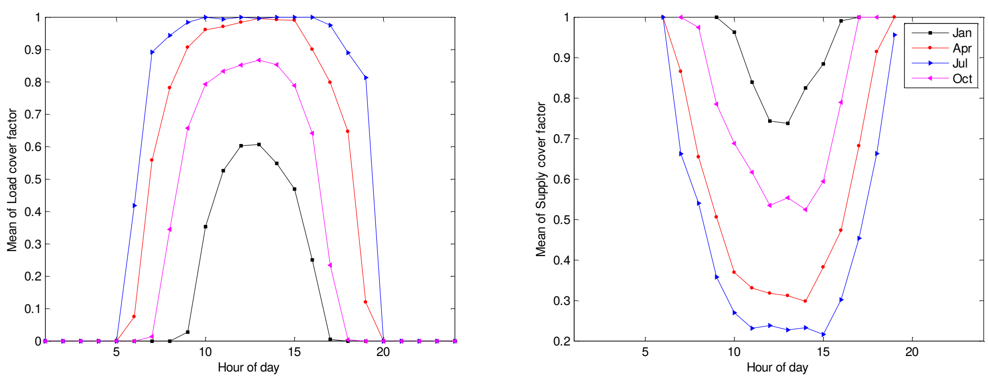


Figure 42. ***Case study SB1.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

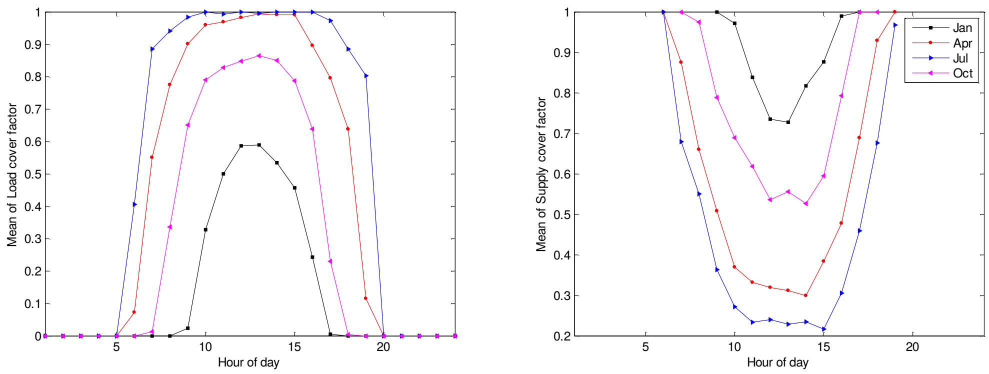


Figure 43. ***Case study SB2.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

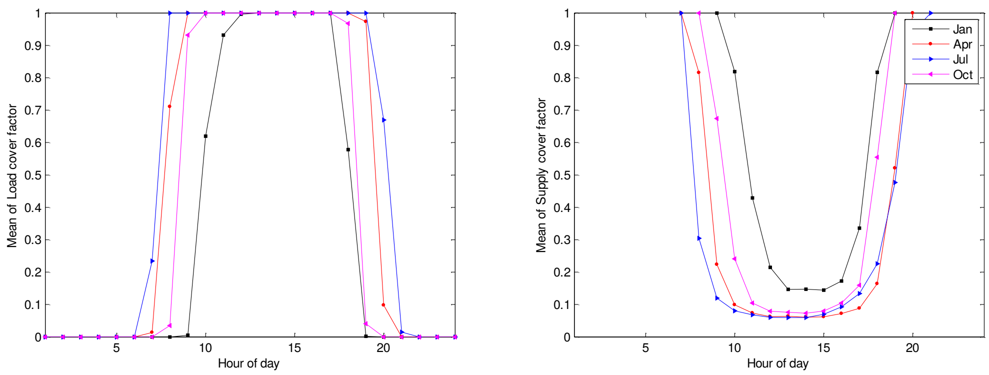


Figure 44. ***Case study SB3.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

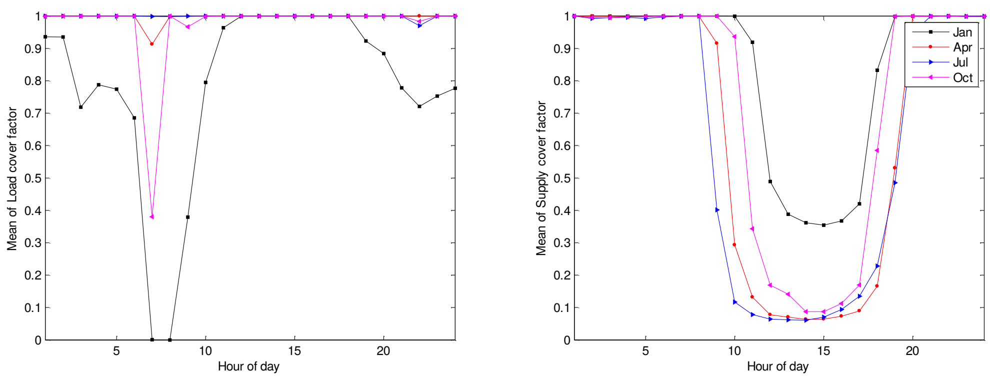


Figure 45. ***Case study SB4.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

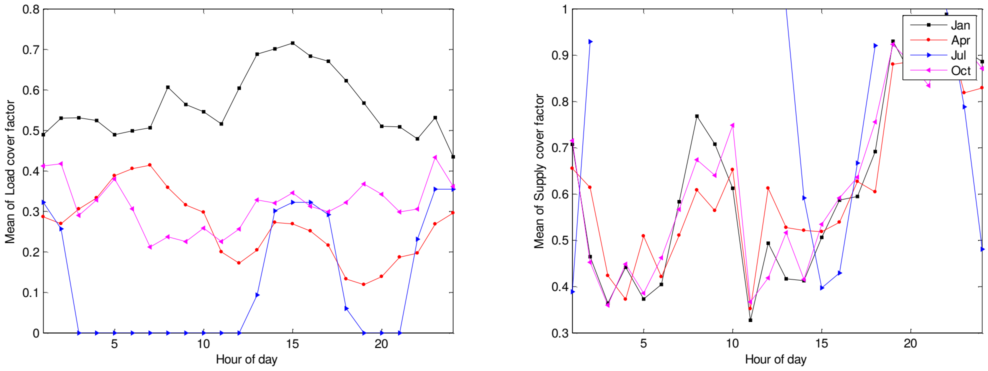


Figure 46. ***Case study SB5.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

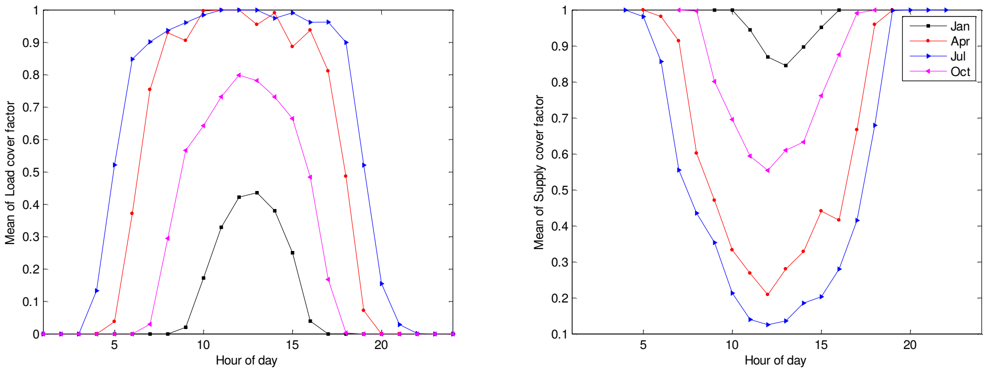


Figure 47. ***Case study SB6.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

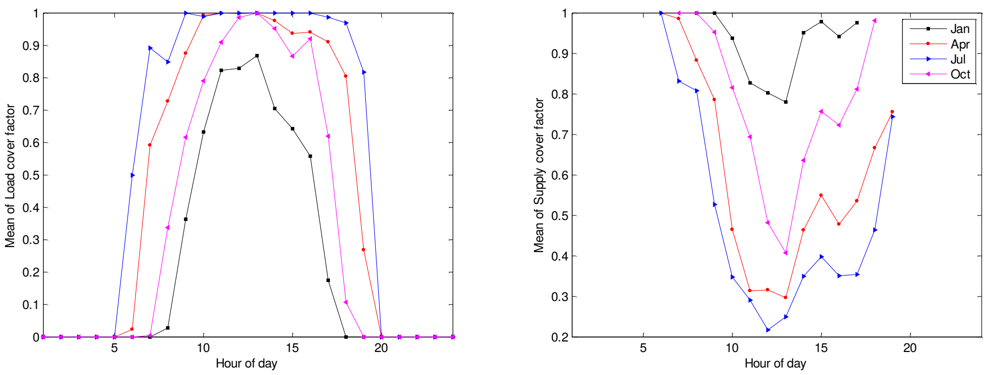


Figure 48. ***Case study SB7.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

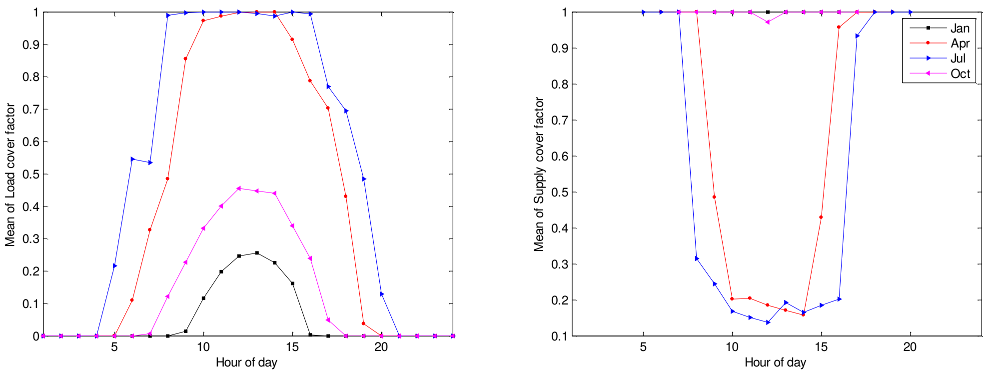


Figure 49. ***Case study SB8.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

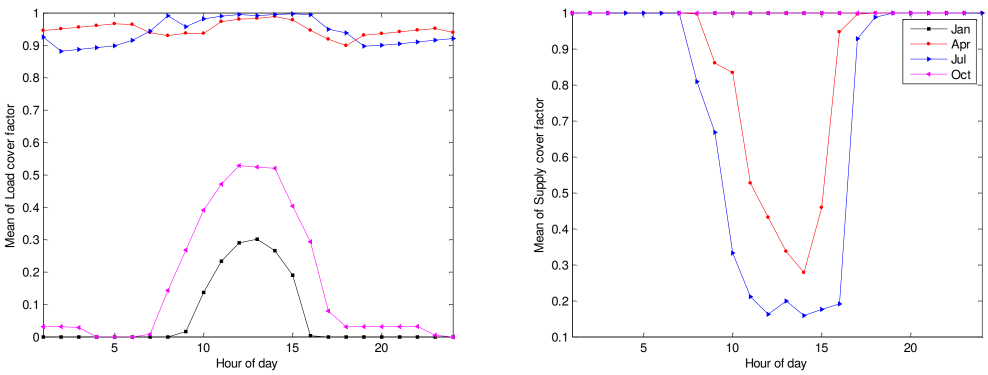


Figure 50. ***Case study SB9.*** *Mean daily load cover factor (left) and supply cover factor (right) for selected four months.*

The SB1, SB2, SB6, MB2, MB3 and MB7 represent so called "typical" zero energy residential building, i.e. PV installation in combination with heat pump, located in heating dominated climate. For these case studies there is a significant seasonal variation of γ_{load} and γ_{supply}, e.g. for SB6 at 2 p.m. γ_{load} varies between 0.38 and 0.99, and γ_{supply} ranges from 0.18 to 0.89. It is a result of big azimuth and altitude angle variations during the year. In consequence of it, during summer months the electricity load during the day is almost fully covered by the on-site generation, and still a significant party of the generated electricity, at noon it may even reach 90%, is exported to the grid (see for example, Figure 36 and Figure 42, right). For the other seasons, γ_{load} tends to decrease (and γ_{supply} increases) reaching minimum in winter period, when the number of hours with on-site generation decreases. In the winter season building will act as consumer, but during hours of maximum solar radiation around 45% and 60% of load can be self-generated, or sometimes electricity may be exported to the grid (γ_{supply} = 0.73 - SB1 and γ_{supply} = 0.84 - SB6). The annual cover factors γ_{load} and γ_{supply} shown in Table 17 and Table 18 vary between 0.25-0.31 and 0.25-0.3, respectively. It is similar to the results presented by Baetens et al. [5], where γ_{load} equals 0.32 ± 0.04 and γ_{supply} is 0.26 ± 0.03 for a zero energy residential building located in Belgium.

Differences between a NetZEB and a building which is not reaching the zero balance can be appreciated comparing the results for the cases MB1 and MB2: in the case of MB1, values of the γ_{supply} are significantly higher than in MB2 (0.59 vs. 0.22), meaning that the self-consumption is higher due to undersized on-site generation compared to MB2.

In case of the SB7 and MB5, which has also PV panels as used as RES but they are located in heating and cooling dominated climate (Spain and Italy, respectively), the γ_{load} has more smooth distribution through the whole year, with a similar daily pattern. The only major difference is in the case of SB7 where γ_{supply} at 14-15 o'clock increases due to midday activities in Spain at home. The annual cover factors γ_{load} and γ_{supply} shown in Table 17 and Table 18 for cases SB7 and MB5 (year 2011) vary between 0.33-0.36 and 0.42-0.45, respectively.

In case of a cooling dominated climate and for an office building, seasonal variations of the cover factors are not significant as it can be appreciated in the case MB4 (see also Figure 37, right), being the values for γ_{load} and γ_{supply} 0.582 and 0.575, respectively.

The SB3 is also located in Spain and it is a very small single family house, where annual on-site electricity generation is four times higher than the annual load. Therefore, for the whole year during the daytime γ_{load} equals 1 but it only constitutes to around 10-20% of the generated electricity. When comparing SB3 with SB4, we can notice the influence of battery on daily patterns of γ_{load} and γ_{supply} factors. By introducing battery, the building becomes almost fully self-sufficient (γ_{load} = 1). Only during winter nights and morning hours in spring and fall, it may happen that on-site electricity storage is not enough to cover the load (γ_{load} < 1), and thus grid support is needed. In consequence of using on-site battery, on-site generation can be also used during nights (γ_{supply} = 1). Moreover, there is fewer hours when SB4 acts as producer ($0 < \gamma_{supply} < 1$), because the first hour of on-site generation is used for recharging the empty batteries after night discharge. The annual cover factors γ_{load} and γ_{supply} in case of SB4 are higher with a factor 2 compared to SB3, see Table 18.

The influence of on-site battery on γ_{load} and γ_{supply} is also visible when comparing SB8 and SB9. For this ZEB, however, the presence of electricity storage is mostly visible in spring and summer time, where the building becomes almost fully self-sufficient. By having battery, in the fall and winter more electricity load is covered by on-site generation. Hence, both the annual value of γ_{load} and γ_{supply} increases by factor 2 and 1.7, respectively.

The MB6 and SB5 are the only case studies with micro CHP as on-site electricity generation where the CHP runs with heat as priority. This operation strategy is clearly reflected in the load cover factor graph, where the γ_{load} is highest in winter and lowest in summer (opposite to the case studies with PV panels). For the SB5 case study γ_{load} never reaches 1, which means that the building needs continuous assistance of electricity for power grid and for MB6 case study γ_{load} equals 1 only in some hours in the morning and the evening in winter (January in the graph, see Figure 40, left). Moreover, in this case the cover factors are influenced by electricity load profile as well as the heat load profile and its control strategy. For example in case SB5, in July between 3 a.m. and 13 a.m. γ_{load} equals zero, which may be a reason that building does not have any space heating demand and the needs of domestic hot water can be met by storage tank, and thus micro CHP is in the off-mode. Also, the γ_{supply} for October, January, and April in both cases increases with the morning and afternoon electricity and hot water consumption peak. Furthermore, there is not such significant seasonal variation of the supply cover factor. The annual supply cover factor γ_{supply} equals 0.585 (SB5) and 0.427 (MB6) and are the highest for all case studies, with the exception of MB4 (a complete different climate) and MB1 which is not actually a NetZEB

The losses-of-load-probability ($LOLP_b$) factor indicates how often the on-site supply does not cover the on-site load. Table 18 presents the $LOLP_b$ factors for all nine simulated case studies and Table 17 for the monitored buildings. For the cases with PV and heat pump, SB1, SB2, SB6, SB7, MB1, MB3, MB5, MB7 and with micro CHP – SB5 around 70% of time the load is not covered by on-site generation and thus the electricity must be delivered for the grid. However, this index does not provide any information about the amount of delivered electricity. When comparing SB3 and SB4 we can see that having on-site battery decreases the time when the building must import electricity from grid, in this particular case studies it decreases by a factor of 2.8. Using the LOLP factor, designer can evaluate various load control strategies. For example, looking at case study SB3 and SB4 we can conclude that having on-site battery for that case increases the time of local generation covering the local demand by 37%.

5.3 GRID INTERACTION FACTORS

5.3.1 GRID INTERACTION FACTORS RELATED TO GRID CONNECTION CAPACITY (E_{DES})

This chapter presents the results of analysis of grid interaction factors based on simulated data for nine case studies and monitored data for seven case studies described in chapter 4. In the first part the factors related to grid connection capacity are discussed. Unfortunately, in the common practice the grid connection capacity is an unknown value during the early design phase. Often, this value is supplied when the building shape, form, energy performance calculations are finished and only minor adjustment to the building design can be made. This issue is also reflected in the analysed case studies, where only in 3 out of 6 simulated buildings the connection capacity is given already during simulation part, i.e. building from Germany - SB3 and 4, Spain - SB7, and Sweden - SB8 and 9.

From Figure 51 to Figure 59 the load duration curve for the generation, load and next exported energy are represented for each test case, using non-normalized values. From Figure 60 to Figure 66 the duration curve of net electricity export normalized with the designed grid connection capacity is depicted. Also the values of $\overline{\mathrm{G_{des}}}$ and $\overline{\mathrm{L_{des}}}$ are shown in the graphs (horizontal red and green dashed lines) together with the normalized value of E_{des} (+1 and -1).

In all the case studies, the electricity generated on site is by photovoltaic panels, except for the case MB6 and SB5. The SB3, SB4, SB8, SB9, MB1, MB2, MB3, MB6 and MB7 are buildings located in the heating dominated climates, where the seasonal mismatch between load and on-site generation is significant. Hence the delivered electricity has very low values compared to high summer export peaks and it spatially uses only around 10% of the available grid connection capacity. For SB8 and SB9 the exported electricity reaches almost the maximum of the allowed grid connection capacity, as for the case MB2 which in fact is a theoretical case based in MB1. The SB7 case study is located in Spain, and it represents a building with more even load and generation distribution through the whole year, which results in similar delivered and exported power peaks, 0.50 and 0.57, respectively. By comparing SB3 with SB4 it can be noticed that the presence of on-site battery does not decrease the high peaks of exported power, but it mostly reduces time when building acts as consumer of electricity, see Table 19. Shape of generation load profile in cases MB6 and SB5 clearly shows the differences between CHP and PV generation profiles, showing the modularity in the CHP power generation.

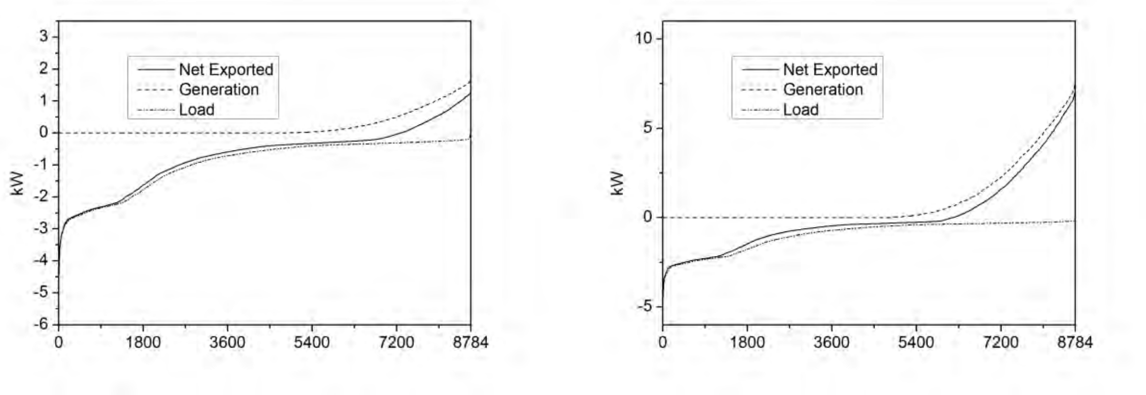


*Figure 51. Duration curve for generation, load and net exported electricity**. Case studies MB1** (left) and **MB2** (right).*

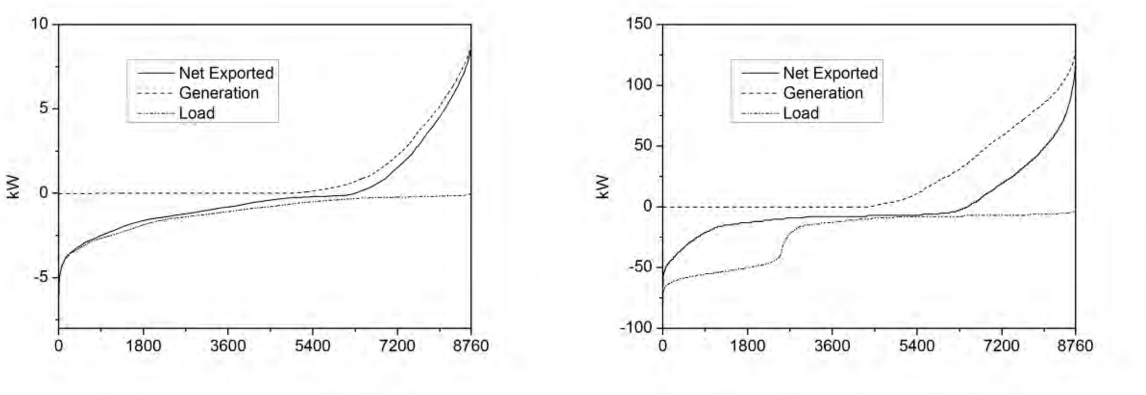


*Figure 52. Duration curve for generation, load and net exported electricity**. Case studies MB3** (left) and **MB4** (right).*

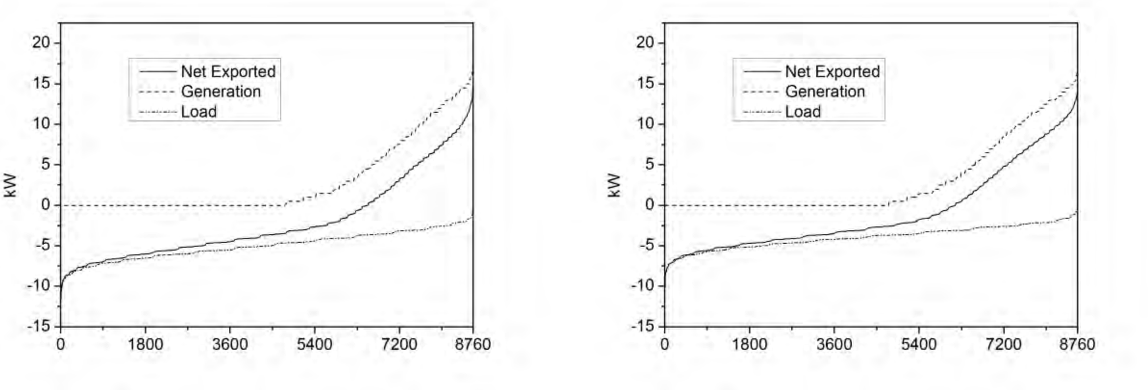


*Figure 53. Duration curve for generation, load and net exported electricity**. Case studies MB5_year 2009** (left) and **MB5_year 2011** (right).*

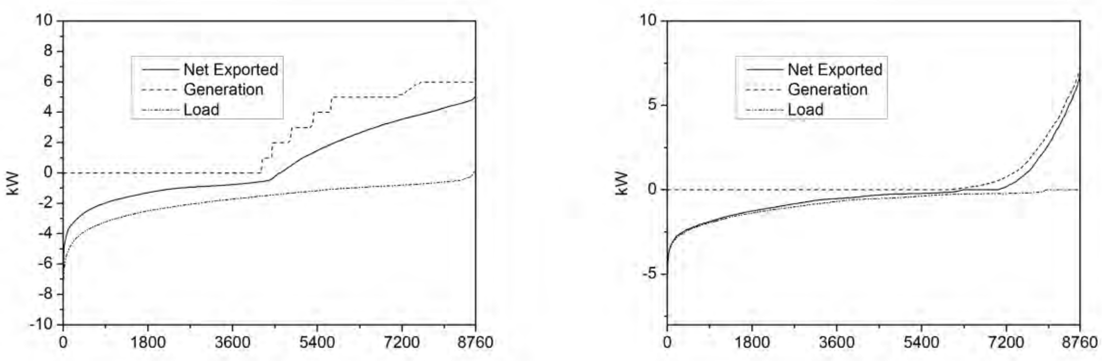


*Figure 54. Duration curve for generation, load and net exported electricity**. Case studies MB6** (left) and **MB7** (right).*

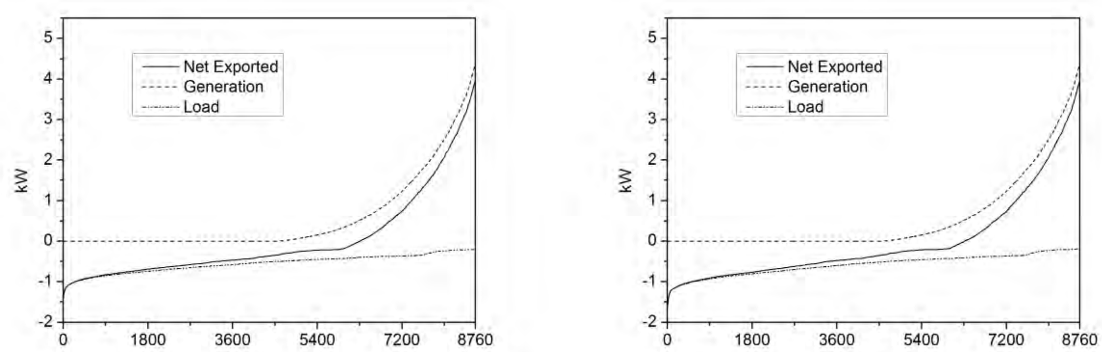


*Figure 55. Duration curve for generation, load and net exported electricity**. Case studies SB1** (left) and **SB2** (right).*

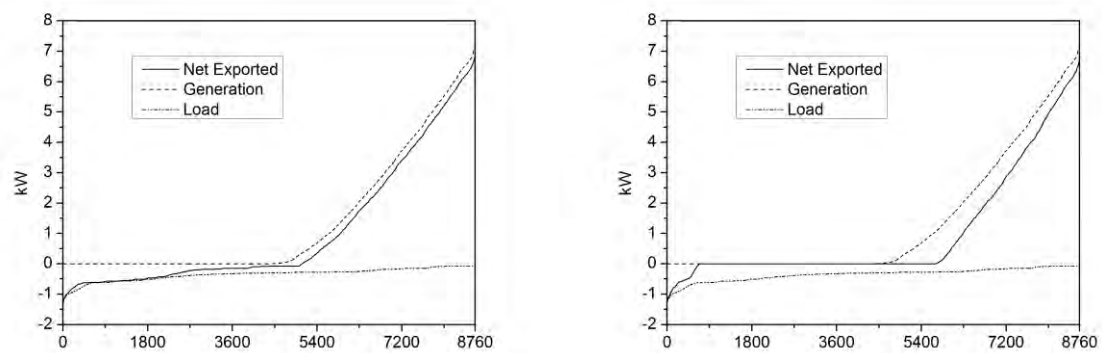


*Figure 56. Duration curve for generation, load and net exported electricity**. Case studies SB3** (left) and **SB4** (right).*

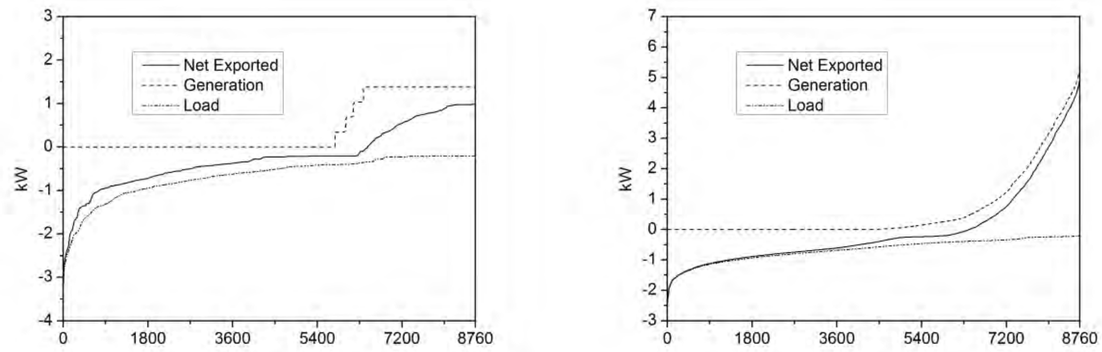


Figure 57. Duration curve for generation, load and net exported electricity***. Case studies SB5*** *(left) and* ***SB6*** *(right).*

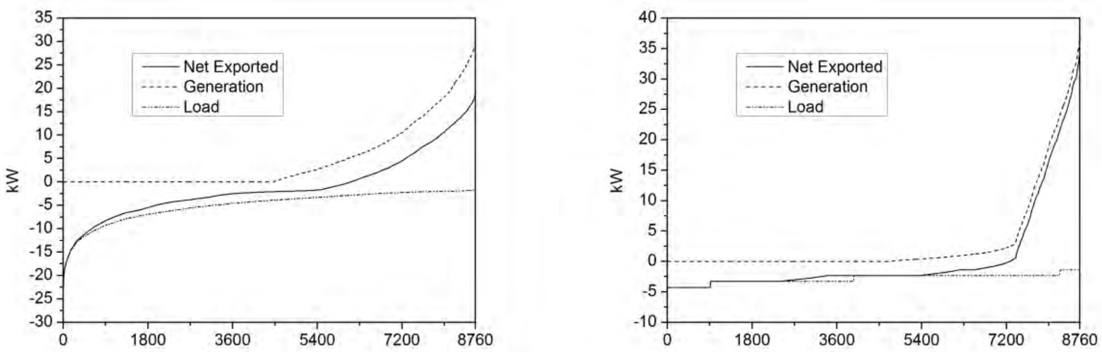


Figure 58. Duration curve for generation, load and net exported electricity***. Case studies SB7*** *(left) and* ***SB8*** *(right).*

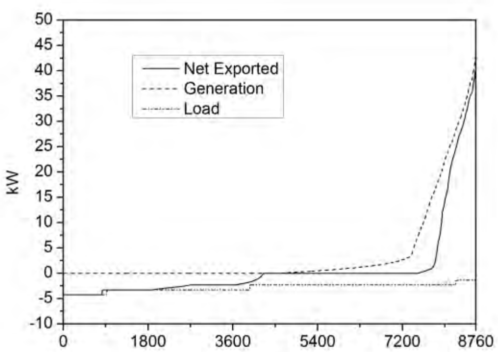


*Figure 59. Duration curve for generation, load and net exported electricity****. Case studies SB9*** *(left)*

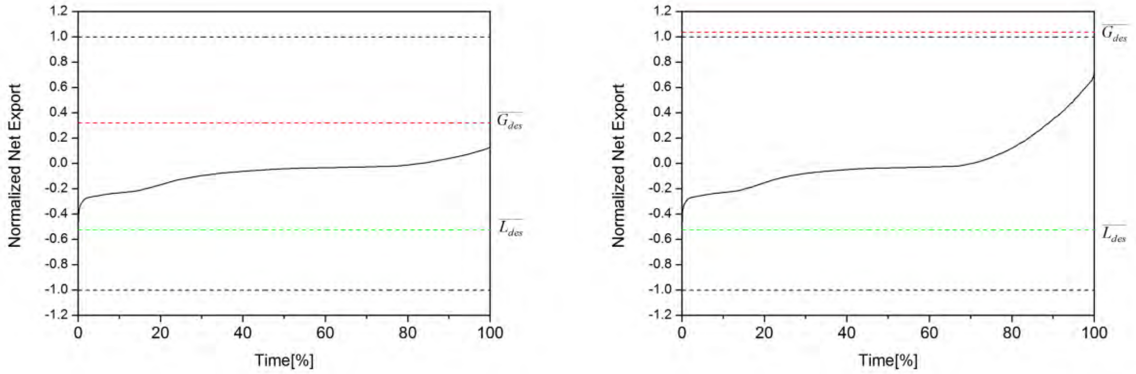


Figure 60. Normalized net exported electricity duration curve. ***Case studies MB1*** *(left) and* ***MB2*** *(right). E_{des}=10 kW*

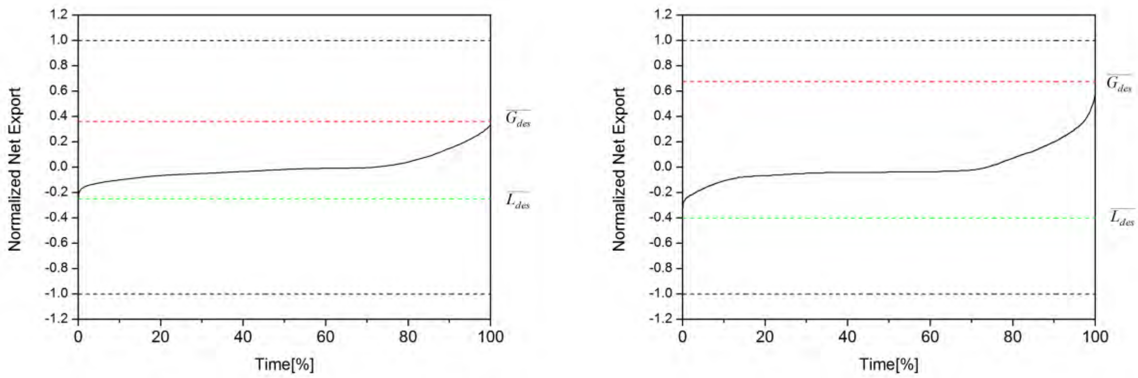


Figure 61.. Normalized net exported electricity duration curve. ***Case studies MB3*** *(left; E_{des}=25 kW) and* ***MB4*** *(right; E_{des}=200 kW).*

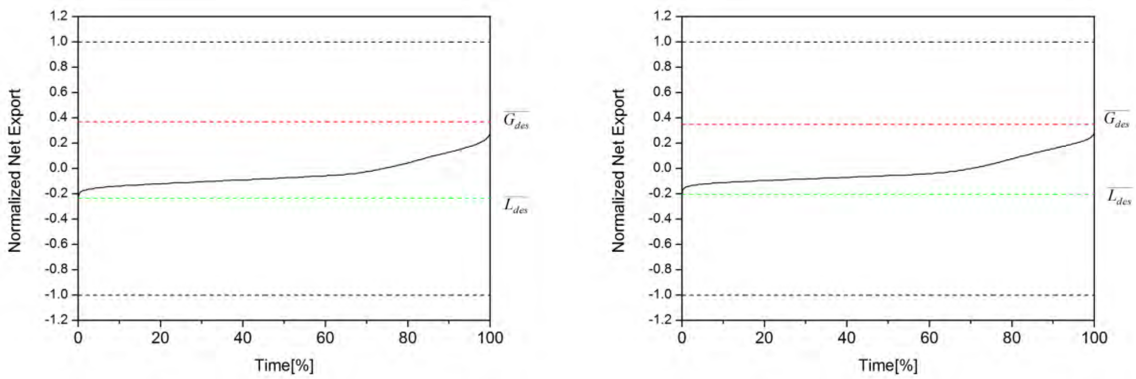


Figure 62. Normalized net exported electricity duration curve. ***Case studies MB5_year 2009*** *(left) and* ***MB5_year 2011*** *(right). E_{des}=50 kW*

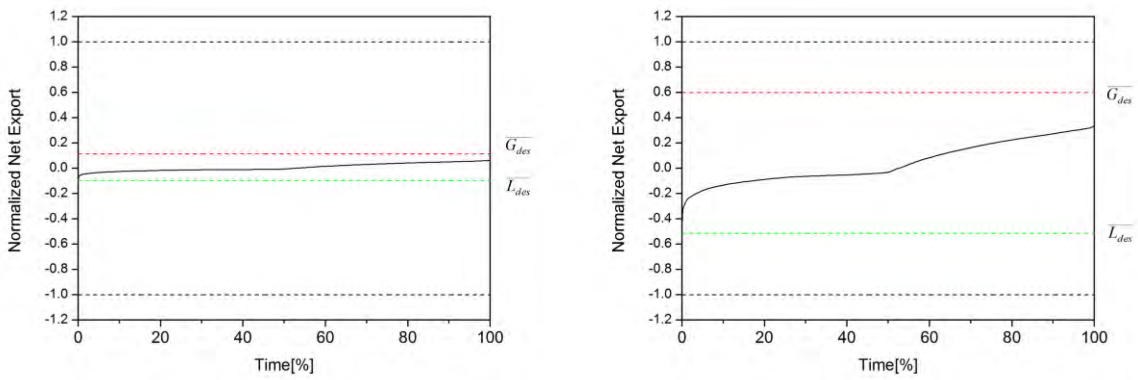


Figure 63. Normalized net exported electricity duration curve. ***Case studies MB6*** *(left; E_{des}=80 kW) and* ***MB7****(right; E_{des}=17 kW).*

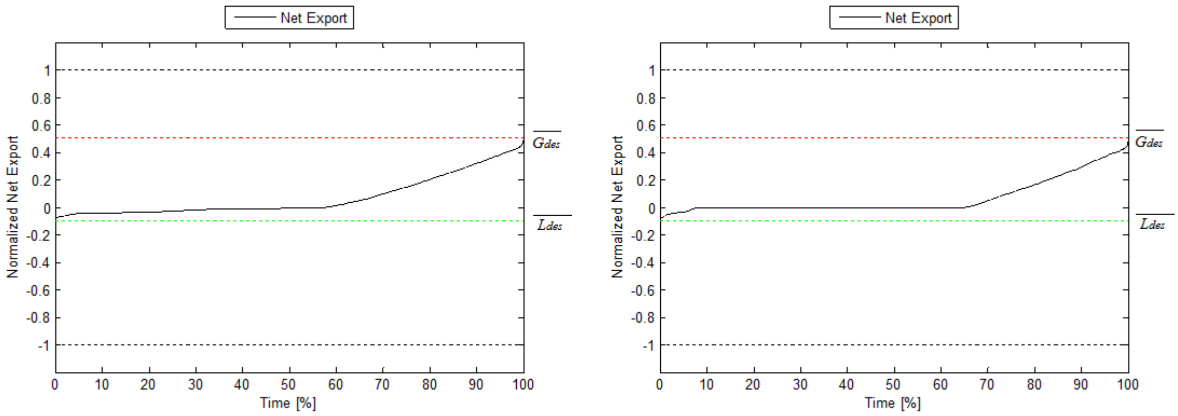


Figure 64. Normalized net exported electricity duration curve. ***Case studies SB3*** *(left) and* ***SB4****(right). E_{des}=15 kW*

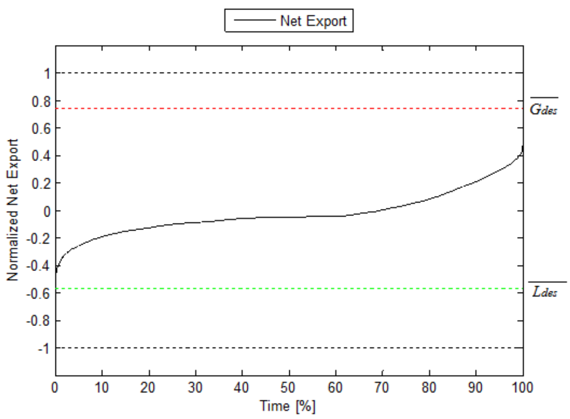


Figure 65. Normalized net exported electricity duration curve. ***Case studies SB7*** *(left). E_{des}=44 kW*

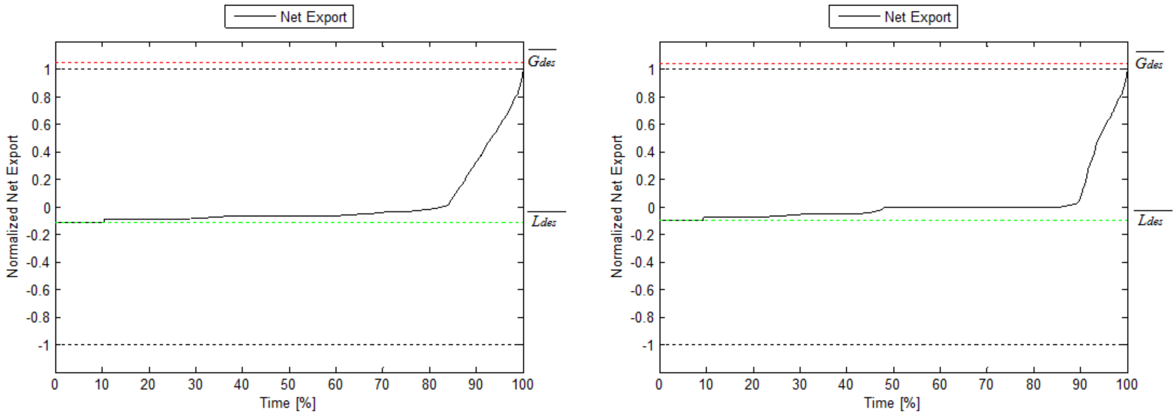


Figure 66. Normalized net exported electricity duration curve. ***Case studies SB8*** *(left; E_{des}=37 kW) and* ***SB9*** *(right; E_{des}=44 kW).*

Table 19. Percentage of time when electricity is delivered or exported and no integration probability for the monitored case studies

	MB1	MB2	MB3	MB4	$MB5_{2009}$	$MB5_{2011}$	MB6	MB7
$P_{E\approx 0}$ [%]	0.4	0.3	0.0	0.5	0.2	0.0	0.4	8.6
Time delivered [%]	82.7	70.0	71.7	73.4	74.2	70.3	52.2	71.5
Time export [%]	16.9	29.7	28.3	26.1	25.6	29.7	47.4	19.9

Table 20. Percentage of time when electricity is delivered or exported and no integration probability for the simulated case studies

	SB1	SB2	SB3	SB4	SB5	SB6	SB7	SB8	SB9
$P_{E\approx 0}$ [%]	0.1	0	0	48.6	0	0.1	0	0	37.5
Time delivered [%]	71.6	71.7	57.6	10.6	73.5	72.7	69.4	82.7	48.1
Time export [%]	28.3	28.3	42.4	40.8	26.5	27.2	30.6	17.3	14.4

Representation of net exported energy in coloured contour graphs gives significant information of when during the whole year the building is exporting or importing energy, depending of the type of building, the generation system and its management system. X-axis in the graphs represents the hours of the day (1-24) and the y-axis are the days of the year (1-365). The levels of colours in the graph represent the amount of power imported from the grid (negative values) and exported electricity (positive values). From Figure 67 to Figure 71, coloured selected test cases are represented. Figure 67 is a typical case of individual house equipped with PV in a heating dominated climate (Denmark), where it clearly can be appreciated that exporting electricity is happening more in summer and midday hours. Figure 68 corresponds to the case study MB4 (office building in Singapore) where almost no difference in the values can be appreciated in non-occupied hours. A complete different profile of net exported energy can be appreciated in Figure 69 which corresponds to the case study MB6 (CHP system). In that case, exporting energy from the building to the grid occurs when CHP is running due to the building heating needs (i.e., mostly in winter and the first hours in the morning). Figure 70 and Figure 71 corresponds to the same building positive energy building without and with battery, respectively case studies SV3 and SB4. It could be appreciated that the use of the battery almost eliminate the need to import energy from the grid between 19 h and 24 h.

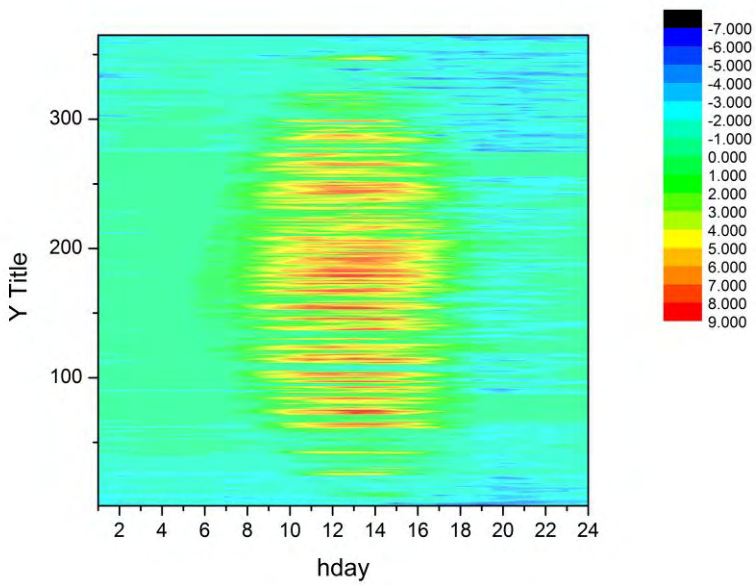


Figure 67. Coloured countour graph of net exported energy. ***Case study MB3***

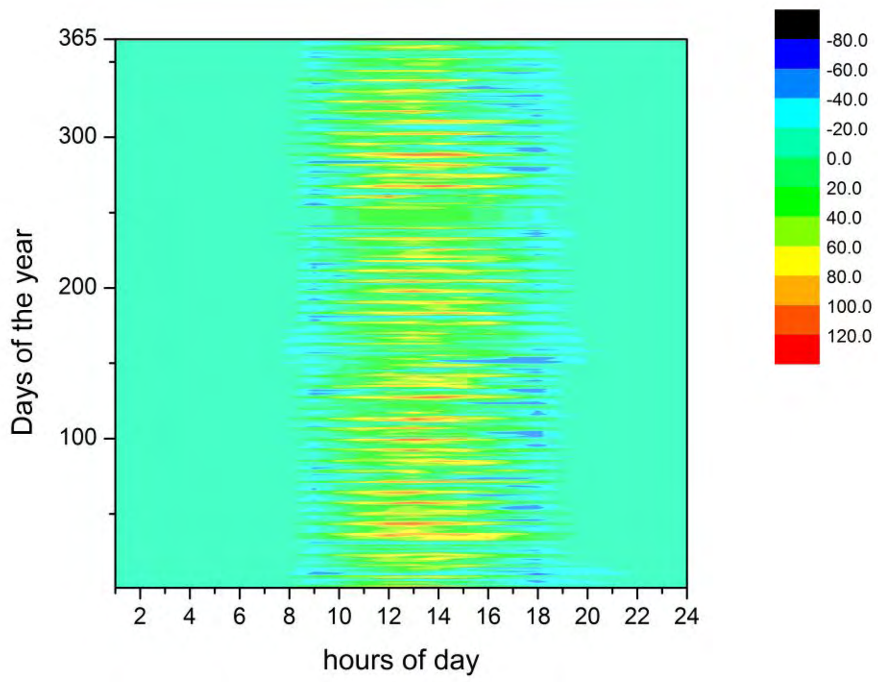


Figure 68. Coloured countour graph of net exported energy. ***Case study MB4***

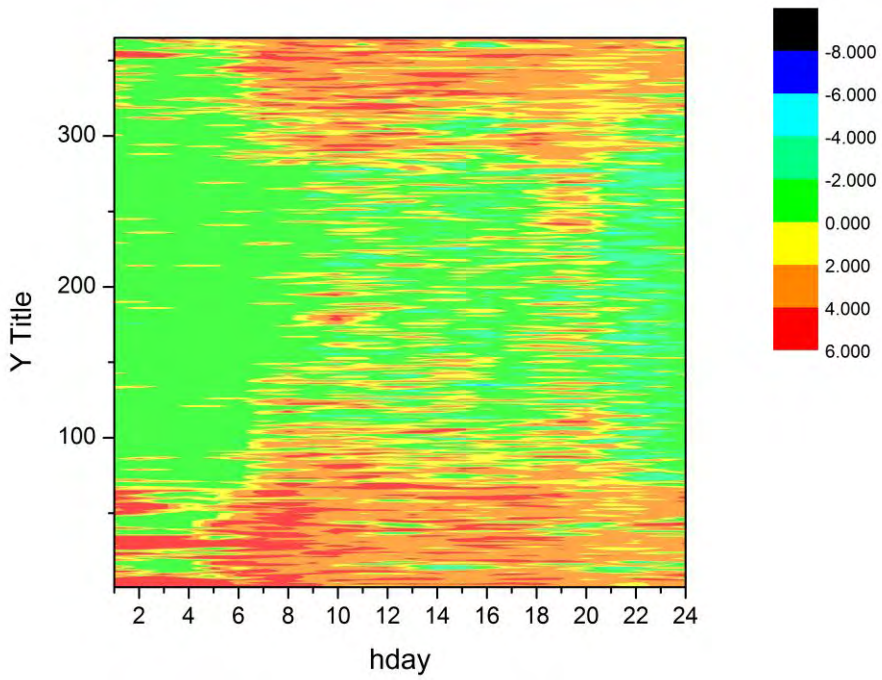


Figure 69. Coloured countour graph of net exported energy. ***Case study MB6***

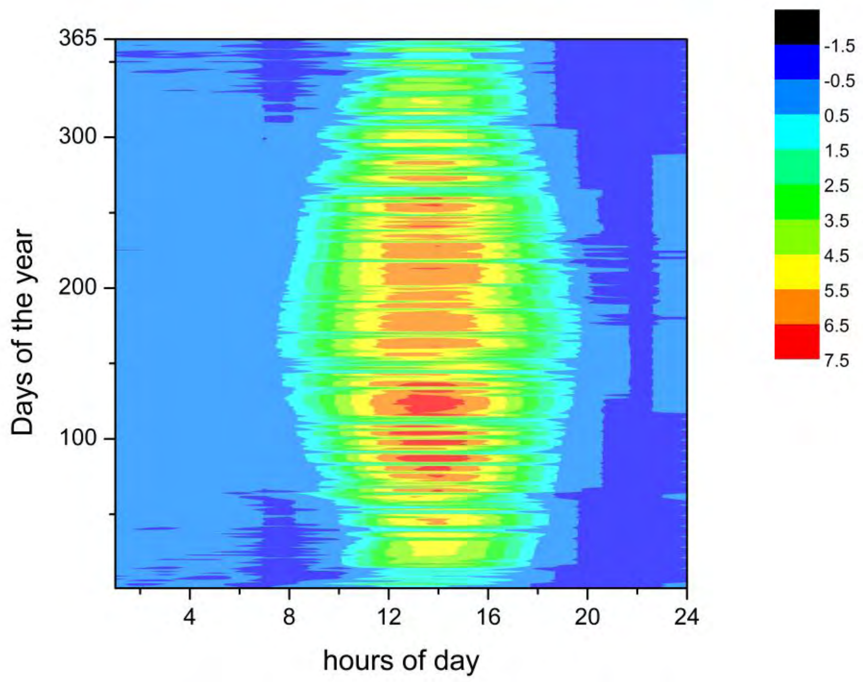


Figure 70. Coloured countour graph of net exported energy. ***Case study SB3***

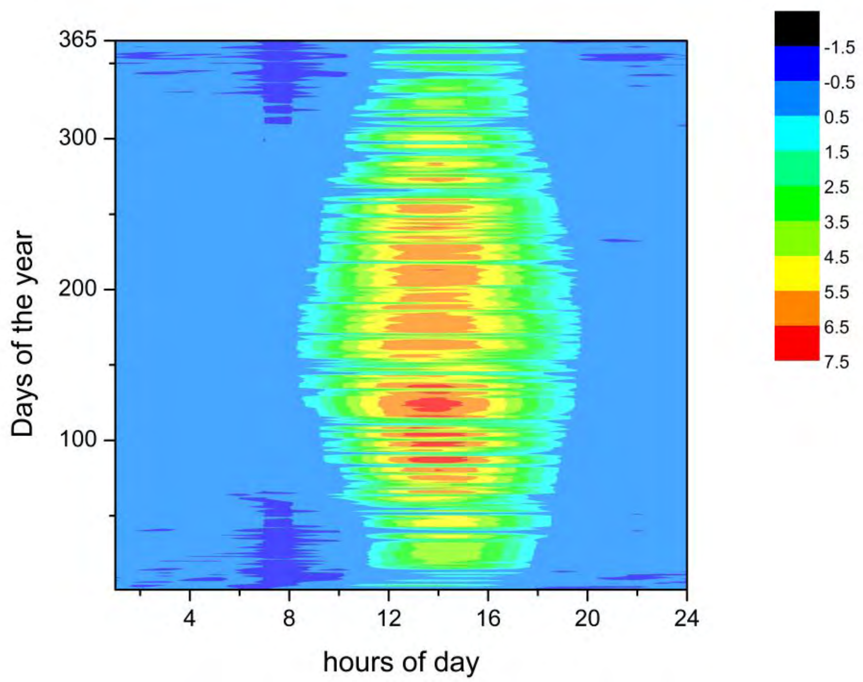


Figure 71. Coloured countour graph of net exported energy. ***Case study SB4***

When looking on the capacity factor $\mathrm{CF_{b,E}}$ it can be concluded that for the simulated cases analysed only around 10% of the available connection capacity is being used. However, the maximum net export at a given time relative to the designed power connection (defined as dimensioning rate, DR), is varying between 0.47 and 0.99, see Table 22. For the monitored cases MB3-MB7, which are real NetZEB or nearly NetZEB, the capacity factor is less than 10% and dimensioning rate is between 0.30 and 0.40, see Table 21. The only exception is MB6 which has a DR value of 0.088, but is also the case which are far to have a zero balance. In general, in the case of individual buildings enough connection capacity is available, and the capacity credit, $\mathrm{E_{c,des}}$, is over 60%. The same trend is observed with MB2 but in that case, as the connection capacity is the same as in MB1 (which is not a NetZEB) and lower than MB3 (which is a similar house in the same country), the capacity credit is less than 30%.. On the other hand, when the NetZEB is compared to the same building acting as only energy consumer, the capacity credit, $\mathrm{E_{c,ref(G=0)}}$, is negative, and the monitored NetZEBs require between 27% and 55% higher connection capacity. This is also in line with the findings of the GM factors in the following.

Table 21. Capacity factor, dimensioning rate and connection capacity credit for the monitored case studies

	MB1	MB2	MB3	MB4	$MB5_{2009}$	$MB5_{2011}$	MB6	MB7
$\mathrm{CF_{b,E}}$	0.091	0.151	0.069	0.094	0.097	0.088	0.026	0.066
DR	0.526	0.725	0.345	0.615	0.318	0.302	0.088	0.404
$\mathrm{E_{c,des}}$	0.474	0.276	0.655	0.385	0.682	0.698	0.912	0.596
$E_{c,ref(G=0)}$	0.000	-0.377	-0.388	-0.538	-0.359	-0.479	0.089	-0.271

Table 22. Capacity factor, dimensioning rate and connection capacity credit for the simulated case studies

	SB1	SB2	SB3	SB4	SB5	SB6	SB7	SB8	SB9
$\mathrm{CF_{b,E}}$	-	-	0.10	0.07	-	-	0.12	0.11	0.10
DR	-	-	0.49	0.48	-	-	0.57	0.99	0.98
$E_{c,des}$			0.509	0.522			0.434	0.013	0.020
$E_{c,ref(G=0)}$			-3.863	-3.738			-0.004	-7.586	-9.143

As mentioned in chapter 2, very useful information for the grid planner would be to estimate how much higher the generation power peak is compared to the load power peak. This information is given by the generation multiple (GM) presented in chapter 3 and Table 23 and Table 24. The GM is calculated for generation and load peak power - $GM_{(g/l)}$ as well as exported and delivered peak power - $GM_{(e/d)}$. By having these two factors for a particular building, it is possible to verify the efficiency of various operation strategies or design options, made possible through Demand Side Management (DSM).

Among the analysed nine simulated case studies, eight have PV installation and one - SB5 a micro CHP. For the simulated buildings with PV the $GM_{(g/l)}$ is above one and varies between 1.32 and 10.75, which means that peak generation is higher than peak load regardless of fulfilling the zero standard, or is above or below the zero limit. In the case of monitored test cases, values of GM are above 1.0 but below 2.0 for all the cases using PV (except for MB1 which is not really a ZEB and MB6 which is the case with a CHP system and far to be a ZEB, too). The coincidence of generation and load results in lower $GM_{(e/d)}$ factors for all the cases, however, without any significant reduction when implementing battery – see $GM_{(e/d)}$ for SB3 and SB4. As in case of SB5 the micro CHP runs with heat as priority, and the $GM_{(g/l)}$ and $GM_{(e/d)}$ are lower than unity, as $GM_{(e/d)}$ for MB6 is. It is convenient to consider in that analysis that a gas consumption occurs simultaneously to exchange with the power grid in the cases of CHP systems and that effect is not caught by the proposed grid interaction factors.

Lack of the grid connection capacity during the design phase of a building hampers calculation of all the above described grid interaction factors. However, some of the information, e.g. GM factors (Table 23 and Table 24) and time when building acts as consumer and as producer (Table 19 and Table 20), can be obtained from duration curves of net export, load and generation, seen from Figure 60 to Figure 66.

Table 23. Generation multiple based on generation/load peak power or exported/delivered peak power for simulated case studies

	SB1	SB2	SB3	SB4	SB5	SB6	SB7	SB8	SB9
$GM_{(g/l)}$	3.39	2.79	5.04	5.04	0.41	2.42	1.32	9.13	10.75
$GM_{(e/d)}$	3.12	2.57	4.86	4.74	0.31	2.30	0.89	8.59	10.14

Table 24. Generation multiple based on generation/load peak power or exported/delivered peak power for monitored case studies

	MB1	MB2	MB3	MB4	$MB5_{2009}$	$MB5_{2011}$	MB6	MB7
$GM_{(g/l)}$	0.612	1.976	1.449	1.688	1.581	1.716	1.166	1.364
$GM_{(e/d)}$	0.268	1.377	1.398	1.557	1.377	1.479	0.767	1.370

Table 25 and Table 26 shows statistical analysis of different GM ratios and design ranges using different percentile values of net exported energy. Figure 72 and Figure 73 (monitored and simulated buildings, respectively) represents the different values of GM ratio using different approach of percentiles, meaning that reduction of the higher percentile (99, 95, 90, etc.) means curtailment on the grid export and increase of the lower percentile (1, 5, 10, etc.) means peak shaving and less power needed from the grid. Figure 74 and Figure 75 also represents different GM but with the hypothesis of reduction of higher percentile but maintain lower percentile equal to 0 (that means no peak shaving in the load side). From Figure 72 and Figure 74 where the results from monitored buildings are presented, trends are very similar for all the buildings which are ZEB or nearlyZEB using PV as the generation system, independently of the climate and the type of building. In case that no peak shaving in the load side occurs, a curtailment of 5% time when exporting power is highest means that GM is below 1.0 in all the cases. By the other hand, if similar “effort” in reducing peak values is done both when exporting energy as when energy is demanded from the grid, GM increases respect $GM_{100/0}$, as the reduction in the delivered side is higher, at least for reductions until 5%. The monitored cases that show different trends are MB1 and MB6. MB1 is a building with 4.5 times less PV than the PV needed to have a zero balance and thus hardy can be comparable with the rest. MB6 is a building which is also far to have a zero balance and it is equipped with CHP and does not have any PV system. Curtailment in the exporting power reduces GM from 0.77 to 0.58 for the test case MB6. More dispersion is observed when analysing the simulated cases due to variety of cases with positive buildings and buildings with PV and CHP. However, the trend that a significant reduction of the GM index when considering reduction of the highest exporting peaks is also confirmed for all the simulated cases which are ZEB or positive buildings using PV.

Table 25. Statistical values and ranges of normalized net exported energy values for monitored case studies. GM corresponds to $GM_{(e/d)}$

	MB1	MB2	MB3	MB4	$MB5_{2009}$	$MB5_{2011}$	MB6	MB7
E_{des}	10.0	10.0	25.2	200.0	50.0	50.0	80.0	17.0
$\overline{L_{des}}$	0.526	0.526	0.249	0.400	0.234	0.204	0.097	0.318
$\overline{G_{des}}$	0.322	1.040	0.361	0.675	0.370	0.350	0.113	0.434
$\overline{ne_{min}}$	-0.526	-0.526	-0.247	-0.395	-0.231	-0.204	-0.088	-0.295
$\overline{ne_{max}}$	0.141	0.7245	0.345	0.615	0.318	0.302	0.067	0.404
$GM_{ne,100/0}$	0.268	1.377	1.398	1.557	1.377	1.479	0.767	1.370
$GM_{ne,99/1}$	0.377	2.174	1.845	1.979	1.349	1.699	1.237	1.866
$GM_{ne,95/5}$	0.299	1.990	1.779	1.765	1.164	1.602	1.697	1.645
$GM_{ne,90/10}$	0.173	1.539	1.500	1.829	0.914	1.402	2.048	1.006
$GM_{ne,75/25}$	0.177	0.451	0.213	0.273	0.069	0.402	2.722	0.000
$A_{ne,100/0}$	0.667	1.251	0.593	1.010	0.549	0.506	0.155	0.699
$A_{ne,99/1}$	0.420	0.940	0.468	0.715	0.411	0.389	0.109	0.538
$A_{ne,95/5}$	0.330	0.751	0.346	0.470	0.329	0.320	0.089	0.362
$A_{ne,90/10}$	0.271	0.582	0.249	0.309	0.268	0.269	0.076	0.224
$A_{ne,75/25}$	0.102	0.155	0.069	0.070	0.120	0.125	0.050	0.063
$GM_{ne,99/0}$	0.219	1.223	1.228	1.203	1.022	1.199	0.684	1.187
$GM_{ne,95/0}$	0.144	0.950	0.897	0.759	0.766	0.966	0.637	0.764
$GM_{ne,90/0}$	0.076	0.670	0.605	0.506	0.554	0.770	0.583	0.381

Table 26. Statistical values and ranges of normalized net exported energy values for simulated case studies

	SB1	SB2	SB3	SB4	SB5	SB6	SB7	SB8	SB9
E_{des}	-	-	15.000	15.000	-	-	44.000	37.000	44.000
$\overline{L_{des}}$			0.101	0.101			0.564	0.115	0.097
$\overline{G_{des}}$			0.509	0.509			0.745	1.049	1.039
$\overline{ne_{min}}$			-0.100	-0.100			-0.566	-0.114	-0.096
$\overline{ne_{max}}$			0.490	0.478			0.502	0.986	0.980
$GM_{ne,100/0}$	3.124	2.568	4.863	4.738	0.315	2.298	0.888	8.586	10.143
$GM_{ne,99/1}$	3.369	3.081	6.695	6.953	0.416	2.658	1.041	7.346	8.687
$GM_{ne,95/5}$	2.825	2.576	9.214	11.103	0.719	2.551	1.144	5.179	5.930
$GM_{ne,90/10}$	2.083	1.893	8.212	$8.5 \cdot 10^3$	0.844	1.966	1.092	2.861	0.947
$GM_{ne,75/25}$	0.292	0.534	5.638	$24.2\ 10^3$	0.239	0.161	0.396	0.382	0.000
$A_{ne,100/0}$			0.592	0.579			1.069	1.101	1.077
$A_{ne,99/1}$			0.502	0.490			0.762	0.959	0.936
$A_{ne,95/5}$			0.424	0.402			0.550	0.710	0.670
$A_{ne,90/10}$			0.361	0.294			0.400	0.444	0.145
$A_{ne,75/25}$			0.175	0.108			0.141	0.055	0.066
$\mathrm{GM}_{\mathrm{ne},99/0}$	2.600	2.130	4.327	4.240	0.313	1.749	0.686	7.346	8.687
$\mathrm{GM}_{\mathrm{ne},95/0}$	1.834	1.510	3.789	3.657	0.311	1.321	0.518	5.179	5.930
$\mathrm{GM}_{\mathrm{ne},90/0}$	1.207	0.991	3.189	2.915	0.258	0.853	0.369	2.861	0.732

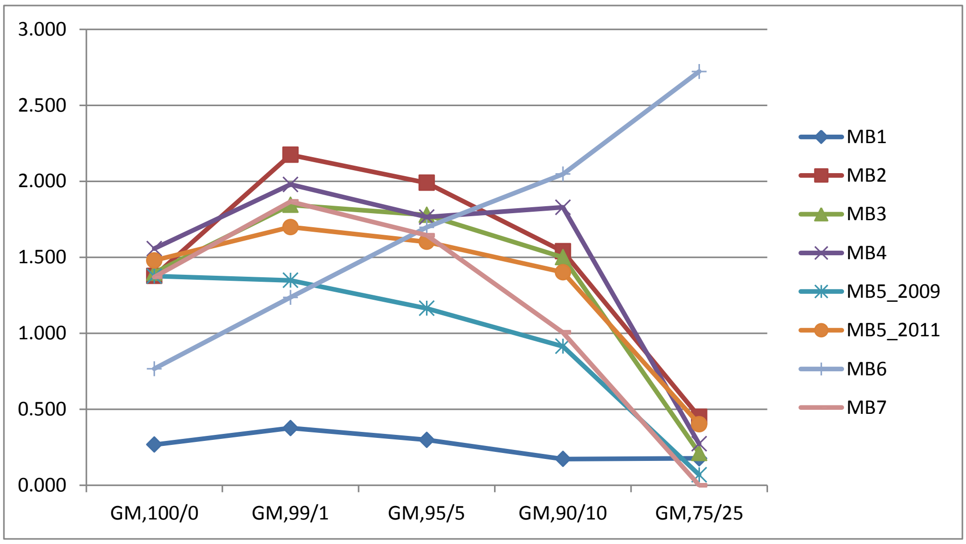


Figure 72. Variation of GM for each test monitored case

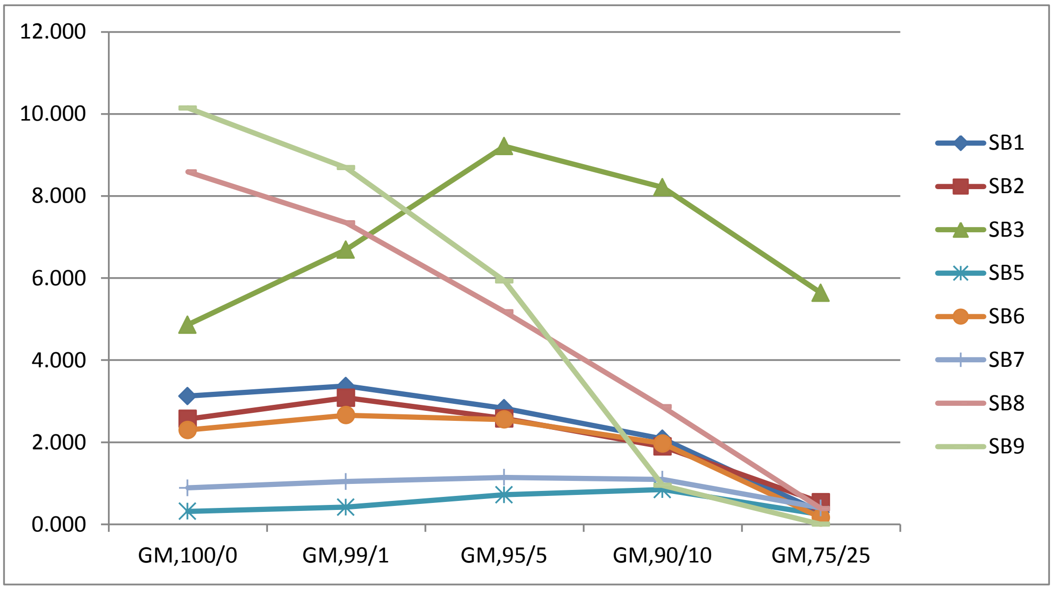


Figure 73. Variation of GM for each test simulated cases

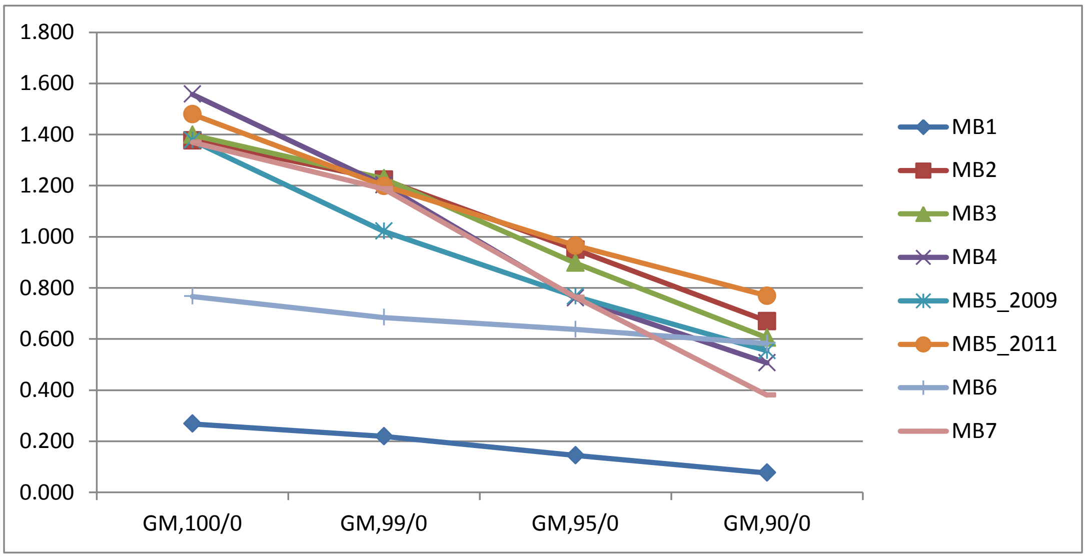


Figure 74. Variation of GM relative to percentile 0% for each test monitored case

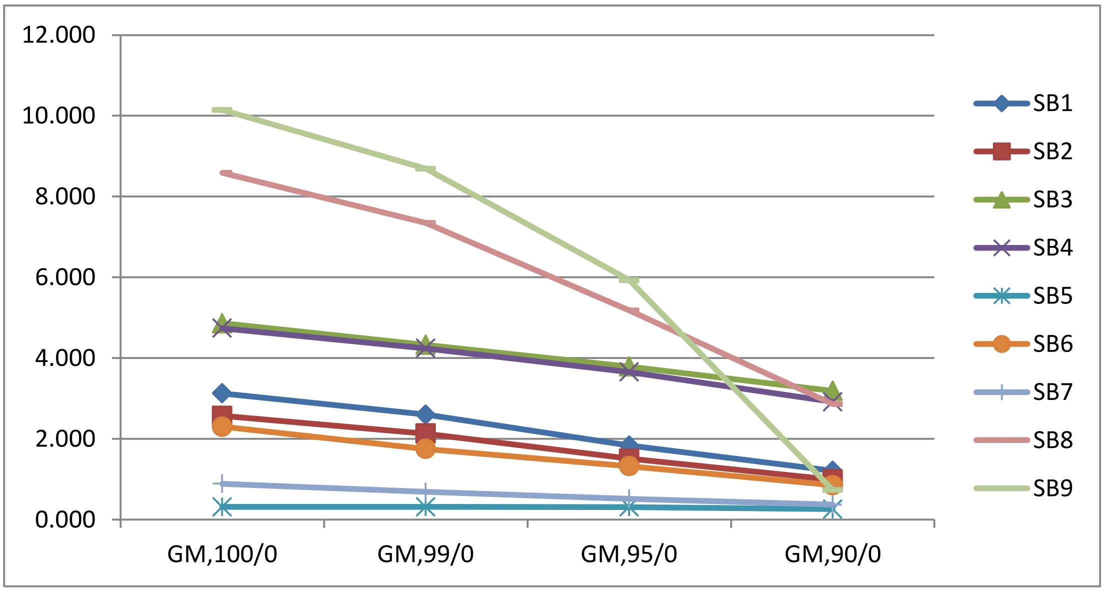


Figure 75. Variation of GM relative to percentile 0% for each test simulated cases

As it was pointed in section 2, one of the interest on deducing relevant grid interaction indicators is the study how a cluster of NetZEB can influence the design of distribution grids. Then a simple hypothesis has been done using the data of single monitored buildings. The hypotheses are that both the connection capacity and the minimum value of net exported energy follow Velander method and the peak value of net exported energy is proportional to the number of buildings within the cluster. Results in the graphs (Figure 76 and Figure 77) shows that for a higher number of NetZEBs in the cluster of buildings (> 100) the GM ratio has values between 2.5 and 3.0. Dimension Rate graph in Figure 77 shows a significant increase of this ratio, but in the majority of cases analysed at least 20% of the connection capacity on the area is still available. We can observe some different curves for cases MB1, MB2 and MB6. As it is stated before, MB1 is far from being a ZEB considering the high energy consumption in the building. For this case, it can be observed that Dimension Rate remains constant as peak generation values are low compared to peak loads, which also make the values of GM below zero. MB2 is a ZEB where the behaviour of GM is similar to the other ZEBs (Figure 76). As DR relates the peak values with the connection capacity, the base case for MB2 has a high DR with a limited connection capacity (which is the same of MB1 with a PV system 4.5 times larger). Case MB6 follows a similar trend but stabilizing at different values (GM $\cong$ 1.5; DR $\cong$ 0.13).

Both in the cases of analysing the buildings individually or in a context of a cluster of buildings, the indexes Generation Multiple (GM), ranges of net exported values (A) and Dimensioning Rate (DR) are appropriate indexes to know the relationship between Exported/Delivered peak values and between the building and the grid through the additional information of the grid capacity. As flexibility needs a comparison between several options compared to a reference case. The referred indexes could be used to compare different options or to compare potential of a building using simple statistical values as the percentiles are.

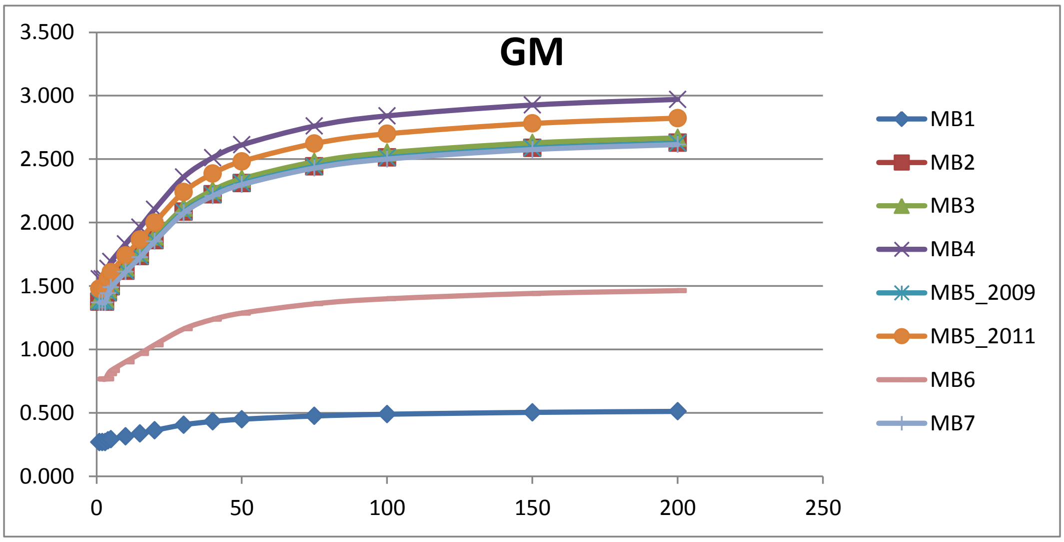


Figure 76. Generation Multiple (GM) for a cluster of NetZEB buildings

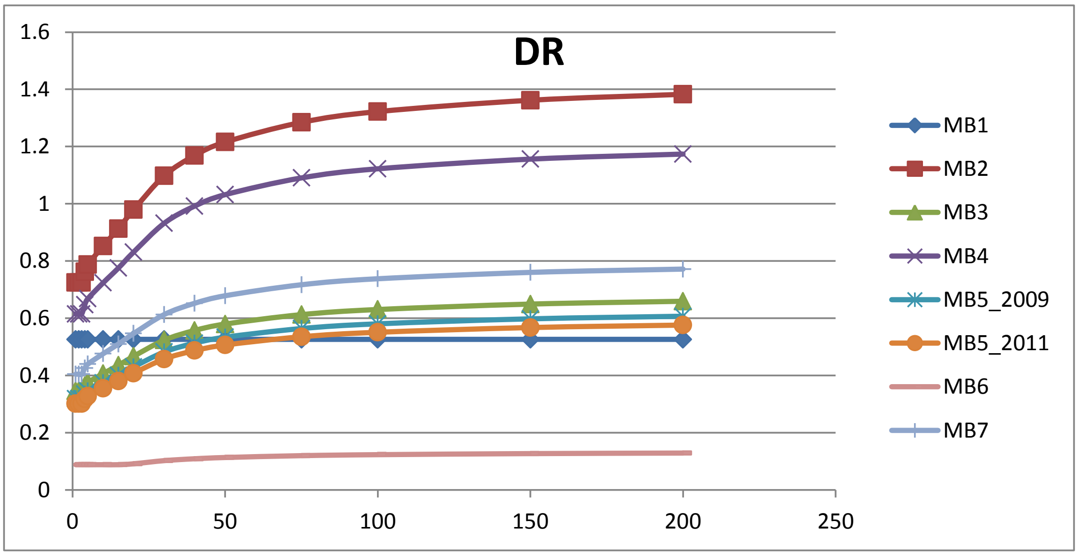


Figure 77. Dimension Rate (DR) for a cluster of NetZEB buildings

5.3.2 PEAKS ABOVE LIMIT / BARRIER

The “peaks above limit” index indicates the part of analysed period that exchanged energy exceeds a certain barrier. This limit should be given by the utility grids. Unfortunately, for most of the case studies the limit is unknown, see Table 28. Percentage of time of peaks above limit, and for the ones where the limit is given, we can deduce that the presence of battery does not change the results significantly. However, we don’t know if and how the value of peaks has changed, which an important input is for grid designers.

Table 27. Percentage of time of peaks above limit for monitored case studies

	MB1	MB2	MB3	MB4	$MB5_{2009}$	$MB5_{2011}$	MB6	MB7
Peaks above limit [%]	0	5	7	0	0	0	0	3
Limit [kW]	5	5	5	150	30	30	40	5

Table 28. Percentage of time of peaks above limit for simulated case studies

Case study	SB1	SB2	SB3	SB4	SB5	SB6	SB7	SB8	SB9
Peaks above limit [%]	-	-	8.9	7.6	-	-	-	5.9	6.6
Limit [kW]	-	-	5	5	-	-	-	20	20

When using this indicator, only the percentage of time is known without any indication of the height of peaks. Similar as evaluating the percentage of time when IAQ is within the limits of a particular class, a possible solution may be a scale of limits with a maximum barrier of grid connection capacity. By doing so, designer can quickly and easily have an indication of how well building design matches the requirements of the grid.

5.3.3 GRID INTERACTION INDEX

The grid interaction index indicates the variability of the exchanged energy between the building and the grid within a year normalized on the maximum absolute value.

For the investigated case studies with simulated hourly datasets, the grid interaction index varies between 0.2 and 0.3 for simulated case studies, see Table 29, and between 0.15 and 0.21 for the monitored case studies. However, with any additional information about the import and export of energy or characterizations of the local grid, drawing any conclusions about the building-grid interaction is rather difficult. The values do not change significantly for different renewable energy technologies, i.e. PV and micro CHP, or systems with or without battery.

Table 29. Grid interaction index for simulated case studies

Case study	SB1	SB2	SB3	SB4	SB5	SB6	SB7	SB8	SB9
f_{grid}	0.242	0.247	0.288	0.264	0.221	0.232	0.272	0.218	0.196

Table 30. Grid interaction index for monitored case studies

Case study	MB1	MB2	MB3	MB4	$MB5_{2009}$	$MB5_{2011}$	MB6	MB7
f_{grid}	0.155	0.2082	0.198	0.156	0.156	0.172	0.191	0.186

5.3.4 GRID CITIZENSHIP TOOL

The aim of this tool is to qualitatively estimate the way that an interconnected component e.g. an energy producing building or a microgrid of such buildings, interacts with a greater power system, e.g. low-voltage power grid. It consists of the following factors: component ratio (CR) – describes the proportion between on-site generation and load; storage ratio (SR) – gives a qualitative indication of how well on-site generation is supported by on-site storage; intermittency ratio (IR) – indicates how reliable the component is at supplying energy. As mentioned in chapter 3 CR and SR factors are between -1 and 1, and IR varies from 0 to 1.

Table 31 summarizes the calculated ratios for the grid citizenship tool described in section 3.5.3. Unfortunately, not for all case studies all input data were available, therefore some results are missing. However, looking on the gathered data it can be concluded that seven case studies, all having PV installation, are not very reliable source of energy and may affect grid's voltage stability, as the IR is close to zero. Only case study SB4, due to presentence of battery, and case study SB5, which is equipped with micro CHP, have more constant availability of assets. High SR values indicate that none of the buildings have significant storage resources, which can broadly be understood as both batteries, heat storage tanks and building construction or HVAC systems. It may result in limited capabilities to quick respond to grid signals / needs. Calculated component ratios for study case SB3, SB4 and SB7 indicates quite good proportion between the generation and load as they are close to zero.

Table 31. Citizenship ratios for case studies

Case study	SB1	SB2	SB3	SB4	SB5	SB6	SB7	SB8	SB9
CR	-	-	-0,190	-0,190	-	-	-0,062	-	-
SR	1	1	1	0,556	1	1	1	1	-
IR	0,216	0,216	0,269	0,431	0,899	0,241	0,247	0,206	0,223*

'-' input data unavailable
* storage capacity not included

This tool gives a quite good estimation of possible negative or positive building's influence on the power grid, with the advantage of not requiring any power grid inputs. Moreover, the grid citizenship tool may have potential to investigate the influence of the energy storage with building construction and/or HVAC systems on the building-grid interaction. However, it should be noted that threshold of good or bad "citizenship" may differ between various power grids and/or particular feeders. Further analysis is needed for buildings connected to more than one utility grid, e.g. power grid and district heating/cooling.In such cases the building's energy system citizenship can be a useful tool for energy system designers and planners.

5.4 RESULTS USING HOURLY OR SUB-HOURLY RESOLUTIONS

Table 32 shows the differences in values of the net exported energy for monitored test cases (MB3, MB6 and MB7) where sub hourly values are available (12 min, 5 min and 1 min, respectively). The values presented in the table are the minimum and the maximum values, together with some statistical quantities. Although differences between hourly and subhourly values at percentiles 1%,, 5%, 99% and 95%, significant differences can be appreciated for peak values. These differences are higher for minimum values (up to 63%), delivered energy, than for the maximum values (up to 15%), exported energy. These results are consistent with previous findings showing that averaging has higher impacts on delivered than exported energy [25]. The explanation for this is that for PV power generation the fluctuations are deviations (due to cloud movements) from a well-defined maximum clear-sky radiation. Averaging moves the occasionally lower values closer to the maximum. For the load, it is the other way around: There is typically a low base load with occasional peaks. Averaging move these high peaks closer to the base load. The results in [25] also shows that despite high impacts of averaging on individual building loads, the impacts on the aggregate load of a building cluster are lower (mainly for net delivered power), since random coincidence smoothens the load. It was found that in simulations of a distribution grid, the simulated voltage levels were robust to averaging of individual load profiles since the voltages depend mainly on the total power flow, to which a big cluster of buildings contributes. In order to characterize grid interaction with NZEB buildings, it is suggested to work with high resolution values (5 min, 10 min. etc) better than working with hourly values. In case of using simulation programs, inputs related to the load (e.g., occupancy profiles) should be able to handle stochastic behaviours. If the interest is to have result at cluster of building level, working at lower resolution (30 min, 1 hour) is enough to have robust conclusions. However, if we have flexible users/buildings that respond automatically to e.g. hourly prices, a problem could be that powers aggregate at the shifts from one price to the next (loads start simultaneously as soon as the price reaches a favourable level), and then the instantaneous powers could be very high – then a higher resolution would be needed also for analysis at cluster level.

Table 32. Statistical analysis of net export for test cases MB3, MB6 and MB7 using subhourly values and hourly averaged values. Values are in kW.

Case study Net Exported	MB3 hourly	MB3 Subhourly -12 min-		MB65 hourly	MB65 Subhourly -5 min-		MB7 hourly	MB7 Subhourly -1 min-
$ne_{min,0\%}$	-6.22	-7.41		-7.03	-11.21		-5.01	-8.16
$ne_{1\%}$	-4.14	-4.39		-3.89	-5.09		-3.19	-3.89
$ne_{5\%}$	-3.14	-3.23		-2.64	-3.21		-2.32	-2.52
$ne_{Q1,25\%}$	-1.42	-1.41		-1.08	-1.13		-1.06	-0.81
$ne_{Q3,75\%}$	0.303	0.286		2.94	3.52		0.00	0.00
$ne_{95\%}$	5.58	5.74		4.48	4.75		3.83	3.99
$ne_{99\%}$	7.64	7.84		4.81	5.00		6.46	6.76
$ne_{max,100\%}$	8.704	9.32		5.39	5.29		6.87	7.88
$ne_{Q3,75\%} - ne_{Q1,25\%}$	1.72	1.70		4.02	4.65		1.06	0.807
$ne_{max} - ne_{min}$	14.93	16.73		12.42	16.57		11.89	16.046

6 CONCLUSIONS AND FUTURE RESEARCH WORK

In this report various load match and grid interaction indicators currently used for evaluating Zero Energy Buildings have been investigated. The main goal of the study was to identify the advantages and drawbacks of the analysed indicators, and indicate which group of users they are most suitable for. The analysis was made using only high resolution data, this means hourly or sub-hourly data from monitored or simulated buildings. Moreover, graphical systems to represent in an understandable way the yearly or daily variation of the indexes have been presented.

6.1 LOAD MATCH FACTORS

The hourly values of the cover factors (namely, the load cover factor and the supply cover factor) give a quite good picture of the correlation between on-site demand and supply of energy. It is possible to illustrate both the daily and seasonal effect, the production pattern of different renewable energy technologies, and applied operation/control strategies. The advantage of factors over energy demand and energy production profiles is the possibility to take into account the influence of different types of storage, e.g. batteries, building thermal mass. Moreover, when computing the load cover factor, we can investigate the influence of different strategies and measures of load modulation, e.g. demand side manager. The hourly supply cover factor is a good indicator of when and how much of the on-site supply is self-consumed, and thus indicates the periods when building acts as supplier of energy. As mentioned by [5], the definition of the cover factors can be extended for non-energy related assessment, e.g. economy, emissions. It should be noted that without knowing the characteristics of the local energy systems, it should not be concluded if high or low cover factors are preferable. The losses-of load probability (LOLP) factor shows how often the on-site supply does not cover the on-site demand, and thus how often energy must be supplied from the grid. Using the LOLP factor, designer can evaluate various load control strategies. The results presented here correspond mainly to all-electrical buildings with the exception of some buildings provided with CHP system. On-going work is carried out recently at international level with the objective to generalize load matching indexes [20] [30] but these have not been analysed in this report.

6.2 GRID INTERACTION FACTORS

Grid interaction, refers to the energy exchange between the building and the power grid. This report has analysed some of these grid interaction indicators from the building perspective. It is clear that detailed analysis the influence of an increasing number of Net ZEB in the grid requires knowledge about the grid topology, the stochasticity of the building consumption, and the control systems in both the building and the grid side. However, part of this knowledge lacks when individual buildings are designed, especially in the early design phases or when simplified energy assessment tools are used. Graphical representation of net exported energy in load duration curves has been proven to be a useful way to concentrate a lot of information in the same graph: delivered and exported peak values, amount of time when the building is exporting or demanding energy to or from the grid, period when the building is self-sufficient if a storage system is present, etc. Several Net ZEBs could be compared if this information is presented in a normalized form related to the connection capacity, together with information on what extent the building is using the grid. Generation Multiple (GM) is an index which relates peak values for exported/delievered energy and also can be used with generation/load values. Dimension Rate (DR) and Connection Capacity Credit ($E_{c,des}$ and $E_{c,ref(G=0)}$) relates the building with the electrical grid although the designed connection capacity, E_{des}, needs to be known which has been proven is not the case in some of the simulated test cases. These indexes can be used to make simple analysis in the case of cluster of buildings. Although some general trends have been identified in the results, it should be noted that further studies are needed in order to define reference GM values for particular building topologies, cluster of buildings, climates, which could be used as a rule-of-thumb for grid/building designers.

Another important aspect is to explore the ability to buildings to contribute in a positive way in a context where a high amount of renewables sources are in the grid, being the buildings themselves part of that system with the introduction of Net ZEB concept. This ability has been introduced has the “flexibility” of the buildings. But although investigations in buildings in Smart Grid has been carried out, the research on how flexibility in buildings can help stabilize the future energy system and thereby facilitate a large role out of renewable energy sources is still in its early beginning. The investigations have mainly focused on how to control a load and not to optimize the flexibility of the buildings. There is at the moment no overview of how much flexibility different buildings and usage of building may be able to offer to future energy systems. Flexibility is given by the storage capacity in the building or the ability to vary its load or curtail its generation system. Number of equivalent hours of storage gives some information about the storage capacity of the building. On the other hand, statistical analysis of net exported energy and grid interaction indexes (Generation Multiple and Dimensioning Rate) give information about peak load variations if certain percentage of time we are able to reduce the loads or curtail the energy generation. Besides Dimensioning Rate, also the Capacity Factor is an index that relates the building with the capacity connection with the grid. In any case, when evaluating the flexibility of a building, it is necessary to compare the behaviour of a building to a reference case or to compare two extreme cases with different strategies. Then information about flexibility will be derived from the comparison of some of the proposed load match and grid interaction indexes. In order to evaluate flexibility from owner/user perspective economical cost and user acceptance are two factors or constraints that have not been analysed in this report and they should be considered in future research.

Finally, report concluded that sub-hourly analysis will give more accurate information and differences in peak values can be significant if hourly data are used respect to sub-hourly data. If detailed grid interaction analysis at individual building level is needed we should work with measured values or go for a detailed sub-hourly simulation. At cluster level, using hourly values is an appropriate solution in most of the cases.

7 REFERENCES

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