Load Matching and Grid Interaction of Net Zero Energy Buildings

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Abstract

“Net Zero Energy Building” has become a prominent wording to describe the synergy of energy efficient building and renewable energy utilization to reach a balanced energy budget over a yearly cycle. Taking into account the energy exchange with a grid infrastructure overcomes the limitations of seasonal energy storage on-site. Even though the wording “Net Zero Energy Building” focuses on the annual energy balance, large differences may occur between solution sets in the amount of grid interaction needed to reach the goal. The paper reports on the analysis of example buildings concerning the load matching and grid interaction. Indices to describe both issues are proposed and foreseen as part of a harmonized definition framework. The work is part of subtask A of the IEA SHCP Task40/ECBCS Annex 52: “Towards Net Zero Energy Solar Buildings”.

1. Introduction

The understanding of a net zero energy building (Net ZEB) is primarily based on the annual balance between energy demand and energy generation on the building site. A Net ZEB is not meant to be an energy autonomous building, such as described in [1]. The concept has been developed based on the experience that seasonal energy storage is not feasible on a single building scale due to the lack of technology, namely for the high exergy energy demands such as electricity. A Net ZEB operates in connection with an energy infrastructure such as the power grid. Figure 1 shows an example of a monitored Net ZEB settlement with 56 terrace houses in Freiburg, Germany [2].

A major communication advantage of the Net ZEB concept is the absence of energy performance indicators such as kWh/m², removing the need to define benchmarks and reference areas. The focus is the balance. This simplicity is a major background for the high political and public acceptance of the concept. It has become part of the current EU [3] as well as the US [4] energy policies. In the recast of the EU Directive on Energy Performance of Buildings it is specified that by the end of 2020 all new buildings shall be “nearly zero energy buildings”.

However, despite the emphasis on the goals, the definitions remain generic and are not yet standardised. The IEA activity “Towards Net Zero Energy Solar Buildings” forms the international platform to harmonize the understanding of Net ZEB´s [5]. This includes a critical literature review [6] and the formulation of requirements [7] as well as a development of a harmonized definition framework [8]. Although building energy needs and on-site generation match on the annual level, large differences may occur for solutions sets on the seasonal, monthly, daily or even hourly match. A harmonized definition should be able to visualize such differences by suitable indicators.

2. Net ZEB Energy Design

As figure 2 illustrates, the energy design of a Net ZEB is based on a two step approach:

- Reducing the amount of delivered energy
- Generating credits by feeding energy into grids.

The minimum amount of credits needed for the Net ZEB rating directly depends on the remaining energy demand. The starting point of the graph may represent the performance of a new building built according to the minimum requirements of the building code or the performance of an existing building prior to renovation. In case the feed-in credits exceed the balance point, such a building is sometimes named *net plus energy building*. Following the idea of photovoltaic power generation using currently available technology on site, the solar exposed area of a building on a given location directly determines the maximum allowable annual energy demand. Due to the decreasing roof space to floor area ratio with increasing building height, such a solution set is mainly favorable for single family homes. It is prominently illustrated to the public with the Solar Decathlon competitions in the US and Europe [9]. Large buildings may involve other renewable energy systems or a combination with on site combined heat and power generation, preferably based on renewables.

Fig. 1. Monitored Net Plus Energy Settlement, Freiburg, Germany [2]

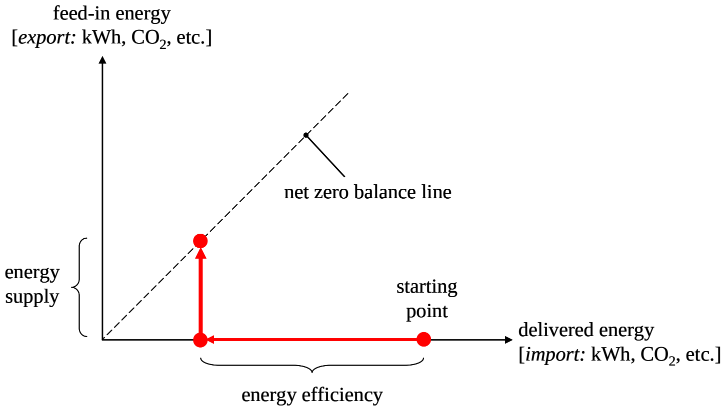


Fig. 2. Graphical representation of the Net ZEB approach [8].

Net ZEBs might differ drastically in terms of:

- the temporal match of the energy generation on site with the building load (load matching)
- the temporal match of the energy transferred to a grid with the needs of a grid (grid interaction)
- the match between the type of energy imported and exported (fuel switching).

Some energy concept may intensify stress on the local grid for example on the seasonal level, thereby worsening its energy or emission performance. The temporal match/mismatch occurs on the daily level - e.g. excess solar power generation during daytime with electricity needs from the grid during night - as well as on the seasonal level (in most climates). Local power grid stress is maximised in concepts based on off-site options to compensate for on-site demands or on-site power generation offsetting fossil fuel utilization for space heating/DHW. Therefore it is essential to make these differences in concepts and performance visible within the definition framework.

3. Load Matching

3.1. Background and Strategies

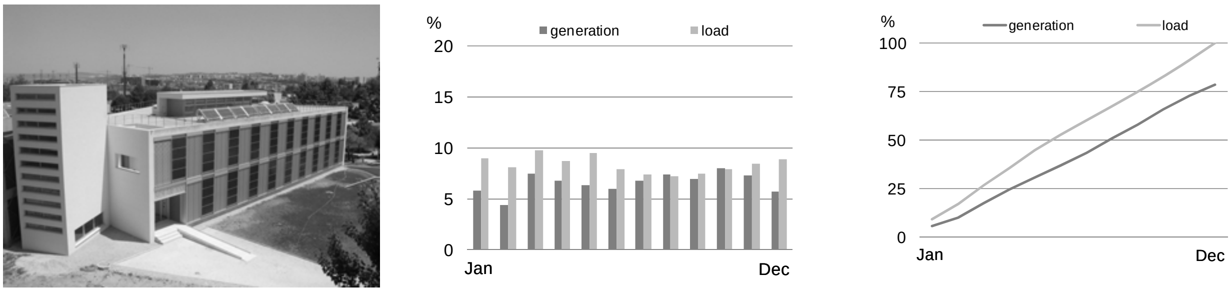
Addressing the load match issue creates the need to detail the energy flows on the level of seasons, months, days, hours etc., depending on the level of accuracy and data availability. The investigation has to be split up into the energy sources in use. Electric loads must include *all* consumption sectors, including appliances and plug loads, to fully characterise a building seen from the grid perspective. This holistic view creates the need to extend the energy planning to more than needed with respect to today's typical building energy code requirements, focusing on HVAC/DHW & lighting demands only. Increasing the match, results in decreasing the need for transportation and storage of energy in the connected grid. Load matching can be detected in practise based on a stored time series of information from the central building (net) electricity meter. Independent metering of the generation is required. Net metering alone is not sufficient. Off-site options such as shares of a wind farm or using green electricity are not considered as their influence is taking into account on the level of the grid, not the building itself.

Matching can be improved in two ways: by adjusting the demand to the generation – so called demand side management (DSM) - and/or by adjusting the generation to the needs. Moreover, on-site energy storage in connection with advanced controls allows covering an increased part of the load by time-shifted utilization of stored energy, generated on site. The disadvantage of all storage options are the energy losses. In a heating-dominated climate, a major decision is the choice of the heating system. All the examples presented here use compression heat pumps, thereby increasing the electric load in times with low solar radiation availability. The amount of seasonal mismatch created by utilizing a heat pump is related to the overall thermal standard of the building. All buildings addressed with fig.3 are high performance buildings in this respect. At the daily level, thermal storage can be applied to improve the correlation of heat pump power consumption and PV yield. Heat supply with a CHP unit would increase the on-site power generation in winter while decreasing it in summer.

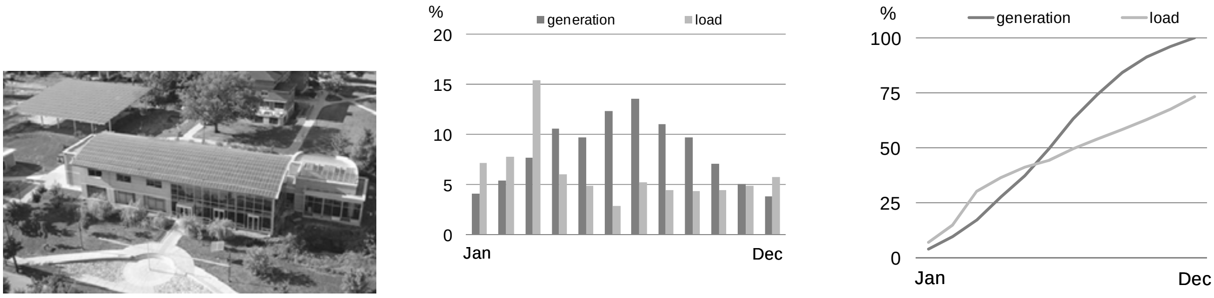
Figure 3 illustrates the annual match of electricity demand and on-site generation for a set of projects under investigation within the IEA expert group. The data shown reflect the climate, the building type, the user behaviour and the energy system applied. All buildings use electricity as the only or dominating (Solar XXI) energy source. On-site generation is based on photovoltaics only. The Solar XXI project might be called *nearly net zero energy building*; the two other examples might be called *net plus energy buildings* as the solar yield exceeds the annual needs.

Widén et al. have theoretically investigated measures to increase the load match for dwellings in high latitude climates, namely the orientation and slope of the PV generator as well as the integration of small battery storage [10]. They conclude that electricity storage (on-site battery storage) and DSM are the most relevant options. While storage mainly reduces the low power demands during nights, DSM cuts the peaks for the grid during the day. As Widén et al. have investigated by simulations, load matching is sensitive to the time resolution considered [11]. Figure 4 analyses the annual matched load of the example Net ZEB using various PV generator sizes and resolutions for the load match analysis. Based on 10 min data resolution not more than 28% of the annual load can be matched. Analyzing the match at the monthly level allows a maximum match of 67%, although the annual yield fully balances the annual demand. Baetens et al. report on simulations for a Belgian dwelling that, considering 1 min data resolution, 42% of the household demand was instantaneously matched, while the fraction decreases to 29% in the case of including the demand for space heating and DHW via heat pump [12]. Due to the difference in the load profiles, the results cannot be considered as valid for other building types, such as offices or schools.

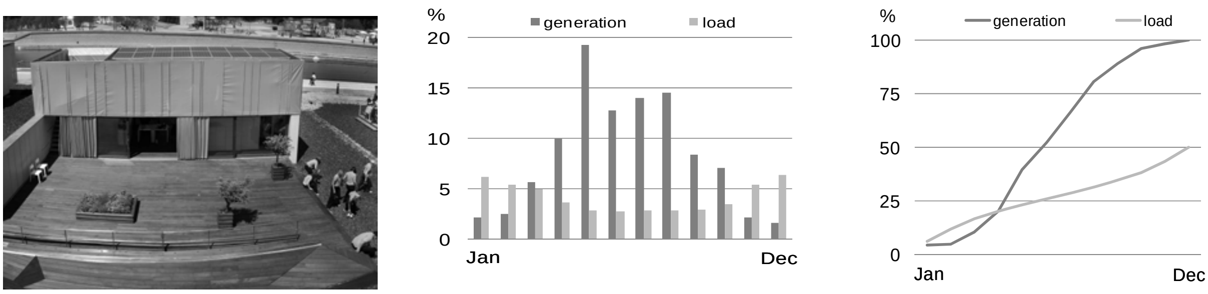
monthly data in sequence   cumulative monthly data



Solar XXI, Portugal [13]



Oberlin College, USA [14]



Solar Decathlon, Germany [15]

Fig. 3: Annual electricity loads and generation profiles based on monthly data. Data include all types of electric loads and refer to measurements, except the Solar Decathlon case where simulation data are shown. Data are normalized with the maximum of the annual total generation and load for each building. Monthly data are given in sequence as well as cumulative to visualize the matching on the monthly level as well as annually.

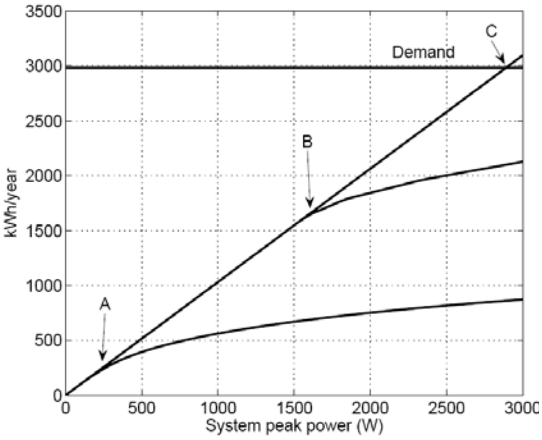


Fig. 4: Simulated load match curves for a dwelling with PV generator of various sizes in the Stockholm climate [11]. The total load only represents household needs; electric heating or DHW is not considered. The lower curve (A) represents the load match based on 10 min net metering (max. 28%); the middle one (B) the monthly balance (max. 68%). The straight line (C) considers the annual balance and shows the match with the demand (103%). The increase in the load match with increasing generator size is limited due to increasing excess electricity generation, especially in the net metering case.

3.2. The Load Match Index

As suggested in literature, the relevant indicator is the so called *solar fraction* describing the ratio of the PV yield to the load. With respect to the fact that other on-site power generation options might be considered, the indicator is named *load match index* within the context of the Net ZEB topic. All generated power exceeding the load is considered as part of the grid electricity, so that the maximum load match index becomes 1 or 100%. As the index strongly reflects the time resolution considered, the time interval must be part of the index name. With increasing time interval, excess production decreases. The annually based load match index of a Net ZEB as well as a net plus energy building is per definition equal to 1. Load match indices based on higher resolution data are averaged to an annual value, keeping the resolution indicator:

$$f_{load,i} = \min\left[1, \frac{\text{on site generation}}{\text{load}}\right] \cdot 100 \quad [\%] \qquad \text{i = time interval (h,d,m)} \qquad (1)$$

or equivalent, but based on net metering instead of load metering:

$$f_{load,i} = \min\left[1, \frac{\text{on site generation}}{\text{net metering} + \text{on site generation}}\right] \cdot 100 \quad [\%] \qquad (2)$$

The presence of on-site battery storage implies that the index must be modified by adding the battery energy balance to the on-site generation. In case the battery is an overall sink within the interval (-), on-site generation decreases; generation increases in the opposite case. Battery storage will be visible on the hourly or daily level only, due to the practical limitations of the storage capacity available with today’s system solutions.

$$f_{load,i} = \min\left[1, \frac{\text{on site generation} + \text{battery balance}}{\text{load}}\right] \cdot 100 \quad [\%] \qquad (3)$$

Figure 5 illustrates the load match index in the resolution of months, days and hours for the projects already addressed within fig. 3 together with the annual averages. Monthly and daily resolutions result in similar annual average load matches, whereas the hourly resolution leads to much lower values, due to the missing PV yield during night.

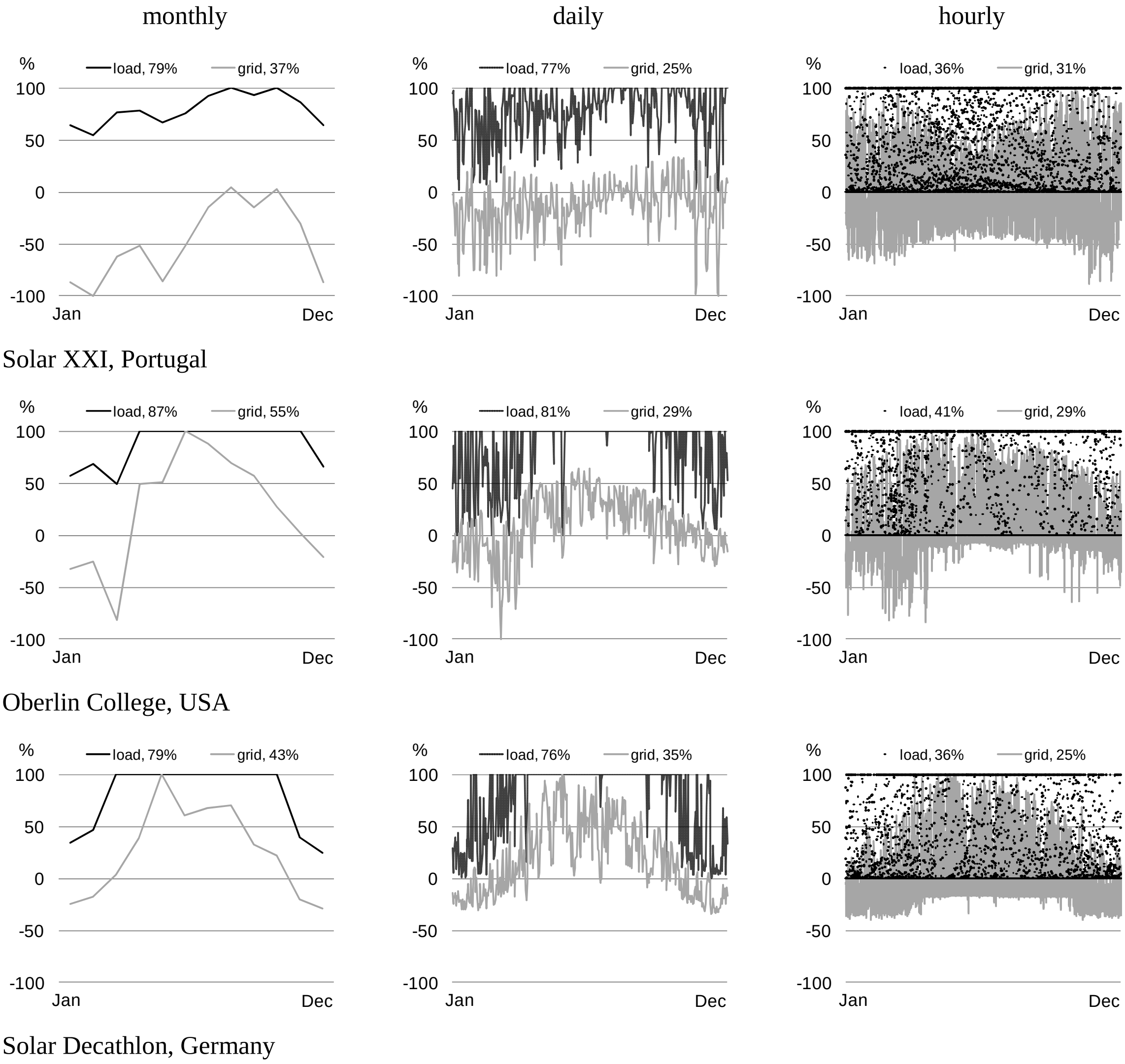


Fig. 5: Load match (f_{load}) and grid interaction indices (f_{grid}, refer 4.2) for all projects addressed in figure 3. Data are given in monthly, daily and hourly resolution together with the annual average for the load index as well as standard deviation for the grid interaction index.

4. Grid Interaction

4.1. Background

Feeding electricity from on-site generation into utility grids is part of the strategy to increase the grids overall system efficiency and the share of power from renewables. On the other hand large scale distributed generation may generate problems with power stability and quality in today´s grid structures, mainly on the local distribution grid level. Developments to so-called “smart grids” are ongoing to fully benefit from distributed generation with respect to the grids primary energy and carbon emission factor as well as the costs. Time-dependent electricity costs (supply) and prices (feed-in) may communicate the needs of the grid to the consumer (the building owner), thereby leading towards improved sizing of the building energy system and DSM as well as integrating appropriate on-site storage options. Within a least-cost planning approach, on-site options have to be compared with measures at the grid level, which take advantage of the economy of scale and equalization of local peaks.

4.2. The Grid Interaction Index

With respect to the fact that the value of exported power is dependent on the local grid performance, the appropriate index from the viewpoint of the building is proposed as *grid interaction index* instead of *grid match index.* Making use of the data already introduced, the grid interaction index is based on the ratio of the net grid metering over a given period (e.g. monthly) compared to the maximum/minimum within an annual cycle. A positive value describes a net exporting building. The *grid interaction index* describes the average grid stress using the standard deviation of the grid interaction over the period of a year:

$$f_{grid,i} = \frac{\text{net grid}}{\max|\text{net grid}|} \cdot 100 \quad [\%] \qquad \text{i = time interval,} \tag{4}$$

$$f_{grid,year} = STD(f_{grid,i}) \tag{5}$$

The index describes the fluctuation of the energy exchange of the building with the grid, not the amount of grid electricity needed. An almost constant import (or export) instead of high fluctuations is characterised by a low value of the annual f_{grid}. Figure 5 includes the grid interaction index in the resolution of months, days and hours for the projects already addressed together with the annual standard deviation. Fig. 6 and 7 summarize the results for the annual indices based on different resolutions. The Solar XXI project profits from the even solar yield during the year although not fully matching the annual energy needs.

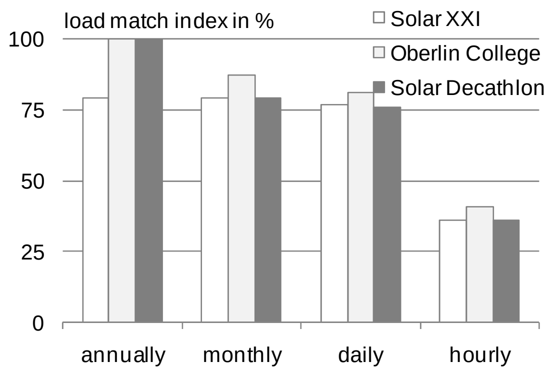


Fig. 6: Comparison of the load match indices based on different time resolutions.

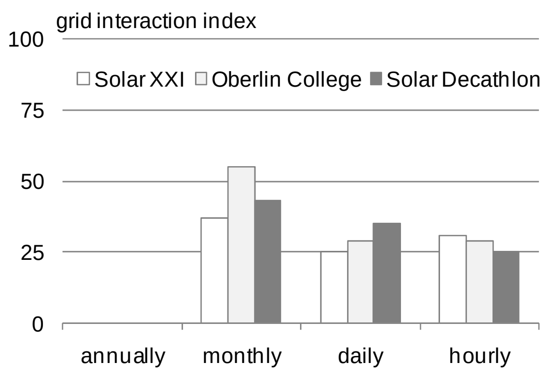


Fig. 7: Comparison of the grid interaction indices based on different time resolutions.

5. Conclusions

The investigation consequently addresses the load match and grid interaction issue on the building level, taking into account energy use and generation on-site. Fuel switching is not yet fully addressed at this stage of work. The investigation focuses on electricity, as the major energy exchanged with a grid in both directions. This includes plug loads and appliances as part of the total load and excludes off-site power generation. With respect to data availability and the suitability for a future spread sheet calculation tool and national building code applications a monthly resolution seems to the appropriate level to characterise the major differences between projects and solution sets. The monthly data consequently address the seasonal effects, reflecting the mismatch of load and generation due to building energy standard, system sizing and climate. Differences between projects are found to be smaller for higher resolution data as long as no on-site battery storage is applied. Indices will be tested with further project data and introduced into the harmonized IEA SHCP Task40/ECBCS Annex 52 definition framework. In the context of the smart grid development high resolution indices describing the interaction of on-site generation, building load and grid might be considered relevant in future.

6. Acknowledgements

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