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Zero Village Bergen: Mismatch Between Aggregated PV Generation and Electric Load in a New Zero Emissions Neighbourhood in Nordic Climate

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Abstract

The Zero Village Bergen is a pilot project in Norway with a total floor area of ca. 92 000 m^2, mainly residential buildings, and being planned with the goal to reach a Zero Emission Building (ZEB) target for the entire neighbourhood on an annual basis. Buildings' energy efficiency and the use of PV on the building roofs are the two measures considered so far. This paper analyses the mismatch between the aggregated electric load and the PV generation. Calculations of the thermal load are also presented and the mismatch is assessed in parallel with assessing the overall goal to achieve the ZEB target on the total energy use. The electric load simulations consider stochastics user profiles, and a sensitivity analysis is performed on all simulations: thermal load, electric load, and PV generation. The results show that while the annual PV generation struggles to cover the annual electric load, the peak power due to the PV generation is 4 times higher than the peak electric load. The mismatch analysis offers useful insights for the next step in the design phase, namely the decision to implement either an all-electric solution with heat pumps in the buildings or a local district heating system with biomass based cogeneration.

***Keywords* - zero emissions, neighbourhood, mismatch.**

1. Introduction

A new settlement is planned nearby Bergen, Norway, with the goal to reach a Zero Emission Building (ZEB) target for the entire neighbourhood on an annual basis, considering the total energy demand of the buildings: heating, cooling, hot water, ventilation, auxiliaries, lighting and plug loads. The Zero Village Bergen is a pilot project of the Norwegian research centre on Zero Emission Buildings.

The Zero Village Bergen consists of a total floor area of ca. 92 000 m^2, with more than 700 dwellings divided between terraced houses (68% of total floor area) and apartment blocks (25%) and some area dedicated to non-residential purposes such as offices, shops, and a kindergarten (7%).

The project is currently in the planning phase and the strategy for achieving the ZEB goal is based on three steps: first, minimize energy demand through energy efficiency of the buildings; second, maximize PV generation on the buildings' footprint; and third, consider additional measures onsite and nearby (e.g. local heating system with biomass based cogeneration). At the current stage the project has reached the evaluation of step two, and the results are presented in this paper.

Fig. 1 shows an image of the site with the different anticipated construction stages (left), and the 3D modelling of the PV system integrated on the buildings (right).

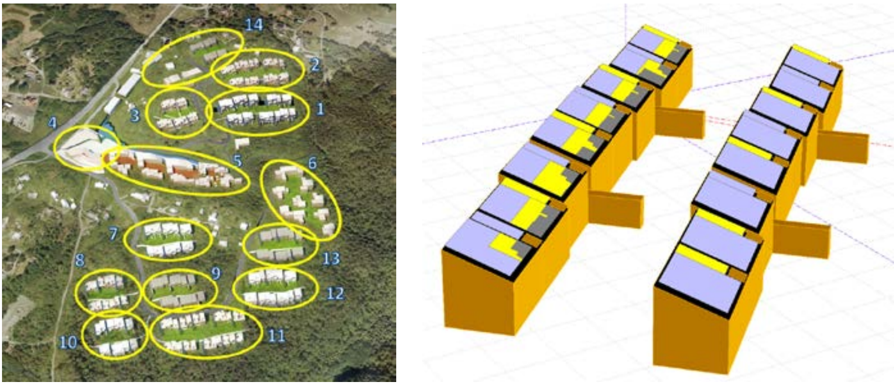

Fig. 1 Overview of the Zero Village Bergen development with construction stages *(left, source: Snøhetta)* and example of a 3D PV system modelling with shading effect *(right, source: PVsyst).*

The main purpose of this paper is to analyse the mismatch between onsite load and PV generation. At this stage – step two – only the *electric specific load* is considered (i.e. ventilation fans, auxiliaries, lighting, plug loads and also cooling in the non-residential buildings) since it is not yet decided whether the *thermal load* (heating and hot water) will be covered by electric solutions, i.e. heat pumps, or other thermal carriers, such as a local district heating system.

PV onsite generation and loads have a temporal mismatch both at a seasonal level and at an hourly level. This mismatch may be considerable; especially in residential buildings since the peak demand is usually in the evening while PV generation peaks in the central hours of the day. Furthermore, the aggregation of several hundreds of household loads is characterized by a certain coincidence factor (often around 0.6), while the PV systems would peak their generation at approximately the same time due to the geographical proximity (meaning a coincidence factor of around 1.0), thus exacerbating the mismatch between aggregated load and aggregated PV generation. The result is an aggregated peak of electricity exported to the distribution grid, which in case of an existing grid might challenge its limits [1] or cause curtailment of the PV generation [2]. In the case of having to build a new power grid extension, as for the Zero Village Bergen, it might otherwise be that the grid's dimensioning should be based on the local peak supply (from the PV) rather than the local peak load.

2. Methods

The primary focus of this paper is on the mismatch between the aggregated electric load and the PV generation. However, calculations of the thermal load are also presented in order to assess the mismatch in parallel with the overall goal of achieving the ZEB target on the total energy use. For further details on the project reference is made to [3]. Both load and generation profiles are presented as hourly averages and are based on the same weather data file in order to guarantee consistency when addressing the mismatch between the two.

Aggregated Building Loads

For residential buildings, stochastic lighting and plug loads hourly profiles are obtained from a Time of Use Data (TUD) methodology [4]. The model considers various appliances, with respective probability of ownership in Norwegian households, and generates stochastic profiles for single households of different sizes from 1 to 5 or more persons per household. As the profiles are calibrated against the best available measurements from various sources, they are assumed to be statistically representative for Norwegian households. Hundreds of stochastic profiles have been generated for each household size and then a weighted average has been calculated considering the national average household size of 2.2 persons per household.

The model generates data on a 1-minute resolution, though the data used in this analysis have an hourly resolution. The reason for it is pragmatic: hourly profiles can be used as input to the thermal modelling of the buildings, for which purpose hourly resolution data are accurate enough due to the inertia of thermal phenomena involved. Nevertheless, the differences between hourly and minute resolution may be significant in terms of peak power. This has been considered when performing the sensitivity analysis.

Electric consumption by the ventilation fans completes the electric load profile of residential buildings. This means simply adding a constant value because the ventilation system in the buildings is a Constant Air Volume (CAV).

For the non-residential buildings the energy demand is calculated directly from real measurements of similar buildings. The hourly electric load is calculated for a typical climatic year based on a methodology presented in [5].

The aggregated load is thus calculated by multiplication by the floor area of the buildings. Figure 2 shows the aggregated electric load for the entire Zero Village Bergen in a typical week in winter and in summer. Note that in summer both the energy use and the duration of power peaks are reduced, but the magnitude of the power peaks is nearly the same as in winter.

The thermal load of residential buildings is calculated by dynamic building energy performance simulations (using the software IDA ICE). Two types of buildings have been simulated: a terraced house and an apartment block. Both buildings have envelope properties that qualify them as passive house buildings according to the Norwegian standard [6]. This includes a balanced CAV ventilation system with heat recovery.

In very well insulated buildings the space heating need is so low that it is lower than the Domestic Hot Water (DHW) need. A passive house has by definition a heating need < 15 (kWh/m^{2}y) while the DHW need used in this study is ca. 24 (kWh/m^{2}y). This is obtained by assuming as input the physical quantity of an average hot water flow of 0.41 (m^3/m^{2}y), as it results from a large survey of approximately 1300 dwellings in Sweden [7]. Additionally, distribution losses have been considered based on reference values from the TABULA project [8], thus increasing the DHW energy demand to ca. 25-27 (kWh/m^{2}y) depending on the building type, see Table 1.

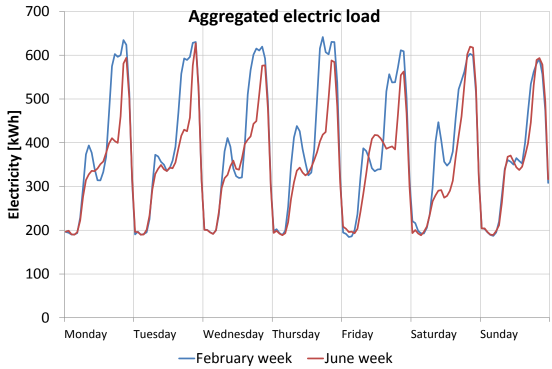

Fig. 2 Typical weekly profiles for the aggregated electric load in winter (blue) and summer (red).

In highly insulated buildings the significance of internal gains, such as from lighting and plug loads, is higher than in conventional buildings. In order to consider this effect, instead of just applying normative tabulated values for both quantity and timing of the internal gains, the aggregated electric load profiles for lighting and plug loads are normalized per square metre of floor area and used as input in the calculation of the thermal load.

For the non-residential buildings, the energy demand is calculated directly from real measurements of similar buildings. The methodology for data collection from monitored buildings and further adjustments, e.g. normalization to a typical climatic year and differentiation between conventional and very energy efficient (passive house) buildings, was developed in [9]. The values presented here are representative averages of very energy efficient buildings, equivalent to passive house buildings.

Aggregated PV Generation

PV generation profiles are obtained using state of the art software (PVsyst) considering the variety of roof orientations and shading effects from a 3D modelling, as shown in Fig. 1.

The available roof area is calculated based on the footprint floor area of the buildings given by the architect, knowing that the roof tilt will be 19°. Considering that the PV is building integrated a high cover ratio of 95% is considered, giving a total PV area of 22 045 m² distributed over six different orientations (-29°, -40°, -45°, -48°, -53° and -60°) all in the South-East range. These orientations are not optimal for the PV system but are dictated by the site's orography and other specific planning constraints including minimization of noise level in outdoor spaces caused by the local airport situated on the North-West of the development site. Simulations are made for a PV monocrystalline silicon module with a rated power of 300 Wp and an efficiency of 18.3% (183 Wp/m² of PV area). In the simulations diverse types of optical and electrical losses were considered, including snow losses [3].

Solar radiation data of good quality is limited in Norway. There are few meteorological stations for which the quality of the measured solar radiation has been cross-checked by ground measurements; one must therefore largely rely on satellite data. Six different datasets have been considered in this study: Nasa-SSE, PVGIS Classic, S@tel-Light, the Geophysical Institute of the University of Bergen, and two from Meteonorm. The Meteonorm datasets from the weather station Bergen/Florida, operated by the Norwegian Meteorological Institute is considered the most relevant dataset for this study.

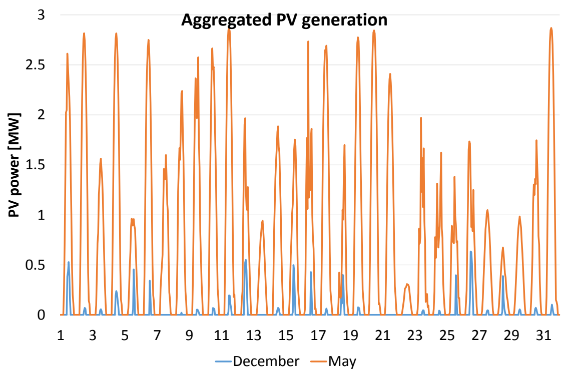

Fig. 3 Aggregated PV generation, months of December (blue) and May (orange).

The total estimated installed power is 4.037 MWp, which produces 2.941 GWh/year. Fig. 3 shows the aggregated PV generation for December and May, the two months with the highest and lowest production, respectively. The fact that the production is better in May than in June or July is mainly due to lower air temperatures that grant the PV modules lower temperature related losses.

Sensitivity analysis

The aim of the sensitivity analysis is to gain a sense of the magnitude by which the results may change, in terms of both energy demand and peak power, depending on the possible changes in some key inputs and parameters. The effect of every single variation is evaluated in itself and no cumulative effect is considered since it is not possible to say a priori how they correlate. In other words, if variation A gives an effect of +3% and variation B also gives an effect of +3%, we cannot conclude that the combined effect of A+B will be +6%. Likewise, if the variation B had an effect of -3% we could not conclude that A and B neutralize each other giving a net zero effect. We simply do not know how these variations correlate to each other in a complex system where the variables influence one another. The results of the sensitivity analysis are presented together with the main results in the next chapter.

For the residential buildings, different boundary conditions and data sources were considered as alternative input and parameter values. For the electric load we considered: the use of tabulated values for lighting and plug loads as from the Norwegian standard [6], the use of better and worse efficiencies for the ventilation fans, the use of 1-minute resolutions data (instead of hourly resolution), and the effect of induction cookers (not considered in the original study [2]). For the thermal load we considered: using the tabulate value for DHW as from the Norwegian standard [6], the use of different weather files, higher indoor temperature, the use of better and worse efficiencies for the ventilation heat recovery, the use of night setback, internal partitions with less thermal mass (in floors, ceilings and internal walls).

For the non-residential buildings, we considered a possible variation of ± 50% on the hourly values, while keeping the same temporal profile. The reason is that though the values come from real measurements of dozens of buildings per each building type, the spread around the average is generally rather high and the small amount of non-residential floor area in the Zero Village Bergen is by no means guaranteed to behave as the average of a much larger sample.

For the PV generation, different boundary conditions and data sources were considered as alternative input and parameter values: different meteorological datasets, different roof area availability, and different PV system efficiencies.

3. Results

The results of the building simulations for the two types of residential buildings are reported in Table 1, showing the energy intensity (kWh/m^2) for all the energy services.

Table 1 Results of the building energy performance simulations.

Energy service [kWh/m^{2}y]	Heating	DHW	Fans and pumps	Lighting	Plug loads	Total
Terraced house	11.8	24.8	3.6	7.6	18.5	66.3
Apartment block	10.2	26.8	4.2	7.7	18.6	67.5

The aggregated results for the whole Zero Village Bergen are summarized in Table 2, showing the total thermal load, the total electric load and the total PV generation, all three accompanied by the variation range resulting from the sensitivity analysis. At aggregated level the Zero Village Bergen has a total thermal need of 3.3 (GWh/y) with a peak load of 1.3 (MW), and an electric need of 3.3 (GWh/y) with a peak load of 0.7 (MW). The PV system generates in total 2.9 (GWh/y) with a generation peak of 2.9 (MW).

Concerning the energy needs, for the thermal load, the high end of the sensitivity analysis is marked by the increased indoor temperature (+30% at 24°C instead of 21°C), while the bottom is marked by a better ventilation heat recovery efficiency (-1% at 90% efficiency instead of 80%). For the electric load, the symmetric range is the effect of the uncertainty considered for the non-residential buildings. For the PV generation, the symmetric range is the effect of the uncertainty on the available roof area (where the plus side considers an extension on the car ports).

Table 2 Summary of results with sensitivity analysis.

	Energy demand [MWh/y]	Peak Power* [MW]
Thermal load	3 283 (-1% +30%)	1.3 (-11% +53%)
Electric load	3 257 (±10%)	0.7 (-5% +12%)
PV generation	2 941 (±15%)	2.9 (±15%)

* Hourly average, without food storage in shop area.

Concerning the peak power, for the thermal load the high end of the sensitivity analysis is marked by the night setback (+53% at 2°C setback delta), while the bottom is marked by a different climate file (-11% with IWEC instead of Meteonorm). For the electric load the high end of the sensitivity analysis is marked by the 1-minute resolution data with consideration of induction cookers (+12%), while the bottom is the effect of the uncertainty considered for the non-residential buildings (-5%). For the PV generation the symmetric range is again the effect of the uncertainty on the available roof area.

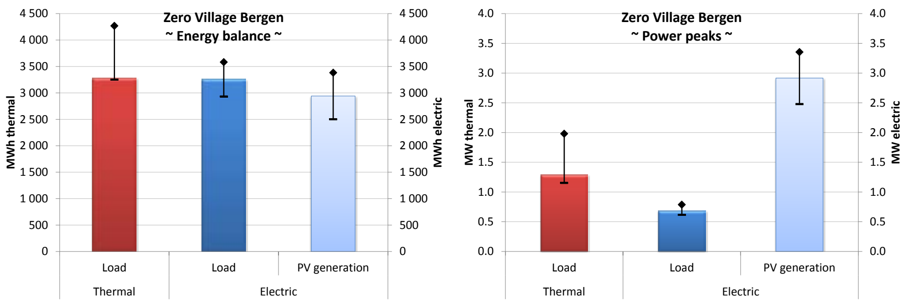

Fig. 4 Aggregated energy balance *(left)* and peak power *(right)* showing the thermal and electric loads and the PV generation, with min-max markers from sensitivity analysis.

The results are shown graphically in Fig. 4, offering at a glance the powerful visual impression that while the PV generation struggles to cover just the electric load, the peak power due to the PV generation is by far higher than the peak electric load, and even higher than both thermal and peak electric loads together.

Since it is not yet decided which energy carrier will be used in the Zero Village Bergen to cover the thermal load, it makes sense for the time being analysing the mismatch between the electric specific load and the PV generation. The two can be plotted in the same graphs, as in Fig. 5, thus showing the net delivered electricity to the Zero Village Bergen. In this case negative values mean net export to the grid. Here the mismatch between electric load and PV generation is evident: there is a large export to the grid in all seasons but winter while there is still a net import (in the evenings) throughout the whole summer.

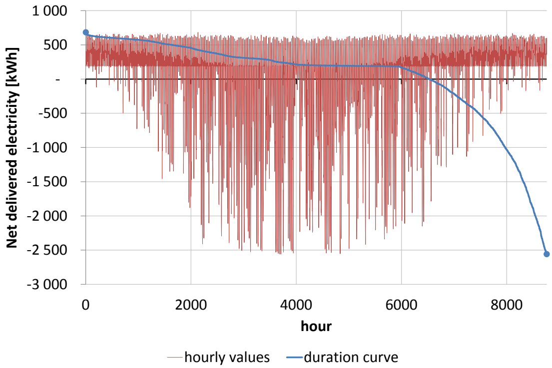

Fig. 5 Net delivered electricity hourly profile (red) and duration curve (blue).

Table 3 summarizes the mismatch numerically, using the indicators suggested in [10]. The coverage factor is 90% while the self-generation calculated on an hourly basis is 32%, meaning that 32% of the load is directly covered by the PV generation and the rest is taken from the grid. The self-consumption, on the other hand, is 36% meaning that 36% of all PV generation is instantaneously matched by the electric load and the rest is exported to the grid.

Table 3 Summary of electric load and PV generation mismatch.

Coverage	Self-generation	Self-consumption	GM generation/load	GM export/import
90 %	32 %	36 %	4.3	3.7

The Generation Multiple (GM) tells what the required grid connection capacity is due to the PV system compared to what it would be due to the load alone. The GM calculated as the ratio between peak generation and peak load is 4.3; this is the worst case since it does not consider the instantaneous match between the two quantities. Calculating the GM as the ratio of peak export over peak import gives a value of 3.7. Either way, the requirement for dimensioning the grid connection capacity is about four times higher with the PV system than it would be without.

4. Discussion and Conclusions

The heating system for the Zero Village Bergen is not yet decided. Namely, the two most probable options on the design table are either an all-electric solution with heat pumps in the buildings, or a local district heating system since a city district heating is not available in the area. The analysis of the mismatch between loads and PV generation offers useful insights for the next step in the design phase.

The first reflection goes to the energy balance and the feasibility of achieving the ZEB goal in the Zero Village Bergen. First of all, it shall be noticed that the goal of balancing the entire energy use is highly ambitious. In comparison, the definition of "nearly ZEB" in the EPBD and related EN norms (e.g. prEN 15603) only requires to "nearly" balance the delivered energy that goes to cover the thermal load of all buildings plus the lighting for non-residential buildings only. Assuming the all-electric solution one avoids the need for any primary energy or carbon emission conversion factor. In this case, even with a seasonal COP of just 2 the Zero Village Bergen would appear as a "Plus Energy" neighbourhood according to the EPBD, see Fig. 4 (left).

Setting the balance goal on the total delivered energy makes things more challenging. The thermal and electric loads happen to be about the same, but the electric load has always to be balanced on a one-to-one basis by the renewable electricity generated onsite or nearby. The thermal load may be easier to balance thanks to favourable conversion factors, as for example in the case of carbon emission factors (or non-renewable part of primary energy) for biomass that are often in the range of 10-70 (gCO_2/kWh) while they are in the range 150-600 (gCO_2/kWh) for electricity [11]. In that case the equivalent thermal load to be covered – after applying the carbon emission factors – would be *de facto* just a small fraction of what is shown in Fig. 4 (left). This seems to suggest that connecting the buildings to a local district heating system with biomass based cogeneration would provide at the same time a small additional thermal load – counted in carbon emissions – and extra electricity generation, so that the overall ZEB goal may actually be reached. This will depend on the specific conversion factors used for biomass and electricity.

The second reflection goes to the peak power and the mismatch between the load and the PV generation. In case of the all-electric solution one may argue that even if the heat pump seasonal COP was rather high, e.g. 4.0, the peak thermal load in the coldest days might be almost the same as what shown in Fig. 4 (right) due to poor operating conditions (low source temperature) frosting on the evaporator side and the need to resource to a top heater (electric), which all contribute to a poor COP, in the worst case of just about 1. In this case the ZEB balance would not be reached (at least not by the PV system alone) but the GM would get significantly reduced to about 1.5 because of the increased peak electric load due to the heat pump system. This means that the local electric grid does not need to be largely over dimensioned due to the PV system: something that might normally be regarded as a positive feature.

In case of local district heating, on top of achieving the ZEB balance more easily, the cogeneration would complement well the PV system because it generates electricity mainly in winter, and because it is possible to modulate its generation during the daily cycle, altogether improving the interaction with the grid. In this case though, the GM would be about 4 as analysed here, see Table 3.

. However, this needs not to be regarded as a negative feature. If one considers the need for charging electric vehicles – particularly relevant in Norway already today –

having a high GM might even be an advantage. It simply means that the dimensioning of the grid connection is based on the PV peak production in summer, but that capacity is free overnight all year round to be used for charging e-vehicles.

The analysis of alternative solutions for the Zero Village Bergen heating system will be performed in future work, as well as the analysis of the e-vehicles charging load will, considering different scenarios of e-vehicles penetration. The analysis of the mismatch between aggregated electric load and PV generation presented in this paper provide useful insights on how to proceed in the next design step for this pilot project.

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