EVALUATION AND OPTIMIZATION OF A SWEDISH NET ZEB - USING LOAD MATCHING AND GRID INTERACTION INDICATORS

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ABSTRACT

Net Zero Energy Buildings, Net ZEBs, is one of many necessary measures for climate change mitigation as they may reduce the energy consumption in the building sector. The Net ZEB interacts with a grid infrastructure. It is therefore important to consider the interaction with the grid in the design phase.

This paper reports an evaluation of a proposed design of a Net ZEB in the south of Sweden evaluating load matching and grid interaction using simulated data sets with hourly resolution. The aim was to find a design with as high load matching and as low grid interaction as possible.

The results show difficulties of achieving a high load matching between the building load and on-site generation, due to the Nordic climate and the relatively low loads during daytime, when the availability of solar energy is high. The building is likely to accomplish the goal of a Net ZEB balance. If higher flexibility is sought, a larger energy storage should be considered.

INTRODUCTION

Buildings today account for 40% of the world´s primary energy use and 24% of the greenhouse gas emissions (IEA, 2010). The building sector is expanding. Therefore, reduction of energy use and the use of energy from renewable sources in the buildings sector constitute important measures required to reduce energy dependency and greenhouse gas emissions.

Today a number of buildings exist where the design principle has been to construct a Net Zero Energy Building, Net ZEB (IEA, 2012). The definition of a Net ZEB may differ, usually it is referred to as a building that provides as much energy as itself uses but interacts with an energy supply system and can export energy when the building's system generates a surplus and import energy when the building's system not supply the quantities of energy required.

To design and build a well functioning Net ZEB that interacts with an existing grid, it is important to consider the interaction with the grid in the design phase. One reason for this is that self-consumption of on-site generation is generally more economically favourable than selling the surplus, in the absence of generous feed-in tariffs. Lower overproduction also lowers the load on the grid and increases the so-called hosting capacity of the grid.

The design may be evaluated by using quantitative indicators to describe load matching and grid interaction (LMGI), where load matching refers to how the local energy supply compares with the building load and grid interaction refers to the energy exchange between the building and the grid. The terminologies are further described in (Voss et al., 2010), (Salom et al., 2011) and (Sartori et al., 2012).

One of the most vital features that LMGI indicators may grasp is the flexibility of a building (Salom et al., 2011). The term flexibility here defined as a building's ability to respond to actions from the residents or the grid; adjusting in order to minimize the stress to the grid. This flexibility could be quantified using suitable LMGI indicators, especially those indicators that provide significant differences if a feed-in strategy is used, prioritizing export of energy from a building to the grid, or if the opposite, load matching is prioritized, trying to match the varying need of energy for a building by energy from renewable sources produced on-site or nearby.

(Voss et al., 2010) concludes that a monthly resolution could be an appropriate level on which load matching and grid interaction could be examined in order characterise differences between projects and solution sets. In a literature review, (Salom et al., 2011) found 14 different LMGI indicators, which they divided into four different categories. The different LMGI indicators were evaluated for a building with and without a battery for storage. The evaluation showed that some indicators are affected by the use of battery storage, but not all. The study concludes that LMGI indicators may add significant value to the output of building performance tools, and give a more complete picture of Net ZEBs.

In the recently published article by (Sartori et al., 2012) the focus is to describe a consistent framework for Net ZEB definitions to make it possible to define consistent and comparable Net ZEB definitions. Within the framework LMGI indicators are addressed.

In Sweden, Skanska Sverige AB has developed a concept for a Net ZEB. However, the load match and grid interaction has not been considered. Therefore, LMGI are considered in this study. The study does not include so called demand side management, DSM.

In addition to studies mentioned above, there are several other studies investigating the impact of on-site generation. Examples may be found in (Hawkes et al., 2005), (Peacock et al., 2006), (Kelly et al., 2008) and (Widén et al., 2009). However, these do not use the terminology; LMGI indicators. LMGI indicators used in this study are originating from (Voss et al., 2010), (Salom et al., 2011) and (Sartori et al., 2012).

Numerous studies has been done on modelling Net ZEBs and the feasibility of different tools. The feasibility of different tools is not within the scope of this study.

The nomenclature section at the end lists the symbols used in this paper.

SIMULATIONS

The case study

The proposed building is a five dwelling terraced house, situated in the city of Malmö in the south of Sweden. The building has a large roof and facade towards south-southwest with integrated PV modules. On the top of the roof, which is horizontal, solar thermal collectors are mounted. They are not integrated. The characteristics of the building are presented in Figure 1 and Table 1. The building is designed to be connected to the electricity grid and district heating network.

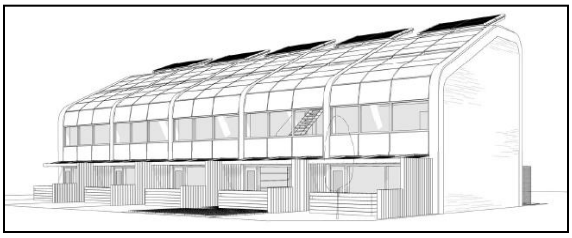

Figure 1 Proposed design of case study building.

Table 1
Characteristics of case study building

CHARACTERISTIC	DATA	UNIT
Orientation of facade and roof with PV (180° = south)	200	°
Slope of roof	20	°
A_C, Conditioned area	703	m^2
$g_{des, PV}$, Installed PV capacity	34	kWp
A_{ST}, Solar thermal collector	108	m^2

In the proposed design, no energy storage is installed in the building; E.g. no battery and no hot water storage tank. Instead, the building relies on the grid and will therefore always export energy when the building's system generates a surplus and import energy when the building's system does not produce the quantities of energy required. However, the district heating network only accepts the building to export heat from the solar thermal collectors when the mean fluid temperature from the solar thermal collector exceeds 75°C. The possibility to export the surplus of the heat to the district heating network has previously been implemented in both residential and non residential buildings in Malmö (City of Malmö, 2007), (Isaksson et al., 2007) and (Eon Energy, 2011).

To investigate LMGI factors, whether it is possible to reduce the building's need for delivered energy and to reduce the peak load, seven different options were examined. The options are described in Table 2. After studying all options, an eighth option was tested, seeking a "best option", based on the results from the prevois options. The strategy were to increase load matching, decrease the amounts of exported heat during the summer, due to the low need of heat during summer.

Table 2
Description of investigated options

	DESCRIPTION
1	Instalment of battery, $SC_{battery}$, 50 kWh
2	Instalment of hot water storage tank, $V_{Storage\ tank}$, 0.75 m^3/dwelling. The ability to export heat to the district heating network is terminated
3	1+2+ Decrease of A_{ST} 50%, increase of $g_{des\ PV}$ 20%
4	Orientation of building -20°
5	Orientation of building -40°
6	Slope of roof and solar thermal collectors +20°
7	Slope of roof and solar thermal collectors +40°

Method

Hourly data sets were generated by simulations, using VIP Energy (Strusoft, 2012). Figure 2 gives an overview of the energy flows and terminology used in this case study.

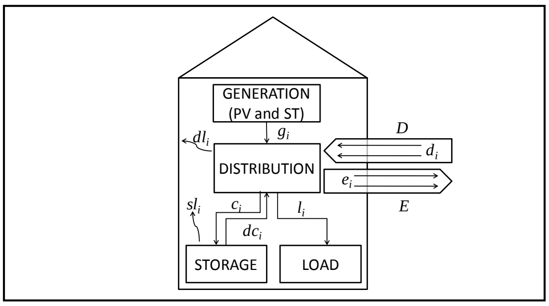

Figure 2 Schematic presentation of energy flows addressed in this study.

To enable analysis in hourly resolution, profiles for electric load for lighting and plug loads, hot water and occupancy were created based on (Bagge, 2011), (Bernardo, 2010) and (SCNH, 2012). The peak load was set to 1.1 kW/dwelling for hot water and 770 W/dwelling for lighting and plug loads. In Figure 3 and Figure 4, the relative load profiles are presented. The maximum internal heat gains from occupancy presence were set to 1.2 W/m^2 with a daily variation as presented in Figure 5. The occupancy presence is assumed not to have a seasonal variation.

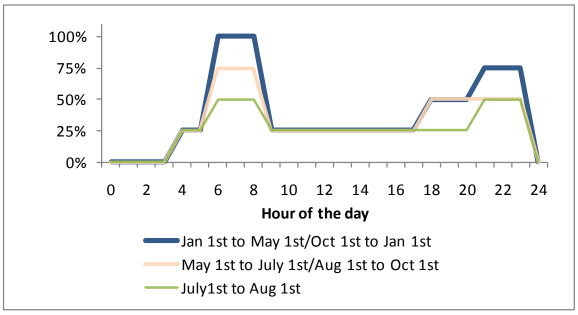

Figure 3 Load profile; hot water.

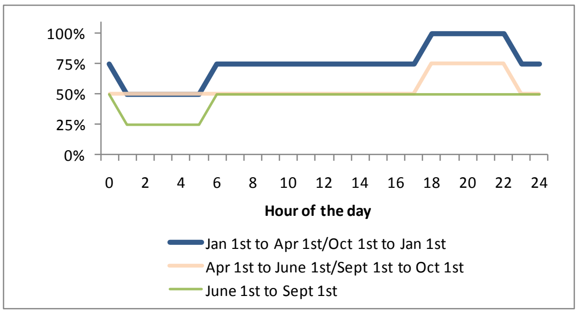

Figure 4 Load profile; lighting and plug loads.

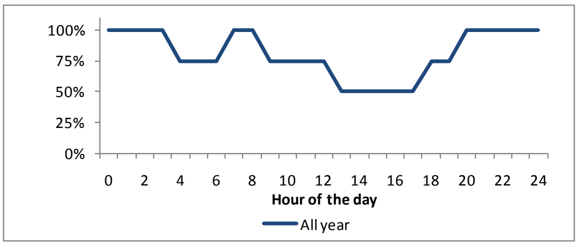

Figure 5 Relative occupancy presence

The chosen software does not include a model for storage losses in batteries. Furthermore, it does not consider distribution losses for heating. These were addressed by applying Equation 1 and Equation 2.

$$sl_{electricty} = 0.01S_{electricity}(t) \qquad (1)$$

$$dl_{heating} = 0.05l_{heating}(t) \qquad (2)$$

The yearly import/export balances were calculated as in Equation 3.

$$\sum_i e_i w_i - \sum_i d_i w_i = E - D \qquad [\text{kWh/m}^2\text{a}] \ (3)$$

The yearly load/generation balance were calculated as in Equation 4.

$$\sum_i g_i w_i - \sum_i l_i w_i = G - L \qquad [\text{kWh/m}^2\text{a}] \ (4)$$

Differences between import/export balance and load/generation balance is expected due to the fact that there will be some self-consumption of energy within the building and storage losses. These two facts reduce the amounts of imported and exported energy, compared to load and generation. Weighting factors, *w*, may differ if asymmetric weighting is preferred (Sartori et al., 2012). However, the Swedish definition of a Net ZEB requires symmetric weighting (SCNH, 2012). The applied weighting factors are according to (SCNH, 2012);

- $w_{electricity} = 2.5$
- $w_{heating} = 0.8$

This study includes all delivered and exported energy to the building, as defined in EN 15217 (SIS, 2007), in contradiction to the Swedish definition of a Net ZEB, which excludes plug loads and appliances (SCNH, 2012). The temporal match between load and generation for electricity and heat were investigated using the *load match index*, which describes the ratio of on-site power generation and load. The definition is described in Equation 5. The load match index was calculated both for heat and electricity on three different time intervals; hourly daily, monthly and by year. When energy is fed into the grid, the load match index is 100%. Regarding the load match index, a high index is preferable if a high on-site coverage of the energy demand is desired.

$$f_{load,i,\mathrm{T}} = \min\left[1, \frac{g_i + dc_i - c_i}{l_i}\right] \qquad [\%] \ (5)$$

To assess the interaction between the building and the electricity grid and district heating network the grid interaction was investigated. The grid interaction is based on the ratio between the net metering (e.g. exported - delivered energy) compared to the maximum exported - delivered energy over a given time period, as shown in Equation 6. Three different time intervals are investigated; hourly, daily and monthly.

$$f_{grid,i,\mathrm{T}} = \frac{e_i - d_i}{max|e_i - d_i|} \qquad [\%] \ (6)$$

It may be argued that both numerator and denominator in Equation 6 should be in absolute terms. However, by not using absolute numbers, the quota shows whether the building exports or import energy. A positive value describes a net exporting building. The average stress on the grid was investigated by calculating the *grid interaction index*. This is defined as the standard deviation of the grid interaction over the year, as shown in Equation 7.

Regarding the grid interaction index, low standard deviations are preferable.

$$f_{grid,i,year,\mathrm{T}} = \mathrm{STD}\big(f_{grid,i,\mathrm{T}}\big) \quad (7)$$

To quantify the stress on the grid, peak export and import for each energy carrier were calculated as well as the duration of high load as in Equation 8 and Equation 9. Low peak loads are preferable.

$$e_{i>lim} = \frac{time_{e_i>lim}}{8760} \quad [\%]\ (8)$$

$$d_{i>lim} = \frac{time_{d_i>lim}}{8760} \quad [\%]\ (9)$$

RESULTS

In Table 4, a summary of all calculations is shown. Based on the studied options, the proposed best option is to:

- Increase the slope of the roof/PV and solar thermal collectors by 20°
- Rotating the building -20°
- Increasing the PV, $g_{des\ PV}$, by 10% + instalment of battery, $SC_{BATTERY}$ 50 kWh
- Reducing solar thermal collectors, A_{ST}, by 50% + instalment of hot water storage tank, $V_{Storage\ tank}$, 0.75 m^3/dwelling. The ability to export heat to the district heating network is terminated

Note that the increase of PV, $g_{des\ PV}$, is only increased by 10% compared to previous investigated option 3; 20%. It is assumed that a 10% increase is enough to reach a Net ZEB balance without increasing the peak load for exported electricity, compared to option 3. Hence, the orientation of the building and roof slope is now more favourable.

The import/export balance and load/generation balance is graphically presented in Figure 6 and Figure 7. Note that the scale in Figure 6 is different and the intersection for the axes is at 110 kWh/m^2a. The configuration is chosen to enable the possibility to grasp differences between the options. Of the investigated measures, all except measures 2 and 7 meet the basic requirement of a positive load/generation- and import/export balance.

Examining the load match index for electricity, in Table 4, the index does not show significantly different values for the different options investigated. Since it is the minimum value presented for load match, the value is zero or close to zero due to the low availability of solar energy in winter.

A small increase of load match, based on monthly resolutions, is seen when the slope of the roof/PV is increased by 20° and the installed kWp of PV is increased. Introducing a battery does not increase the load match index. However, the grid interaction index based on hourly resolution, peak load for exported electricity and duration of high load for exported electricity decreases slightly when a battery is used.

The option to terminate the ability to export heat to the district heating network and instead install a hot water storage tank reduces the yearly load match for heat, from 74 % to 25 %, and increases the grid interaction index based on hourly resolution, from 18 % to 23 %. The grid interaction based on daily and monthly resolution decreases from 44 % to 29 % and 70 % to 41 % respectively. Furthermore, as a corollary; peak load for exported heat, and duration of high load for exported heat, drops to zero.

The monthly load distribution, exported energy, load match and grid interaction were investigated further in order to discern differences between the most interesting options; base case, option 1, option 2 and "best option". The results are presented in Figure 8. The small differences in monthly load match and grid interaction for electricity is not possible to discern in the resolution used in Figure 8.

The instalment of a hot water storage tank in each dwelling and terminating the ability to export heat to the district heating network is clearly shown. The graphic load match profile and grid interaction are similar for option 2 and "best option", even though A_{ST} is reduced by 50% in the latter option.

In contradiction to the difficulties to distinguish differences in the monthly load match and grid interaction profiles for electricity, examining the monthly load distribution and exported energy shows differences when battery storage was installed. Roughly, the instalment of a battery allows the building not to import electricity during the period May-August. The monthly quantities of exported electricity were also reduced during the period. Comparing the base case and the first option, the reduction is almost 1 MWh/month.

Increasing PV by 10% + instalment of a battery results in roughly the same quantities exported electricity monthly, compared to the base case during the same period. When hot water storage tanks were installed in the dwellings, the need for heat from the district heating network during the summer was significantly reduced. During the period May-August the need was nearly zero, compared to the base case, a reduction of roughly 1 MWh of heat/month. As mentioned earlier exported heat is reduced to zero.

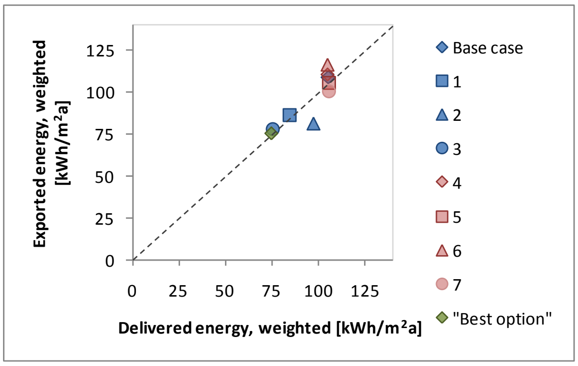

Figure 6 Import/export balance for the investigated options

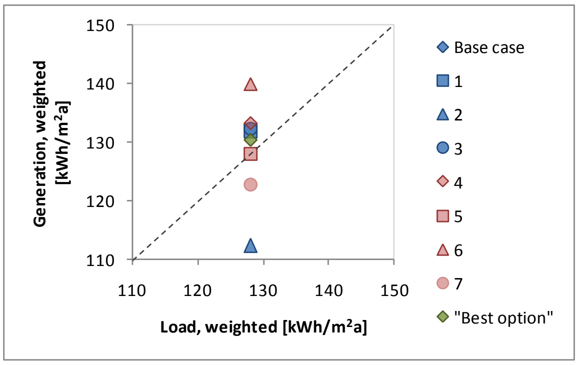

Figure 7 Load/generation balance for the investigated option

Table 4

Summary of energy balance and LMGI indicators for all investigated options

INDICATOR	BASE CASE	OPTIONS							BEST OPTION
		1	2	3	4	5	6	7	
Import/export balance [kWh/m²a, weighted]	4	2	-16	2	5	0	12	-5	1
Load/generation balance [kWh/m²a, weighted]	4	4	-16	4	5	0	12	-5	2
$f_{load, electricity, hourly}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$f_{load, electricity, daily}$ [%]	1%	1%	1%	1%	1%	1%	1%	1%	1%
$f_{load, electricity, monthly}$ [%]	4%	4%	4%	5%	4%	4%	5%	4%	5%
$f_{load, electricity, yearly}$ [%]	100%	100%	100%	100%	100%	100%	100%	100%	100%
$f_{load, heat, hourly}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$f_{load, heat, daily}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$f_{load, heat, monthly}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$f_{load, heat, yearly}$ [%]	74%	74%	25%	23%	75%	72%	78%	69%	24%
$f_{grid, electricity, year, hourly}$ [%]	22%	19%	22%	20%	22%	22%	22%	22%	20%
$f_{grid, electricity, year, daily}$ [%]	42%	42%	42%	40%	42%	42%	41%	43%	40%
$f_{grid, electricity, year, monthly}$ [%]	65%	65%	65%	60%	65%	66%	63%	68%	60%
$f_{grid, heat, year, hourly}$ [%]	18%	18%	23%	23%	18%	18%	18%	18%	23%
$f_{grid, heat, year, daily}$ [%]	44%	44%	29%	29%	44%	45%	43%	46%	29%
$f_{grid, heat, year, monthly}$ [%]	70%	70%	41%	41%	70%	68%	72%	67%	41%
$e_{max, electricity}$ [kW]	37	36	37	44	37	35	39	34	43
$e_{max, heat}$ [kW]	61	61	0	0	61	59	64	56	0
$d_{max, electricity}$ [kW]	4	4	4	4	4	4	4	4	4
$d_{max, heat}$ [kW]	16	16	16	16	16	16	16	16	16
$e_{electricity>Lim\ 20\ kW}$ [%]	6%	5%	6%	7%	6%	6%	7%	5%	7%
$e_{heat>Lim\ 20\ kW}$ [%]	6%	6%	0%	0%	7%	6%	7%	6%	0%
$d_{electricity>Lim\ 5\ kW}$ [%]	0%	0%	0%	0%	0%	0%	0%	0%	0%
$d_{heat>Lim\ 10\ kW}$ [%]	5%	5%	5%	5%	5%	5%	5%	5%	5%

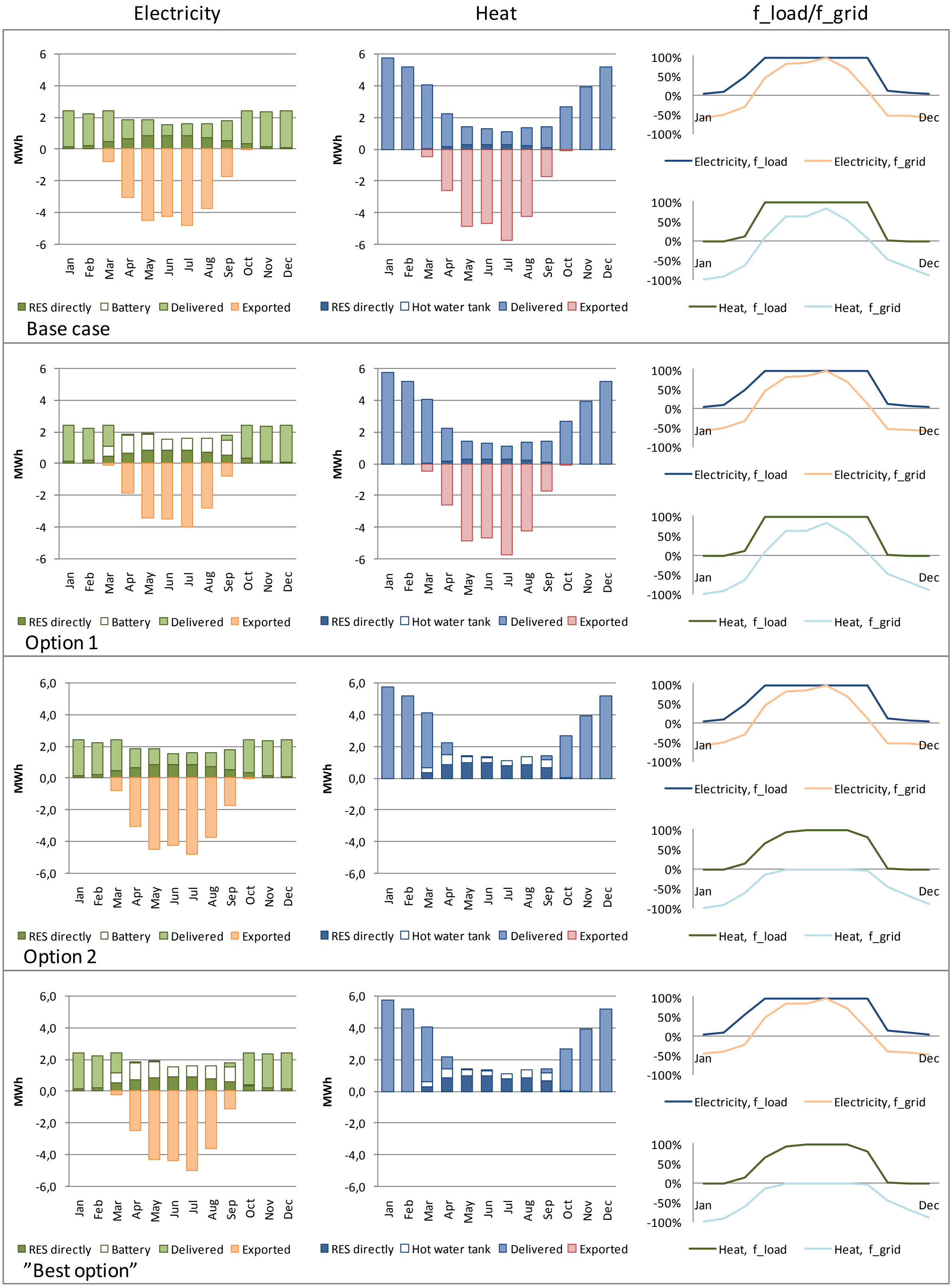

Figure 8 Monthly load distribution and exported energy for electricity (left column) and heat (middle column). Monthly load match and grid interaction for electricity and heat in the right column. Base case, option 1, option 2 and "best option" are presented.

DISCUSSION AND RESULT ANALYSIS

The results show the difficulty of achieving a high load match for the studied building when the evaluated resolution is lower than one year. The cause is mainly due to two aspects. The first aspect is the fact that the building is situated in a Nordic climate where the heating demand is high in winter when the available solar energy is low. The second cause is that the building is designed for dwellings and therefore assumed to have relatively low loads for plug loads, lighting and hot water during daytime, when the availability of solar energy is high.

Introducing small energy storage systems, e.g. hot water tanks or batteries, results in small effects on load match and grid interaction. This indicates a need for larger energy storages in a Nordic climate if a higher flexibility of buildings is desired. Architectural changes (e.g. slope of roof) and adjustment to the location (e.g. orienting the building towards south) shows small or no effect on the building's flexibility (e.g. LMGI indicators). However, it affects the Net ZEB balance.

The used indicator for load matching presents the minimum load match over a period. If an average (e.g. arithmetic mean) load match had been calculated, there might have been greater difference between the options. However, an average load match would not grasp the flexibility of a building. It would rather show an indication of a load match, possible to achieve if the ability to store energy within the building would had been sufficient.

If the goal is that the building should not export heat to the district heating network and still achieve Net ZEB balance, this is possible by redesigning the building as described in the "best option". However, if heat and electricity would have the same weighting factors, the PV yield would not be enough.

(Salom et al, 2011) concludes that a higher resolution is needed, probably less than ten minutes, to capture a dynamic behaviour of a building, especially regarding peak load and generation. Other studies, mentioned in the introduction (Hawkes et al., 2005), (Peacock et al., 2006) and (Kelly et al., 2008), shows that load and generation fluctuates at a much higher resolution than one hour.

A recent study compared simulations based on one-minute resolution and one-hour resolution for PV yield in combination with electric load profile for a residential house (Widén et al, 2010). This study shows that the differences in matched, exported and imported electricity only give overall differences in order of a few percent, when the resolution is improved from one-hour to one-minute. (Widen et al, 2010) concludes that the difference would have an insignificant impact on the calculations conducted within their study.

Based on the previous studies it may be concluded that hourly resolution is sufficient to grasp the load match for solar energy in the design phase. However, to thoroughly study peak loads and on site generation, a higher time resolution is needed. Especially if micro-combined heat-and-power systems are included.

One-hour resolution may be sufficient when a proposed building is in the concept design stage. A higher resolution should be used, when the building design is defined more in detail. Furthermore, the proposed best solution should be subject to a sensitivity analysis before final decisions, regarding the design of the building and on site generation, are made.

CONCLUSIONS

This work presents the Net ZEB balance and flexibility of a Net ZEB residential building designed to be built in Sweden. The building is likely to achieve a Net ZEB balance. However, the proposed "best option" may be a more suitable design, reaching the Net ZEB balance without exporting heat to the district heating network in summer.

If a higher flexibility is required, a larger energy storage should be considered. Energy storage has previously been determined to have the best potential of achieving a better match between load and production in terms of solar fraction, i.e. load match (Widén et al, 2009).

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NOMENCLATURE

A	Area
c	Charging energy to storage
d	Delivered energy
D	Delivered energy, weighted
dl	Distributions losses
dc	Discharge energy from storage
e	Exported energy
E	Exported energy, weighted
f_{grid}	Load match index
f_{load}	Grid interaction index
g	Generated energy
G	Generated energy, weighted
i	Energy carrier
l	Load
L	Load, weighted
lim	Desirable limit
PV	Photovoltaic

S	Stored energy
SC	Storage capacity
sl	Storage losses
ST	Solar thermal
t	Time step, 1 hour
T	Evaluation period, hourly, daily, etc
V	Volume
w	Weighting factor

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