Net zero energy balance for high-rise buildings

Monika Hall, Achim Geissler

Institute of Energy in Buildings, University of Applied Sciences and Arts Northwestern Switzerland
St. Jakob Strasse 84, CH – 4132 Muttenz, monika.hall@fhnw.ch

Abstract

To date, typical net zero energy buildings are single family or small apartment buildings with sufficient area available on the roof for a PV-system large enough to match the annual load with its electricity yield. Can large buildings of up to 40 floors also achieve a net zero balance for HVAC only and/or achieve net zero energy building status? The analysis presented here is based on the simulation of two multifamily dwellings and two office buildings, one each with a square and a stretched footprint. PV on the roof and integrated in all façades is considered.

A wide range of parameters is investigated in regard to their impact on the zero energy balance: climate, insulation standard, heating system, thermal losses for storage and distribution for domestic hot water and heating, energy load for electric devices and lighting, distances and heights of adjacent buildings, orientation of the building, self-shading due to balconies, size of useful PV areas and performance of the PV-system.

The main results can be summarized as follows:

- net zero balance for HVAC only can be achieved for up to 40 floors for all variants studied but one
- The five main parameters in regard to achieving a net zero energy balance are
  - low heat demand
  - efficient electric devices and lighting,
  - the type of heating system,
  - the actually available area for PV and
  - the overall efficiency of the PV-system.
- As the number of floors increases, the fraction of the PV yield attained from the roof decreases. It follows that:
  - a small change in energy demand or PV yield have a large impact on the net zero balance
  - high-rise buildings need to be more energy efficient than low-rise buildings.

Keywords: BIPV, net zero energy, energy efficiency, facade integrated PV, high-rise building, self-consumption

1. Background

1.1 Net zero energy balance

Typical net zero energy buildings to date have two to four floors. This fits to single family buildings and small apartment dwellings. If the number of floors increases, the ratio of roof area to heated floor area decreases and the roof area becomes too small to host the necessary photovoltaic (PV) system. In this case, PV also has to be installed in the façade. Figure 1 shows examples of existing buildings, which have PV integrated in the façade. Some of the buildings shown are able to fulfill a plus energy balance (total energy (TE) zero balance >100%).

The efficiency of lighting, plug loads and PV-system, the insulation level, the numbers of floors, the actual façade and roof area which can be used for PV, the compactness and the shading are parameters which impact the energy demand and the PV yield. The goal of this paper is to show the boundaries and possibilities of achieving a net zero energy balance for HVAC only (HVAC zero balance) and for total energy (TE zero balance) with high-rise buildings (Figure 2).

Figure 1: Retrofit of multifamily buildings in Chiasso (114%) [1], Romanshorn (107%) [1] und Zürich (Internet), Retrofit office building Flumroc in Flums (115%) [1], Attachment Bracher+Schaub AG in Ormalingen (96%) [1].

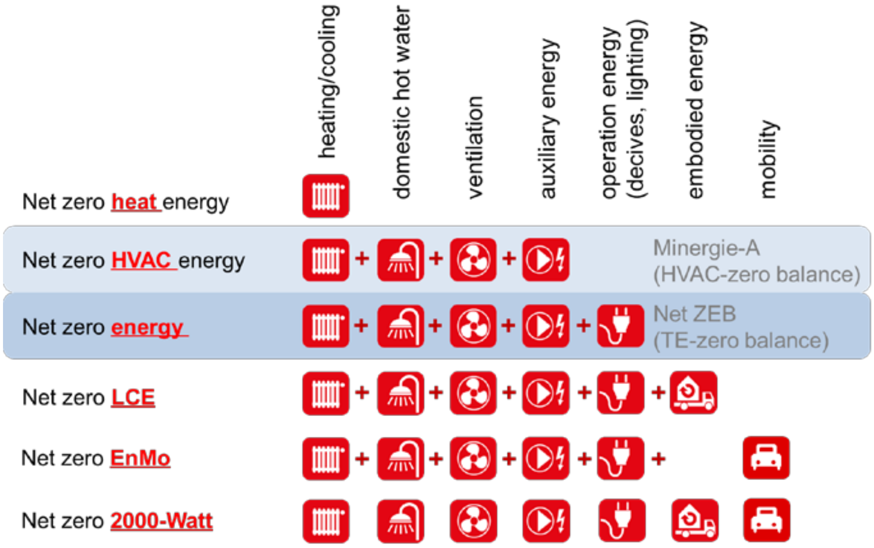

Figure 2: *Scope of different net zero energy balances [2] (LCE: Life Cycle Energy, EnMo: Energy&Mobility, 2000-Watt: 2000-Watt Society).*

1.2 Research Method

The analysis presented here is based on the simulation of two multifamily dwellings and two office buildings, one each with a square and a stretched footprint:

- V1: multifamily dwelling with stretched footprint, 6 flats per floor
- V2: multifamily dwelling with square footprint, 4 flats per floor
- V3: office building with stretched footprint
- V4: office building with square footprint

The following wide range of parameters is investigated in regard to their impact on the HVAC and TE zero balances (the base variant is given in **bold**):

- climate (**Bern**, Davos, Lugano),
- heat demand (**60%**,110% standard for new building),
- heating system (**gas system**, district heating, heat pump),
- thermal losses for storage and distribution for heating and domestic hot water (**10%/40%**, 50%/60%),
- energy load for electric devices and lighting (high, **low**),
- shading due to different distances and heights of adjacent buildings
- orientation of the building (stretched building: **S/N**, E/W),
- self-shading due to balconies (multifamily dwellings only),
- size of useful PV areas (multifamily dwellins only) and
- overall performance of the PV-system (**14%**, 22%).

It is assumed that all applicable areas of the roof and the facade are used for PV (Figure 3). The number of floors varies from two up to 40.

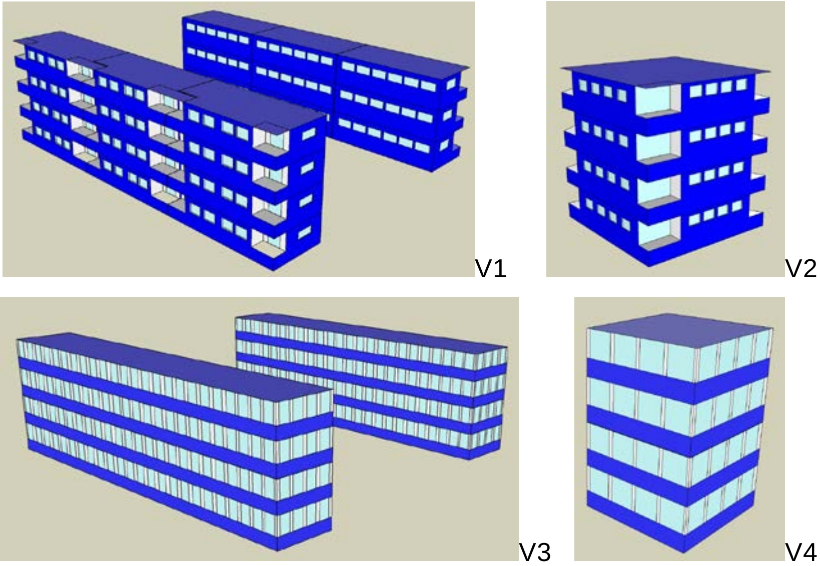

Figure 3: *Façade layout for the four basic building variants for an example of four floors each. The roof and the façade surfaces colored in dark blue host PV.*

1.3 Definitions

HVAC	demand for heating, domestic hot water, ventilation (cooling is not considered)
HVAC zero balance	net zero energy balance for HVAC: annual PV yield is larger than HVAC demand
TE	total energy demand: HVAC, lighting, plug loads (devices)
TE zero balance	net zero energy balance for TE: annual PV yield is larger than TE demand
primary energy	calculated with Swiss national factors: gas: 1.0, electricity/PV yield: 2.0

2. Basic data

Table 1 summarizes the main dimensions and the energy data of the buildings. The energy values are chosen such that the shaded 4-floor apartment dwelling with a stretched footprint meets the Minergie-P requirement of 60% of the standard heat demand for new buildings. It is assumed that the office building has a parapet (1.4 m high) and band windows (1.9 m high). This leads to a window area fraction of 58% of the façade.

The heating demand is calculated according SIA 380/1:2009. The standard values for domestic hot water are chosen according SIA 380/1:2009: apartment dwelling 20.8 kWh/(m^2a), office building 6.9 kWh/(m^2a). The efficiencies of the heating systems for heating/hot water are: gas: 0.95/0.92, district heating: 0.98/1, heat pump: 4.3/2.8. Distribution and storage losses: heating 10%, hot water 40%.

The average demand per household incl. lift is 1'780/2'890 kWh/a (low/high, Table 2). This values show a reasonable range which could be found in the literature.

The PV yield is calculated with an overall performance of 14% and 22%. The PV-system on the roof is east/west orientated with a slop of 10°. This configuration achieved the highest yield.

Table 1: Main dimensions for all variants V1-V4 (left) and energy data for base variants and lower insulation floor as an additional variant (right) [3].

Parameter	Apart. dwell. (V1/V2)	Office build. (V3/V4)
Building depth, m	11.5/21.8	11.5/21.8
Building length, m	63.7/21.8	63.7/21.8
Floor height, m	2.85	3.3
Netto-living area, m^2	87	-
number of flats per floor, -	6/4	-
Number of floors, -	2 … 40	2 … 40
Heated area per floor, m^2	684/441	732/473
window N, %	21/24	58
window S, %	35/24	58
window E/W, %	7/24	58
Window area, m^2	1.6 x 1.3	windowband
Number per floor, -	E/W: je 1/4	-
	N: 18/4	-
	S: 12/4	-
Balcony door, m^2	3 x 2.1	-
Number per floor, -	S: 6 / N/S/E/W: je 1	-

Parameter	Base	Variant "heat demand 110%"
U_{opaque}, W/(m^2 K)	0.20*	0.48**
U_{window}, W/(m^2 K)	0.90	1.4
g-value, -	0.50	0.60
Glazing fraction of window, - 0.80		
Red. factor to unheated basement, - 0.73		
massive construction		
*U-value = 0.15 W/(m^2 K) + 30% heat bridge **U-value = 0.40 W/(m^2 K) + 20% heat bridge		

Table 2: High and low electricity demand for dwellings [4] *and office buildings* [5] *per heated floor area.*

	Apart. dwelling, [kWh/(m^2 a)]			
	stretched		square	
demand	low	high	low	high
lighting/plug loads	15.3	24.5	15.8	25.3
lift	0.35	0.88	0.36	0.90
mech. ventilation with heat recovery 0.3 m^3/(h m^2)	2.2	3.1	2.3	3.4

Office building, [kWh/(m^2 a)]		
demand	low	high
lighting	7	24
devices	3	25
mech. ventilation with heat recovery 0.3 m^3/(h m^2)	1	3

The buildings are surrounded with four buildings. The buildings adjacent to the stretched building are six floors high. The buildings adjacent to the square building are six (stretched footprint) and ten floors (square footprint) high, respectively (Figure 4). The shading effects of the adjacent buildings are calculated for each floor with ESP-r [6]. The resulting shading factors are considered for calculations of heat demand and PV yield. The impact on the PV yield of different distances and heights of the adjacent buildings are shown in Figure 5.

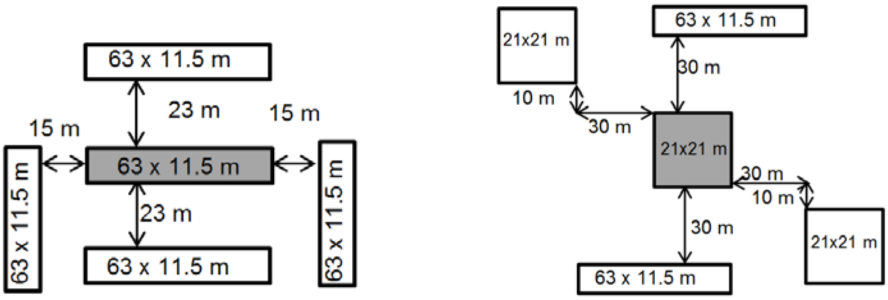

Figure 4: Shading situation for basis variants, distance and location of adjacent buildings (right: V1, V3, left: V2, V4).

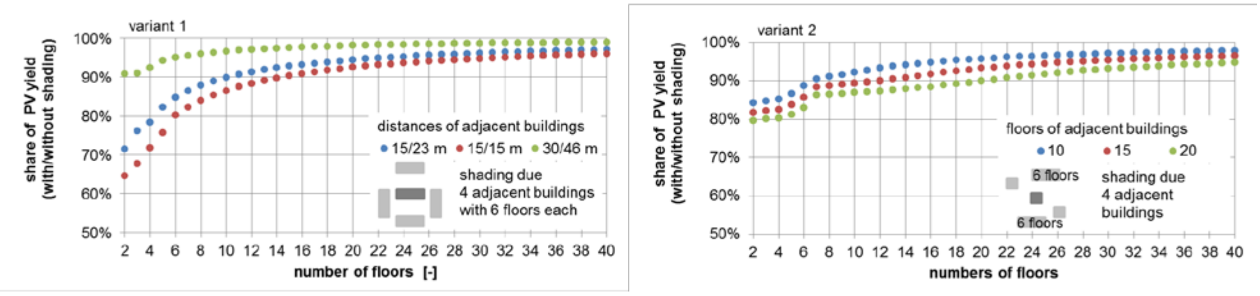

Figure 5: V1: share of shaded/unshaded PV yield for different distances of the adjacent buildings. V2: share of shaded/unshaded PV yield depending on the height of the square adjacent buildings.

3. Results

3.1 PV yield

The share of PV yield from the roof and the façade is shown in Figure 6. The share of the roof yield decreases clearly with an increase in the number of floors. The rate of decline mainly depends on the façade area per floor which is useful for the integration of PV. Approx. 57% of the façade area is used for PV in the apartment dwelling and approx. 42% in the office building.

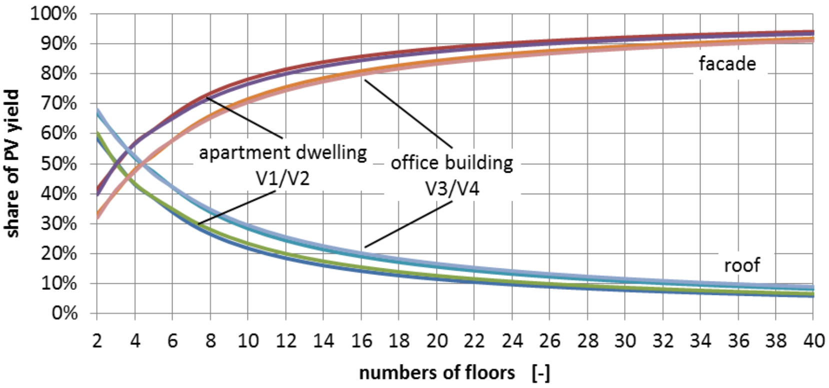

Figure 6: Share of roof PV yield and facade PV yield for all variants.

3.2 Parameter study

In each variant one parameter only is changed from its base value. The impact of a selection of the parameters is shown for two examples of V1 in Figure 7. The results for all cases considered can be found in [7].

In general, the HVAC zero balance with a gas system is possible for up to 40 floors (black lines). The TE zero balance is possible for up to 31 floors for a low total load (grey dots, blue arrow), and with a high load for two floors only (grey line, blue arrow).

The right side of Figure 7 shows the same building with a heat pump. In this case the TE zero balance can be reached easier. HVAC zero balance and TE zero balance with low demand is possible up to 40 floors. With a high demand for plug loads and lighting, the TE zero balance is possible for a building with nine floors (blue arrow, figure on the right).

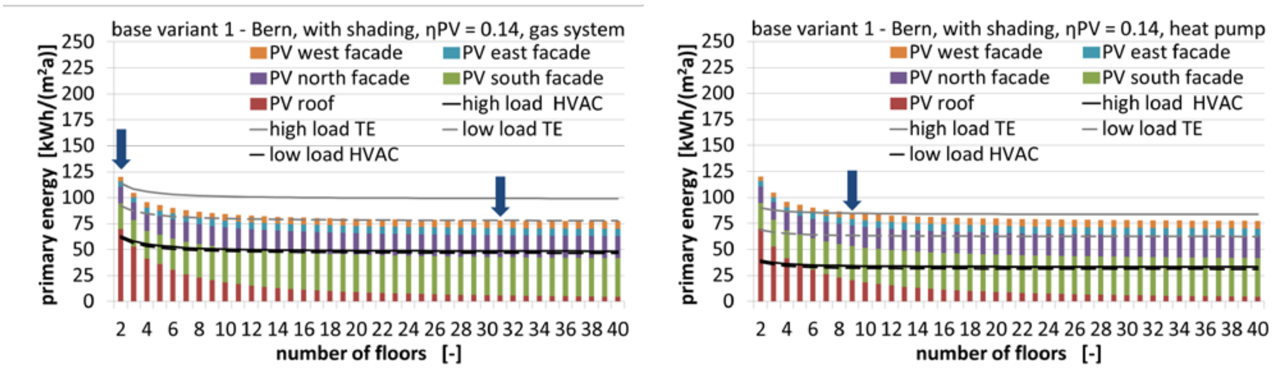

Figure 7: V1, load und PV yield in primary energy for 2 up to 40 floors with a gas system (left) and heat pump (right) (16/25 kWh/(m^2 a) low/high electricity load).

Figure 8 gives an overview of the possible number of floors for a TE zero balance of V1 for all variants. Both a gas system and a heat pump are covered. The results for district heating are quite similar to the results with a heat pump. Therefore, they are not shown here. Also not shown is the HVAC zero balance, because this can be achieved up to 40 floors for all cases but "south railing only, with gas system".

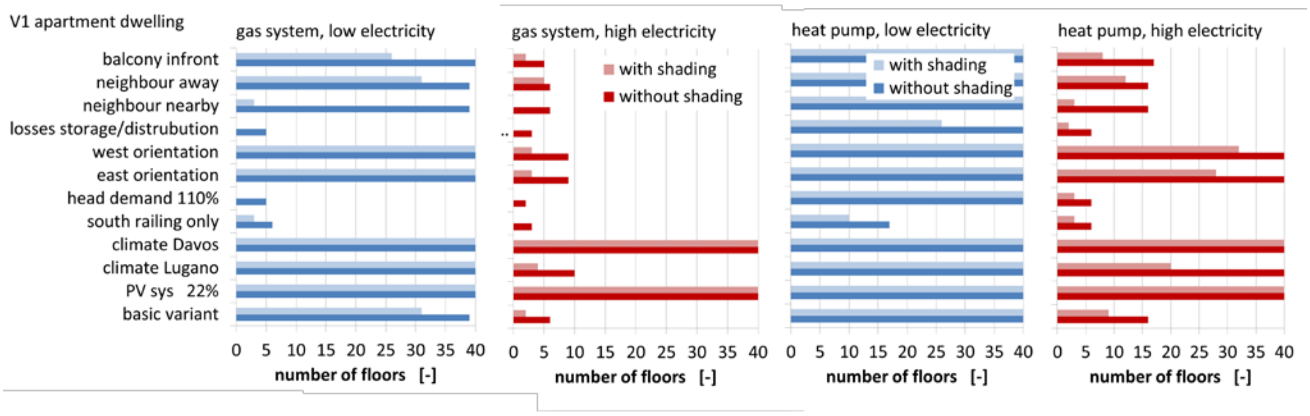

Figure 8: V1, number of floors for a TE zero balance (16/25 kWh/(m^{2}a) low/high electrical load).

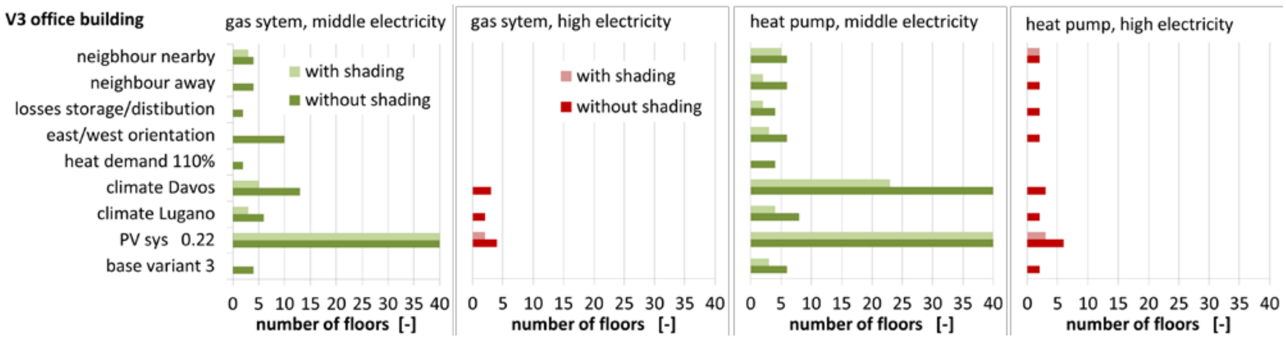

Figure 9: V3, number of floors for a TE zero balance (30/49 kWh/(m^{2}a) middle/high electrical load).

For V1 – the stretched apartment dwelling – with a low electrical demand for plug loads and lighting the TE zero balance can be achieved for a high number of floors. With a high electrical demand, a heat pump or district heating is preferable. V2 shows similar results as V1. Over all V1 has a slightly higher potential for a TE zero balance due to the better ratio of façade area to heated floor area compared to V2. For both variants, district heating shows the best results. This is due to the low system COP of the heat pump for domestic hot water. The energy demand with a heat pump is about 10% higher than with district heating. This is not a large difference; however it shows how sensitive the balance is due to the effect of decreasing PV yield with increasing numbers of floors.

Figure 9 gives an overview for V3. Again, the HVAC zero balance is not shown because it can be achieved for up to 40 floors for all considered cases. Additionally, the TE zero balance with low electrical demand is not shown because this also can be achieved for all cases up to 40 floors except for the cases "heat demand 110%" and "thermal losses" with a gas system. With high electricity demand the TE zero balance can be achieved only for buildings with a few floors in a few cases. To show the impact of the parameters an additional middle electricity demand of 30 kWh/(m^2 a) for devices/lighting and 2 kWh/(m^2 a) for mechanical ventilation is given, therefore. The TE zero balance for 40 floors is only possible with a PV performance of 0.22 for all heat devices. The high solar radiation in Davos helps to increase the number of floors for a TE zero balance. A high performance of the PV system is preferable, naturally. District heating and heat pumps show the same results, because the domestic hot water demand of an office building is very small. V4 shows similar results to V3 and is not shown here, therefore.

The impact of different parameters on zero energy balances could be summarized in three classes:

high
- Energy efficiency of the devices
- Heating system
- Head demand
- Solar gain
- Size and overall performance of the PV-system
- Thermal losses of storage and distribution for heating/domestic hot water

middle
- Ambient temperature
- Shading from adjacent buildings nearby/further away
- Shading from high/low adjacent buildings

low
- East/west orientation instead of south/north orientation (stretched building)
- Self-shading due balconies in front of the building
- footprint

For the design of buildings aimed to meet a zero energy balance following priority sequence is derived from the results described above:

1. priority
   - Low heat demand
   - Low electricity demand for plug loads and lighting
   - Heating device: district heating or heat pump
   - Large areas for PV in facades and on the roof
   - High overall performance of the PV system
   - Low thermal losses for storage and distribution for heat/domestic hot water

2. priority
   - Shading due to adjacent buildings (taking influence usually not possible)
   - Avoid shading by protruding balconies
   - Give preference to east/west orientation for stretched buildings if possible

4. Praxis

The results described above which were gained by simulation were compared to a refurbishment of a multifamily dwelling in Chiasso (Viridén + Partner AG, CH). The façade integrated PV system covers seven of eight floors and the balcony parapet (façade system size 52.6 kWp). There is PV on the roof of the building and on five parking garage roofs (roof system size 36 kWp). The roof also hosts a thermal solar collector (43 m^2). As different PV modules are used for the façade and the roofs, an average performance of the PV-modules of approx. 14% is assumed. Therefore, the performance of the PV-System is slightly lower than assumed in the theoretical study. The overall load (TE zero balance floor) is 46 kWh/(m^2 a)) final energy. This case compares well with V2, a square footprint, climate Lugano, heat pump, eight floors and low energy demand (Figure 10). This comparison shows that the basic assumptions for the study seem well chosen and the results can be used as design guideline.

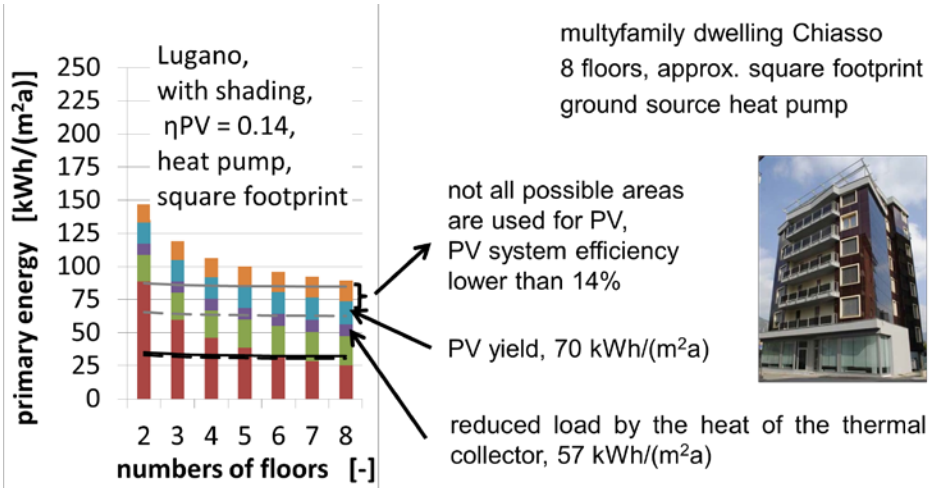

Figure 10: Comparison of a multifamily dwelling in Chiasso with the square footprint basic variant, a heat pump and climate Lugano.

5. Self-consumption

The self-consumption is an important topic for buildings with PV systems. The self-consumption rate describes the fraction of the energy consumption (load) that can be immediately covered by the PV yield. This is discussed with V1, heat pump and 13 floors. 13 floors are chosen, because the share of the roof PV yield to total PV yield is already quite low. Due to the six floor high adjacent buildings, starting at the roof the PV covers floor by floor from the top downwards. This sequence has the advantage that the floors without shading are covered first.

The HVAC zero balance can be achieved with PV on the roof and on the façades of the top three (just) to four (with south and north facades only) floors (black line). The TE zero balance cannot be achieved for the example 13 floor building (light grey line).

The self-consumption rate increases from 17% (PV on the roof only) up to a maximum of 28 % w/ heat pump run-times at night only and 40% with heat pump run-times restricted to daytime, respectively. These rates require that all the façades of all 13 floors are equipped with PV (dotted grey lines meet the x-axis).

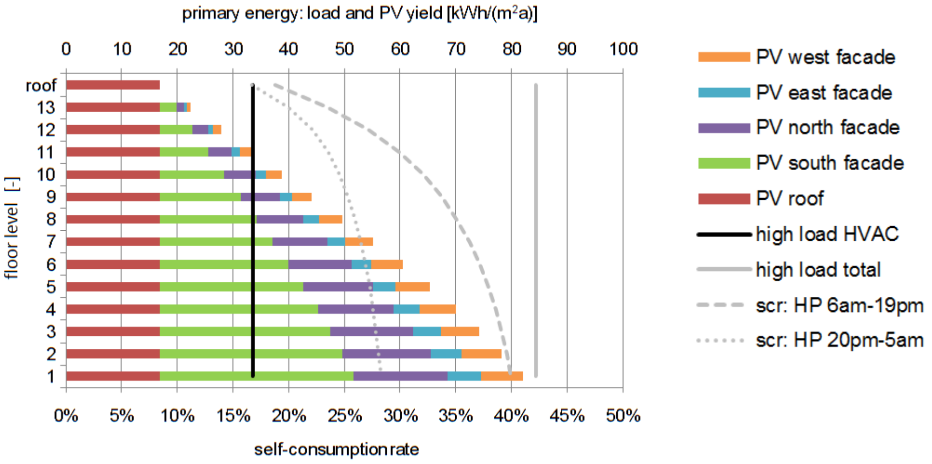

Figure 11: Load, PV yield and self-consumption rate due to PV configuration floor by floor (base variant 1 with high load and heat pump, climate Bern). The calculations are based on load profiles for hot water: multifamily building no. 6 (Polysun), lighting/devices: multifamily building 5 households (Polysun), ventilation: 2-step model [5] *(Menn C., IEBau)*

6. Summary

Multifamily dwellings and office buildings with a square and a stretched footprint with up to 40 floors are considered for a net zero energy balance. A wide range of parameters is investigated in regard to their impact on the zero energy balance.

The main results gained by the simulation based research described above can be summarized as follows:

- Only the HVAC zero balance can be achieved for up to 40 floors for all variants studied but one
- The five main parameters in regard to achieving a HVAC or TE zero energy balance are
  - efficient electric devices and lighting,
  - low heat demand,
  - the type of heating system,
  - the actually available area for PV and
  - the overall efficiency of the PV-system.

The results show that a net zero energy balance for HVAC only or for total energy can be achieved for large multifamily dwellings and office buildings of up to 40 floors. To this end, however, apart from a well-insulated building envelope, electronic devices, lighting and PV systems with a very high efficiency are necessary. With further improvements in the efficiency of devices, lighting and PV-systems, reaching the "zero" will become easier.

Acknowledgments

The presented study was funded by the Swiss Federal Office of Energy SFOE, project "Möglichkeiten und Grenzen von grossen Nullenergiegebäuden" SI/500950-0.

7. References

[1] “Schweizer Solarpreis.” [Online]. Available: www.solaragentur.ch.

[2] M. Hall, “Nullenergiegebäude - die nächste Generation energieeffizienter Bauten. IEA EBC Annex 52/SHC Task 40,” Schlussbericht, BFE 103324/154384, www.fhnw.ch/habg/iebau, 2014.

[3] M. Hall and A. Geissler, “Möglichkeiten und Grenzen von grossen Nullenergiegebäuden,” *Bauphysik*, vol. 38, no. 1, pp. 38–49, 2016.

[4] S. Gasser, “Revision SIA 380/4, Teilprojekt 8: Strombilanzmodell für Wohnbauten,” SIA und Amt für Hochbauten der Stadt Zürich, 2014.

[5] Merkblatt SIA 2024, “Standardnutzungsbedingungen für Energie – und Gebäudetechnik.” 2006.

[6] “ESRU, ESP-r (open source): A Building and Plant Energy Simulation Environment. University of Strathclyde, Glasgow; http://www.esru.strath.ac.uk. Programm Version 2013.” .

[7] M. Hall and A. Geissler, “Möglichkeiten und Grenzen von grossen Nullenergiegebäuden,” Schlussbericht BFE SI/500950-01, www.fhnw.ch/habg/iebau, 2015.