GRID IMPACT OF A NET-ZERO ENERGY BUILDING WITH BIPV USING DIFFERENT ENERGY MANAGEMENT STRATEGIES

K. Klein[1]; D. Kalz[1]; S. Herkel[1]

1: Fraunhofer-Institute for Solar Energy Systems. Heidenhofstr. 2, 79110 Freiburg, Germany

ABSTRACT

A net-zero energy office building with Building-integrated photovoltaics (BiPV), a heat pump with cooling functionality and TABS as a heat distribution system is simulated in dynamic thermohydraulic simulations in Dymola. The focus of the evaluation is the electricity exchange with the grid. The temporal mismatch between local electricity production and electricity consumption is evaluated using established indicators such as the autonomy and self-consumption. Moreover, it is analyzed during which times electricity is consumed from the grid, and how high the fraction of Wind and PV in the energy mix is during the time of consumption. The latter is quantitatively expressed using the Grid Support Coefficients GSC_{abs} and GSC_{rel} proposed by the authors.

HVAC operation accounts for roughly 43% of the total electricity consumption of the considered building. With a conventional HVAC control concept based on heating and cooling curves, an annual autonomy rate of 42% and a self-consumption rate of 43% are achieved. In an alternative control scheme, the trajectory of heat and cold delivery to the zones is altered such that the self-consumption of the locally produced electricity is maximized. The remaining electricity demand for HVAC operation, which has to be covered from the public grid, is shifted to times of a high availability of Wind and PV power in the energy system. With this energy management scheme, the autonomy and the self-consumption rate are increased to 50% and 53%, respectively. The fraction of Renewables in the electricity consumed from the public grid is increased by 15% (relative). Thermal comfort in the offices is only moderately affected by the shifting of the heating and cooling loads.

Keywords: Net-zero energy buildings, BiPV, grid-supportive, heat pumps, simulation

INTRODUCTION AND GOALS

As part of the Energy transition, the German federal government plans to cover at least 80% of its electricity consumption with renewables by the year 2050 [1]. The largest part of the renewable electricity will be generated by Wind and PV plants [1]. Due to the volatile nature of Wind and PV power, it is expected that the availability of electricity in the German energy system will fluctuate significantly. Consequently, not only the quantity, but also the time of energy consumption or production will become a relevant requirement to "grid-supportive" electricity consumers and producers. Buildings using heat pumps, compression chillers or CHP units can serve as such by adapting the operation of local heating and cooling energy production according to the availability of electricity in the grid and store the energy in thermal form.

The present study investigates how the net power exchange of a net-zero energy office building equipped with BiPV, a ground-coupled heat pump and Thermo Active Building Systems (TABS) coincides with the availability of electricity in the power grid. In office buildings, the local production also partly coincides with local electricity demand during occupancy as well as cooling loads in summer. It is analyzed to what extend the operation strategy of the heat pump or chiller can influence the overall grid exchange of a net-zero energy office building. In this case, TABS is utilized to activate the building mass as a thermal energy storage. The influence of this thermal activation of the building structure on indoor comfort is evaluated.

REQUIREMENTS TO GRID-SUPPORTIVE BUILDINGS

The grid interaction of a net zero energy building is typically assessed in terms of the autonomy (also called load cover factor), which is the percentage of the electric load covered by local production, and the self-consumption rate (also called supply cover factor), which represents the fraction of the locally produced electricity which is consumed on-site. [2] In this article, the cover factor is defined as the ratio between the locally produced and the consumed electricity, regardless of the temporal mismatch between production and consumption.

In addition, the absolute and relative Grid Support Coefficients GSC_{abs} and GSC_{rel} are proposed in order to assess whether electricity from the public grid is consumed at times with a high or a low availability of renewables in the energy system. GSC_{abs}(WPC) is the fraction of Wind and PV energy in the consumed electricity, relative to the average fraction of renewables during the evaluation period. [3] A value greater than one indicates that electricity is consumed at an above-average availability of wind and PV in the grid. GSC_{rel} relates the value of GSC_{abs} to the worst and best achievable values on a scale of -100 to 100 in order to increase the comparability of the results. In this study, the fraction of Renewables in the German electricity mix for 2023 is used for the assessment, which was calculated from historical data and scaled with the projected future Wind and PV power from [4]. However, GSC can be applied to any meaningful, time-resolved reference quantity such as the Residual load, price signals or a time-resolved primary energy factor of the electricity mix. [3]

SIMULATION MODEL

Considered Building and office zones

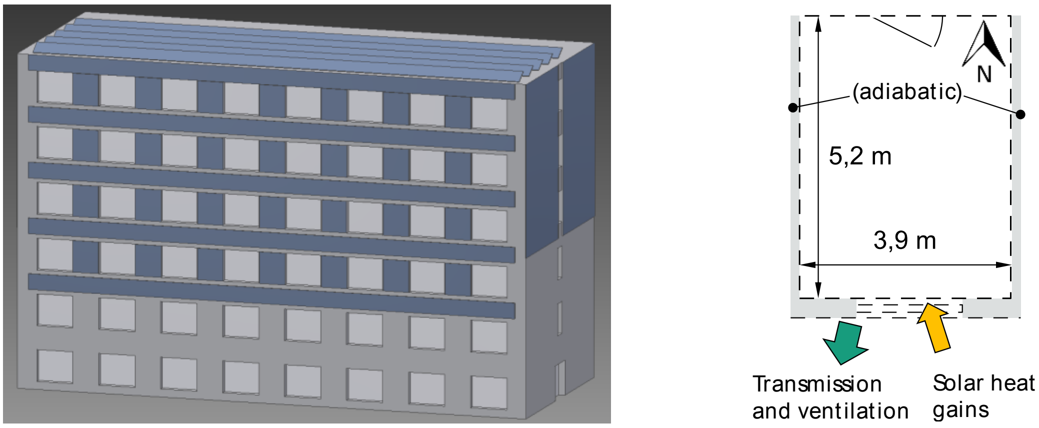

Figure 1: Building including BiPV panels in blue and geometry of south-facing office

The building considered in this study represents a generic “typical” European office building located in Mannheim/Germany. It is six storeys high and divisible into eight rows of geometrically identical three-zone-cells. Seven of these rows of cells consist of one north-facing two-person office, one south-facing two-person office, as well as a connecting corridor. The building has a floor area of 2433.6 m^2, a specific heat consumption of 33.4 kWh/m^2a and a specific cooling energy consumption of 26.7 kWh/m^2a.

Thermal properties	**Value**	**Unit**	**Offices properties**	**Value**	**Unit**
U-value of exterior walls	0.24	W/m^2K	Zone width	3.9	m
U-value of roof	0.2	W/m^2K	Zone depth	5.2	m
U-value of windows	1.0	W/m^2K	Zone height	3	m
g-value of windows	0.58	-	Window area (glazing)	4.68	m^2

Table 1: Geometry and properties of two-person office zone in compliance with EnEV 2014.

Usage and heat gains

It is assumed that the offices are partially occupied during workdays between 7 a.m. and 6 p.m. The assumed occupancy factor is 0.36 during the first and last two working hours as well as during noon (12 p.m.-1 p.m.) and 0.7 during the other working hours. During occupancy, the ventilation rate is 30 m^3 per person and hour. During absence, the ventilation rate is the natural air infiltration rate (air leakage) of 0.3 h^{-1}. No heat recovery is assumed.

The heat gains from people and appliances are 70 W/person and 100 W/person, respectively. It is assumed that a continuous lighting controller keeps the illuminance on the working surfaces at or above 300 lux. All assumptions concerning the usage and heat gains comply with the standard DIN-V EN ISO 18599:2011-12.

Heat and Cold supply and hydraulic system

A variable-speed, brine-water ground-coupled heat pump with cooling functionality is used as a heat and cold generator. Its specifications are taken from the data sheet for the first compressor stage of the Dimplex SI 75 TER+. Its rated heating and cooling capacities are linearly scaled to 150% in order to match the load requirement of the building. The thermal energy is delivered to the zones using Thermally Activated Building Systems (TABS), which are centrally located inside the 30 cm concrete floor slabs. The north-facing and the south-facing zones have separate hydraulic circuits.

Building-Integrated Photovoltaics

The BiPV system is designed such that the annual local energy production approximately covers the annual electricity consumption. The PV modules used are Schott Perform Poly 245, which consist of 72 polycristalline cells with an efficiency of 15% at standard test conditions. A total of 422 modules are installed: 151 on the southern façade, 88 each on the eastern and western façade and 95 on the roof. The roof-mounted modules are inclined 30°, whereas the façade-mounted modules are vertical. An inverter efficiency of 98% as well as 15% overall losses due to shading, reflection and dirt are assumed.

Simulation setup

The software environment Dymola 2014 is used for the thermohydraulic simulations. The zone model used is a 5R1C model in compliance with the modeling standards of DIN EN ISO 13790. Most other models (e.g. TABS, Pumps, valves), are taken from the Modelica Buildings library. The simulation comprises one year in 1-hour resolution.

ENERGY MANAGEMENT STRATEGIES

Reference controller: Optimized heating and cooling curves

In the reference variant, the supply water temperatures to the zones is determined by heating and cooling curves, which are linear functions of the moving 24 hour mean of the ambient temperature. The offset and slope of the heating and cooling curves as well as the temperature limits for heating and cooling operation are optimized using GenOpt such that the operative room temperatures below 20 °C and above 26 °C during occupancy and the thermal energy consumption for one year are minimized. The pumps in the TABS circuits are operated continuously with a mass flow rate of 15 kg/(m^2h).

Alternative energy management scheme

The goals of the presented energy management scheme are a) to maximize self-consumption of the locally produced electricity and b) to consume as much of the remaining electricity consumption as possible during times with a high share of Wind and PV power in the grid.

First, the daily thermal energy demand for the zones is determined using the simulation results from the reference case, which is equivalent to an ideal load prediction. The thermal energy is then allocated to the hours with the highest surplus local PV energy after substraction of non-shiftable loads (lighting, miscellaneous loads for appliances, and heat pump operation for the conventionally-conditioned zones). In case there is no or insufficient surplus local PV energy available during one particular day, the remaining thermal demand is allocated to the hours of the day with the highest share of Wind and PV power in the grid. The load shifting is constrained by the maximum capacity of the heat pump and the maximum transmittable thermal power to the zones. In order to increase the latter, the heating curve is increased by 3 K and the cooling curve is lowered by 3 K compared to the optimized heating and cooling curves in the reference controller.

RESULTS

Annual and monthly electric energy balance of building

The simulated building consumes 71.2 $\mathrm{MWh_{el}}$ of electricity per year. HVAC operation, which comprises the heat pump compressor energy for heating and cooling as well as pump electricity, accounts for 43% of the consumption. Miscellaneous loads for appliances and lighting, which can be classified as non-shiftable loads, account for 37% and 20%, respectively. The annual electricity production by BiPV is equivalent to 96.5 % of the electricity consumption.

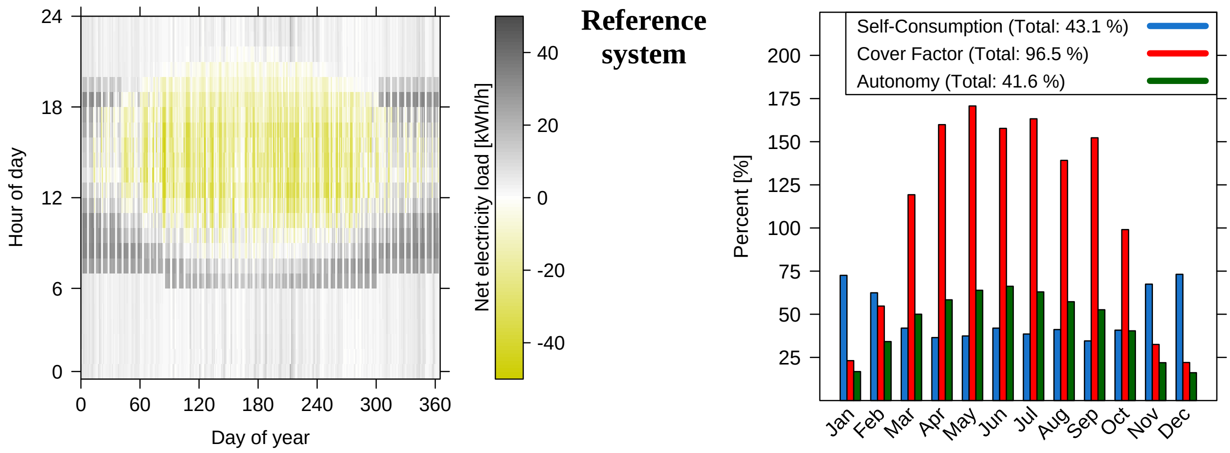

Figure 3: Results for the reference case. Left: Carpet diagram of the net electric load. Right: monthly self-consumption, cover factor and autonomy.

In the reference case with a conventional controller, the self-consumption in the base variant is only 43% and the autonomy is 41.6% due to the temporal mismatch between electricity production and consumption. Even in the summer months, when the cover factor reaches values close to 175%, the autonomy never exceeds 75%.

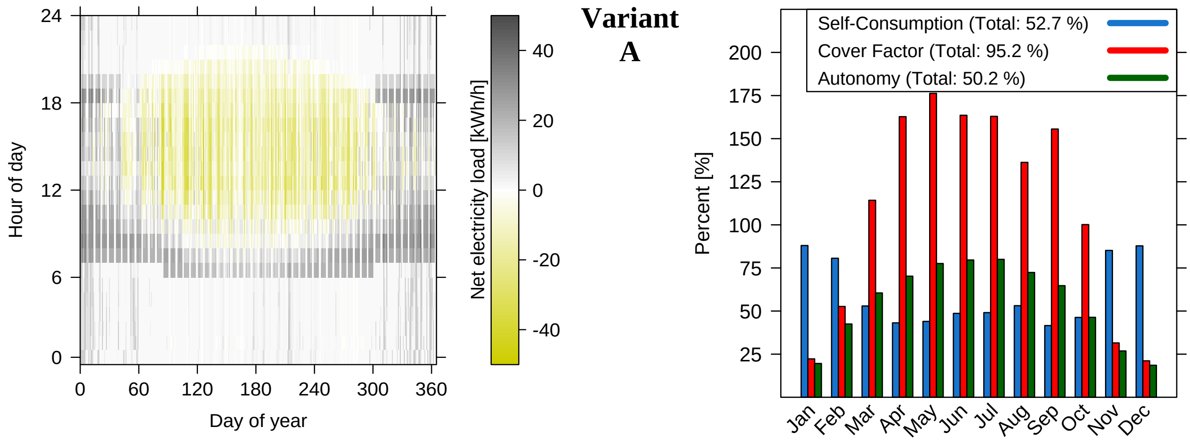

Figure 4: Results of the alternative load management scheme. Left: Carpet diagram of the net electric load. Right: monthly self-consumption, cover factor and autonomy

Using the altered energy management scheme ("Variant A"), the self-consumption and autonomy can be increased by roughly 9% (absolute). As shown in figure 4, grid consumption during the night is almost completely avoided since heat pump operation is shifted to the day. The total electricity consumption increases slightly since the seasonal performance factor of the heat pump drops from 6.52 to 6.09 due to the shifted heating and cooling curves.

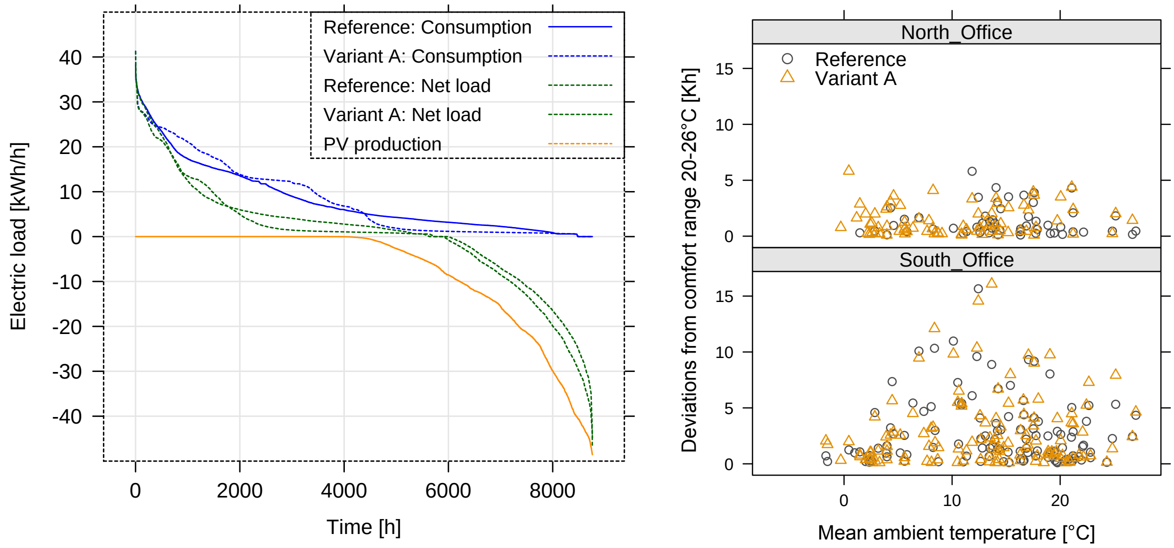

Figure 5: Left: Ordered load duration curve of consumption, net load and PV production for both variants. Right: Daily comfort violation over the mean ambient temperature

The altered energy management scheme leads to a much flatter load duration curve of the net grid exchange (figure 5, left). During 3753 hours, the building has nearly no power exchange with the grid (net load < 2 kW_{el}), which is nearly 2.5 times longer than in the reference variant. At the same time, the peak load hours (net load > 28 kW_{el}) are reduced by roughly the same factor. Thermal comfort is only moderately affected by the load shifting. In the north-facing office, deviations from the comfort range are below 5 Kelvin-hours, whereas in the south-facing office, comfort violations are several times higher throughout the year for both controllers, which is a result of higher solar heat gains.

	Comfort violations	**Grid consumption above 28 kW$_{el}$**	**GSC$_{abs}$/ GSC$_{rel}$ (for fraction of Wind and PV in 2023)**		
	North offices/ South offices		*Grid consumption*	*Feed-in*	*Heat pump compressor*
Reference	73 / 316 Kh	211 hours	0.84 / -50.6	1.55 / 70.9	1.02 / -0.5
Variant A	104 / 336 Kh	91 hours	0.97 / -25.6	1.53 / 71.6	1.41 / +74.7

Table 1: Comfort deviation and grid support for reference and alternative scheme.

With the alternative energy management scheme, the heat pump compressor's electricity consumption achieves a GSC$_{abs}$(WPV) value of 1.41, which means that operates at times during which the share of Renewables in the electricity mix is 41% higher than average. A GSC$_{rel}$ value of 74.7 indicates that this value is relatively close to the optimum (100). Even though the grid consumption is reduced in quantity, its Grid Support Coefficients are only slightly improved. This is due to the non-shiftable loads, which occur mostly in the morning and evening, when the availability of Wind and PV power is low, as well as the high coincidence of local PV availability and Wind and PV availability in the grid.

CONCLUSION

In the considered net-zero energy office building, roughly 43% of the electricity consumption is used for HVAC operation, nearly in equal parts for heating and cooling. By shifting this load according to the presented energy management scheme and storing the thermal energy in the building mass, self-consumption and autonomy are increased by about 9% each. However, the time structures of grid consumption and feed-in, which are reflected by the Grid Support Coefficients (GSC$_{abs}$ and GSC$_{rel}$), can only partly be influenced by due to the limited shiftable load and finite power of the heat pump. The prevalence of excess PV production in summer and low autonomy in winter highlights the limitations of load shifting using heat pumps.

The effect of the load shifting on comfort in the office zones is limited. This shows that TABS allow to store significant amounts of heat and provide a high degree of flexibility for the operation of the heat and cold generators. In order to fully seize the potential of net-zero energy buildings as grid-supportive electricity consumers, storages and producers under consideration of cost and comfort constraints, a combination of various measures has to be taken. These measures include the use of technical storages, "fuel-switch" between multi-energy heat and cold generators, and predictive control strategies for zone conditioning. Such concepts will be studied more thoroughly and presented by the authors in future work.

ACKNOWLEDGEMENT

The work presented in this article is part of the project "Netzreaktive Gebäude" funded by the German Ministry of Economic Affairs and Energy under the code 03ET1111A.

REFERENCES

1. German Federal Ministry of Economics and Technology: Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply, 2010: Berlin.
2. Salom, J. et al.: Analysis of load match and grid interaction indicators in net zero energy buildings with simulated and monitored data. Applied Energy, 2014. 136: p. 119-131.
3. Klein, K. et al.: Netzdienlicher Betrieb von Gebäuden. Bauphysik, 2014. 36(2): p. 49-58.
4. German Transmission system operators : Grid Development Plan 2013, second draft, part 1. 2013; Available from: http://www.netzentwicklungsplan.de/en/.