Potential of covering electricity needs of a flat of a MFH with decentral compact heat pumps with PV – Simulation study for different DHW profiles and PV field sizes

Toni Calabrese[1], Fabian Ochs[1], Dietmar Siegele[1] and Georgios Dermentzis[1]

[1] Unit for Energy Efficient Building/University of Innsbruck, Innsbruck (Austria)

Abstract

Heat pumps in combination with PV are discussed as one of the key technologies in a future sustainable energy system. A simulation study of a flat in a multi-familiy-house (MFH) with decentral compact heat pumps and with a photovoltaic (PV) field was performed in the CARNOT/Simulink simulation environment in order to evaluate the potential to reduce the purchased grid electricity. PV electricity is self-consumed covering electric power requests for heating, ventilation, appliances and Domestic Hot Water (DHW) preparation. Three different electric power profiles for DHW preparation and two PV fields (roof, roof and façade) were analyzed.

The results of the simulations show that just a small percentage (below 26%) of electricity demand can be covered from PV field energy. The installation of a PV field also on the façade of the flat does not reduce significantly the purchased electricity (-11% in best of cases), while the use of daily electric storage could be evaluated to decrease further the purchased electricity (maximum reduction of -27%). The use of annual primary energy factor instead of monthly values overestimates the reduction of primary energy demand in all cases compared to the case without photovoltaic system.

Keywords: MFH, compact heat pumps, deep renovation, PV self-consumption, DHW profiles

1. Motivation

One of the promising technologies investigated within IEA SHC task 56 for a future sustainable energy system is represented by the heat pumps in combination with PV systems. Heat pumps systems represent one of the most versatile technology and can be used for heating, cooling and Domestic Hot Water (DHW) preparation. Electricity produced by the photovoltaic (PV) system can cover the electric demand for appliances and can be further used for the heat pump. Such a system can significantly reduce the purchased electricity (i.e. the non-renewable primary energy demand) of a building and the potential of this reduction is influenced, for example, by the PV sizes and the total electric demand of the building.

A simulation study is useful to show the influence of relevant parameters of such a system (e.g. PV sizes, profile of electric demand) on the purchased grid electricity and can give some additional information about possible optimization of the system in order to decrease further the amount of electricity from the grid.

An annual simulation in the CARNOT/Simulink simulation environment for a flat of a typical Multi Family House (MFH) was performed to evaluate the amount of the PV electricity self-consumed in case electric power requests for HVAC system, appliances and DHW preparation are considered. Three different electric power profiles for DHW preparation and two PV fields (roof, roof and façade) were analyzed.

2. Building model and simulation study

2.1 Building and PV field sizes

Fig. 1 shows the multy-family-house (MFH) with 10 flats considered for the simulation study. Detailed information about the building model are available in [1]. The roof and the façade oriented to South-East were assumed available for the installation of the PV field. Two different PV sizes configurations were simulated: a PV field installed only on the roof and a PV installed on the roof and on the façade (see Tab. 1). For both PV sizes, the total PV electricity production was correspondingly divided by 10 and this electricity was considered available

doi:10.18086/eurosun2018.02.01 Available at http://proceedings.ises.org

for one single flat. The electric power demand of the flat of the first floor oriented to North-East (highlighted in red in Fig. 1) for appliances, ventilation, heating and DHW preparation was considered in this study.

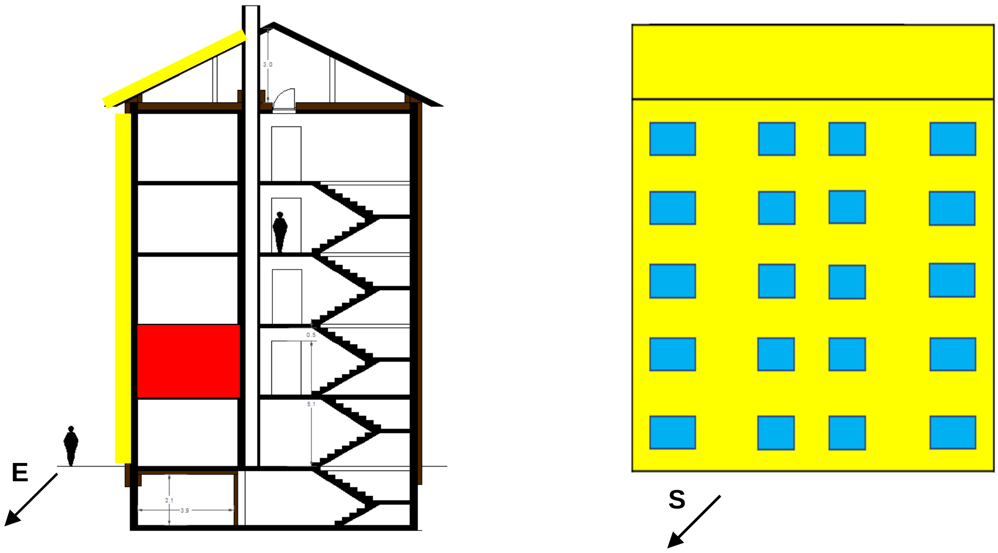


Fig. 1: View of the MFH (10 flats, 2 flats for each floor). The roof and the entire opaque façade area oriented to South-East (highlighted in yellow) were assumed available for installation of the PV field

Tab. 1: Data of PV field sizes considered for one flat

	roof	**roof&façade**
Slope	30°	30° (roof) & 90° (façade)
PV size [m^2]	8.2	19.8
Peak power [W_p]	1250	3000

2.2 HVAC system and DHW production

The analyzed flat is heated with a compact supply air – exhaust air heat pump in combination with MVHR (see Fig. 2 and [2] for details). Such a system can be completely integrated into the façade and represents a good solution for deep energy renovation of a flat in a MFH, especially in the case in which centralized renovation solutions are not practicable. The air is extracted from bathroom and kitchen, cooled in the MVHR unit and the remaining enthalpy is used as source for the heat pump. The fresh air is heated by a pre-heater, a Heat Recovery Ventilation (HRV) or Energy Recovery Ventilation (ERV) unit, the condenser of the heat pump and, additionally, a post-heater if the power of heat pump is insufficient, before it is supplied and distributed to the flat. The air distribution system is placed in the corridor and supplies fresh air to the sleeping room, child room and living room. An electric radiator is placed in the bathroom for comfort reasons.

Two different DHW production systems were investigated in this study: electric boiler and ambient air-to-water heat pump.

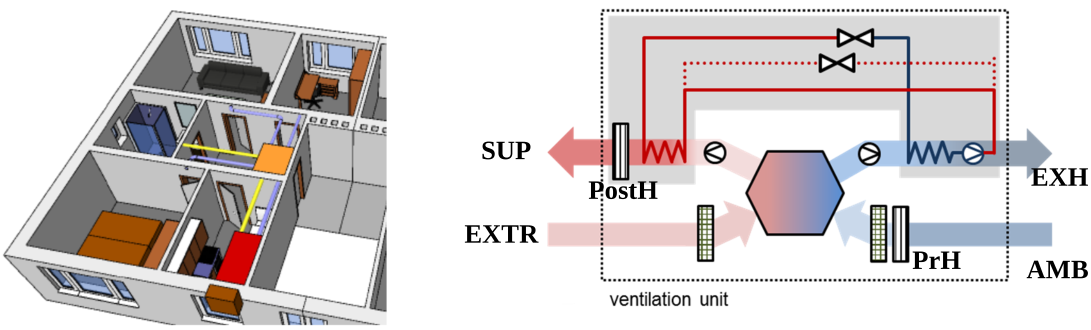


Fig. 2: 3D view of the flat with the supply air heat pump system (left) and scheme of the heat pump in combination with HRV (right). "PostH" and "PrH" represent the post-heater and the pre-heater, respectively [3]

2.3 Electricity demand

Fig. 3 shows the electric power profile of the appliances (see Tab. 5 in appendix for details) corresponding to an electricity demand (Wel) of 2650 kWh/a distributed to the different rooms of the flat. Six rooms (i.e. six thermal zones) were defined in the flat model: kitchen (KI), sleeping room (SL), corridor (CO), bathroom (BA), child room (CH) and living room (LI). The same profile was assumed for each day of the year. The electric profile is the same for SL and CH, while no appliances were assumed for BA and CO.

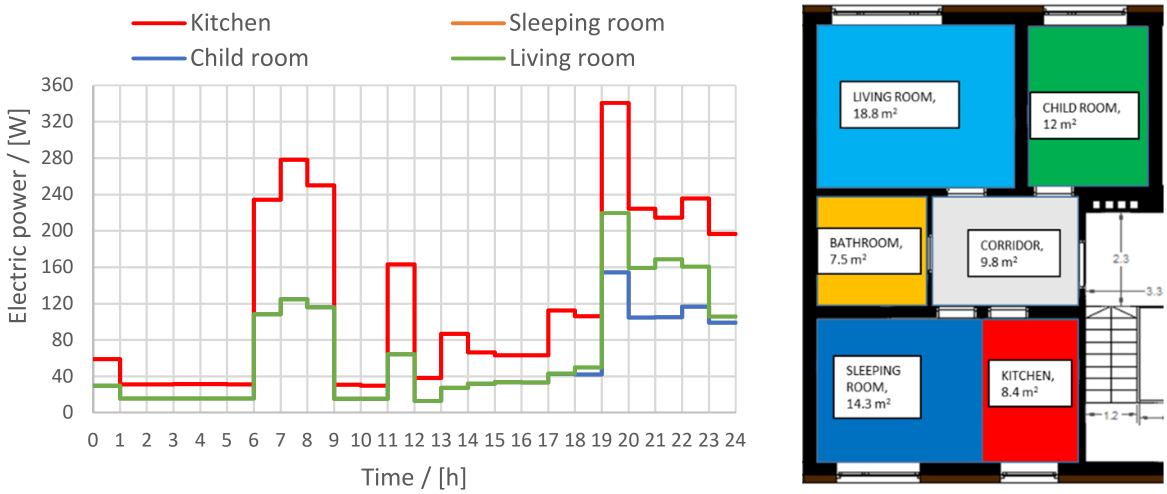


Fig. 3: Electric power profile (left) of the appliances for each room of the flat (Wel = 2650 kWh/a) and floor plan of flat (right).

A balanced ventilation system with a constant airflow rate of 120 m^3/h was assumed. Specific Fan Power (SFP) of 0.45 Wh/m^3 for both fans (i.e. supply and extract airflow rate) was assumed to take into account the electric power supply of the ventilation system (electricity demand of 946 kWh/a).

The flat under study with a heating demand (HD) of 33.4 kWh/(m^{2}a) was heated during the winter with a supply air-exhaust air heat pump (with post-heater) and an additional electric radiator placed in the bathroom for comfort reasons (see Fig. 4 and [2] for details). Because of the relative low power of the heat pump (650 W), a relatively high percentage (26%) of the HD is covered by direct electric heating.

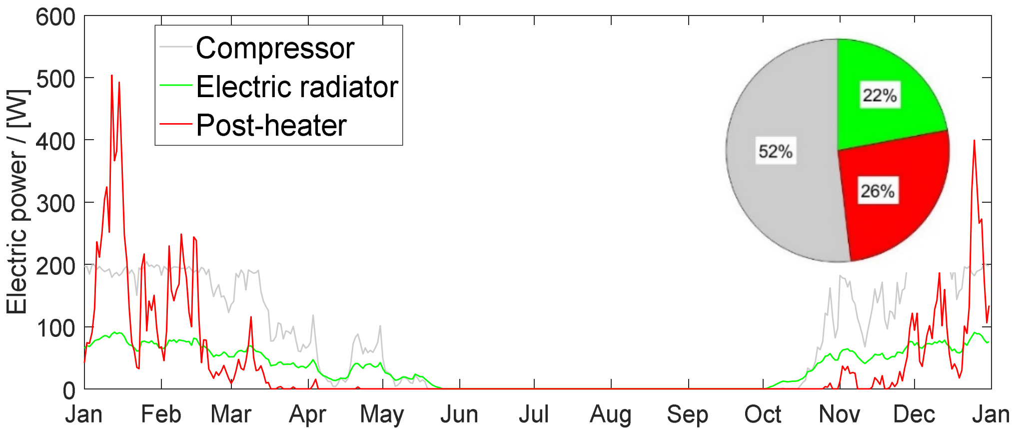


Fig. 4: Daily average values of the electric power request of the heating system (Wel = 1292 kWh/a)

Three different profiles for domestic hot water (DHW) energy demand (see Tab. 2) were considered in this study. DHW(3) is a variation of DHW(2) assuming a preparation with air-to-water heat pump instead of direct electric heating.

Tab. 2: Details of the three DHW profiles considered in the simulation study

Case	Preparation	Profile	Energy [kWh/a]	Electricity [kWh/a]
DHW(1)	Electric	Flat	2190	2190
DHW(2)	Electric	Hourly	2404	2404
DHW(3)	Heat pump	Hourly	2404	906

2.4 Simulation study

The assumption in this simulation study is that the electricity of the PV field first covers the appliances electricity demand and only the remaining PV electricity is available to cover the electric power demand of the HVAC system (i.e. ventilation, heating and DHW preparation). The rest of PV electricity is injected to the grid. Fig. 5 shows the simplified scheme of the modelled system. In the model, the balance between the PV production and the electric demand is done each 10 minutes and then the values are integrated to calculate the PV self-consumed and the amount of electricity that is covered by the grid.

Two different PV field configurations (see Tab. 1) and three electric demands for DHW preparation (see DHW(1), DHW(2) and DHW(3) in Tab. 2) were considered in this simulation study. In the following sections "Demand(1)", "Demand(2)" and "Demand(3)" indicate the total electric demand if DHW(1), DHW(2) and DHW(3) are considered, respectively.

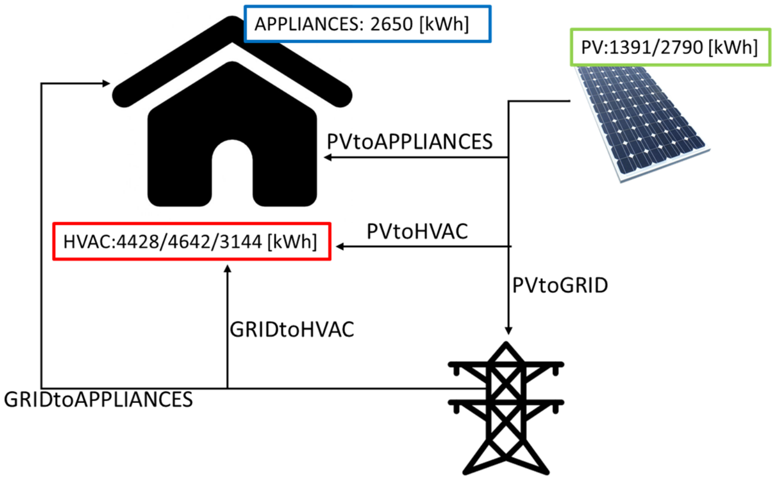


Fig. 5: Simplified scheme of the simulated coupled HVAC – PV system with PV energy production and electricity demand. Two different PV sizes (i.e. PV on the roof (1391 kWh/a) or also on the façade (2790 kWh/a)) and three electricity demands depending on the DHW profile (see Tab. 2) were considered. REMARK: "HVAC" indicates the sum of ventilation, heating (with HP) and DHW preparation.

3. Results and discussion

The monthly electricity energy flows of the system for all the cases are shown in Fig. 6. During the summer, the electric power request for heating is zero (see Fig. 4) which leads to the lower electricity demand compared to the winter time. In all cases and for each month, the PV production can only partially cover the electricity demand. Even if the best case is considered (i.e. PV(roof & façade) and Demand(3) in July), electricity from grid is needed to cover the remaining electricity demand.

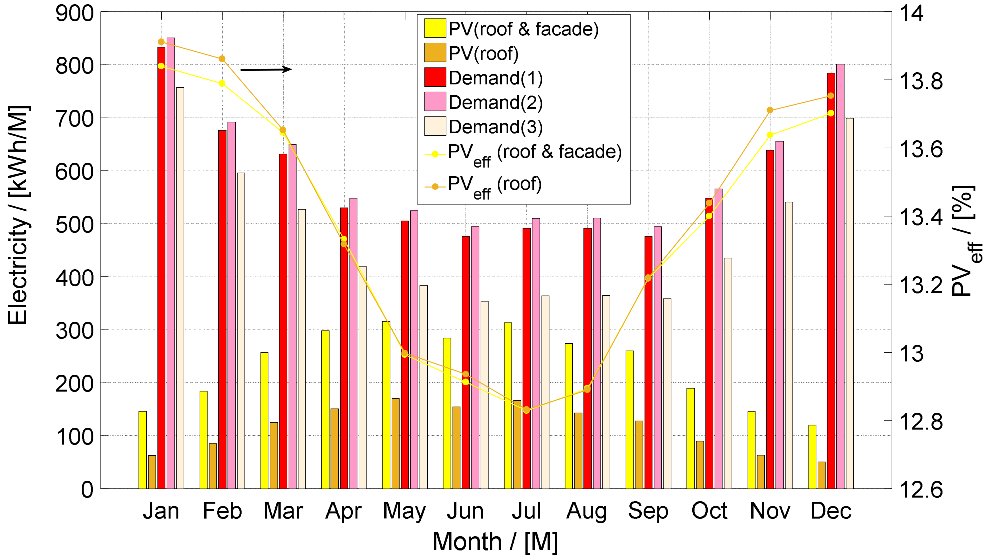


Fig. 6: Monthly electricity balance of the system. The PV production (with PV efficiency on the right axis) of the two investigated PV sizes and the three investigated electricity demands are shown

Fig. 7 shows the electricity balance of the PV system depending on the PV size and electricity demand. For all cases, PV electricity can cover a small percentage of the electricity demand with a maximum value of 18% and 26% in case PV is installed on the roof or also on the façade, respectively. For all the three investigated electricity demand profiles, the purchased electricity decreases in case PV is installed also on the façade and this reduction is of -10% in case Demand(3) is considered. This reduction is limited by the fact that only the 30% of the PV produced by the PV on the façade is self-consumed, while the rest (969 kWh) is fed to the grid (see Fig. 8). These results are confirmed by Thür et al. [4] who analyzed the influence of the PV field size on the self-consumed electricity for a Single Family House heated by a heat pump. These results show that only a relative small reduction of the purchased electricity (-7%) can be obtained in case PV area is doubled (40 m^2 instead of 20 m^2).

Fig. 8 shows that the 46% of the PV production is fed to the grid in case PV is installed on the roof and façade. This non self-consumed PV electricity is fed to the grid in the summer period (see Fig. 9) and, to a much less extent, during the winter time. Thus, there is a good potential to reduce further the purchased electricity. More efficient control strategies (e.g. for DHW preparation) or electric storage (i.e. batteries) could be considered to reduce the amount of electricity purchased from the grid, especially if PV is installed also on the façade.

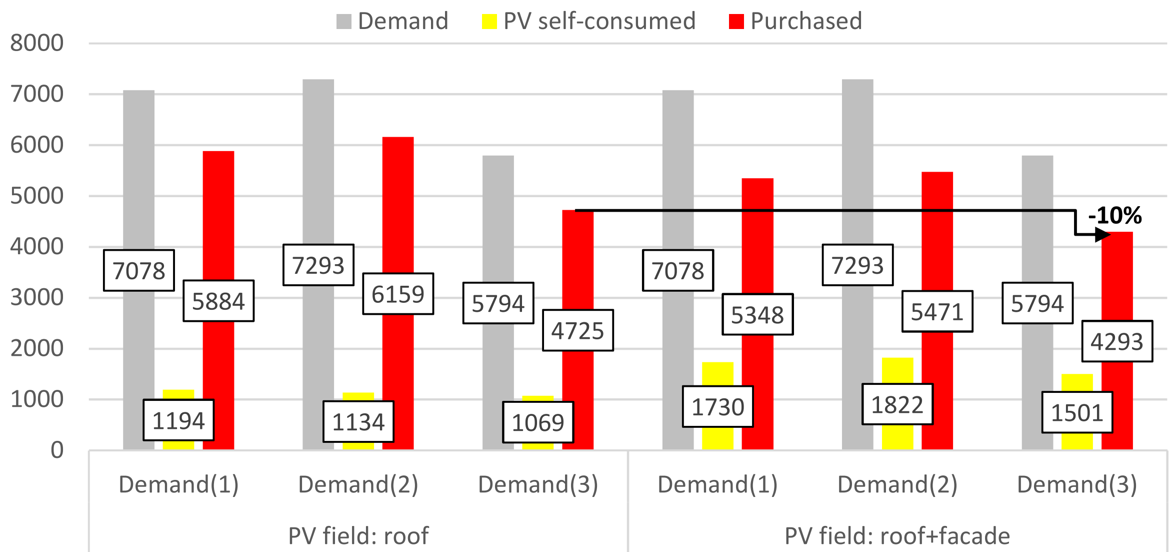


Fig. 7: Annual electricity demand, PV self-consumed and purchased grid electricity depending on the PV size and electricity demand

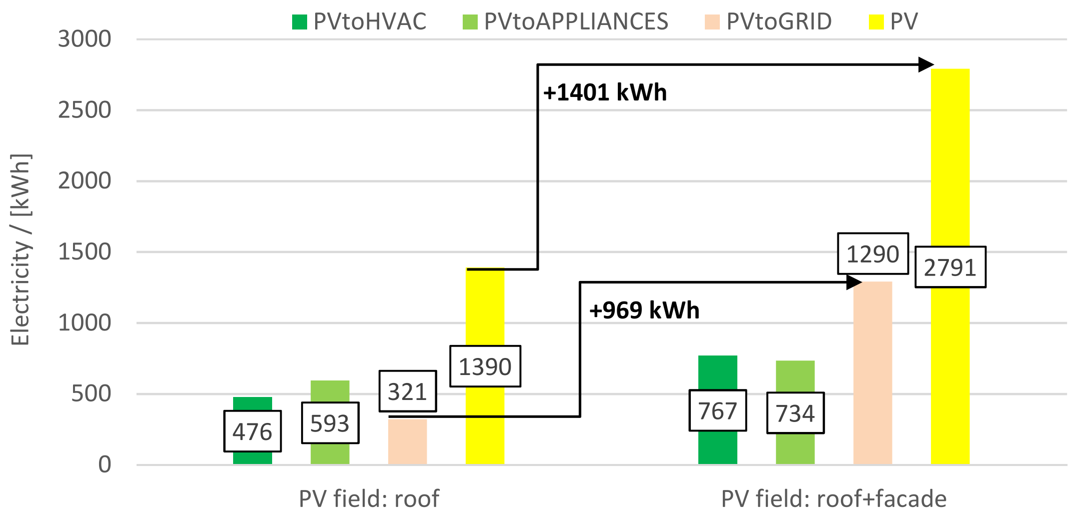


Fig. 8: Use of PV electricity depending on the PV size in case Demand(3) is considered

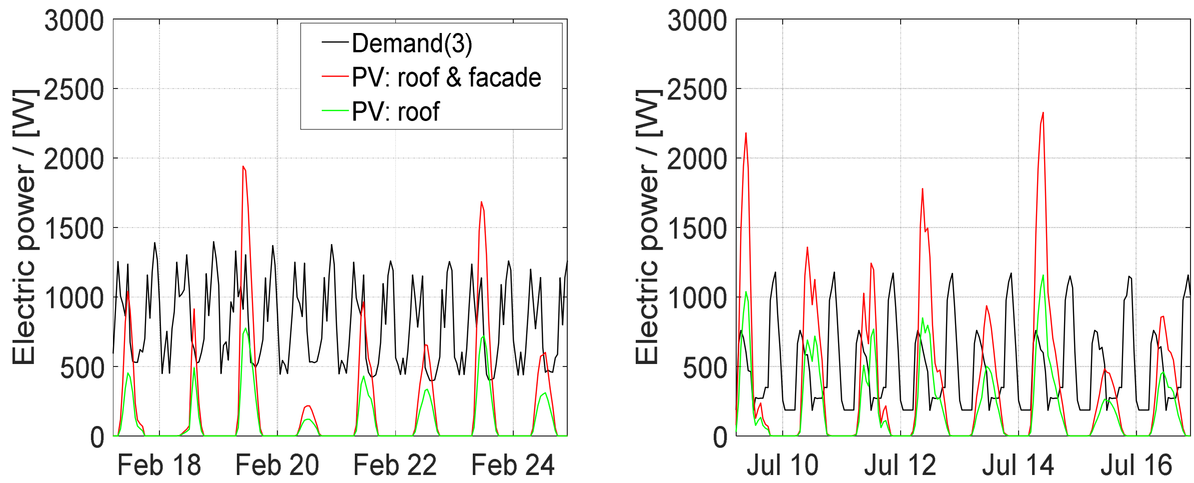


Fig. 9: PV production and electric demand (only Demand(3) is shown) during a winter period (left) and summer time (right)

The use of electric storage has a minor influence on the purchased electricity in case PV is installed just on the roof (see Fig. 9) due to the undersize of PV field compared to the electric demand (reduction of purchased electricity of 7% in case of Demand(3) if annual electric storage is considered, see Fig. 10). Electric storage can play a more important role in case PV is installed on the façade and on the roof with a reduction of the purchased electricity of 27% if daily electric storage and Demand(3) are considered.

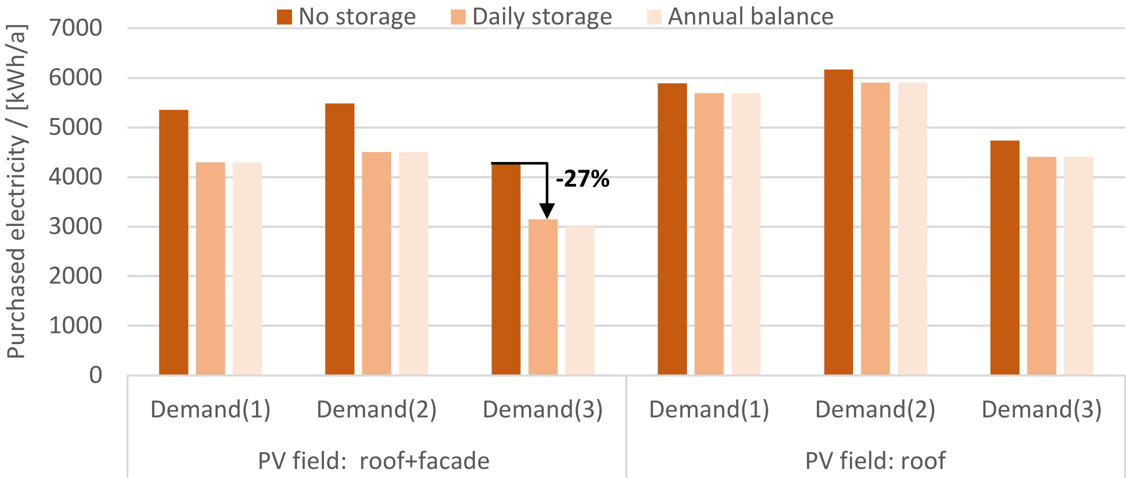
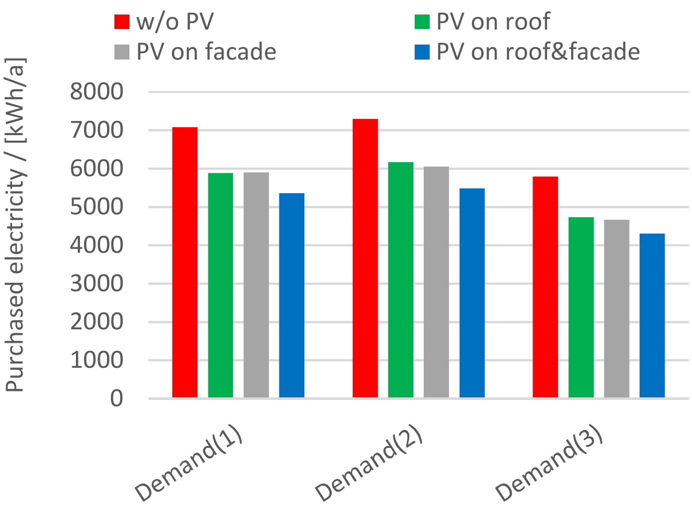


Fig. 10: Annual purchased electricity depending on the capacity of electric storage ("No storage" and "Daily storage") and in case an annual electricity balance is considered ("Annual balance")

As shown previously in Fig. 8, the electricity produced by the PV field installed on the façade of the flat is 1401 kWh, which is almost equal to the electricity production of the PV field installed on the roof (i.e. 1390 kWh). A simulation study of the flat in case of PV installed only on the façade was performed and the results of the comparison with the others PV sizes is reported in **Fehler! Verweisquelle konnte nicht gefunden werden.**. Even if the PV area is bigger on the façade of the flat (11.6 m^2) compared to the PV area on the roof (8.2 m^2), the PV production (see Fig. 8) and the purchased electricity are almost the same (with a difference below 2%, see Fig. 12) for the two cases (i.e. "PV on roof" and "PV on façade") for the three electric demand investigated. The same reduction of the purchased electricity (compared to the case without PV) can be obtained through the installation of a PV field on the roof or on the façade, but the economic comparison between the two solutions of energy renovation should consider the higher investment costs in case of PV installed on the façade (due to the bigger PV area for each flat). Furthermore, in reality, a reduced yield for PV on the façade should be expected because of shading in many locations.



	roof	**facade**
Slope	30°	90°
PV size [m^2]	8.2	11.6
Peak power [W_p]	1250	1750

Fig. 11: Annual purchased electricity for the three electric demand investigated (i.e. Demand(1), Demand(2) and Demand(3)) depending on the PV size. "PV on facade" indicates that the PV is installed just on the facade of the flat (A_{PV} = 11.6 m^2)

3.1 Evaluation of non-renewable primary energy consumption

The installation of a PV system on the roof (and the façade) of the building can reduce the (non-renewable) primary energy (PE) consumption of the flat. However as previously shown, there is a strong mismatch between high electricity demand in winter and PV excess electricity production in summer. This has influence on the value of electricity with respect of the time of electricity production.

The seasonal variation of renewable electricity production in the energy mix can be taken into account, by monthly primary energy conversion factors (f_{PE}). Two scenarios for monthly f_{PE} are presented in [5] and considered in this study, depending on the different scenarios of the share of renewable energy in the energy mix (10% hydro, 10% wind and 10% PV for f_{PE1} and 10% hydro, 30% wind and 30% PV for f_{PE2}). f_{PE} are higher during the winter season (maximum value of 2) compared to the summer period (see Fig. 12 and Fig. 13). The average annual value is 1.64 and 0.77 for f_{PE1} and f_{PE2}, respectively. The electricity mix 10%-10%-10% (i.e. f_{PE1}) shows similar seasonal variation as the actual electricity mix in Austria (OIB, ENTSO-E, Statistik Austria). The monthly f_{PE} and the purchased electricity are lower during the summer and this explains the lower PE consumption during the summer for all cases shown. In case f_{PE2} is considered (Fig. 13), monthly PE demand during the summer (May-Aug) is very low (below 31 kWh/M) for all the three cases investigated.

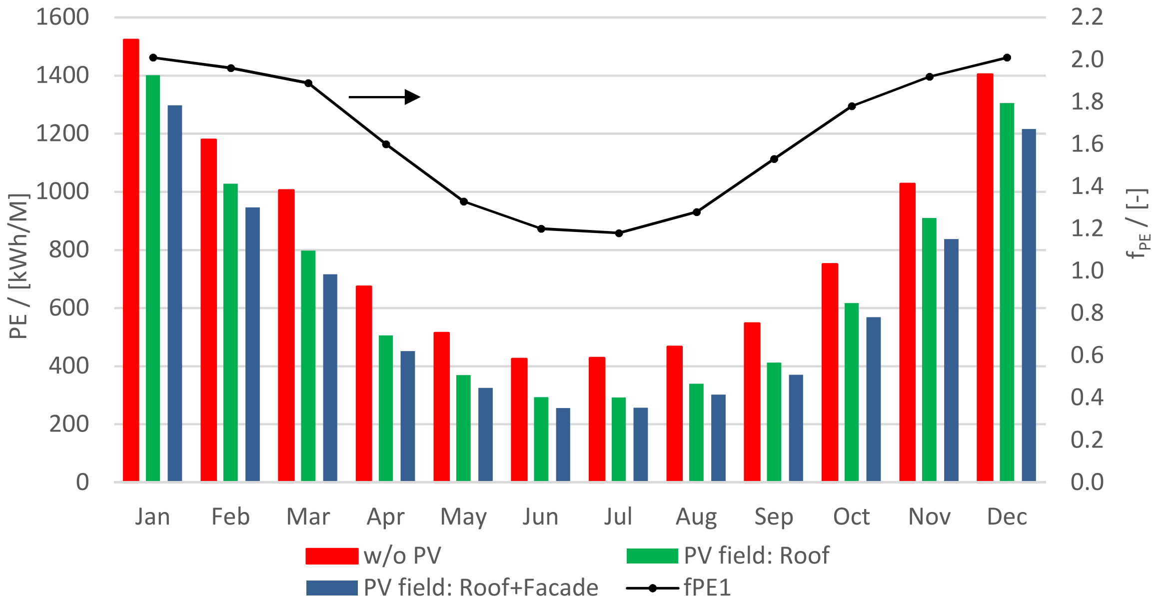


Fig. 12: Monthly Primary Energy (PE) demand with (for the two PV fields considered) and without PV field and monthly PE conversion factors (f_{PE1}, annual average value of 1.64) [5] in case Demand(3) is considered.

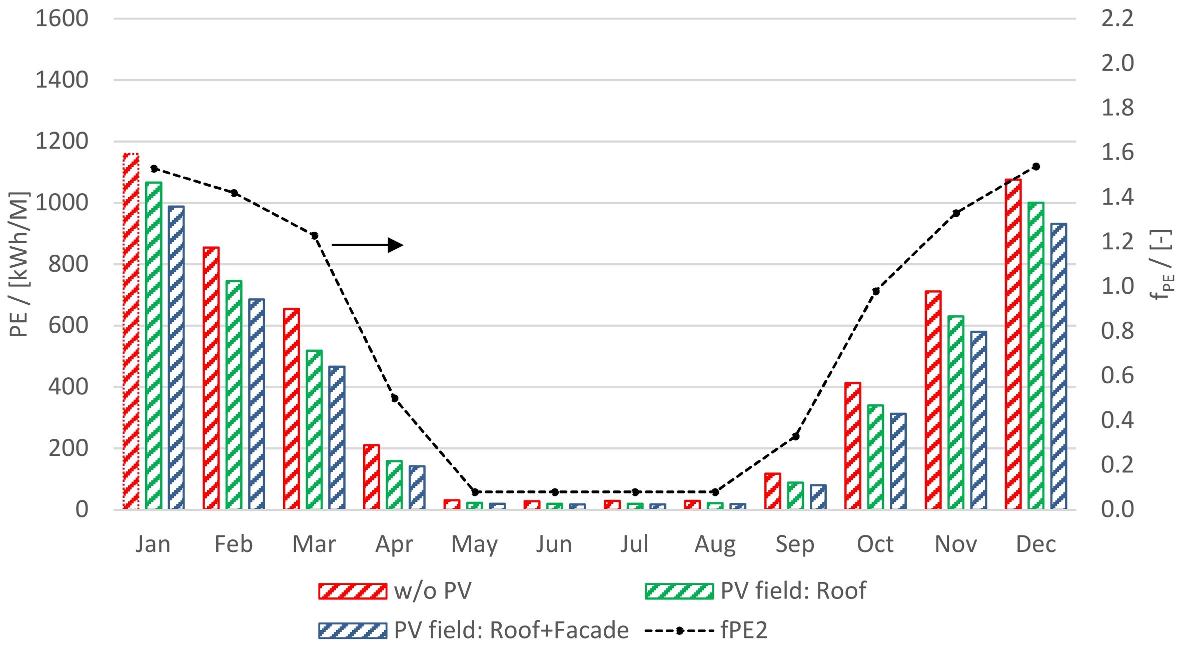


Fig. 13: Monthly Primary Energy (PE) demand with (for the two PV fields considered) and without PV field and monthly PE conversion factors (f_{PE2}, annual average value of 0.77) [5] in case Demand(3) is considered.

The influence of the PE conversion factor f_{PE} and of the PV size on the annual PE demand is shown in Tab. 3. A reduction of the annual PE demand of -17% and -24% (for f_{PE1}) and of -13% and -20% (for f_{PE2}) can be obtained in case PV is installed on the roof only or also on the façade. If the PV field is installed on the roof and on the façade, a reduction of annual PE demand of 8% (compared to the case of PV on the roof only) can be obtained. This is because a large percentage (70%) of the additional PV electricity produced by the PV field of the façade is fed to the grid (especially during the summer season) and cannot be self-consumed. In case PV is installed on the roof and on the façade, the saving of PE is higher in case of annual f_{PE} compared to the case in which monthly f_{PE} values are considered (-26% instead of -24% in case of f_{PE1} and -26% instead of -20% in case of f_{PE2}). In case an annual primary energy conversion factor is considered, the relative deviation of PE (i.e. ∆PE(roof) or ∆PE(roof&façade)) does not depend on its value.

The relevant influence of the electric storage on the purchased electricity was shown in Fig. 10. Tab. 4 shows the potential of further reduction of PE demand in case an electric storage is considered (i.e. daily storage). The importance of a storage is less relevant in case of PV installed on the roof (ΔPE is increased from -18% to -24%) unlike from the case in which PV is installed also on the façade, where the PE demand could be decreased by 46%. It is also interesting to note that a daily electric storage (in case of PV installed on the roof) could lead the PE to a value of 7226 kWh/a (in case of f_{PE} = 1.64), almost equal to the PE in case of PV installed on the roof and façade without storage (7059 kWh/a).

Tab. 3: Annual PE demand and relative deviation of PE (respect to the case without PV) depending on the PV field and f_{PE} in case Demand(3) is considered

	PE [kWh/a]			∆PE	
	w/o PV	**PV on roof**	**PV on roof&façade**	**∆PE (roof)**	**∆PE (roof&façade)**
Monthly f_{PE1}	9945	8266	7541	-17%	-24%
Monthly f_{PE2}	5314	4628	4257	-13%	-20%
Annual f_{PE1} = 1.64	9507	7762	7059	-18%	-26%
Annual f_{PE2} = 0.77	4432	3619	3291	-18%	-26%

Tab. 4: Annual PE demand and relative deviation of PE (with respect to the case without PV) depending on the PV field, electric storage and f_{PE} in case Demand(3) is considered

	PE [kWh/a]					ΔPE [%]			
		No storage		Daily storage		No storage		Daily storage	
	w/o PV	**PV on roof**	**PV on roof& façade**	**PV on roof**	**PV on roof& façade**	**ΔPE (roof)**	**ΔPE (roof& façade)**	**ΔPE (roof)**	**ΔPE (roof& façade)**
f_{PE1} = 1.64	9507	7762	7059	7226	5162	-18%	-26%	-24%	-46%
f_{PE2} = 0.77	4432	3619	3291	3369	2407	-18%	-26%	-24%	-46%

4. Conclusions

The potential of covering electricity needs (for HVAC system, appliances and DHW preparation) of a flat of a renovated MFH with PV system was investigated for different electric power profiles and PV sizes.

PV electricity can cover a small percentage of the electricity demand with a maximum value of 26% in case PV is installed on the roof and façade and heat pump is used for DHW preparation (i.e. Demand(3)). The installation of an additional PV field on the façade must be carefully evaluated (the additional investment costs have to be considered) because the saving of purchased electricity is in the range of 9% - 11% for all cases compared to the case in which PV is installed just on the roof. The installation of a PV on the roof or on the façade of the flat leads to the same reduction of purchased electricity, even if the PV area available for each flat on the façade is bigger compared to the area available on the roof of the building.

The use of electric storage reduces the purchased electricity, especially if PV is installed on the roof and façade, with a reduction of 27% in case heat pump is used for DHW preparation and daily electric storage is considered.

A maximum reduction of PE demand of 24% (compared to the case without PV system) can be obtained in case

PV is installed on the roof and façade and a monthly primary energy conversion factor with an annual average value of 1.64 is assumed. PE demand can be significantly reduced (-46% in case of Demand(3) and PV on the roof and the façade) compared to the case without PV in case a daily electric storage is considered. The saving of PE demand is slightly overestimated (between 1% and 6% depending on the case) in case of annual f_{PE} compared to the case in which monthly f_{PE} values are considered.

5. References

[1] System Simulation Models, Residential Buildings – Part B, Ochs F., Siegele D., Calabrese T., Dermentzis G., Venus D., IEA SHC TASK56 – Building Integrated Solar Envelope Systems (unpublished)

[2] Ochs F., Dermentzis G., Siegele D., Façade Integrated MVHR and Heat Pump, in: 12th Conference on Advanced Building Skins 2-3 October 2017, Bern, Switzerland, 2017.

[3] Siegele. Optimization and Appliance of small Air Exhaust Heat Pumps with Focus on Alpine Regions, PhD Thesis, Work in progress (link)

[4] Thür A., Calabrese T., Streicher W., Smart Grid and PV driven Heat Pump as Thermal Battery in Small Buildings for optimized Electricity Consumption, 2018, Solar Energy https://doi.org/10.1016/j.solener.2018.08.087

[5] F. Ochs, G. Dermentzis, Evaluation of Efficiency and Renewable Energy Measures Considering the Future Energy Mix, in: 7th Int. Build. Phys. Conf. IBPC2018, 23-26 Sept., New York, USA, 2018.

6. Appendix

Tab. 5: Electric power (W) of the appliances for the different rooms of the flat

Hour	Kitchen	Bedroom	Childroom	Living room
0-1	59.2	29.8	29.8	29.8
1-2	31.3	15.7	15.7	15.7
2-3	31.3	15.7	15.7	15.7
3-4	31.4	15.7	15.7	15.7
4-5	31.4	15.7	15.7	15.7
5-6	31.2	15.7	15.7	15.7
6-7	234.2	108.2	108.2	108.2
7-8	278.1	124.8	124.8	124.8
8-9	250.2	116.0	116.0	116.0
9-10	30.8	15.4	15.4	15.4
10-11	29.8	15.5	15.5	15.5
11-12	163.3	64.2	64.2	64.2
12-13	38.5	13.1	13.1	13.1
13-14	86.7	27.2	27.2	27.2
14-15	66.4	32.0	32.0	32.0
15-16	63.1	33.5	33.5	33.5
16-17	63.2	33.5	33.5	33.5
17-18	112.4	42.8	42.8	43.3
18-19	106.2	42.1	42.1	49.9
19-20	340.7	154.4	154.4	219.8
20-21	224.3	104.7	104.7	159.4
21-22	214.5	105.0	105.0	168.9
22-23	235.6	116.6	116.6	160.5
23-24	196.5	99.0	99.0	105.9