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Cost-optimal nZEB HVAC configurations with onsite storage

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Abstract. By 2021, all new buildings in the European Union must be nearly zero-energy buildings in order to contribute to the achievement of the EU-CO_2 neutrality by 2050. As the technical options to achieve highly-efficient building envelopes are available and well-known, there is no doubt that the most promising Heating Ventilation and Air Conditioning systems will include heat pumps and photovoltaic panels. However, there exist ongoing discussions on the optimal system layout and the integration of storage to achieve nZEB. In particular, there are some good arguments in favour of very low demand, while contrariwise also high flexibility is seen as an important feature to enable so-called grid-reactive operation of the building stock. Integration of onsite storage and its influence on the energy demand of the buildings and the corresponding electric load profile with focus on peak power is investigated.

1 Introduction

1.1 nZEB and flexibility

By 2021, all new buildings in the European Union (EU) must be nearly zero-energy buildings (nZEBs) in order to contribute to the achievement of the EU-CO_2 neutrality by 2050. As the technical options to achieve highly-efficient building envelopes are available and well-known, there is no doubt that the most promising Heating Ventilation and Air Conditioning (HVAC) systems will include heat pumps (HPs) and photovoltaic (PV) panels. However, there exist ongoing discussions on the optimal system layout and the integration of storage to achieve nZEB. In particular, there are some good arguments in favour of very low demand, while contrariwise also high flexibility is seen as an important feature to enable the so-called grid-reactive operation of the building stock.

A techno-economic analysis of different technologies including passive components i.e. envelope, Mechanical Ventilation with Heat Recovery (MVHR), Shower Drain Water Recovery (SDWR), active components i.e. heat pump (HP), direct electric heating (DE), renewables (RE) (e.g. PV) as well as storage can be performed to identify cost-optimal solutions and combinations depending on the type of building (i.e. residential and non-residential buildings) as well as on the application i.e. heating, cooling, Domestic Hot Water (DHW), lighting, appliances. Herein, the investigation should include the HP integration together with locally available RE energy sources for application in nZEBs. In this context, a special focus is the optimization of the HP control and onsite storage integration and the interaction with the electricity grid (electricity purchase and sell).

According to the Energy performance of buildings directive (EPBD), an nZEB is a nearly zero- energy building, which has a very low energy demand due to efficiency measures that include efficient HVAC technology (e.g. HP) and utilization of RE to meet the very low demand to a considerable extent. Yet, in the EU member states nZEBs are defined following the national standards. In this regard, each member state provided its own national definition with sometimes significant differences in terms of energy consumption (heating, cooling, hot water, auxiliary consumers and appliances), maximum limits, conversion factors, etc. (see [1,2]).

The Net Zero Energy Building (NZEB) is better known internationally and outside Europe. A NZEB can be realized as a "grid-connected building that on annual basis generates the same amount of energy from on-site RE energy sources as it consumes" (IEA SHC T40/ HPT A40). It is worth mentioning that this definition lacks clarity with regard to the interpretation of system boundaries, energy flows, weighting factors (i.e. conversion factors), etc. Theoretically, an NZEB might be a building with relatively high overall heat transfer coefficient (U-value) and, thus, high heating demand and to compensate for that is equipped with a very large PV system. In this regard, such an NZEB would generate a large PV-surplus in summer, whereas in winter the energy demand has to be covered from the power grid (so-called winter gap). As a general rule, in multi storey buildings the available area for PV compared to the treated area is not sufficient to achieve the net zero balance even if the building is highly efficient [3,4,5,6].

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1.2 Energy Storage

1.2.1 Overview

Energy storage can be beneficial in terms of buffering mismatch between energy source and energy demand. In a future energy system with volatile RE energy sources (wind, solar) energy storage is required to bridge short-term mismatch (day-night), mid-term mismatch (couple of days to few weeks) and seasonal mismatch (summer-winter). The seasonal pattern can be seen on both, the energy source side (hydro, solar) and demand side, i.e. space heating (SH).

Fig. 1 gives an overview of the existing electric and thermal energy storage. While long-term electric storage systems are typically large-scale central units, short term electric storage can be scaled for a wide range of applications and can be applied in buildings. Sensible long-term thermal energy storage is typically applied in district heating (DH) systems [7], while sensible short term storage is integrated in smaller units into the building. Latent and thermo-chemical storage play still a minor role in practice, but extensive research is ongoing [8].

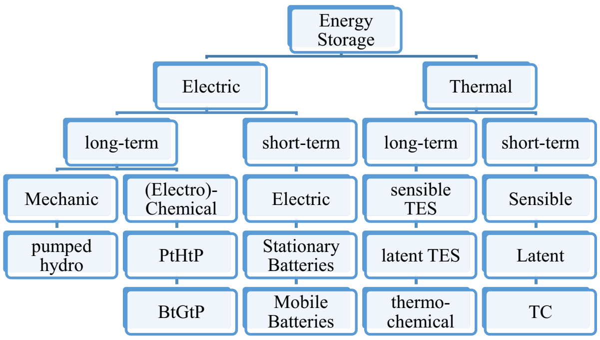

Figure 1. Overview of electric and thermal energy storage (TES); PtHtP: Power to Heat to Power BtGtP: Biomass to Gas to Power [11].

For the design of energy storage, it is crucial to determine the storage capacity, the storage discharge and charge power as well as the storage efficiency. Storage can be integrated into the energy system in large central units or decentral in buildings.

1.2.2 Energy Storage in Buildings

Concerning the storage of energy on-site (at the building level), two types of energy storage are possible:

- Electric: Buildings equipped with a PV system can largely benefit from the introduction of batteries that allow direct consumption of the electricity generated. Careful dimensioning of the batteries, based on the analysis of the installed power and consumption, is necessary to optimize costs. Self-discharge and energy consumption for battery management have to be considered.

- Thermal: The storage of domestic hot water is already widespread in residential buildings. It is possible to store hot water when more energy is available (e.g. PV for HP) or when electricity prices are lower. The main disadvantage compared to simultaneous production and use is related to the efficiency of the storage system, which usually consists of steel water tanks with thermal insulation. The storage efficiency depends on the surface-to-volume ratio, the operating temperature and the storage period. It is also possible to use coupled storage systems for domestic hot water preparation and SH water ("tank in tank" or stratified tank).

Solid sensible storage is either a massive part of the building (e.g. walls, floors, ceilings) known as thermal activation of building systems (TABS) or fillings made of gravel or rocks. Such storage systems are therefore often integrated directly into the respective building and are short term storages (1 to max. 2 days). The thermal building mass can be heated/cooled passively by the environment (e.g. solar gains) or actively. Such active solid storage can in principle be operated with liquid (hydronic systems) or air as a heat transfer medium. Fig. 2 gives an overview of building-integrated storage systems.

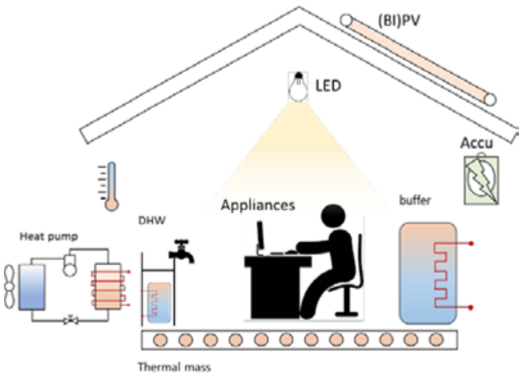

Figure 2. Schematic presentation of (thermal and electric) energy storage in buildings.

Table 1 gives an overview of building-integrated storage and potential storage capacities. In combination with a heat pump, with an average Coefficient of Performance (COP) of 3, the thermal storage capacity can be approximately converted to electric storage capacity. For DHW the daily electric storage potential is 2.3 kWh.

For a typical Single Family House (SFH) the daily electricity consumption (appliances, lighting, etc.) is ranging between 6 kWh/d in summer and 8 kWh/d in winter.

Table 1. Energy storage in buildings and storage capacity; example SFH, 140 m².

Energy	Type	Typical Size	Capacity
Electric	Battery	1 kWh/kW$_p$	6 kWh$_{el}$
Thermal (hydronic)	DHW buffer	100 to 150 l	7 kWh$_{th}$ 50/10 °C
Thermal (hydronic)	SH buffer	1000 l	23 kWh$_{th}$ 50/30 °C
Thermal mass	TABS	200 Wh/K/m²	28 kWh$_{th}$/d $\Delta T = 1$ K

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1.2.3 Energy Flexible Buildings

Through energy storage, energy flexibility in buildings could provide generating capacity for energy grids, and better accommodate RE sources in energy systems. There is also seen a potential to reduce costly upgrades of energy distribution grids.

The main challenge is providing thermal comfort, reducing thermal losses while ensuring an economic benefit for the building owner/operator and the utility, see (IEA EBC, Annex 67).

1.3 Future sustainable energy scenario

As shown in [9,10], for the example in Tyrol (Austria) a future sustainable energy system for the building sector is possible, see Fig. 3, but, given the limited potential of RE, only under the following conditions:

- Significant reduction of the load (new buildings in Passive House Standard, renovation quality of the building stock as close as possible to Passive House standard)
- Heat Recovery (mechanical ventilation, waste water)
- Phase-out of fossil energy systems and massive application of HP
- Improvement of efficiency in appliances and in HP applications
- Decarbonisation of DH system (waste heat, biomass, solar thermal)
- Massive increase of RE energies (hydro, wind, Solar) in the electricity generation
- Installation of storage capacity to bridge daily, weekly and seasonal mismatch between load and demand.
- An important hypothesis is that the potential of biomass in the building sector is limited as it will be required in industry and transport

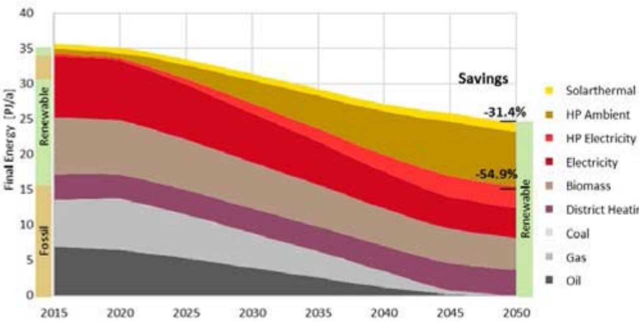

Figure 3. Ambitious Scenario of reduction of final energy demand in the building sector by means of deep thermal renovation and phase-out of coal, oil and gas in Tyrol [10]. Remark: Tyrol's electricity is certified as 100 % renewable, mainly from hydro power plants, ca. 20 % are imported from Norway, in Austria the ca. 75 % of the electricity is renewable.

1.4 Aim of this work

The aim of this work is to show for the investigated virtual cases the potential of integrating passive and active solar technology and the role of onsite storage. A methodology was developed to analyse and compare different solutions.

While previous studies on energy storage in buildings, energy flexibility, demand-side management, and model predictive control focused on the micro-economic aspect, this work investigates the influence of onsite storage on a macro-economic scale. It is important to determine the reduction of the grid electricity demand and the PV excess electricity depending on the sizing of the (thermal and/or electric) storage. The research question is, whether in a 100% RE-based scenario (which requires large storage capacities), onsite storage will play a significant role. Furthermore, it is investigated how onsite storage capacity influences the required back-up power or central storage capacity.

2 Methodology

2.1 Building Model

A simple and fast dynamic simulation model is required to predict the load of different building types (SFH, Multi Family House - MFH, office, etc.) with different HVAC systems (e.g. HP), DHW and appliances profiles as well as storage options (thermal, electric) and PV integration. A simple dynamic 1-zone lumped capacity model (see Fig. 4) was developed in Matlab (ode15s solver) with the following features:

- Single zone, lumped capacity
- Resistance model for wall / window
- Solar Heat Gain Coefficient (SHGC) with angle dependence, constant shading
- Constant effective air exchange (optionally with heat recovery efficiency of 0.6)
- Constant internal gains
- Climatic data hourly resolution (Meteonorm, based on OIB-6, B8110-5 (Innsbruck)
- Detailed calculation of solar radiation (Perez)
- Heating with hysteresis with HP or DE
- (cooling optional)
- HP (Carnot, Carnot performance factor)
- DHW with "daily storage tank" (charging 5 hours during the day with heat pump or direct electric), DHW priority
- Heating buffer optional (1-node lumped capacity dynamic model)
- Profile for electricity (appliances) according to APCS (2021, 15 min resolution) [19]
- PV system with temperature-dependent efficiency and inverter
- Dynamic battery model (simple capacity model; charge rate (c-rate) = 0.5; minimum State of Charge (SoC_{min}) = 0.2)
- Cross-validated against CarnotUIBK [20] (Matlab/Simulink) and , TRNSYS

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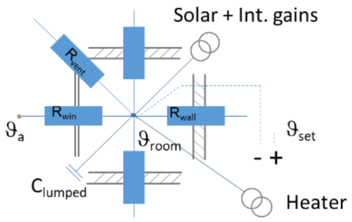


Figure 4. Simple dynamic 1-zone lumped mass building model.

The following set of equations is solved with a maximum time step of 1 hour using Matlab (ode15s) solver. Results are post-processed with 1 h resolution.

Building

$$\frac{d\vartheta_{zone}}{dt} = \frac{1}{C_{zone}}(-\dot{Q}_{loss} + \dot{Q}_{gain} + \dot{Q}_{SH}) \quad (1)$$

Thermal storage

$$\frac{d\vartheta_{buf}}{dt} = \frac{1}{C_{buf}}(-\dot{Q}_{loss,buf} + \dot{Q}_{heat,buf} - \dot{Q}_{SH}) \quad (2)$$

Electric Balance

$$P_{el,tot} = P_{SH} + P_{DHW} + P_{app} + P_{aux} \quad (3)$$

$$P_{el,grid} = P_{el,tot} - P_{el,PV,AC} - P_{bat,AC} \quad (4)$$

Battery

$$\frac{dC_{bat}}{dt} = P_{bat} \quad (5)$$

$$P_{bat} = P_{\mathrm{charge}} - P_{\mathrm{discharge}} - P_{\mathrm{standby}} - P_{\mathrm{loss}} \quad (6)$$

$$P_{bat} = min(P_{bat}; c_{rate}C_{bat}) \cdot (SoC > SoC_{min}) \& (SoC < SoC_{max}) \quad (7)$$

PV

$$P_{el,PV,AC} = \eta_{inverter} \cdot P_{el,PV} - P_{inverter,standby} \quad (8)$$

$$P_{el,PV} = \left(\left(\vartheta_{ref} - \vartheta_{module}\right) \cdot K_T + 1\right) \eta_{\mathrm{gen}} \cdot I_{\mathrm{sol}} \cdot P_{PV,peak} \quad (9)$$

$$I_{\mathrm{sol}} = RF \cdot (K_{dir} \cdot I_{dir} + K_{dif} \cdot I_{dif}) \quad (10)$$

2.2 DHW and Appliances profile

For all residential buildings, simplified DHW and appliances profiles are assumed. As an example, the charging profile for SFH is reported in Fig. 5. The DHW tapping profile is based on EN 16147, profile M with 5.8 kWh/d. A small DHW store of 120 l is assumed and three different simplified charging strategies are investigated. Daytime charging between 09:00h and 15:00h, night-time charging between 18:00h and 23:00h and morning/evening charging between 6:00h and 9:00h as well as 19:00h and 22:00h. For the results presented here the evening profile was used.

The appliances have a resolution of 15 min and besides a seasonal variation, weekdays and weekends are distinguished, see Fig. 6.

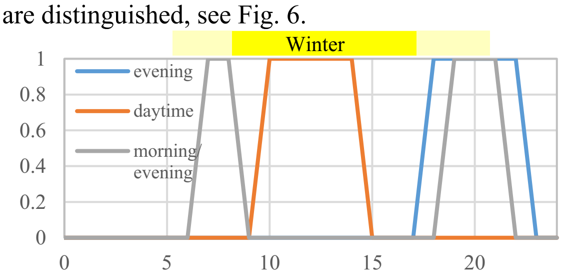
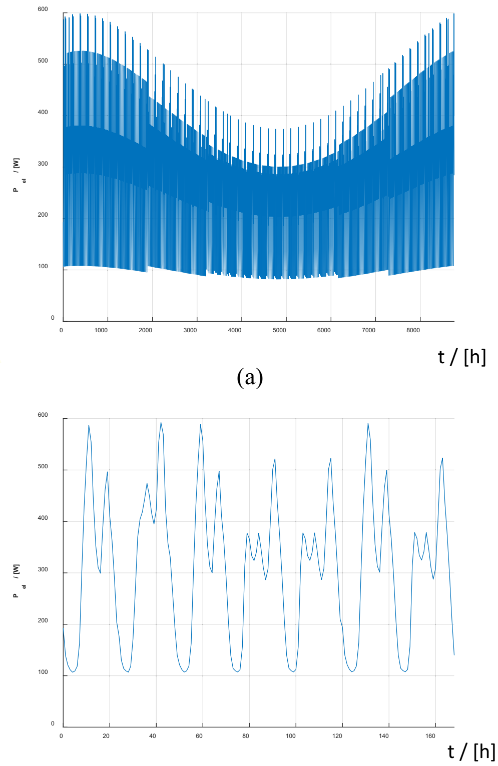


Figure 5. DHW charging profiles as well as an indication of winter (dark yellow) and summer (light yellow) sunshine duration in Innsbruck.



(a)

(b)

Figure 6. Appliances, APCS (2021, 15 min resolution) [19] (a) year (b) week in January.

2.3 Key performance indicators

The supply cover factor (SCF) and load cover factor (LCF), depend on the PV own consumption ($W_{PV,\,own}$) and are typically used to evaluate the performance of PV and energy storage. as ratio with respect to the total by PV produced electricity (W_{PV}) or total electricity demand of the building ($W_{El,tot}$), respectively, and are determined on simulation time step level.

$$SCF = W_{PV,own} \;/\; W_{PV} \quad (11)$$

$$LCF = W_{PV,own} \;/\; W_{El,tot} \quad (12)$$

The non-renewable primary energy demand ($PE_{non\text{-}RE}$) is used to evaluate the environmental impact. The primary energy conversion factor $f_{PE,non\text{-}RE}$ depends on the scenario for the future development of the electricity mix. Currently it is 2.3 on European average.

$$W_{El,grid} = W_{El,tot} - W_{PV,own} \quad (13)$$

$$PE_{non\text{-}RE} = W_{El,grid} \cdot f_{PE,non\text{-}RE} \quad (14)$$

From the macro-economic point of view, the primary energy savings are more relevant. To account for different scenarios for the future electricity mix, i.e. with different RE shares (hydro, wind, PV) and time of electricity buy and sell, monthly conversion factors are recommended to calculate the primary energy demand (PE / [$kWh_{PE}/(m^2\,a)$]) or the CO_2 emissions (CO_2 / [$kg/m^2\,a$)]), see [12].

For the case study of the SFH, the following economic parameters (Annuity Method) were applied

- Period of Consideration 20 yrs.
- Interest Rate (nominal) i = 3 %

$$TAC = EAC + MC + OC \quad (15)$$

$$EAC = IC \cdot i \,/\, (1 - (1+i)^{-L}) \quad (16)$$

with Investment Costs (IC)

- PV 1500 €/kWp L = 20 yrs.
- Battery 1000 €/kWh L = 10 yrs.

and Operation (OC) and Maintenance (MC) costs

- Electricity buy $cost_{el,b}$ = 0.25 €/kWh
- Electricity sell $cost_{el,s}$ = 0.04 €/kWh
- Maintenance/Repair 5 % of TAC

Electricity costs (buy) are assumed to be average over the consiration period of 20 years with an moderate annual increase of 3 % based on the current electricity costs of 0.185 €/kWh.

2.4 Building Stock Model

The aim of this work is to predict the electric load curve of the building stock with different options of onsite PV and energy storage (thermal, electric). The building stock of Tyrol (Austria) is taken as an example. It is represented by 6 types of prototypical buildings (based on Scenario Energy Autonomy Tyrol). Each building is equipped with either a heat pump, a direct electric heating system and represents different load patterns for the electricity grid. Buildings heated with biomass or connected to DH system represent an appliance- (and auxiliary-) based load only. The scenario assumes a total phase-out of fossil heating systems (i.e. no gas and oil boiler). The schematic representation of the building stock is shown in Fig 7.

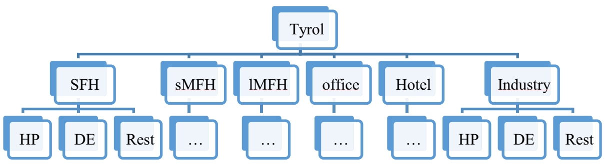


Figure 7. Structure of the simplified building stock model; HP: Heat pump; DE: Direct electric heating; Rest: Biomass, District Heating.

Each building is simulated with its individual energetic quality (i.e. heating demand), with different heating technology (see table 2), with and without PV, without as well as with small or large battery storage. The energetic building quality represents the average status of 2050, according to the above mentioned scenario.

The following results focus on the residential buildings with 21 % SFH, 29 % s-MFH and 11 % l-MFH in Tyrol. Remark: The share of the non-residential buildings is approx. 14 % in terms of the number of buildings, and 30 % in terms of gross floor area final energy consumption, see [13]. Table 3 summarizes the number of the residential buildings and the available PV area per building (roof only).

Remark: according to [11] approx. 3300 GWh of PV (net balance) would be required for an energy-autonomous building stock in Tyrol in 2050, i.e. additional 2100 GWh would have to be installed on roofs of offices and industry buildings and on open space. Only the PV installed on the roofs of the residential buildings are considered in the following sections (results and discussion).

Table 2. Share of the different HVAC types in the analysed residential building categories (in % relative to the gross floor area [m²GFA]); scenario Tyrol, 2050 [11].

	SFH	s-MFH	l-MFH
HP	56	53	55
DE	3	2	3
Biomass	3	27	9
DH	38	18	33

Table 3. Gross floor area, available roof surface, number of buildings and installed PV peak power per building type [11].

	SFH	s-MFH	l-MFH
Gross floor area [m^2_{GFA}]	182.9	405.3	2090.1
No. floors	2	3	10
Roof surface [m^2]	91.5	135.1	209.0
No of buildings	106579	67592	5063
Installed PV [kWpeak]	5	8	12
PV Yield [GWh/a]	1200 (1047 kWh/kW$_p$)		

All new buildings follow the Passive House standard, all existing buildings are refurbished with Passive House components, which leads to average energy levels reported in Table 4.

Table 4. Final energy for space heating (SH), domestic hot water (DHW) and appliances of the average residential buildings depending on the heating technology according to scenario Tyrol 2050 [11].

	SFH		
	Specific FE consumption		
Buildings heated with:	SH	DHW	Appliances
	[kWh/(m^2 a)]		
Biomass	60.0	22.7	12.25
DH	45.1		
DE Heating	37.8		
HP (heat)	37.8		
	s-MFH		
	Specific FE consumption		
Buildings heated with:	SH	DHW	Appliances
	[kWh/(m^2 a)]		
Biomass	53.3	20.0	11.84
DH	41.8		
DE Heating	31.8		
HP (heat)	31.6		
	l-MFH		
	Specific FE consumption		
Buildings heated with:	SH	DHW	Appliances
	[kWh/(m^2 a)]		
Biomass	51.5	21.3	11.17
DH	34.3		
DE Heating	30.7		
HP (heat)	35.9		

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3 Results

3.1 Energy Demand and Load

The daily electric energy for SH, DHW, auxiliary (aux), appliances and the sum of all (total) is shown for the SFH with heat pump in Fig. 9.

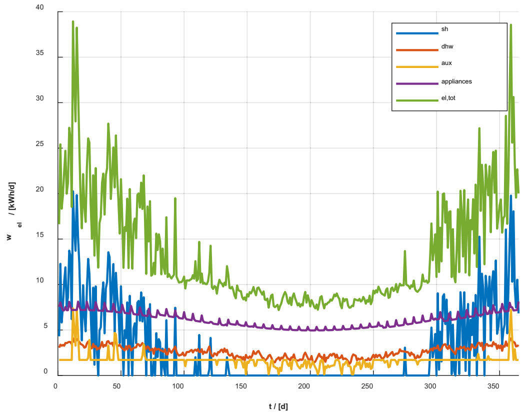


Figure. 9. Daily electric energy for space heating (sh), domestic hot water auxiliary (dhw), auxiliary (aux), appliances and total for the SFH (140 m²) with heat pump.

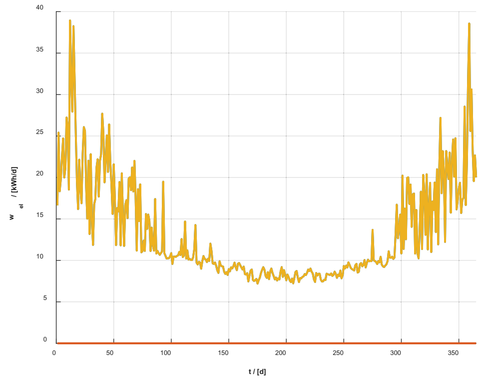
For the planning of the required storage capacity in a building, the total electricity demand, the peak load and the PV yield are required. These are summarized in Table 5.

Table 5. Total electricity demand of the SFH (5 kW_P), the s-MFH (8 kW_P) and the l-MFH (12 kW_P); PV Net Peak Power: max([$P_{El,grid}$;$P_{PV,excess}$]).

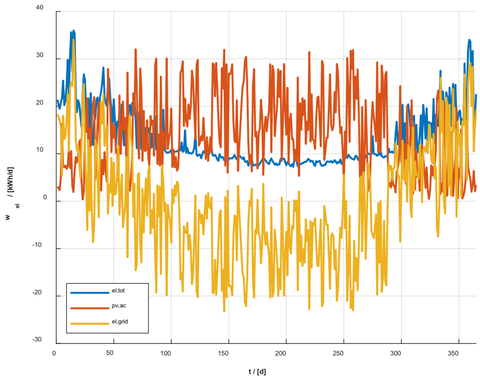
		Total electr. demand / [kWh]	Load / [W]	PV yield / [kWh]	PV Net Peak Power [W]
SFH	DE	13376	4946	5235	4011
	HP	5157	1975		
	Rest	2247	603		
s-MFH	DE	93331	11308	8376	6250
	HP	38090	4066		
	Rest	4798	1281		
l-MFH	DE	143928	53130	12564	7400
	HP	55183	21044		
	Rest	23340	6231		

3.2 Electric Energy Balance with onsite PV and storage

The daily sum of the electric load is shown for the SFH in Fig. 10 (a) for the case with heat pump without PV, in (b) with 5 kW_p PV, in (c) with PV and small battery (6.67 kWh) and in (d) with PV and large battery (8 x 6.67 kWh). It is noteworthy that instead of a larger battery also thermal storage (i.e. buffer) could be used, however, for sake of simplicity, only electric storage (in addition to the DHW storage and thermal mass of the building) is presented here. It is also important to mention that space heating buffer would only be effective in winter and more effective in case of DE heating, which however represents only a small share of the building stock. The corresponding electric load for the grid (positive buy, negative sell) is also shown.



(a)



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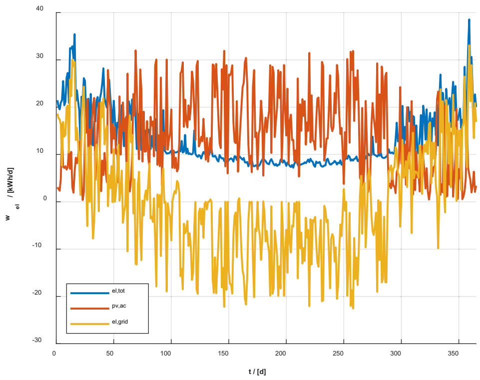
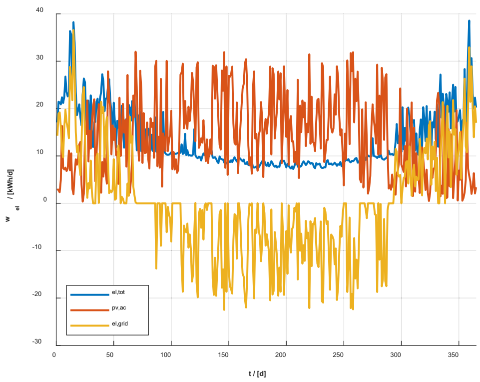


(c)



(d)

Figure 10. Example of electric load (daily sum) of the SFH with heat pump (a), with heat pump and PV (b), heat pump, PV and small battery (c) as well as heat pump, PV and large battery (d).

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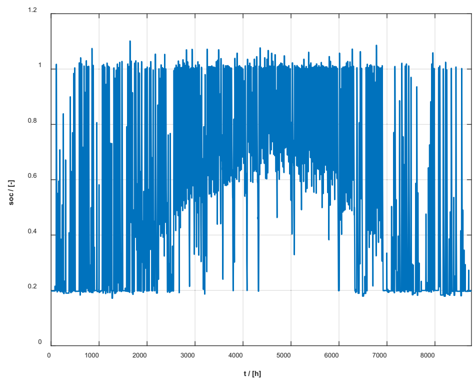
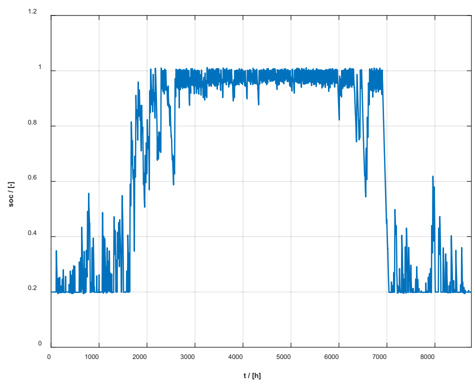
With PV (independent of the presence of a battery) the daily sum of the excess PV is in the range of 22 kWh/d (peak) while in winter the PV does hardly influences the peak of the grid load because of too little production in winter and long nights. Even with large battery, neither the peak load in summer nor the peak load in winter is significantly reduced. The battery operation is effective mainly in the interim season (March, April as well as September, October).

It can be understood from the state of charge of the battery (see Fig. 11 (a) for small battery and (b) for large battery) that further increase of the capacity is of limited use. The battery is fully charged most of the time in summer and empty most of the time in winter. In consequence, there is also no relevant capacity for electricity buffer from PV of other buildings in summer, neither surplus of electricity for other buildings in winter, in case of a heating dominated climate like Innsbruck.

In Fig. 12 the resulting load curves are shown for the SFH with heat pump in (a), for direct electric heating in (b) and for the case of biomass or district heating (i.e. appliances and aux. only) in (c). In all three cases, a significant reduction of the grid electricity consumption can be seen with the 5 kW_p PV system. With a small battery, the excess electricity can be significantly reduced and also further decrease of the electricity required from the grid can be seen. A larger battery allows for a further decrease. However, in all cases the battery does not influence the peak power.

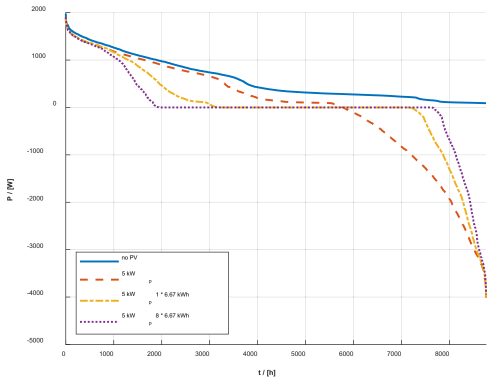


(a)

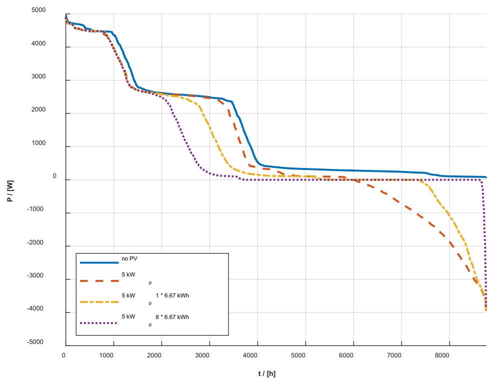


(b)

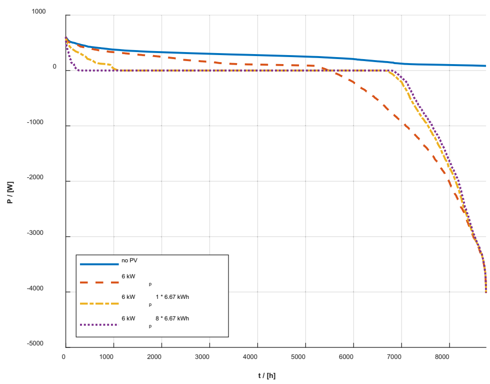
Figure 11. State-of-charge (soc) of the battery for (a) small battery (6.67 kWh) and (b) large battery (8 x 6.67 kWh).



(a)



(b)



(c)

Figure 12. Example of electric load (hourly, sorted) of the SFH with heat pump (a), DE heating (b) and Biomass/DH (c) without PV, with PV with small (1 x 6.67 kWh) and large (8 x 6.67 kWh) battery.

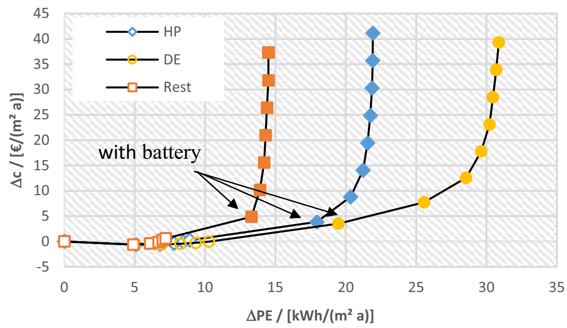
The load and supply cover factor is summarized in Table 6 for all cases. Both, load and supply cover factors can be increased significantly using a small battery; while there is a limited effect of increasing the capacity. In case of the s-MFH and l-MFH the contribution to PV remains below 50 % even with the large battery SCF and LCF should not be used to evaluate and compare different HVAC, RE and storage solutions.

Table 6. Load cover factor and supply cover factor (in brackets) for the three building types, without, with small and with large battery; Rest: buildings heated with biomass and district heating.

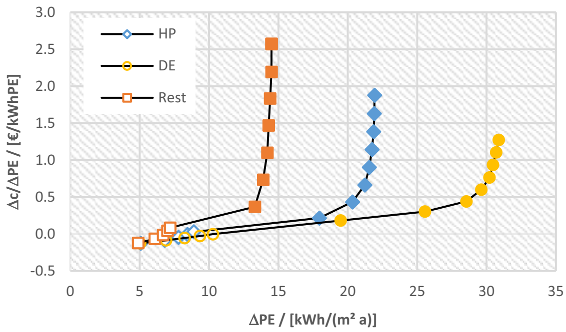
		PV	PV + small bat.	PV + large bat.
SFH	DE	.12 (.30)	.20 (.56)	.35 (.89)
	HP	.26 (.26)	.52 (.52)	.64 (.64)
	Rest	.48 (.21)	.89 (.38)	.97 (.42)
s-MFH	DE	.11 (.35)	.16 (.51)	.29 (.91)
	HP	.25 (.32)	.39 (.50)	.37 (.73)
	Rest	.46 (.27)	.77 (.44)	.92 (.53)
l-MFH	DE	.06 (.68)	.06 (.74)	.08 (.93)
	HP	.16 (.60)	.17 (.77)	.22 (.96)
	Rest	.35 (.65)	.40 (.75)	.51 (.95)

3.3 Techno-economic Analysis

Using the SFH as an example, a techno-economic analysis (see above for the assumptions) is performed. The PE savings (ΔPE) are calculated with respect to the reference case (no PV) for varying sizes of PV system (from 1 to 5 kW_p) and for different battery capacities (for 5 kW_p from 1 to 8 times 6.67 kWh). The highest PE savings are possible in case of DE heating, while only a small PV system (i.e. 1 kW_p) is economically feasible (minimum of Δc). Only a small PV system (< 3 kW_p) is economic in case of biomass and DH (Rest) and savings are relatively low. In all cases, it can be observed that PV combined with small battery allows for significant PE savings, however, it is not economically feasible.



(a)



(b)

Figure 13. Cost difference Δc (a) and cost intensity (Δc/ΔPE) vs. primary energy savings ΔPE with respect to the reference (no PV); example of SFH with DE heating, with HP and rest (biomass, DH); f_{PE} = 1 kWh_{PE}/kWh_{el}. Solid filled points include also a battery; empty marker without battery, filled marker with battey.

On micro-economic scale, in a SFH with HP, which represents a large share of the future building stock, a PV system with a maximum 4 kW_p is economic, a small battery leads to significant savings but is associated with a significant increase of annual costs.

On macro-economic scale and with regard to achieving the climate goals, instead, the PV system should be obviously as large as possible.

3.4 Electric Energy Demand Building Stock

With the share of building types (SFH, s-MFH, l-MFH) and the corresponding share of heating systems (HP, DE and rest (biomass, DH)) the total electric load of the residential building stock (acc. to the scenario Tyrol 2050) can be calculated, see Fig. 14.

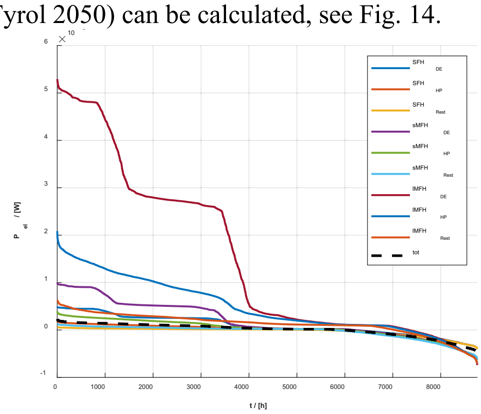


Figure 14. Load curve (sorted hourly values of the electric load) for the different building types and heating systems, example of the case with PV (acc. to table 4).

In Fig. 15 the load curves represent an average residential building, i.e. the total load curve divided by the total number of residential buildings for the case without PV, with PV, with PV plus small battery and with PV plus large battery. The load curve is dominated by the SFH with HP as it represents the majority of the buildings acc. to the scenarios in [11].

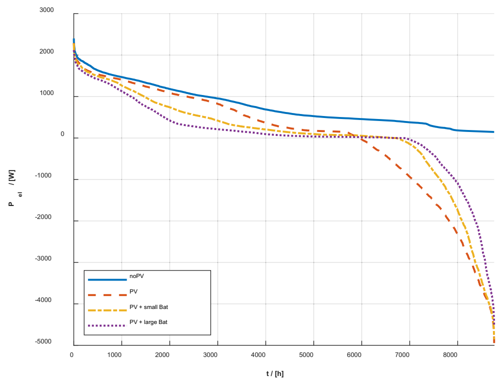


Figure 15. Total (average residential building i.e. total electricity consumption divided by total number of residential buildings) load duration curve (in hourly resolution, sorted) without PV, with PV acc. to table 2 and 3,with PV and small battery (6.67 kWh) as well as with PV and large battery (8 x 6.67 kWh).

Again, extensive use of PV has a significant influence on the bought and sold electricity, however, the peak load is hardly reduced even with large storage capacity in the buildings. The peak power is ca. 2350 W without PV, 2250 W with PV and 2100 W with PV plus large storage for electricity delivered from the grid. The excess PV electricity supplied to the grid is 4950 W with PV and 4550 W with PV and large battery. Overall with or without onsite storage for the average building the grid has to be capable of a capacity of approx. 5000 W.

4 Discussion and Conclusions

Future new as well as deep renovated buildings, so-called nZEBs, will have a relatively low heating demand (new down to ca. 15 kWh/(m² a); average around 45 kWh/(m² a), acc. to [11]) and a correspondingly short heating season (from October to April). The DHW demand is of the same order of magnitude (typically between 10 and 20 kWh/(m² a)). Assuming heat pumps being the standard heating system in the future (the assumption here is that the share of buildings that will be heated with biomass or district heating systems increases such that the final energy delivered by biomass and district heating systems remains approx. constant), the total electric demand for SH and DHW in case of HP is in the range of 10 kWh_{el}/(m² a) and 25 kWh_{el}/(m² a) and of the same order of magnitude as the electricity demand for appliances (typically between 15 kWh_{el}/(m² a) and 20 kWh_{el}/(m² a)). On a nZEB SFH with 5 kW_p PV system, the net PV yield is of the same order of magnitude as the annual total electricity demand. Hence, only ca. 50 % of the final energy of the building is thermal energy and thus thermal storage could theoretically cover also only around 50 % of the total energy demand (SH + DHW), while electric storage (i.e. battery) could cover theoretically 100 % of the total demand (SH + DHW + appliances). In MFH, because of the relatively small roof area related to the GFA, the theoretical contribution of PV is significantly less.

Overall, onsite storage (thermal and electric) can be beneficial to reduce the grid electricity demand, however, the grid load (i.e. peak power, both electricity buy and electricity sell) is hardly reduced by onsite storage. From the micro-economic view, small PV systems can be economic feasible, battery storage not.

Hence, if at all, extensive onsite storage should be considered only on short and mid-term to promote the extended use of PV in buildings (in particular when buyback tariffs are low). On macro-economic scale, in spite of energy savings, an additional application of storage in buildings or use of existing storage (overheating of thermal building mass or buffer tanks) will lead to higher losses without reducing the peak loads or the central storage capacity.

In a future step, the investigation will be extended to include non-residential buildings (offices, schools, hotels, industry, etc.) which account to approx. 30 % of the final energy in Tyrol.

Based on the presented results design guidelines can be elaborated for building located in heating dominated climates like Innsbruck. Furthermore, the results can be used to further foster and optimize nZEB design and implementation and the role of storage.

Evaluation of integration of RE and onsite storage (grid flexibility) must include all energy consumers (i.e. space heating (and cooling), domestic hot water preparation, auxiliary energies and appliances/lighting). In order to evaluate the time of consumption, either monthly primary energy factors should be used and/or time depending electricity prices for buy and sell.

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Nomenclature

Acronyms	
Aux	Auxiliary
BtGtP	Biomass to Gas to Power
c-rate	Charge Rate
COP	Coefficient of Performance
DE	Direct Electric
DH	District Heating
DHW	Domestic Hot Water
EPBD	Energy performance of buildings directive
EAC	Equivalent Annual Cost
EU	European Union
GFA	Gross Floor Area
HP	Heat Pump
HVAC	Heating Ventilation Air Conditioning
IC	Initial Cost
L	Lifetime
MC	Maintenance Cost
MVHR	Mechanical Ventilation with Heat Recovery
MFH	Multi Family House
nZEB	nearly Zero Energy Building
NZEB	Net Zero Energy Building
OC	Operative Cost
PV	Photovoltaic Panels
PtHtP	Power to Heat to Power
PE	Primary Energy
RE	Renewable
RF	Reduction Factor
SDWR	Shower Drain Water Recovery
SFH	Single Family House
SHGC	Solar Heat Gain Coefficient
SH	Space Heating
SoC	State of Charge
TABS	Thermal Activation of Building Systems
TAC	Total Annual Cost
Symbols	
ϑ	Temperature [°C]
C	Capacity [Wh]
I	solar irradiation [W]
i	nominal interest rate
K	correction factor
P	Electric Power [W]
$\dot{Q}$	Thermal Power [kWh]
W	electric energy [kWh]
η	efficiency [-]
Subscripts	
AC	Alternative current
app	Appliances
b	Buy
bat	Battery
buf	Buffer
dif	Diffuse
dir	Direct
el	Electricity
gen	generation
ref	Reference
s	Sell