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Sizing of Electrical and Thermal Storage Systems in the Nearly Zero Energy Building Environment – A Comparative Assessment

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***Abstract*—In order to determine the most suitable storage system for buildings with photovoltaics (PVs), a holistic analysis of the energy consumption is often required. In that sense, this paper provides a comparative assessment of thermal and battery storage in the context of nearly zero energy buildings (NZEBs). A NZEB with a PV, heat pump and a radiant floor has been considered for this purpose. The comparison is conducted in terms of the self-consumption rate and the net present value. In addition, a control strategy that maximizes the buildings self-consumption has been developed for the NZEB with thermal storage. For the NZEB with a battery, a common rule-based strategy has been employed. The results indicate that for smaller capacities, the thermal storage is better at improving self-consumption. Moreover, under a pure self-consumption scheme, battery storage becomes economically viable if investment costs are lower than 200 EUR/kWh.**

***Index Terms*—Battery storage, building model, photovoltaics, self-consumption, thermal storage.**

I. Introduction

The European Union aims to improve energy efficiency by 32.5% until 2030 [1]. This calls for significant action, especially in the building sector, as it accounts for about 40% of the overall energy consumption. In order to meet this goal, existing buildings should be transformed into nearly zero energy buildings (NZEBs) by reducing their energy intensity and by integrating renewable energy sources to meet their local demand [2]. Nevertheless, as climate conditions and building stock characteristics vary geographically, it is up to Member States to provide country specific NZEB definitions [3].

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In countries with high solar irradiation, for example, it may be economically viable to install rooftop photovoltaic (PV) generators [4]. The profitability of such systems often depends on the inherent self-consumption of the building [5]. One of the ways to achieve higher self-consumption rate (SCR) is by electrifying the building heating system [6]. However, additional measures are necessary to significantly reduce the energy flows between the building and the grid. This can be achieved by utilizing the storage capabilities of buildings, either in the form of deferrable end use appliances [7], building thermal inertia [8] or by integrating a battery [9] or thermal storage system [10]. There have been numerous publications dealing with battery and thermal energy storage systems in buildings [11]. However, the number of papers that provide a comparison of these storage alternatives, such as [12], are limited.

This paper aims to investigate the energy performance of a NZEB with a PV system under the operation of two distinct energy storage technologies - an electrical and a thermal storage. Simple rule-based control strategies are used to simulate their operation. Because of the intrinsically different technical capabilities of the storage technologies, the comparison is conducted in terms of the SCR and the net present value (NPV).

II. Building model

It has been assumed that building heating and cooling demand are met by an air-to-water heat pump connected to a radiant heating system, while a rooftop PV generator supplies part of the electricity demand. To increase its flexibility, as shown in Fig. 1, the building is equipped either with a hot water tank (thermal storage) or a battery storage system (electrical storage). The building is modelled with the dynamic building model presented in [13].

A. Thermal power

The thermal power demand of the building P_{th} is calculated using the following equation:

$$P_{th}(t) = P_{th,des}(t) \left(1 - \frac{\bar{T}_{ex}(t) - T_{des}}{T_{off} - T_{des}}\right) \tag{1}$$

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where $P_{th,des}(t)$ denotes the thermal power required by the building when the effective outside temperature $\bar{T}_{ex}(t)$ is equal to the design temperature T_{des}. T_{off} represents the temperature at which the heating/cooling is switched off. When $\bar{T}_{ex}(t)$ is lower than a certain threshold T^h_{off}, heating is required and the heating system turns on. Thus, $T_{off} = T^h_{off}$ is substituted in the equation (1). Similarly, if $\bar{T}_{ex}(t) \geq T^c_{off}$, cooling is required and hence, $T_{off} = T^c_{off}$. Suitable values are also substituted for the design temperature T_{des} when determining heating demand ($T_{des} = T^h_{des}$) and cooling demand ($T_{des} = T^c_{des}$). The effective outside temperature $\bar{T}_{ex}(t)$ is calculated as a moving average of the previous $\bar{\phi}$ values of the external temperature $T_{ext}(t)$ allowing the building thermal dynamics to be taken into account. The parameter $\bar{\phi}$ is determined by (2) and denotes the building's time shift.

$$\bar{\phi} = \frac{\sum_{i=1}^{N} (UA)_i \, \phi_i}{\sum_{i=1}^{N} (UA)_i \, \phi_i + H_{ve}} \tag{2}$$

In (2) $(UA)_i$ is the thermal transmittance of the i-th surface of the building envelope, ϕ_i denotes the characteristic time shift of each surface, while H_{ve} is the equivalent ventilation-thermal transmittance. A time shift ϕ represents the time delay between the maximum of a cause and the maximum of its effect. Note that, N is the total number of building surfaces.

B. Domestic hot water (DHW)

The power required for domestic hot water preparation can be calculated with the following equation:

$$P_{dhw}(t) = \dot{m}_w c_w \left(T_{w,out}(t) - T_{w,in}(t)\right) \tag{3}$$

where $\dot{m}_w$ is the mass flow of the consumed hot water, c_w is the specific heat capacity of water, while $T_{w,out}(t)$ and $T_{w,in}(t)$ are the temperatures of the domestic hot water and cold water coming from the mains, respectively.

C. Radiant floor

The temperature of the radiant floor $T_{rf}(t)$ at time step t is calculated as:

$$T_{rf}(t) = T_{w,rf}(t) - \frac{P_{th}(t)}{S_{rf} U_{rf}} \tag{4}$$

where $T_{w,rf}(t)$ is the temperature of the water contained in the radiant floor pipes, S_{rf} is the surface of the radiant floor heating and U_{rf} represents its equivalent transmittance. The water temperature can be calculated using the following equation:

$$T_{w,rf}(t) = T_{in}(t) + \Delta T_{rf,rated} \left(\frac{P_{th}(t)}{S_{rf} K_{rf,rated}} \right)^{\frac{1}{n_{rf}}} \tag{5}$$

where $T_{in}(t)$ is the desired room temperature inside the building, $\Delta T_{rf,rated}$ is the rated temperature difference between the circulating water and the inside ambience, $K_{rf,rated}$ is the rated power output of the radiant floor per surface unit and n_{rf} is the emitter exponent of the system. It has been

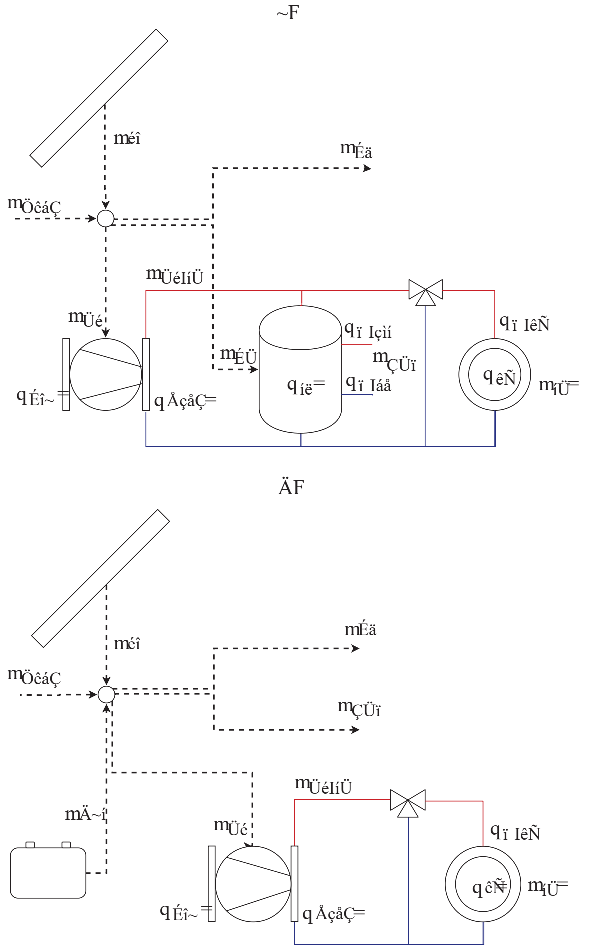

Fig. 1. System configuration a) NZEB with thermal storage and b) NZEB with battery storage.

assumed that the room temperature is constant and equal to a set-point temperature (20^{o}C when heating and 25^{o}C when cooling).

D. Heat pump (HP)

The thermal power output of the heat pump $P_{hp,th}(t)$ at time step t is a product of the heat pump electric power $P_{hp}(t)$ and its coefficient of performance $COP(t)$ or energy efficiency ratio $EER(t)$, depending on the operating mode. Hence, the thermal power of the heat pump in heating mode is equal to:

$$P_{hp,th}(t) = P_{hp}(t) COP(t) \tag{6}$$

while in cooling mode it is equal to:

$$P_{hp,th}(t) = P_{hp}(t) EER(t) \tag{7}$$

The $COP(t)$ and $EER(t)$ are calculated as the product of the heat pumps efficiency η_{hp} and Carnot's efficiency, represented as a function of the evaporator $T_{eva}(t)$ and condenser $T_{cond}(t)$ temperatures.

$$COP(t) = \eta_{hp} \frac{T_{cond}(t)}{T_{cond}(t) - T_{eva}(t)} \tag{8}$$

$$EER(t) = \eta_{hp} \frac{T_{eva}(t)}{T_{cond}(t) - T_{eva}(t)} \tag{9}$$

Temperature drops of 5 K and 10 K are assumed to occur at the indoor and outdoor heat exchangers of the heat pump, respectively.

E. Thermal storage system (TSS)

The thermal storage serves the heating demand and domestic hot water consumption of the building. It is heated by a heat pump and an electric heater (EH). It has been assumed that the temperature field inside the thermal storage is homogeneous. Hence, the one node model of a thermal storage is used [14] and the temperature of the thermal storage $T_{ts}(t)$ is determined by a discrete form of the dynamic energy balance equation:

$$\rho_w c_w V_{ts} \left(T_{ts}(t) - T_{ts}(t-1)\right) = \sum P_k(t)\Delta t \tag{10}$$

where ρ_w and c_w are the density and specific heat capacity of water, V_{ts} is the volume of the storage tank and Δt denotes the duration of one time step. The sum $\sum P_k(t)$ represents the thermal power balance of the storage:

$$\begin{aligned} \sum P_k(t) = P_{hp,th}(t) + P_{eh}(t) - P_{th}(t) - P_{dhw}(t) \\ -S_{ts} \frac{\lambda_{ts}}{d_{ts}} \left(T_{ts}(t) - T_{ex}(t)\right) \end{aligned} \tag{11}$$

Equation (11) takes into account the power supplied to the thermal storage by the heat pump $P_{hp,th}(t)$ (calculated by (6)) and the electric water heater $P_{eh}(t)$, as well as the power supplied by the thermal storage for the heating demand $P_{th}(t)$, the hot water demand $P_{dhw}(t)$ and the heat losses. The heat losses are given by the last term in (11), where S_{ts}, λ_{ts} and d_{ts} denote the total surface, the thermal conductivity and the thickness of the thermal storage tank, respectively. It is assumed that the tank is located in a poorly isolated area of the building and that the ambient temperature surrounding the thermal storage is equal to the external temperature.

F. Battery storage system (BSS)

At each time step, the energy stored in the battery $E_{bat}(t)$ is calculated as the sum of the energy stored at the previous time step $E_{bat}(t-1)$ and the change in energy due to charging or discharging:

$$E_{bat}(t) = E_{bat}(t-1) - kP_{bat}(t)\Delta t \tag{12}$$

In the equation above $P_{bat}(t)$ denotes the battery power. It is negative when the battery is charging and positive when the battery is discharging. Moreover, k denotes the losses occurring from charging and discharging. It is equal to $1/\eta_{dis}$ when the battery is discharging and equal to η_{ch} when the battery is charging. Note that, η_{ch} and η_{dis} are the charging and discharging efficiency of the battery, respectively.

III. Control strategies

A. NZEB with thermal storage

A rule-based control algorithm has been developed for a NZEB with thermal storage. The control algorithm, depicted in Fig. 2, aims to improve building self-consumption by utilizing the surplus PV generation. When $\bar{T}_{ex}(t) \leq T^h_{off}$ and the building requires space heating, the heat pump is used to convert surplus PV power to heat. The control algorithm employed in this case is shown on the left side of the diagram in Fig. 2. The surplus energy is used to increase the temperature of the thermal storage and can be later used to cover the space heating $P_{th}(t)$ and hot water demand $P_{dhw}(t)$. In case $T_{ts}(t)$ exceeds the maximum temperature T_{up}, the heat pump is turned off and $P_{th}(t)$ and $P_{dhw}(t)$ are supplied only by the thermal storage. On the other hand, when $T_{ts}(t)$ falls below the minimum acceptable temperature T_{down}, the heat pump operates at its rated capacity $P_{hp,rated}$ and an additional thermostatically controlled electric heater is turned on.

When the building has no heating demand, the surplus PV is captured by the electric heater. During this time, the heat pump is either turned off or operates in cooling mode, i.e. bypasses the hot water tank and directly feeds the radiant floor. Hence, the water in the tank is heated only by the electric heater. In order to utilize the surplus PV generation most effectively, instead of a simple on/off thermostatic control, a modulating control has been imposed on the electric heater. When the temperature of the thermal storage falls below T_{down}, the thermostatic control still applies and the electric heater is turned on, heating thermal storage with a power of $P_{eh,rated}$. The control algorithm used for this purpose is shown on the right side of Fig. 2.

B. NZEB with battery storage

Similarly, a simple rule-based strategy aiming to maximize building self-consumption is also used to control the battery. The battery starts charging as soon as there is surplus energy generated by the PV and discharges when the building consumption exceeds PV generation. At each time step, the algorithm simulating the battery's operation takes into account the stored energy at the previous time step and checks whether charging/discharging would violate the battery capacity and power constraints.

IV. Case study

A single house with a total floor area of 150 m^2 and a PV generator with installed capacity of 6.105 kW was considered in the analyses. The input parameters for the building model are shown in Table I. The hourly diagrams for the PV generation P_{pv} and electricity consumption P_{el} were obtained from [15] and correspond to household number 93 of the database. The electricity consumption was initially obtained in a disaggregated form, separately for each appliance. Hence, the electricity consumption corresponding to the air conditioner was eliminated and P_{el} was calculated as the sum of the electricity consumption of all other appliances. Consequently, the heating/cooling system can be separately modelled. It was

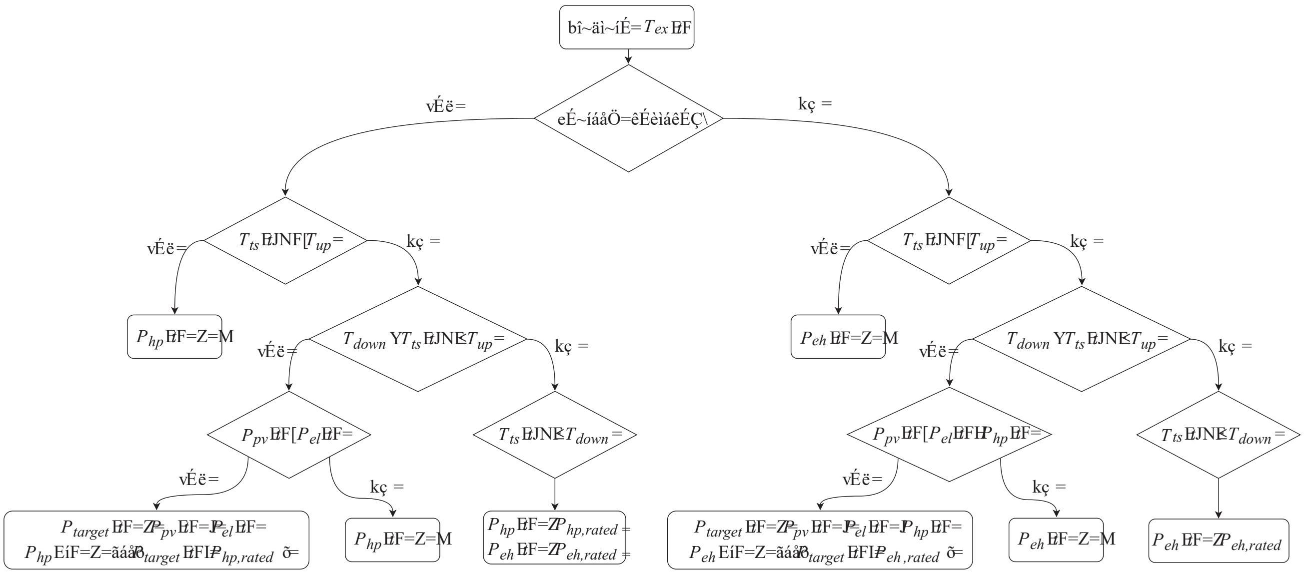

Fig. 2. Control algorithm for NZEB wih thermal storage.

also assumed that the building is equipped with a DAIKIN air-to-water heat pump [16]. The daily hot water consumption profile was generated using the standard profiles given in [17]. The hot water consumption for the whole year was then calculated by multiplying the daily profile by a random number between 0.8 and 1.2 to avoid an identical daily profile. Then, it was adjusted so that the associated energy use amounts to approximately 5 kWh per day, assuming a 45^oC temperature difference ($T_{w,out} = 55^o$ C, $T_{w,in} = 10^o$ C), according to EN 16147:2011 [17]. The ambient temperature data was obtained from Meteonorm [18]. Interpolation was used to convert hourly data into time series with a 15 min time step.

For the economic analysis, the NPV was calculated based on the methodology provided in [19]. The electricity prices used in the analyses are provided in Table II.

TABLE I
INPUT DATA FOR THE BUILDING MODEL

Element	Data
Building cell	$A = 150$ m^2; $U = 0.3\frac{W}{m^2K}$; $\phi = 8$ h; $P_{th,des} = 5$ kW; $H_{ve} = 0\frac{W}{m^2K}$; $T^h_{des} = -3^o$C $T^c_{des} = 47^o$C; $T^h_{off} = 17^o$C; $T^c_{off} = 26^o$C;
Radiant floor	$\Delta T_{rf,rated} = 20^oC$; $S_{rf} = 80$ m^2; $n_{rf} = 1.1$; $K_{rf,rated} = 60\ \frac{W}{m^2}$; $U = 6\frac{W}{m^2K}$;
Heat pump	heating: $P^{rated}_{hp,e} = 2.41$ kW; $\eta_{hp} = 0.45$; cooling: $P^{rated}_{hp,e} = 3.05$ kW; $\eta_{hp} = 0.35$; $COP = 4.66$; $EER = 3.98$;
Thermal storage system	$V_{ts} = [150, 600]$l; $\lambda_{ts} = 0.04\frac{W}{mK}$; $d_{ts} = 0.08$ m; $T_{up} = 80^o$C; $T_{down} = 40^o$C; $T_{set} = 50^o$C;
Battery storage system	$E^{max}_{bat} = [1, 10]$ kWh; $E^{min}_{bat} = 0$ kWh; C-Rate = 0.5; $\eta_{bat} = 0.92$;

TABLE II
ELECTRICITY PRICES

Type of cost	Amount (cEUR/kWh)
Netted Cost	11.58
Grid Demand Cost	5.82
Services of General Interest Charge	0
Fixed Cost	35.20

For the NZEB with thermal storage, tank volumes in the range of $V_{ts} = [150, 600]$ litres were examined. It was assumed that the investment cost of the TSS is 1 EUR/litre. Similarly, battery storage capacities in the range of $E^{max}_{bat} = [1, 10]$ kWh were considered for the alternative NZEB scenario. Investment cost of 200 EUR/kWh for the battery and 350 EUR/kW for the inverter were assumed for this case. A pure self-consumption scheme where the consumer is given no reimbursement for the energy he supplies to the grid was considered.

V. RESULTS AND DISCUSSION

When the NZEB is equipped with a thermal storage, the stored surplus PV generation can only be used to cover the heating and hot water consumption. When a battery is installed instead, the captured surplus energy can be later be used to cover all electric loads, including the heating and hot water consumption. In this sense, the thermal storage is more limited in the flexibility it provides to the building. Nevertheless, it is able to store large amounts of energy (a 150 litres TSS is equivalent to about 7 kWh) and can thus result in comparable SCRs with the ones obtained when a battery is installed. The SCR is especially important when a pure self-consumption scheme is examined since it has dominant influence on the cost-effectiveness of the system.

Fig. 3 shows the daily consumption and generation profiles of the NZEB with thermal storage and battery for a typical day in May. It should be noted that when a thermal storage is considered, the heat pump should operate at higher temperatures compared to the case where it only supplies the radiant floor. Consequently, the heat pumps has a lower COP and higher electricity consumption when directly coupled with a thermal storage. However, because of the flexibility provided by the thermal storage, the heat pump can be modulated to utilize the surplus PV generation in an efficient way. On the other hand, when a battery is installed, the heat pump is driven only by the demand of the radiant floor and thus uses less electricity. The reason for this are the lower temperatures of the radiant floor (20^{o}C - 34^{o}C) which result in higher COPs.

As shown in Fig. 4, the proposed control scheme for the NZEB with a thermal storage is quite successful in obtaining a high SCR. For smaller storage capacities, in particular, thermal storage results in higher SCRs than when a battery is installed. For the conducted analyses, it was found that when the hot water tank is larger than 480 litres and battery capacity exceeds 7.8 kWh, the battery becomes more effective in improving the self-consumption of the building. This is a result of the battery's ability to cover all types of electric loads. Even for smaller batteries, the building has no grid interaction during the majority of the evening hours, which cannot be the case

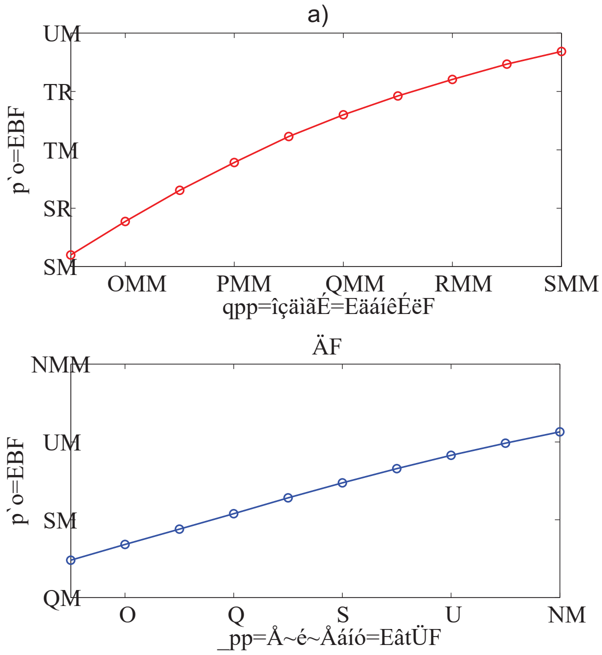

Fig. 4. SCR of the NZEB for different a) TSS and b) BSS capacities.

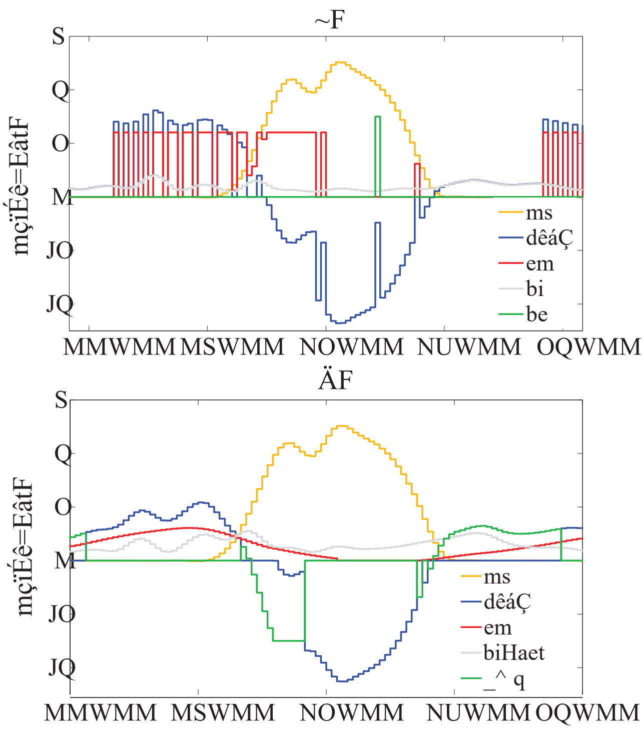

Fig. 3. Daily generation and consumption profiles for a typical day in May of an NZEB with a) thermal storage ($V_{ts} = 300$ l) and b) battery ($E_{bat} = 6$ kWh).

for the thermal storage, as depicted in Fig. 3. It is evident that the comparison of the thermal and battery storage system purely based on their technical performance is rather limited. Moreover, the prosumer's choice of a storage system and its size will likely be governed by the system's economic performance. Hence, numerous calculations have been conducted to assess the economic viability of an investment in a storage system, assuming an existing PV installation.

A battery is not yet viable considering the lowest current market prices for residential batteries of 600 EUR/kWh [19]. This is the reason behind the investment cost assumption in the previous section. A break-even point, for which identical NPVs were obtained for both systems, was achieved when the battery has a capacity of 4.2 kWh and the volume of the thermal storage is 310 litres. An investment in both storage systems in this case, however, was found not to be profitable. It should be noted that these NPV values are obtained in the context of the assumed pure self-consumption scheme. The economic viability of the system will change as the price for the electricity fed into the grid increases. Nevertheless, the results show that even under the worst case circumstances, coupling a heat pump with a thermal storage and using a modulating control of the electric heater may result in positive NPVs for higher TSS capacities. On the other hand, in order for batteries to become viable in this type of a scenario, the associated investment costs need to be equal to or lower than 200 EUR/kWh.

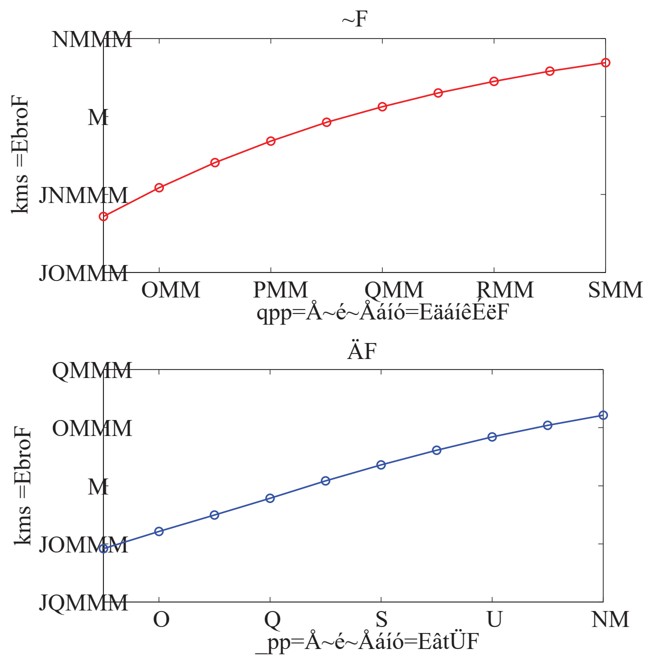

Fig. 5. Economic performance of the system for different storage capacities.

VI. Conclusion

As prices of PVs continue to decline, an increase of rooftop PV installations on NZEBs is expected. However, the mismatch between the generation and consumption of such buildings can reduce their economic viability. This issue has been addressed by considering the integration of a storage system in a NZEB. A NZEB with a PV, heat pump and a radiant floor was analysed in which either a thermal or a battery storage is integrated. A parametric analysis has been performed to investigate how the capacity of each storage system affects the techno-economic performance of the NZEB. Furthermore, a sensitivity analysis has been conducted to determine the intersection point of storage capacities that result in the same NPV.

In the case of a NZEB with thermal storage, the excess PV generation was utilized in the form of hot water that could later be used for heating and domestic hot water. Coupling a thermal storage tank of volumes between 150 and 480 litres with the heat pump under the proposed control scheme has a better ability to improve the NZEB's SCR than batteries with capacities of up to 7.8 kWh. Assuming Greek retail electricity prices and no reimbursement for the surplus PV generation, the intersection point of storage capacities that result in the same NPV was found when a 310 litre hot water tank and a 4.2 kWh battery were used. These results were obtained for a 200 EUR/kWh investment costs for the battery. It was found that under this pure self-consumption scheme more expensive batteries were not economically viable.

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