Economic Assessment of Lithium-Ion Battery Storage Systems in the Nearly Zero Energy Building Environment

Angelos I. Nousdilis, Eleftherios O. Kontis Georgios C. Kryonidis,
Georgios C. Christoforidis, and Grigoris K. Papagiannis

***Abstract*—Scope of this paper is to deliver a complete techno-economic model for the economic assessment of lithium-ion battery energy storage systems in the framework of the nearly zero energy buildings (NZEB). The proposed model simulates the combined operation of photovoltaics, solar thermal generators, heat pump generators, electrical and thermal storage devices in order to represent efficiently the typical characteristics of NZEBs. The model takes into account the thermal and electrical needs of the building, typical electricity prices, household electrical consumption profiles, weather data and typical costs for lithium battery energy storage systems. Using these inputs, an optimization procedure is applied and the optimal size, in terms of net present value, for the lithium-ion battery energy storage system is derived.**

***Index Terms*—Electrical storage, lithium-ion batteries, nearly zero energy buildings, photovoltaics, thermal storage.**

I. Introduction

European Union's target for 2030 include the transformation of the existing building stock to Nearly Zero Energy Buildings (NZEBs) [1], [2]. NZEBs are characterized by reduced net-energy demand, since the major part of their thermal and electrical energy needs are covered locally by renewable energy sources (RESs), especially photovoltaics (PVs).

Consequently, in the following years, a considerable amount of intermittent solar generators will be connected in the existing distribution grids, posing new technical challenges for distribution system operators (DSOs). The most important of them include overvoltages, protection, stability and congestion issues. An efficient solution to tackle these technical challenges is to store locally the excess of PV energy, using energy storage systems (ESS) [3].

Residential ESS are mainly based on battery technologies. Among the available solutions, lead-acid batteries are the dominant technology for small scale applications [4]. Compared to other technologies, lead-acid batteries present high reliability, low self-discharge as well as low maintenance and investment cost. On the other hand, they have short lifetime and low energy and power density. Thus, it is expected that in the near future lead-acid batteries will be replaced by lithium-ion ones, which present higher energy efficiency and better aging characteristics [5], [6].

Therefore, there is a strong need to evaluate the profitability of residential ESSs based on lithium-ion batteries. Towards this objective, in [7] the economic viability of second use electric vehicle batteries for energy storage application in the residential sector is evaluated, while in [8] and [9] the profitability margins of adding lithium-ion battery SSs (BSSs) to existing residential grid-connected PV plants is investigated. The corresponding results reveal that the present costs of lithium-ion batteries are too high to allow economically viable investments. However, the above-mentioned studies do not take into account the impact of thermal storage systems (TSS), solar thermal (ST) and heat pump (HP) generators on the optimal size of the electrical BSS.

Concerning the above-mentioned issue, the scope of the paper is to develop a complete techno-economic model to evaluate the economic viability of electrical ESSs based on lithium-ion batteries in the NZEB environment. The combined operation of PVs, HP and ST generators, TSS and BSS is simulated by a full set of equations, describing the coupled behavior of each component in the NZEB context [10]. The proposed model receives as inputs: i) technical data related with the building energy systems and the building shell, ii) economical data such as the typical cost of lithium-ion batteries and electricity prices, iii) typical electricity consumption profiles related with the electrical power consumed for lighting and household appliances, and iv) weather data. Initially, the model calculates the total thermal and electrical needs of the building, using the available climate data. Afterwards, the optimal size, in terms of net present value (NPV), for the lithium-ion BSS is determined by applying an optimization scheme.

Angelos I. Nousdilis, Eleftherios O. Kontis, Georgios C. Kryonidis, and Grigoris K. Papagiannis are with the Power Systems Laboratory, School of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece, GR 54124, (e-mail: angelos@auth.gr, kontislefteris@gmail.com; kryonidi@ece.auth.gr; grigoris@eng.auth.gr).

Georgios C. Christoforidis is with the Western Macedonia University of Applied Sciences, Kozani, Greece, (e-mail: gchristo@teiwm.gr).

This work has been co-funded by the European Union and National Funds of the participating countries through the Interreg-MED Programme, under the project "PV-ESTIA - Enhancing Storage Integration in Buildings with Photovoltaics".

The work of Georgios. C. Kryonidis and Eleftherios. O. Kontis was conducted in the framework of the act "Support of PhD Researchers" under the Operational Program "Human Resources Development, Education and Life-long Learning 2014-2020", which is implemented by the State Scholarships Foundation and co-financed by the European Social Fund and the Hellenic Republic.

Citation Information: DOI: 10.1109/SIELA.2018.8447149

II. Building Model

The adopted building model [10] takes into account PV systems, ST and HP generators, TS and BS systems. The mathematical description of these components as well as the control strategies, used for the charge/discharge of TSSs and BSSs are described in detail in the following subsections.

A. Heating and Cooling Load

The thermal power required at each time instant for the heating of the building, $P_{th,H}$, can be estimated as:

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

where $P_{th,des,H}$ is the thermal power, required for the heating of the building under the designed conditions, while $T_{des,H}$ is the external temperature, used for the design of the heating system. Moreover, $T_{off,H}$ is the nominal temperature at which building losses and gains are balanced and the heating system is switched off. Finally, $\bar{T}_{ext}$ is the effective outdoor temperature based on the characteristics of the building and the actual external temperature T_{ext}. The $\bar{T}_{ext}$ temperature is defined as the simple moving average of the previous $\bar{\phi}$ values of T_{ext}. Where $\bar{\phi}$ is the nearest integer of the effective time shift of the building, defined as:

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

where ϕ_i and $(UA)_i$ are the characteristic time shift, as defined by EN ISO 13786:2007 [11], and the surface thermal transmittance of the i-th external wall, respectively, while H_{ve} is the equivalent ventilation-thermal transmittance based on air change rate.

The thermal power required for the cooling of the building, $P_{th,C}$, is calculated as:

$$P_{th,C} = P_{th,des,C}\left(1 - \frac{\bar{T}^*_{ext} - T^*_{des,C}}{T_{off,C} - T^*_{des,C}}\right) \tag{3}$$

where T^* is the so-called "sol-air temperature" [12], $T_{off,C}$ is the nominal temperature in which the cooling system is deactivated, while $\bar{T}^*_{ext}$ is the simple moving average of the previous $\bar{\phi}$ values of T^*_{ext}

B. Heating and Cooling System Terminal

In this paper, a radiant floor is considered as the heat terminal unit. Water and floor temperature evolution is simulated through a simplified resistance model [10], as presented in (4)-(6).

$$\Delta T_{RF} = T_{w,RF} - T_{in} = \Delta T_{RF,nom}\left(\frac{P_{th}}{S_{RF}K_{RF,nom}}\right)^{\frac{1}{n_{RF}}} \tag{4}$$

$$T_{f,RF,H} = T_{w,RF,H} - \frac{P_{th,H}}{S_{RF}U_{wf}} \tag{5}$$

$$T_{f,RF,C} = T_{w,RF,C} + \frac{P_{th,C}}{S_{RF}U_{wf}} \tag{6}$$

where $T_{w,RF}$ and T_{in} is the temperature of the water within the radiant floor and the internal air temperature of the building, respectively. Please note that in this paper, the internal air temperature is considered equal to the corresponding set-point value. Additionally, ΔT_{RF} is the nominal difference between the mean temperature of the water and the internal air, while n_{RF} is the emitter exponent of the radiant floor and $K_{RF,nom}$ is the nominal thermal output per surface unit. Moreover, $T_{f,RF}$ stands for the floor temperature, while S_{RF} is the total surface of the radiant floor and U_{wf} is the thermal transmittance between the circulating water and the flood surface.

C. Domestic Hot Water Production

The power required for the production of domestic hot water (DHW) can be evaluated as:

$$P_{DHW} = d_w c_w (T_{DHW} - T_{aqua}) \tag{7}$$

where d_w is the supply of domestic hot water in Kg/s, while c_w is the specific heat capacity of the water. T_{DHW} is the desired temperature of the DHW, whereas T_{aqua} can be considered equal to the outdoor temperature.

D. PV System

The power produced by the PV system can be efficiently calculated using the following set of equations [10]:

$$P_{PV} = n_{PV}\eta_{inv}\eta_{PV}S_{PV}I_{sol} \tag{8}$$

$$\eta_{PV} = \eta_{PV,ref}[1 - \beta_{PV}(T_{PV} - T_{ref,PV})] \tag{9}$$

$$T_{PV} - T_{ext} = (219 + 819K_t)\frac{NOCT - 20}{800} \tag{10}$$

where, η_{inv} is the efficiency of the inverter, n_{PV} is the number of the installed PV modules, while S_{PV} is the surface of each module. Moreover, η_{PV} is the actual efficiency of the PV modules at the operational temperature T_{PV}, while $\eta_{PV,ref}$ is the efficiency of the PV modules at the reference temperature $T_{ref,PV}$. Additionally, β_{PV} is a temperature penalization factor depending on the PV technology and $NOCT$ denotes the nominal operating cell temperature. Finally, I_{sol} is the clear sky irradiation and K_t is the clearness index.

E. Heat Pump Generator

In this paper, air to water electrically-driven HPs are considered. To ensure that the thermal load of the building is covered under any conditions, the nominal capacity of the HPs is chosen to be equal with the peak thermal load. The performance of the HPs can be evaluated using the following equations:

$$COP = \eta_{HP,H}\frac{T_{cond}}{T_{cond} - T_{eva}} \tag{11}$$

$$EER = \eta_{HP,C}\frac{T_{eva}}{T_{cond} - T_{eva}} \tag{12}$$

The HP efficiency η_{HP} can be considered with sufficient accuracy as a constant value [10]. Additionally, in this paper, the same η_{HP} is adopted for both the heating mode and the production of DHW. The values of T_{cond} and T_{eva} depend on the provided service [10]. At the indoor of the HP heat exchanger (water side), a temperature droop equal to 5 K is considered. Moreover, a drop of 10 K is assumed at the outdoor of the HP heat exchanger (air side).

F. Solar Thermal Generator

The operation of the ST generator is simulated using the following mathematical model [10]:

$$P_{th,ST} = n_{ST}\eta_{ST}S_{ST}I_{sol} \tag{13}$$

$$\eta_{ST} = F_R(\tau\alpha)_n A - B \tag{14}$$

where

$$A = (1 - b_0(1/cos\theta - 1)) \tag{15}$$

and

$$B = \frac{F_R U_L(T_{ST,in} - T_{ext})}{I_{sol}} \tag{16}$$

In the above equations, n_{ST} and η_{ST} denote the number of solar collectors and their efficiency, respectively. S_{ST} is the surface of each collector, while F_R is the solar thermal removal factor. Furthermore, $(\tau\alpha)_n$ is the transmittance-absorptance product for normal incidence irradiance, while b_0 is the incidence angle modifier coefficient for single-cover solar thermal collectors, and θ is the angle between the beam radiation and the normal to the solar thermal collectors. Finally, U_L is solar thermal frontal losses and $T_{ST,in}$ is the temperature of the thermal storage.

G. Thermal Storage System

For the adopted TSS, the thermal power balance equation at the j-th time step of the analysis can be written as:

$$\begin{aligned} V_{TS}\rho_w c_w(T^j_{TS} - T^{j-1}_{TS}) = & P_{th,ST} + P_{th,HP,TS} - \\ & P_{th,DHW} - P_{th,TS,H} - \\ & P_{th,TS,ls} \end{aligned} \tag{17}$$

where V_{TS} is the total volume of the TSS, while ρ_w is the density of the water. Moreover, T^j_{TS} and T^{j-1}_{TS} are the temperatures of the water at the TSS at the j and $j-1$ time step of the analysis, respectively. $P_{th,ST}$ and $P_{th,HP,TS}$ are the powers provided by the ST generator and the HP to the TSS, respectively. On the other hand, $P_{th,TS,H}$ denotes the power exported from the TSS for heating purposes, while $P_{th,DHW}$ is the power used for the production of DHW. Finally, $P_{th,TS,ls}$ stands for the power losses of the TSS and can be calculated as:

$$P_{th,TS,ls} = S_{TS}\frac{\lambda_{TS}}{s_{TS}}(T_{TS} - T_{ext,TS}) \tag{18}$$

In the above equation, S_{TS}, λ_{TS} and s_{TS} are the total surface, the thermal conductivity, and the thickness of the TSS. Moreover, $T_{ext,TS}$ is the TSS room temperature. Further information concerning the control strategy of the TSS can be found in [10].

Algorithm 1 Pseudocode for the control strategy of the BSS

Define upper/lower SOC limits, i.e. SOC_u and SOC_l.
if $P_{PV} > P_{load}$ **&&** $SOC < SOC_u$
    Battery charges
elseif $P_{PV} > P_{load}$ **&&** $SOC \geq SOC_u$
    No action
elseif $P_{PV} < P_{load}$ **&&** $SOC > SOC_l$
    Battery discharges
elseif $P_{PV} < P_{load}$ **&&** $SOC \leq SOC_l$
    No action
end if

H. Battery Storage System

The electrical power balance equation can be written as:

$$P_{PV} + P_{grid} + P_{bat} = P_{load} \tag{19}$$

where

$$P_{load} = P_{HP} + P_{el} \tag{20}$$

In the above equations, P_{grid} denotes the electrical power imported from the main utility grid, P_{bat} is the electrical power of the BSS, and P_{el} is the electrical power, used for lighting and household appliances. Finally, P_{HP} is the electrical power of the HP, which can be easily computed using the following equations:

$$P_{HP,H} = \frac{P_{th,H}}{COP} \tag{21}$$

$$P_{HP,C} = \frac{P_{th,C}}{EER} \tag{22}$$

Concerning the control strategy of the BSS, a simple scheme that maximizes the self-consumption ratio is adopted. More specifically, in case the PV power exceeds the total load demand, the BSS starts the charging procedure by absorbing the surplus of the generated power up to the maximum permissible value. On the other hand, if the PV generated power is lower than the load demand, the BSS discharges. During this process, the upper and lower limit of the state of charge (SOC) of the BSS is taken into account. The adopted control strategy is analytically presented in Algorithm 1.

III. Economic Evaluation of BSS

Nowadays, the majority of PV installations in the residential sector are operated under net-metering (NeM) schemes [13], [14]. In these policies, prosumers can offset the imported energy from the grid with electrical energy generated from a local PV system. The prosumers are then charged for a certain billing period according to their net energy consumed. The time period during which the produced PV energy can be netted against the imported energy is characterized as netting period [14]. In case the generated energy exceeds the consumed throughout the netting period, a compensation may be provided for the excess energy at a certain sale price (sp).

In this paper, the economic viability of lithium-ion BSS is investigated assuming a full NeM scheme [14]. In the examined scheme, the netting period is considered equal to one hour. This paper examines two cases in which excess energy is either compensated using the system marginal price (SMP) of the Greek electricity market or not compensated at all. Moreover, the billing is performed assuming two distinct charge categories: i) The fixed cost (fc), that includes transmission and distribution systems constant charges, standing fees, etc, and ii) the netted-cost (nc), which is the prosumer charge calculated using the net energy consumed during the billing period.

A 20-year economic analysis is performed based on the following procedure: Initially, the exported energy to the grid (E_{exp}) and the netted energy (E_{net}) are calculated. For a typical day, these energies can be defined by the aid of Fig. 1 as follows:

$$E^{P}_{exp} = B + D \tag{23}$$

$$E^{P}_{net} = A + F + E - B - D \tag{24}$$

$$E^{PB}_{exp} = B \tag{25}$$

$$E^{PB}_{net} = A + F - B \tag{26}$$

Eq. (23) - (24) stand for the case in which only the PV system is considered, while Eq. (25) - (26) refer to the case of an integrated PV-BSS.

For a specific year of investment (t), the NPV of the installed BSS (npv^t) is computed as:

$$npv^{t} = \sum_{n=1}^{N} \frac{cf^{t,n}_{in} - cf^{t,n}_{out}}{(1+i)^{n}} - \left[capex_{B}(1+a)^{t-1}\right] \tag{27}$$

Here N denotes the lifetime of the lithium-ion batteries. A typical system with a depth of discharge equal to 80% can perform more than 8000 cycles of operation [15]. Therefore, assuming a full operation cycle during each day of the year, N is considered equal to 22 years and no replacement is foreseen for the batteries during the analysis period. Moreover, in (27), i is the discount rate, while a stands for the inflation rate. $cf^{t,n}_{in}$ and $cf^{t,n}_{out}$ are the cash in and out flows, respectively. Finally, $capex_B$ is the capital investment cost of the BSS.

The cash flow out is related with the operation and maintenance costs of the BSS ($opex_B$) and is calculated according to (28). On the other hand, the cash flow in represents the profit from the use of the BSS and can be derived using (29).

$$cf^{t,n}_{out} = opex_{B}(1+a)^{t-1}(1+a)^{n-1} \tag{28}$$

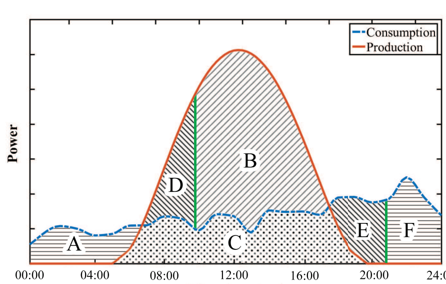

Fig. 1. Typical household consumption and generation profiles.

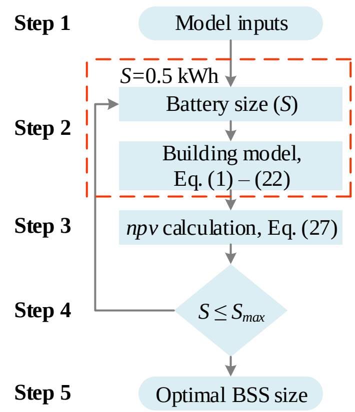

Fig. 2. Proposed techno-economic model.

$$cf^{t,n}_{in} = (c^{t,n}_{P} - c^{t,n}_{PB}) - (pr^{t,n}_{P} - pr^{t,n}_{PB}) \tag{29}$$

Where, $c^{t,n}_{P}$ is the electricity cost of the base scenario, where only the PV system is considered, while $c^{t,n}_{PB}$ is the corresponding cost when an integrated PV-BSS is assumed. These values are obtained using (30) and (31), respectively. Moreover, $pr^{t,n}_{P}$ and $pr^{t,n}_{PB}$ correspond to prosumer profit due to the compensation for excess energy and are obtained using (32) and (33), respectively.

$$c^{t,n}_{P} = \left[\sum_{k=1}^{K}(E^{k,P}_{net}nc^{t}) + fc^{t}\right](1+a)^{n-1} \tag{30}$$

$$c^{t,n}_{PB} = \left[\sum_{k=1}^{K}(E^{k,PB}_{net}nc^{t}) + fc^{t}\right](1+a)^{n-1} \tag{31}$$

$$pr^{t,n}_{P} = \left[\sum_{k=1}^{K}(E^{k,P}_{exp}sp^{t})\right](1+a)^{n-1} \tag{32}$$

$$pr^{t,n}_{PB} = \left[\sum_{k=1}^{K}(E^{k,PB}_{exp}sp^{t})\right](1+a)^{n-1} \tag{33}$$

Here, K is the last billing period of year n. For different investment periods, all values, i.e., nc, fc, and sp can be calculated as:

$$[nc^{t}\ fc^{t}\ sp^{t}] = [nc\ fc\ sp](1+a)^{t-1} \tag{34}$$

IV. Proposed Techno-economic Model

The proposed techno-economic model is presented in Fig. 2 by means of a flowchart. The model consists of 5 main steps, described in detail below:

Step-1:. *Initialization phase*. In this step, several technical and economical data are provided as inputs to the model. More specifically, the required inputs include: i) technical parameters related with the building shell and the energy systems of the building, ii) economical parameters such as the typical cost of lithium-ion batteries and electricity prices, iii) typical electricity consumption profiles related with the electrical power consumed for household appliances and lighting, and iv) historical weather data, used to evaluate the thermal energy

TABLE I
TECHNICAL AND ECONOMICAL PARAMETERS

Building Cell	Radiant Floor	PV Generator
A=300 m^3	$\Delta T_{RF,nom}$=20 K	S_{PV}=1.5 m^2
U=3.56 W/(m^{2}K)	S_{RF}=80 m^2	n_{PV}=40
ϕ_i=8 h	$K_{RF,nom}$=60 W/(m^2)	η_{inv}=0.85
H_{ve}=0 W/(m^{2}K)	n_{rf}=1.1	$\eta_{PV,ref}$=0.13
$T_{des,H}$=-3 ^{o}C	U=6 W/(m^{2}K)	$\beta_{T,PV}$=0.004 1/K
$T_{des,C}$=47 ^{o}C	$T_{off,H}$=17 ^{o}C	$T_{ref,PV}$=25 ^{o}C
$P_{th,des}$=3.75 kW	$T_{off,C}$=26 ^{o}C	$NOCT$=45 ^{o}C
TSS	**ST Generator**	**HP Generator**
V_{TS}=0.5 m^3	s_{ST}=3 m^2	$P_{HP,max}$=4.125 kW
S_{TS}=3.5 m^2	n_{ST}=1	$n_{HP,H}$=0.45
$T_{TS,set}$=50 ^{o}C	F_R=0.8	$n_{HP,C}$=0.35
$T_{TS,up}$=60 ^{o}C	$(\tau a)_n$=0.7	**BSS**
$T_{TS,down}$=42 ^{o}C	U_L=5 W/(m^{2}K)	SOC_u=90%
$T_{TS,max}$=90 ^{o}C	b_0=0.1	SOC_l=20%
λ_{TS}=0.04 W/(mK)	θ=0.3839	$cost_{battery}$=600 €/kWh
s_{TS}=0.08 m		$cost_{inverter}$=200 €/kW
Economical Parameters		
a=2%	nc_1=0.174 €/kWh	fc=35 €/year
i=5%	nc_2=0.165 €/kWh	

needs of the building. Weather data and consumption profiles, used in this paper, are presented in Fig. 3. Technical and economical parameters are summarized in Table I. Concerning electricity costs, typical values of the Greek System are used. Based on the netted energy (whether it is over or below 2000 kWh), the netted-cost receives two separate values, namely n_{c1} and n_{c2}, respectively. Finally, in the presented analysis $opex_B$ is neglected [16].

Step-2:. *Evaluation of thermal and electrical energy needs.* In this step, the thermal and electrical energy needs of the building are calculated on a 15 minute basis using the profiles of Fig. 3. Thermal needs are estimated using (1) - (18), while electrical needs are calculated from (19) - (22) assuming a specific size S for the BSS. Concerning the first algorithm iteration, it is assumed that S is equal to 0.5 kWh. During the first iteration, the base scenario, where only the PV system is installed, is also simulated in order to evaluate (30).

Step-3:. *npv calculation.* Here, (23) - (26) are computed and the npv^t of the investment is derived using (27). The corresponding result is stored to a vector, named as $\boldsymbol{PS_s}$.

Step-4:. *Stopping criterion.* If the size S of the BSS is greater than a maximum user-defined value (S_{max}), the algorithm proceeds to Step 5. Otherwise, the procedure moves back to Step 2, by setting S=S+0.5.

Step-5:. *Optimal BSS size.* In this step, a search algorithm is used to determine the maximum value of $\boldsymbol{PS_s}$. This value actually corresponds to the optimal size of the BSS.

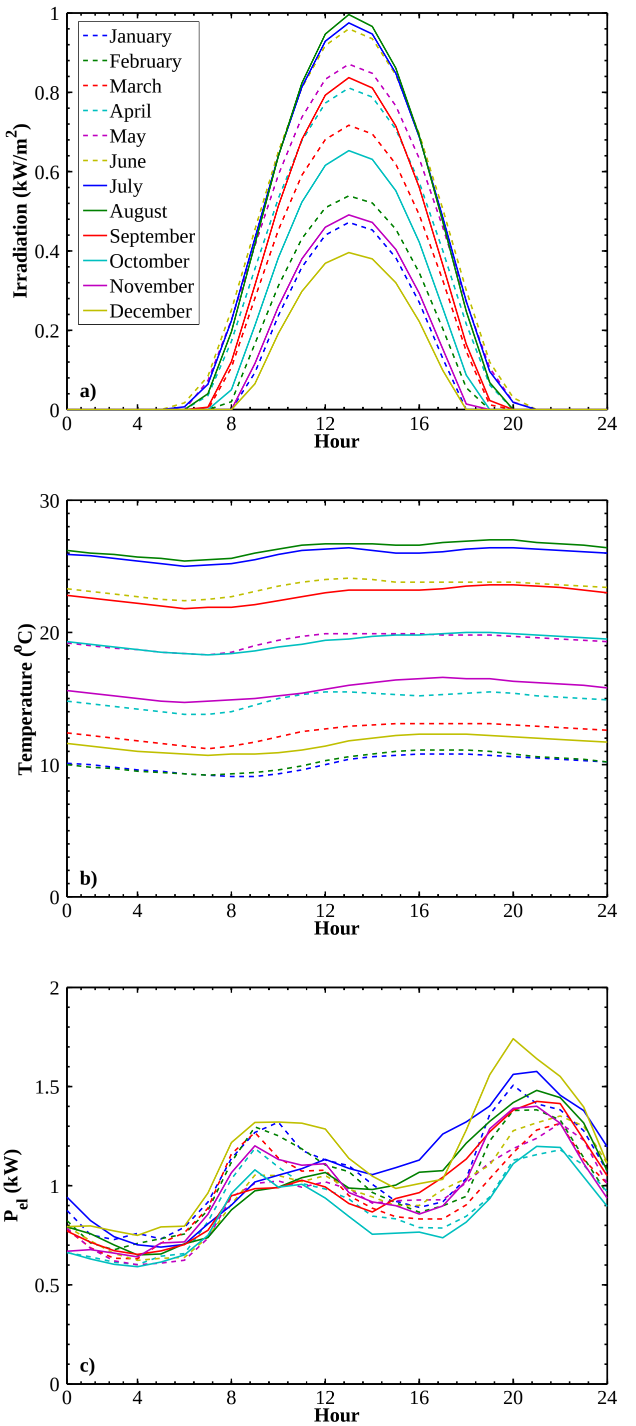

Fig. 3. Typical daily: a) irradiation, b) temperature, and c) consumption profiles.

V. SIMULATION RESULTS

In this Section, indicative results for the proposed model are presented. More specifically, a 20-year economic analysis is performed assuming a typical three-phase house installation, located in the central Greece. The total floor area of the house is considered equal to 100 m^2, while its height is assumed

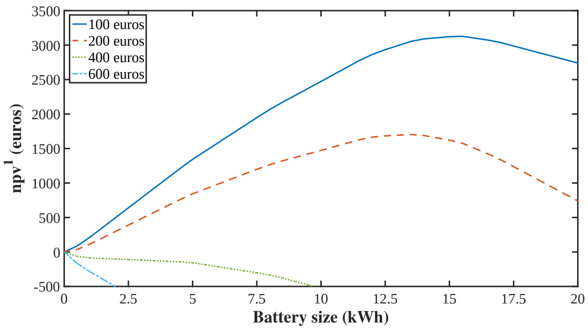

Fig. 4. NPV under a full net metering scheme. Excess energy is compensated with SMP.

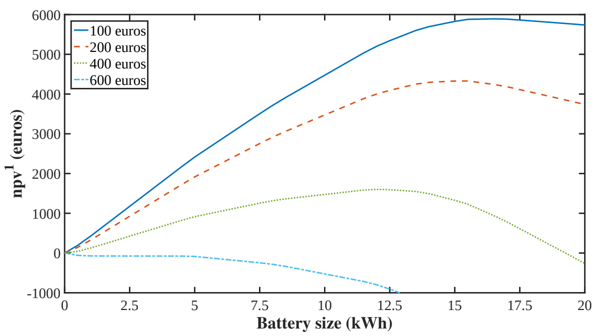

Fig. 5. a) NPV and b) IRR under a full net metering scheme. Excess energy is not compensated.

equal to 3 m. The internal air temperature of the house is assumed to be constant and equal to 26 ^{o}C and 20 ^{o}C during the cooling and the heating mode, respectively. The supply for DHW is considered constant and equal to 10 kg/min. The temperature of the DHW is 45 ^{o}C.

Indicative results for the two examined NeM policies are presented in Figs. 4 and 5, respectively. As shown, under the examined NeM policies and with the current prices, the installation of BSS is not profitable for the prosumer. Therefore, a parametric analysis for different BSS prices is conducted. The analysis reveals that the installation of BSSs can become profitable if the corresponding prices are reduced. Additionally, it is worth noticing that the profitability is considerably increased for prosumers operated under NeM policies in which the excess of energy is not compensated.

VI. Conclusions

In this paper, a techno-economic model is developed to facilitate the economic assessment of lithium-ion BSSs in the framework of NZEBs. The proposed model simulates the combined operation of PVs, thermal and battery storage systems as well the operation of ST and HP generators to represent efficiently the typical characteristics of NZEBs. It receives as inputs several technical and economical parameters, typical consumption and weather data. Initially, using these inputs, the model evaluates the thermal and electrical energy needs of the building. Afterwards, an optimization procedure is applied and the optimal size for the lithium-ion BSS is derived.

Using the proposed model, the economic viability of lithium-ion BSSs for a typical household installation, located in the central Greece, is evaluated. The simulation results reveal that with the current market prices, the installation of BSSs is not recommended, since standalone PV systems can generate more profits. However, the conducted analysis reveals that as the BSS prices decrease, the profitability is increased, outperforming the NPVs of standalone PVs. Therefore, in the next few years a high number of BSSs is expected in the building environment. In this context, the proposed method can be a valuable tool for the economic analysis and the optimal sizing of household BSSs.

References

[1] European Union, On the Energy Performance of Buildings. Directive 2010/31/EU of the European Parliament and of the Council (recast), Official Journal of the European Communities, Brussels, May 2010.

[2] European Commission, "Green Paper: A 2030 climate and energy framework", Communication COM(2013) 169, 27/03/2013.

[3] J. Moshovel, K.-P. Kairies, D. Magnor, M. Leuthold, M. Bost, S. Gahrs, E. Szczechowicz, M. Cramer, and D. U. Sauer, "Analysis of the maximal possible grid relief from pv-peak-power impacts by using storage systems for increased self-consumption," *Applied Energy*, vol. 137, pp. 567 – 575, 2015.

[4] N.-K. C. Nair and N. Garimella, "Battery energy storage systems: Assessment for small-scale renewable energy integration," *Energy and Buildings*, vol. 42, no. 11, pp. 2124 – 2130, 2010.

[5] K. Divya and J. Ostergaard, "Battery energy storage technology for power systems. an overview," *Electric Power Systems Research*, vol. 79, no. 4, pp. 511 – 520, 2009.

[6] J. Hoppmann, J. Volland, T. S. Schmidt, and V. H. Hoffmann, "The economic viability of battery storage for residential solar photovoltaic systems. a review and a simulation model," *Renewable and Sustainable Energy Reviews*, vol. 39, pp. 1101 – 1118, 2014.

[7] R. Madlener and A. Kirmas, "Economic viability of second use electric vehicle batteries for energy storage in residential applications," *Energy Procedia*, vol. 105, pp. 3806 – 3815, 2017, 8th International Conference on Applied Energy, ICAE2016, 8-11 October 2016, Beijing, China.

[8] S. Barcellona, L. Piegari, V. Musolino, and C. Ballif, "Economic viability for residential battery storage systems in grid-connected pv plants," *IET Renewable Power Generation*, vol. 12, no. 2, pp. 135–142, 2018.

[9] K. Uddin, R. Gough, J. Radcliffe, J. Marco, and P. Jennings, "Techno-economic analysis of the viability of residential photovoltaic systems using lithium-ion batteries for energy storage in the united kingdom," *Applied Energy*, vol. 206, pp. 12 – 21, 2017.

[10] D. Testi, E. Schito, and P. Conti, "Cost-optimal sizing of solar thermal and photovoltaic systems for the heating and cooling needs of a nearly zero-energy building: Design methodology and model description," *Energy Procedia*, vol. 91, pp. 517 – 527, 2016, proceedings of the 4th International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2015).

[11] EN ISO 13786:2017 Thermal Performance of Building Components - Dynamic Thermal Characteristics. Brussels: European Committee for Standardization (CEN), 2008.

[12] P. O'Callaghan and S. Probert, "Sol-air temperature," *Applied Energy*, vol. 3, no. 4, pp. 307 – 311, 1977.

[13] I. Koumparou, G. C. Christoforidis, V. Efthymiou, G. K. Papagiannis, and G. E. Georghiou, "Configuring residential PV net-metering policies a focus on the mediterranean region," *Renewable Energy*, vol. 113, pp. 795 – 812, 2017.

[14] G. C. Christoforidis, I. P. Panapakidis, T. A. Papadopoulos, G. K. Papagiannis, I. Koumparou, M. Hadjipanayi, and G. E. Georghiou, "A model for the assessment of different net-metering policies," *Energies*, vol. 9, no. 4, 2016.

[15] Datasheet Fronius Energy Package. Available online: http://www.fronius.com/ /downloads/Solar

[16] D. Parra and M. K. Patel, "Effect of tariffs on the performance and economic benefits of pv-coupled battery systems," *Applied Energy*, vol. 164, pp. 175 – 187, 2016.