ELECTRIC VEHICLE BATTERIES IN ENERGY STORAGE SYSTEMS: AN ECONOMIC ANALYSIS FOR SWISS RESIDENTIALS

C. Menn; A. Geissler

Institut Energie am Bau, St. Jakob-Strasse 84, 4132 Muttenz

ABSTRACT

Battery energy storage (BES) systems for residential buildings can contribute to power grid stability. The demand for decentralized storage capacity in Switzerland is expected to rise due to political decisions that facilitate renewable energies with power fluctuations such as photovoltaics (PV). Using lithium based BES to meet this demand could have a significant environmental impact as a result of energy intensive production-processes. Furthermore, currently available conventional BES (C-BES) systems are not economically viable. Within this context, a second use of electric vehicle batteries for 2nd-life-BES (2nd-BES) can be an environmentally sound alternative that facilitates grid integration of residential PV-systems.

A model describing the economic viability of 2nd-BES based on the Net Present Value (NPV) method is presented. On the basis of one example building each, results are given for single-family-houses (SFH) and multi-family-houses (MFH), focusing particularly on the market situation found in Switzerland.

Results show a cost advantage for 2nd-BES in MFH compared to C-BES systems if a Cycle Life (CL) of 800 and more is available. In SFH, a 2nd-BES shows only a slightly better economic performance than a C-BES system if a CL of 4800 and more can be guaranteed. Notwithstanding the relatively low Levelized Cost of Electricity (LCOE), the NPV for both 2nd-BES and C-BES in both SFH and MFH is negative. Reasons for this are high initial system costs and an electricity tariff scheme with low incentives for consumers to store electricity.

In this paper, only the current tariff structure in Switzerland is considered. However, alternative tariff schemes, e.g. real time pricing for residential consumers, have become reality in some countries. The impact of such tariff schemes on the economic performance of 2nd-BES is left to future research.

Keywords: Battery 2nd-use, residential energy storage, PV, cycle life, net present value, Levelized Cost of Electricity

1. INTRODUCTION

Recent cost calculations on nuclear power plants [1,2] and governmental commitment to mitigate climate change are in favour of renewable energies. Among renewable energies building integrated photovoltaics (PV) are expected to play a major role in the process of energy source transition due to a high technical potential [3] and public acceptance [4,5]. However, the grid integration of PV generated electricity and its impact on power quality is one relevant technical barrier to PV deployment [6]. In the electrical grid, power supply and demand has to match at any given time. A high fraction of often volatile PV generated electricity can lead to a disruption of this balance and jeopardize grid stability [7].

Battery energy storage (BES) is one effective measure to overcome problems of frequency fluctuation [8]. For BES in dwellings, lithium based batteries are most suitable due to high efficiencies and long Cycle Life (CL, defined as the number of charge/discharge cycles available prior to the end of useful life) [9]. Current studies show that conventional lithium based BES (C-BES) are not viable economically in the near future [10,11]. Besides weak economic performance, C-BES cause significant environmental impact due to energy intensive production-processes [12,13]. Within this context, a reuse of electric vehicle batteries, after their automotive life, in residential 2nd-life-BES (2nd-BES) can be an environmentally sound alternative. However, not much attention has been given to the economic viability of 2nd-BES.

In this paper a model to describe the economic viability of 2nd-BES and the combined PV-2nd-BES system based on the Net Present Value (NPV) method is proposed. The model is based on the prosumers' perspective, considering Swiss market conditions in 2015. An optimal size for both the PV installation and the 2nd-BES for economic viability is derived. Furthermore, the minimum necessary CL of 2nd-BES is quantified. Finally, the key factors for profitability of 2nd-BES are identified.

2. SYSTEM DESCRIPTION

The economic viability of 2nd-BES is calculated for Single-Family-Houses (SFH) and Multi-Family-Houses (MFH) based on one example building each. The building technology and heat demand correspond to a typical energy efficient building in Switzerland. For both building types, the Swiss average household of 3 people is assumed [14]. The example MFH consists of 7 housing units (Swiss average: 5.4 [14]). Both the SFH and MFH have a mechanical ventilation system with heat recovery. The heat generation systems for the SFH and MFH are an air source heat pumps (ASHP) and ground source heat pumps (GSHP), respectively. The buildings are located in the city of Olten.

Both C-BES and 2nd-BES are embedded in an alternating current (AC)-coupling system. The BES is charged if generated PV power exceeds the demand and storage capacity is available. If the BES is fully charged, excess electricity is fed into the power grid. The BES is discharged if the demand exceeds PV output and capacity is available. BES charge/discharge from/into the grid is not possible. This system typology is quite typical for residential buildings [11,15–17]. Both BES topologies are identical but differ in technological and economic input parameters. The PV-system is south-oriented with a 30° tilt angle and consists of polycrystalline cells. Power output is calculated by the simulation software Polysun® [18].

3. INPUT PARAMETERS

3.1. Technological parameters

The PV system size can be from one to 30 kW_p. This range covers a majority of PV installations in Switzerland [19]. BES usable capacities can be from one to 40 kWh.

C-BES typically has the maximum depth-of-discharge (DOD max.) set to 80 % of the nominal capacity [20–22]. Charge/discharge efficiency is 90 % [20–22]. Furthermore, a 0.1 % self-discharge per day is included in the calculation [23]. CL of C-BES is assumed to be sufficient to avoid battery replacement during the 25 years' time frame investigated [24]. Neither casing or cables nor AC/DC inverter are replaced during that period.

2nd-BES are considered to have a 60 % DOD max. due to battery degradation during automotive life. A 0.3 % self-discharge per day is considered [23]. It is assumed that at the end of each year 1 % of the installed nominal capacity needs to be replaced due to battery degradation. For 2nd-BES, battery life in terms of CL available is varied (200-6400). Charge/discharge efficiency and useful life of casing and inverter correspond to the C-BES.

The electricity load for the heat pump and auxiliary energy is calculated with Polysun® [18] and is 3'250 kWh/a for the SFH and 11'540 kWh/a for the MFH, respectively. The electricity load for ventilation is 360 kWh/a for the SFH resp. 3'030 for the MFH [25]. The electricity load for domestic equipment is 3'330 for the SFH resp. 20'300 kWh/a for the MFH [26].

3.2. Economic parameters

C-BES system costs consist of 1'040 CHF per kWh nominal capacity and 10'240 CHF base costs for casing, cables and AC/DC inverter (initial costs). A 2nd-BES induces initial costs similar to a C-BES. However, costs per kWh nominal capacity of 140 CHF [27] are significantly below those for a C-BES system. A yearly decrease of 3 % is considered for 2nd-BES nominal capacity costs. Battery replacement is assumed to cost 100 CHF per occurrence.

PV-system costs are 1'870 CHF/kW_p [16]. In addition, expenses for installation, cabling and maintenance are included with 9.5 % of the total PV-system costs [16].

The current Swiss subsidy-scheme for PV-systems [28] is taken into account by the model. This consists of a base contribution of 1'400 CHF issued for every PV system. Additionally, 500 CHF grants are issued per kW_p.

Two different tariffs for electricity drawn from the grid are considered here, a ‘High Tariff’ (HT) and a ‘Low Tariff’ (LT). The HT is valid between 6 a.m. and 9 p.m. during workdays and from 6 a.m. to 12 p.m. on Saturdays. The HT in the first year after installation is 0.23 CHF/kWh and the LT is 0.16 CHF/kWh [29]. After that the tariff development follows the scenario as described below. Feed-in remuneration is assumed to be 0.08 CHF/kWh [29,30].

Two different scenarios in regard to tariff development during the time frame investigated are considered. The scenarios are based on the price trend, estimated within the Swiss Energy Strategy 2050 [31,32]. The scenario "Business As Usual" (BAU) assumes a continuation of current energy policies and results in an electricity price increase of 0.52 % p.a. In the "New Energy Policies" (NEP) scenario, policies towards 1-1.5 tons of carbon emissions p.c. are assumed which imply an electricity price increase of 0.9 % p.a.

An inflation-rate of 0.84 % [33] and a discount-rate of 3 % are considered [34].

4. TECHNO-ECONOMIC MODEL

In Table 1 the most important parameters of the techno-economic model are specified.

Table 1: nomenclature Techno-Economic Model.

Parameter	Description	Value
t	Index for yearly balance $\mathrm{t} = 1, \dots, \mathrm{T}; \mathrm{T} = 8760$	hours
j	Indices for time frame investigated $\mathrm{j} = 1, \dots, \mathrm{J}; \mathrm{J} = 25$	years
$\mathrm{E_{Bc}}$	Nominal capacity of BES	kWh
$\mathrm{E_{Bav}}$	Usable capacity of BES	kWh
$\Delta\mathrm{E_{B,t}}$	Nominal BES discharge during the hour t	kWh
η_B	Discharge efficiency	-
$\mathrm{TR_{EG,j}}$	Total feed-in payback for year j (PV to grid)	CHF
$\mathrm{TC_{El,j}}$	Total electricity costs in year j	CHF
$\mathrm{TC_{PV,j}}$	Total costs for PV-system in year j	CHF
$\mathrm{TC_{B,j}}$	Total costs for BES in year j	CHF
$\mathrm{E_{PV,j}}$	Net electricity amount generated by PV in year j	kWh
$\mathrm{r_{nom}}$	nominal discount rate	-
$\mathrm{SOC_t}$	State of charge at the end of hour t	-
ρ_{mdod}	Maximum depth of discharge	-
$\mathrm{CL_{use,j}}$	Elapsed Cycle Life of BES in year j	-
$\theta_{\mathrm{CL,t}}$	Binary variable for Cycle Life in hour t, values [0,1]	-

The NPV of PV-BES represents the sum of discounted cash flows within the time frame investigated minus total initial investments acc. to eqn. (1). A nominal discount rate is considered in the calculation based on Karathanassis [35].

$$\mathrm{NPV_{PVB,J}} = \sum_{\mathrm{j}=1}^{\mathrm{J}} \frac{\mathrm{TR_{EG,j}} + \left(\mathrm{TC_{El,j}} \middle| \mathrm{E_{PV,j}} = 0\right) - \mathrm{TC_{El,j}} - \mathrm{TC_{PV,j}} - \mathrm{TC_{B,j}}}{(1 + \mathrm{r_{nom}})^{\mathrm{j}}} - \mathrm{TC_{PV,0}} \quad \text{[CHF]} \qquad (1)$$

The internal rate of return (IRR) signifies the discount rate r_{nomIRR} for which the NPV acc. to eqn. (1) equals zero after 25 years. The payback period (PBP) is defined by the year in which the sum of cash flows in eqn. (1) exceeds initial investment, given that $r_{nom} = 0$.

Levelized costs of electricity (LCOE) represent the sum of discounted BES costs per kWh net discharged electricity over the time frame investigated as defined by eqn. (2).

$$\mathrm{LCOE_{B,J}} = \frac{\mathrm{TC_{B,0}} + \sum_{\mathrm{j}=1}^{\mathrm{J}} \frac{\mathrm{TC_{B,j}}}{(1 + \mathrm{r_{nom}})^{\mathrm{j}}}}{\sum_{\mathrm{t}=1}^{8760} \left(\Delta\mathrm{E_{B,t}} \middle| \Delta\mathrm{E_{B,t}} < 0\right) \cdot \eta_\mathrm{B} \cdot J \cdot (-1)} \quad \text{[CHF/kWh]} \qquad (2)$$

Usable BES capacity is the actual amount of energy that can be extracted acc. to eqn. (3).

$$\mathrm{E_{Bav}} = \mathrm{E_{Bc}} \cdot \rho_{\mathrm{mdod}} \qquad (3)$$

One CL is counted for hour *t* if SOC reaches 1-DOD-max. acc. to eqn. (4).

$$\theta_{\mathrm{CL,t}} = \begin{cases} 1 & \mathrm{SOC_{t-1}} \neq 1 - \rho_{\mathrm{mdod}},\ \mathrm{SOC_t} = 1 - \rho_{\mathrm{mdod}} \\ 0 & otherwise \end{cases} \qquad (4)$$

$CL_{use,j}$ for year j is calculated as acc. to eqn. (5).

$$CL_{use,j} = \sum_{t=1}^{T} \theta_{CL,t} \tag{5}$$

5. RESULTS

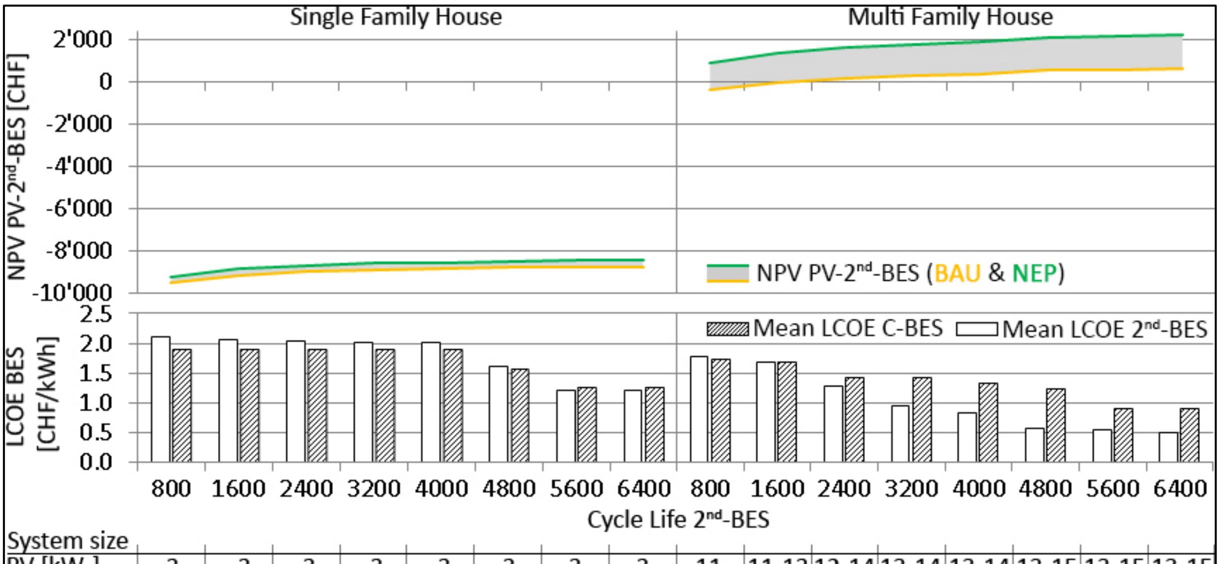
5.1. system size, Quality requirements and Profitability

Optimal system size differs between building types and CL available (Figure 1). A 2nd-BES usable capacity of 1-2 kWh for SFH and 3-7 kWh for MFH are found to be best if 4800 CL or more are available. Optimal PV-size is found to be 3 kW_p for SFH and 11-15 kW_p for MFH.

2nd-BES is in most cases economically advantageous as compared to C-BES for both building types investigated (Figure 1). In SFH, LCOE of 2nd-BES are generally below C-BES if usable capacity exceeds 1 kWh. However, cost advantages remain relatively small notwithstanding increasing CL available. In MFH, 2nd-BES systems are more favourable than C-BES if a CL of 800 is exceeded. This cost advantage increases with an increase of available CL.

Profitability differs between building types and system components. For SFH, a 3 kW_p PV reduces the yearly energy bill by 452 CHF (-33 %) and a NPV of 3’200 CHF results over 25 years (NEP-scenario, PBP: 9 years, IRR: 12 %). By including a 2 kWh 2nd-BES, more energy from the power grid is substituted and an additional 86 CHF p.a. can be economized. However, the resulting higher self-consumption rate (57 % to 71 %) decreases revenues from excess generated electricity by 40 CHF thus BES contribution is 46 CHF p.a. These revenues do not cover 2nd-BES (CL 6400) system costs over the time frame investigated (2nd-BES NPV: -11’600 CHF) and consequently, a NPV of -8’400 CHF results for the PV-2nd-BES. As shown in Figure 1, no profitable PV-2nd-BES system combination can be found for SFH.

In contrast to SFH, a PV-2nd-BES for MFH is profitable if CL exceeds 1600 cycles in the scenario BAU and already at 200 cycles in the NEP scenario (Figure 1). E.g. a 15 kW_p PV reduces the energy bill by 2'405 CHF p.a. (-34 %) and results in a NPV of 13’300 CHF after 25 years (NEP-scenario, PBP: 11 years, IRR: 9 %). By adding a 7 kWh 2nd-BES (6400 CL), additional gains of 164 CHF p.a. occur. This revenue does not cover total 2nd-BES costs over the time frame investigated (NPV: -11’100 CHF). Nonetheless, in combination with the PV system a NPV of 2’200 CHF results after 25 years (NEP-scenario, PBP: 16 years, IRR: 4 %).



System size																
PV [kW_p]	3	3	3	3	3	3	3	3	11	11-13	12-14	13-14	13-14	13-15	13-15	13-15
BES [kWh]	1	1	1	1	1	1-2	2	2	1	1	1-2	2	2-3	3-6	3-7	4-7

BES: Battery Energy Storage, PV: Photovoltaics, C: Conventional, NPV: Net Present Value, LCOE: Levelized Cost of Electricity, BAU: Business as Usual, NEP: New Energy Policies

Time frame investigated: 25 years

Figure 1: NPV and mean LCOE for SFH- and MFH-PV-2nd-BES with optimal system size.

5.2. Sensitivity analysis

Based on a ±33 % value variation of a number of parameters a sensitivity analysis of the NPV of 2nd-BES is conducted. Results show that the parameters “initial system cost” and “HT price” can be seen to have the largest impact (Figure 2). A 33 % decrease of initial 2nd-BES-system costs unsurprisingly improves the NPV by a large margin (31 %). The 33 % increase of HT electricity price increases the NPV by 13 %. This strong dependency of BES economic performance and electricity market prices can also be found in previous research on PV-BES systems [10,11]. Furthermore, a relatively strong decrease in NPV is found (-10 %) if DOD max. is lowered further to 40 %. For system optimization interdependencies of parameters need to be considered, e.g. a DOD max. reduction can increase expected CL of 2nd-BES.

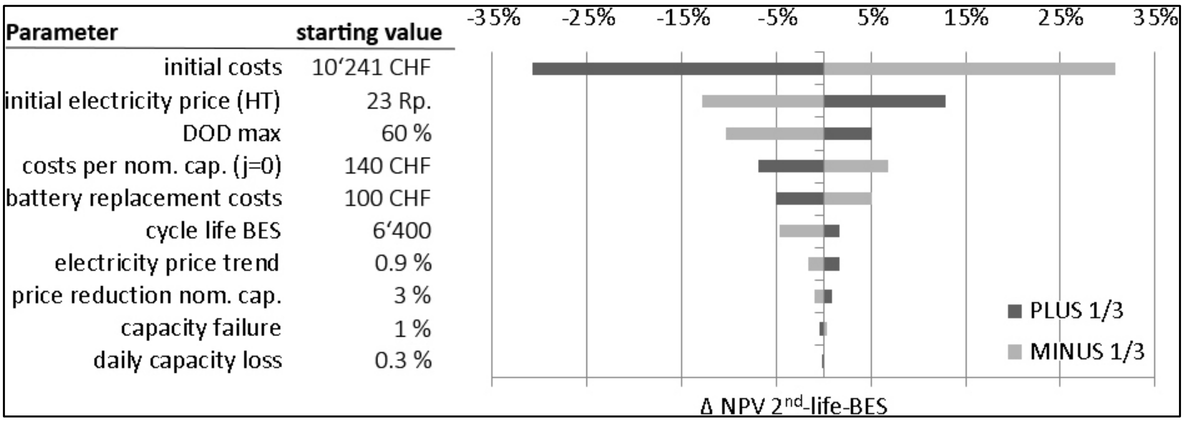


Figure 2: sensitivity analysis for MFH, scenario NEP, 15 kW_p PV- 7 kWh 2nd-BES (6400 CL).

6. CONCLUSIONS

PV systems in combination with 2nd-BES (PV-2nd-BES) can be dimensioned for MFH such that they are economically viable. For SFH, no economically viable PV-2nd-BES system can be found under current market boundary conditions. This is mainly due to the optimal system size of PV-2nd-BES, which is larger for MFH than for SFH.

Under current market boundary conditions, no profitable 2nd-BES system dimensions for either SFH or MFH can be found. Nonetheless, mean LCOE in MFH 2nd-BES systems is favourable as compared to C-BES mean LCOE, provided that more than 800 cycles are available per battery in the 2nd-BES system. SFH 2nd-BES are more favourable than C-BES systems if CL > 4800 can be guaranteed. However, mean LCOE of 2nd-life BES fall only slightly below C-BES systems and remain on a high level. Main drivers for more economically viable 2nd-BES are a reduction of initial system costs and an adapted structure of electricity prices.

Results shown here will contribute to the product development of 2nd-BES. Producers can use the design values “min. CL”, “max. initial system costs” and “DOD max. configuration” as target values or threshold values. Furthermore, the findings in regard to optimal system size can contribute in project assessment to maximize profits.

The results are based on a very simple, current Swiss electricity tariff scheme for residential consumers. The results show the importance of introducing alternative pricing-models. The model developed can be used in future research to assess the economic viability of BES in combination with more sophisticated tariff schemes. Current Swiss tariffs do not take the positive impact of local storage capacity on power grid stability and the reduction of the necessity to reinforce the power grid into consideration.

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