BATTERY STORAGE SYSTEMS FOR BUILDING APPLICATIONS

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GENERAL RELEVANCE

Ambitious goals in term of renewable energy penetration and C02 emission reduction have been set worldwide and at a country level [1], [2]. Within this context, as depicted in several references [1-6], electricity storage will play a crucial role in enabling next phase of the energy transition and in decarbonising key segments of the energy market. In the incoming years, battery energy storage systems BESS can be grouped in three main usage-categories: (i) stationary, (ii) electric vehicles (EVs) connected to building (the so-called vehicle to building V2B) and iii) second-life systems. The first ones are, and they will be, more and more deployed in (i) buildings for increasing energy renewable self-consumption and compensating daily volatility of renewable energies and in (ii) power grid to provide ancillary services (frequency control, peak shaving, etc.). Batteries in EVs will also be deployed to provide ancillary services to the grid (V2G) or to building (V2B). Second-life batteries, coming from aged EVs, could be deployed with reduced performances for grid and building applications from 2023 (the forecasted date for large amount of aged cells from EVs).

Various battery technologies are used for both stationary and EV applications [7-8]. The lead-acid (PbA) and lithium-ion (Li-ion) are dominating the market but other technologies are co-existing such as nickel-cadmium, nickel-metal hybride and nickel-iron (NiCd/NiMeH/Ni-Fe), sodium−sulfur (NaS), sodium-nickel-chloride (NaNiCl), redox-flow batteries vanadium- (V-Redox) and zinc –Bromine (ZnBr). The main battery characteristics are listed in table 1. The cycle life is the number of charge/recharge cycles that the battery can support before its capacity falls under 80% of the initial value. The manufacturers also give the value in percentage of the maximum depth of discharge (DOD), where DOD is the complement of the state of charge of the battery (SOC). Typically, Li-ion have maximum DOD ~80%-90%, and PbA ~50%. Note that the larger the DOD every cycle, the smaller the available cycle times will be.

Table 1: Main characteristics and performance of various battery technologies, data source 2011 [8]

Technology	Energy efficiency (%)	Self discharge (days/%[1])	Gravimetric energy density (Wh/kg)	Volumetric energy density (Wh/L)	Cycle life (cycles)	Float life (years)	Working temperature (°C)
Pb-acid	70-90	3-15	20-50	50-80	500-2000 4500*	5-15	10-45
NiCd	60-87	3	50-80	40-100	1500-3000	-	-40-60
Li-ion	85-100	3-15	60-200	200-400	1000-10’000	5-15	-
NaS	75-92	0-0.05	110-240	150-250	>2500	10-15	270-350
NaNiCl	70-90	0.06	100-200	150-180	>2500	10-14	270-350
VaRedox	60-85	Lot of days	10-30	15-33	10’000-13’000	10-15	5-45

For the home storage application, the lead-acid and lithium-ion technologies coupled with PV [10] are commonly used. PbA batteries represent one of the oldest and most developed battery technologies. There are many existing installations which have been in operation for up to 20 years. Their biggest advantage is the low cost compared to other storage systems, demonstrated recyclability [11], while their limited lifetime with a limited number of cycles is the biggest disadvantage. Improved version of flooded lead-acid (FLA) are sealed lead acid valve-regulated lead-acid VRLA batteries such GEL and absorbed glass mat AGM, GEL having lower charging power. They are recommended to be used with PV because of their low maintenance and extended depth of charge resilience. Ongoing R&D is focused on extending lifetime and improving performance both in terms of charge acceptance and in their ability to operate partial state of charge applications. Advanced lead-carbon batteries as well as lead crystal batteries are claimed to have better performance and still good recyclability.

Li-ion has become the most important storage technology in the area of portable and mobile applications (e.g. laptop, cell phone, electric bicycle, and electric car) within a few years. In stationary applications, Li-ion can be found in variable size from few kWh of capacity up to hundreds of MWh. Their advantages are high density energy, good round trip efficiency (>85%), fast response in milliseconds, low self-discharge rate, high power charge and discharge, and high cycle life. Significant resources will continue to be spent on improving the performance, cost, systems integration, production processes and safety [9]. Demonstrating recyclability and reducing operating temperature are also required. Li-ion batteries decline in the following sub-technologies: lithium polymer batteries (LiPo) with highest energy density, lithium iron phosphate (LFP), li-ion manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium ion titanate (LTO). The commonest chemistries for residential BESS are NMC- graphite or iron-phosphate, since they have a quite important energy density (120-160 Wh/kg) and long lifecycle (up to 10000 full equivalent cycles). LTO have a very high number of cycles 15.000-20.000. Compared with PbA, Li-ion batteries cost more up front, but the extra efficiency means you can potentially spend less per kilowatt-hour of capacity over the lifespan of the battery. Moreover, Li-ion lasts longer and have faster charge rate and can be put through deeper cycles. The energy density has increase a lot last decade, passing from 60-70 Wh/kg up to 140/200 Wh/Kg for modern NCM graphite li-ion cells [12].

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[1] Self discharge is expressed here in days/% and means the number of days it takes for a 1% loss

DC/AC-POWER CONVERSION

BESS are composed of cells which are charged and discharged at DC current. The maximum charge and discharge rate depends on the batteries size and cell technology. To guaranty lifetime and security, a battery management system (BMS) is embedded into the Li-ion systems to monitor cells voltage, temperature as well as to control the maximum allowed charge and discharge current. There is generally no BMS for lead-acid batteries which are totally passive. As the battery is DC and since the building is connected to an AC grid with a majority of AC consumers, a reversible DC/AC converter, called charger-inverter is needed. The charger convert AC to DC, and the inverter DC to AC. For Li-ion, this charger inverter is talking via a communication link with BMS which define the maximum charge and discharge DC current. Some BESS manufacturer also propose to integrate the charger inverter within the BESS. To store and restore electrical energy, the BESS is coupled to the AC grid and the PV system in different manners. The PV system can be coupled in DC to the BESS with the help of a DC/DC converter. The alternative is to connect the PV system to BESS after solar inverter (AC coupling).

Finally, the typology of the Grid - BESS - PV system - Consumers must be defined with three main possibilities: (i) consumers and loads must be fully secured, (ii) few loads must be secured, and (iii) no load must be secured by the BESS that only restore energy with a permanent connection to the grid. The two last cases correspond to the context of a house connected to the grid in a built environment where the grid is supposed more reliable than the BESS. In this case, the PV system in AC is also connected to the grid side with no limitation of PV power. As most of loads (except the secured ones) are also connected to the grid side as well, the power of the charger inverter is only dimensioned by the power of the BESS and not the loads.

RELEVANCE IN BUILDING COMPETITIONS & LIVING LABS

In buildings, energy storage combined with intermittent renewable systems is a common solution for increasing the use of low-carbon energy produced on-site. The use of electric storage batteries was already part of the SD US 2002 competition. Until 2007, SD houses were not connected to the grid and the installation of batteries was mandatory. In SD Europe, batteries have been authorized since 2010, with limited power and capacity. As the buildings are connected to the grid, installing large electrical storage capacities to make the house autonomous no longer made sense. The average battery size has therefore decreased from 85 kWh (SD US 2007) to 13 kWh (SD US 2017) and 5 kWh (SD EU 2014). By limiting storage capacity, limiting the PV production and minimizing the perceived energy of the grid, the SD rules force candidates to reduce their consumption as much as possible and implement advanced control strategies. In European SD competitions, the criteria for evaluating the energy contest and the score assigned to SD houses have evolved over the years. The contest "*Positive Electrical Balance*" was worth 75 points (out of a maximum of 120 points concerning energy) in 2010 and more than 25 points in 2014. Since SD EU 2014, rules have been in place to evaluate the interaction between SD houses and the grid. They take into account the ability to avoid power peaks at the building level but also the ability of the building to reduce grid power peaks. Apart from electrical characteristics and performance of BESS, the working temperature of BESS as well as the battery cells technology are of primary importance for SD. If lead-acid have lower capacity at low temperature, battery management system of Li-ion automatically switch-off the battery at low temperature and low cell voltage. Other bigger BESS such as Tesla Powerpack have their own battery temperature regulation system with heating and cooling. This regulation consumes energy in addition to the intrinsic self-discharge rate of the cells and the charger inverter consumption. It is therefore important that the battery have sufficient cycle to maintain by itself at the right temperature (23°C +/- 4°C optimum for Li-ion NMC) thanks to the charge and discharge current during cycles. Also, proper ventilation, natural or mechanical ventilation is mandatory if BESS electrolyte can generate toxic and inflammable gas. Finally, since sustainability is a criterion for SD, the LCA of BESS with the chosen technology must be carried out considering both embodied energy and delivered energy during the whole BESS cycle life.

PERFORMANCE INDICATORS FOR BESS

The performances of a BESS is related with the technology characteristics listed in table 1 as well as its sizing and integration. In particular, the BESS is defined by its capacity (strictly related to the energy that could be stored in), the equivalent series resistance (strictly related to the power that could be deployed with). The regulation strategy and dimensioning is decisive for qualifying the performance of the installation. Several strategies can be identified. An **energy strategy** aims to reduce dependence on the grid and thus increase the building's self-consumption ratio (SCR) and self-sufficiency ratio (SSR). An **economic strategy** considers variations in the price of perceived energy from the grid, increases the economic profitability of the installation and reduces payback time. SCR and SSR indicators are calculated with the help of the following equations, where E represent energy yearly flows:

$$SCR:\ Self-Consumption\ \ Ratio=\frac{E_{self-consumed}}{E_{self-produced}}=\frac{E_{consumed}-E_{fromgrid}}{E_{consumed}-E_{fromgrid}+E_{togrid}}$$

$$SSR:\ Self-Sufficiency\ \ Ratio=\frac{E_{self-consumed}}{E_{consumed}}=\quad 1-\frac{E_{fromgrid}}{E_{consumed}}$$

An **ecological strategy** takes into account the ecological impact of the installation. Indeed, the installation must lower the carbon footprint of the building by limiting the use of fossil energy delivered by the grid that is not constant and depends on its mix source (fossil, wind, hydro, nuclear, etc.) [13]. Assessment (LCA) should be computed in order to have an overall vision of the BESS impact [11][14-15]. It is worth noting that a BESS having a reduced ageing will live for longer time, and consequently it will store more renewable energy Therefore, the environmental indicator gas warming potential GWP in kg eq CO2 and cumulative energy demand in MJ must be expressed per unit energy total delivered energy in MWh. The total delivered energy will depend on the BESS size and cycle life.

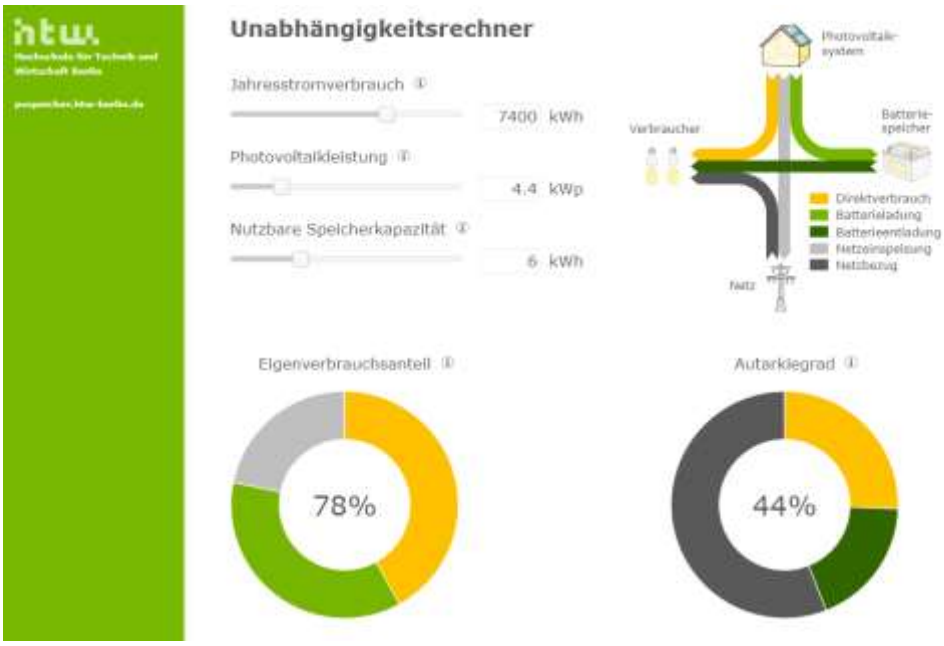
There are other criteria defined by the SD rules such as smoothing the power peaks consumed by the SD house or help the grid to compensate for overloads. These strategies can be combined to meet several objectives. The regulatory choices and the importance given to each of these strategies will be influenced by the competition rules and the scoring criteria.

BASIC BESS SIZING

The main important physical parameters to consider when dimensioning BESS are the following: capacity, maximum number of cycles, maximum allowed depth of charge to avoid irreversible damage, maximum charge and discharge rate. The prerequisite to design a storage system for stationary application is to know the PV production and the electrical consumption. As a rule of thumb the size of the BESS should not exceed 30-40% of the overall average daily consumption, or should be able to bring an autonomy of 4h-8h duration. The nominal power of the inverter to be connected with the BESS should not exceed 60% of the PV peak power production.

A family house located in Neuchatel (CH) and designed for four persons is taken a case study. The house has an energy reference area of 140 square meters. A passive house standard design would lead to a yearly electrical consumption is 4200 kWh including 2800 kWh for the appliances. A design that complies with current minimal standards in Switzerland would lead to a yearly consumption of about 7400 kWh with 4200 kWh for appliances. With a target of a minimum PV coverage ratio of 60% and energy yield of 130 kWh/m2, the required PV surface is 34 m2. Considering an average daily energy consumption of 20 kWh, the capacity of a battery corresponding to 30-40% of this energy would be between 6 and 8 kWh.

For better insights about BESS sizing before performing simulations, a web-based design tool can be found in [16] with an illustration figure 1. This simple digital tool estimates the self-sufficiency and self-consumption rates as well as battery use. Taking again the example of a house with 4.4 kWp installed power and 7400 kWh energy consumption, variable battery capacities 4, 6 and 8 kWh lead to variable self-consumption (70%, 78% and 85%) and self-sufficiency (40%, 44% and 47%). However, this tool has strong limitations because it is not possible to model the technical installations and equipment of a specific building.



Unabhängigkeitsrechner

Jahresstromverbrauch: 7400 kWh

Photovoltaikleistung: 4.4 kWp

Nutzbare Speicherkapazität: 6 kWh

Figure 1: Digital tool for BESS sizing [16]

<u>BUILDING SYSTEMS SIMULATIONS WITH PV AND BATTERIES</u>

The behavior of a BESS coupled with building systems and PV can be simulated [17] with the help of building simulation software such as Polysun [18]. As an example, a two-floor house in Neuchâtel is considered with the following characteristics:

- Energy reference area: 140 m2
- Yearly heating demand: 30 kWh/m2
- Domestic hot water DHW consumption: 5.8 kWh/day (200 l@ 50°C)
- Residential electrical consumption profile 3500 kWh/year.

To optimize the self-consumption, the 10 kW heat pump is fed and driven in priority by the PV roof top production, see figure 2.

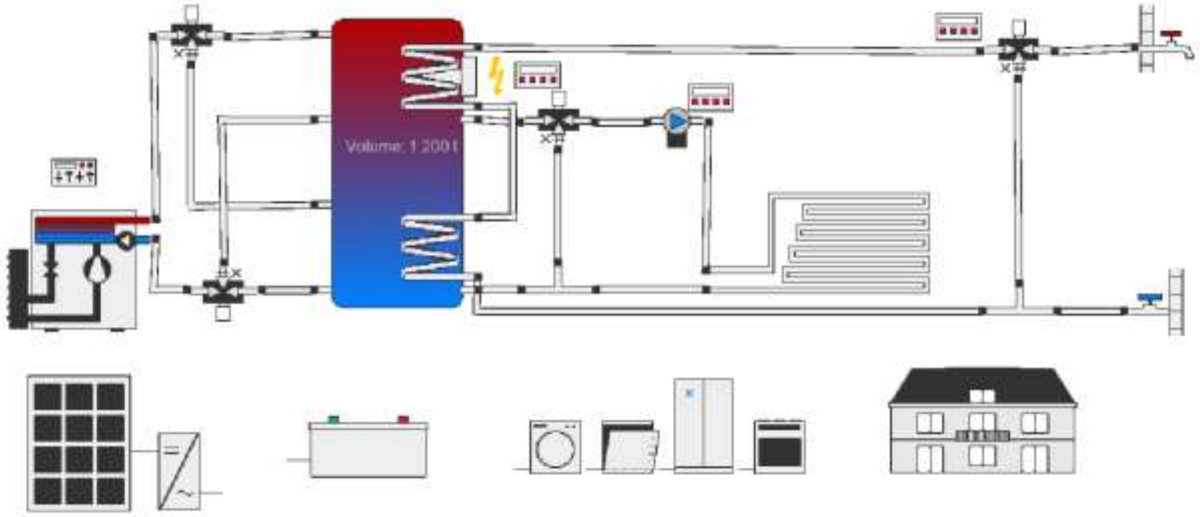


Figure 2 : Building system simulations with variable PV coverage and battery capacity for a low consumption building 140 m2 equipped with a PV driven heat pump for heating and domestic hot water, Polysun model 56c [18]

A first set of simulation is presented in table 2: variable PV coverage with installed power 4, 5.6, 8.1 and 11.8 kWp (Poly-Si @ 45° South), as well as variable battery storage capacities 0, 4 and 8 kWh (Lithium-Fe-P Sonnen, 10'000 cycles AC coupling). Comparing the three first columns, the self-consumption already go from zero with No PV to 42% with PV without BESS. Then, adding the BESS 4 kWh brings an additional self-consumption of 27% (42% to 69%). Increasing PV and BESS size, self-consumption reaches a maximum of 78.4% for the median coverage 80% (5.6 kWp) and BESS 8 kWp, but deceases when PV coverage is further increased because un-consumed energy is injected into the grid. Note that, the introduction of an electrical vehicle would dramatically increase both the electrical consumption of the house and the self-consumption for the large PV installation as well. Considering the self-sufficiency ratio, an increasing of the PV coverage from 59% (4 kWp) to 158% (11.8 kWp) leads to a maximum value of 59% (BESS 8 kWh). Nevertheless, self-sufficiency of 45% is already obtained with 5.6 kWp of PV and a BESS of 4 kWh.

To determine the **optimum BESS size maximizing self-consumption**, a fix PV coverage of 80% of the electricity consumption is considered (5.6 kWp) and the BESS size varies from zero to 32 kWh (see table 3). The self-consumption ratio rapidly reaches a maximum value of ~80% for BESS 10-12 kWh. A bigger BESS capacity may be chosen in order to guarantee the self-consumption level over years. This would compensate the loss of battery capacity per year in % which depends on the number of cycles and deep cycles. Increasing BESS size, self-sufficiency increases up to 47.5% with the largest battery 32 kWh, which is lower than the PV coverage ratio. From the **environmental** point of view, since the battery has embodied energy, the battery size must be minimized.

Table 2: Variable PV coverage and BESS capacity in kWh.

Variable PV size kWp Variable BESS size kWh	**NO PV BESS 0**	**PV 4 BESS 0**	**PV 4 BESS 4**	**PV 5.6 BESS 4**	**PV 5.6 BESS 8**	**PV 8.1 BESS 4**	**PV 8.1 BESS 8**	**PV 11.8 BESS 4**	**PV 11.8 BESS 8**
PV coverage [%]	0	59	58	80	80	118	118	157	158
PV production [kWh]	0	4080	4080	5767	5767	8698	8698	11795	11795
Energy from grid[kWh]	6883	5233	4591	4004	3797	3596	3366	3340	3072
Energy to grid [kWh]	0	2379	1070	1872	1249	4223	3570	6963	6265
Elect Consump. [kWh]	6883	6935	7007	7226	7213	7396	7383	7498	7484
Self-Consumption[kWh]	0	1702 (42%)	3011 (69%)	3896 (67.6%)	4519 (78.4%)	4476 (51.5%)	5128 (59%)	4833 (41%)	5531 (46.9%)
Self-Sufficiency [%]	0	25	34	45	47	51	54	55	59
Battery cycles [-]	0	0	665	883	882	843	845	812	813
Bat. loss capacity [%/y]	0	0	2	2.6	3.9	3.3	4.3	3.5	4.2

Table 3: PV coverage 80% PV 5.6 kWp, Variable BESS capacity in kWh

PV 5.6 kWp Prod. 5782 kWh/year Variable BES size kWh	**BESS 0**	**BESS 4**	**BESS 6**	**BESS 8**	**BESS 10**	**BESS 12**	**BESS 14**	**BESS 16**	**BESS 32 2x16**
Energy from grid [kWh]	4808	3996	3838	3794	3779	3826	3842	3866	3786
Energy to grid [kWh]	3424	1881	1489	1262	1092	1114	1076	1027	893
Elect Consump [kWh]	7166	7226	7216	7213	7213	7212	7211	7211	7208
Self-Consump [kWh]	2358 (40.8%)	3902 (67.5%)	4293 (74.2%)	4520 (78.2%)	4690 (81.1%)	4668 (80.7%)	4707 (81.4%)	4756 (82.3%)	4890 (84.6%)
Self-Sufficiency [%]	32.9	44.7	46.8	47.4	47.6	46.9	46.7	46.4	47.5
Battery cycles [-]	0	906	918	997	883	874	851	839	828
Bat. loss capacity[%/y]	0	3	4.4	4.1	3.3	2.6	2.2	1.8	1

BESS ECONOMIC ANALYSIS

We will consider the case study described above with a retail tariff equal to CHF 0.22 per kWh and feed-in equal to CHF 0.085 per kWh. From a user perspective, the revenue is equal to the difference between the cost of a grid-connected solar home battery system and the cost of grid as a zero-investment generator producing at the retail price. Accordingly, the energy fed to the grid should also be taken into account as a negative cost as follows:

$$Revenue = \left(E_{consumed} - E_{fromgrid}\right) \times Tariff_{retail} + E_{togrid} \times Tariff_{feedin}$$

For the example above, considering a 5.6 kWp PV installation and without any BESS, the yearly revenue would be CHF 810.-. Adding an 8 kWh BESS would increase the revenue only by CHF 50.- (total of CHF 860.-). This shows that an amortization of a BESS in such case would be almost impossible. However, the price of BESS has already dramatically decreased the last decades and second-life battery systems are emerging and might provide interesting economic models.

An **economic optimum** could be calculated by comparing the yearly amortization of the initial investment for PV plus BESS with the revenue as defined above.

MONITORING AND CONTROL, ENERGY MANAGEMENT SYSTEMS

To prevent any unsafe operating conditions, industrial BESS are already equipped with Battery Management Systems (BMS) that monitors the state of charge of the BESS, cell voltage and current as well as temperatures. Typically for lithium-ion battery, BMS must communicates with the charger inverter to give the maximum charge and discharge current which depends on cell technology, cell’s temperature and state of charge.

To be able to regulate the installation according to the desired strategies (see section *Performance indicators for BESS applications*), the building must be equipped with electricity meters to measure (i) PV production, (ii) the energy delivered by the grid and that provided by the grid, (iii) the consumption of the SD house and (iv) the energy stored in the battery. Meters dedicated to specific devices or services (e.g. heating system, EV, domestic appliances etc.) can also be considered. These allow detailing the building's consumption, to understand the users' habits and to use possible patterns for predictive purposes for BESS regulation. Energy management system integrating specific algorithms can be implemented to drive the BESS with charge and discharge current, possibly some load time shifting can be done (heat pump, washing machine …). For basic self-consumption strategies, the PV inverter manufacturer generally offer self-consumption solutions with the monitoring and control of the PV production, consumption and battery monitoring (SMA, Kostal…).

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