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Pre-feasibility Study of Li-Ion Battery Energy Storage Facility

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Zusammenfassung

Dieser Bericht fasst die Ergebnisse einer ersten Untersuchung (Kosten-Nutzen-Analyse) von potenziellen Geschäftsanwendungen und den wirtschaftlichen Wert eines Batteriespeichersystems (BESS) in einer Unterstation zusammen. Die Studie wurde in Zusammenarbeit mit Swissgrid durchgeführt. Die untersuchten Hauptanwendungen waren: Primärfrequenzregelung, Spannungsregelung und Unterstützung der Wiederherstellung vom Netzbetrieb nach einem grossen Blackout (s.g. Schwarzstart).

Verschiedene Grössen von BESS in MW und MWh wurden unter Berücksichtigung der Batteriealterung analysiert. Die Simulationen zeigten, dass die Batterie eine Restkapazität von etwa 82-85% nach 15 Jahren Betrieb haben kann. Ein BESS mit einer Leistung über 20 MW zeigt einen positiven NPV-Wert. Die Amortisationszeit hängt sehr stark von der Steuerstrategie ab und kann zum Beispiel für einen 30 MW BESS zwischen 9 und 13 Jahren variieren.

Résumé

Ce rapport résume les résultats d’une étude préliminaire (Cost Benefit Analysis) dont le but est d’analyser les opportunités de business et l’aspect économique de banc de batteries (BESS) installés dans des sous-stations électriques en Suisse. L’étude a été menée en collaboration avec Swissgrid. Les applications en ligne de mire incluent: les contrôles de fréquence, contrôle tension et la remise en service du réseau après un blackout, p.ex. (black start). Différentes dimensions des systèmes (BESS) ont étés prises en considération d’un point de vue puissance installée en MW et MWh, ceci prenant en compte la capacité des bancs de batteries, leur vieillissement et la stratégie des systèmes de contrôle de charge. Des simulations ont montré des capacités résiduelles des batteries de 82-85% après 15 ans d’opération.

D’un point de vue économique, les bancs de batteries de puissances supérieures à 20 MW montrent au long du cycle de vie et une « Net Present Value » (NPV) positive. Le remboursement des investissements est très dépendant de la méthode de contrôle et planification. Il peut varier de 9 à 13 ans pour des bancs de 30 MW.

Abstract

This report summarizes the results of an initial investigation (cost-benefit analysis) of the potential business applications and the economic value of a battery energy storage system (BESS) in a transmission substation in Switzerland. The study has been carried out in collaboration with Swissgrid. The main targeted applications include primary frequency control, voltage control and support of the system restoration after a major blackout; i.e. black start.

Differing sizes of BESS in MW and MWh have been analyzed, taking into account battery capacity aging effects and battery state of charge control strategies. Simulations have shown that the battery can have a residual capacity of about 82%-85% after 15 years of operation. A BESS with a rating above 20 MW shows a positive NPV value. The payback time very much depends on the control strategy and can vary, for example, from nine to 13 years for a 30 MW BESS.

Abbreviations

BESS	Battery energy storage system
CBA	Cost-benefit analysis
E	Energy
EoL	End of life
ESS	Energy storage system
FERC	Federal Energy Regulatory Commission
IRENA	International renewable energy agency
Li-ion	Lithium-ion
NPV	Net present value
P	Active power
PRL	Primary control reserves
Q	Reactive power
ROI	Return on investment
S	Apparent power
SoC	State of charge
Steco	Steering committee

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1. Technology review

Energy storage

Energy storage is becoming an important element in modern power systems, and may help to improve operation and efficiency at the different stages of the power delivery value chain (Figure 1).

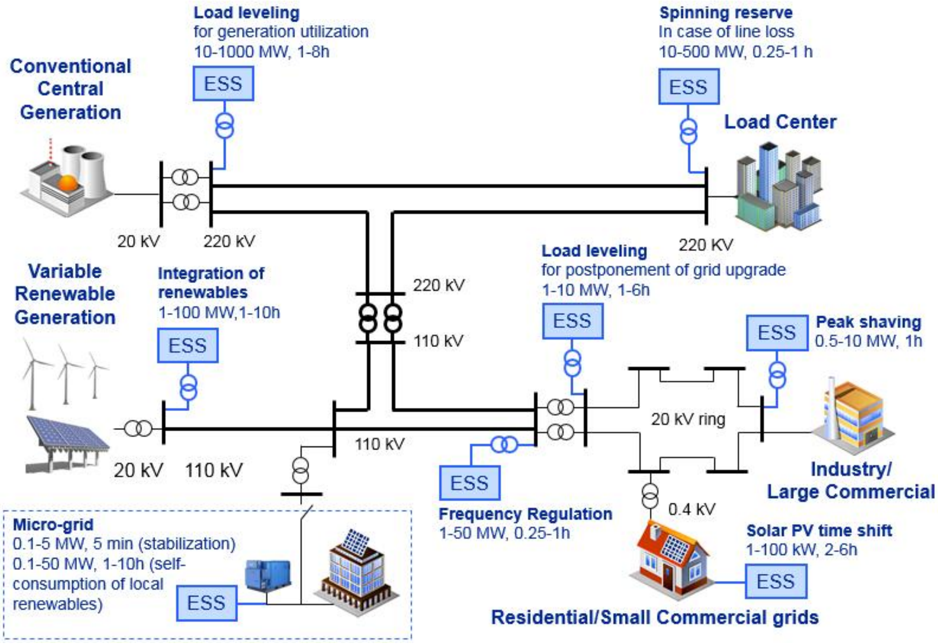
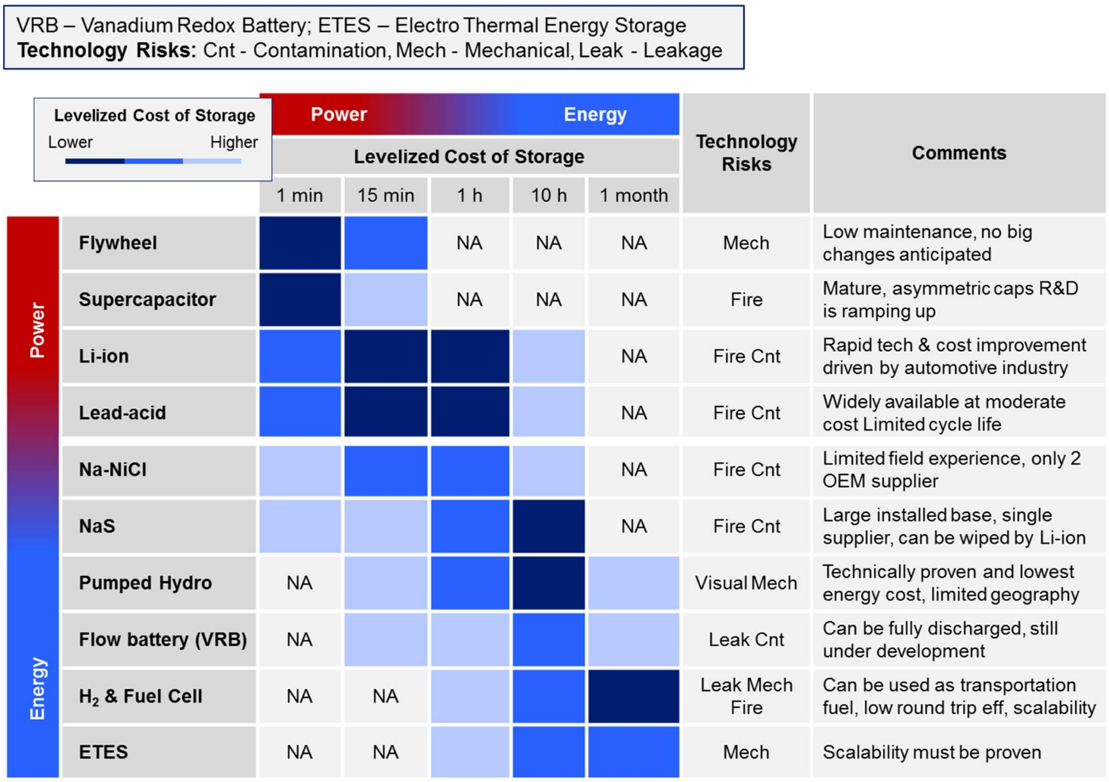


Figure 1. Applications of energy storage in power systems [1].

A large number of battery energy storage systems (BESS) are available at the commercial stage as listed in Figure 2, summarizing findings from [1], [2]. Their economic feasibility varies depending on the targeted discharge or operation time, efficiency, safety, life-time requirements, etc. From the point of view of applications that are potentially interesting for a grid operator (e.g. ancillary services for frequency and voltage stability, black start or system restoration, etc.), the discharge time needed may vary in the range of 15 to 60 minutes [2]. Simultaneously, primary frequency control applications in particular require a large number of cycles; in fact, primary frequency control operates continuously. It has been broadly accepted in technological circles that today the most economically and technically suitable technology for these applications is lithium-ion batteries. Additional evidence of this technology as specifically suited to power applications is shown by the increasing number of commercial installations worldwide. Indeed, this type of battery has been recognized as the most promising technology for power applications due to the combination of efficiency, initial costs and the maximum number of charging cycles [1]; see Table 2 and Figure 1 in [3], [1], [18],[16], [20]-[22].



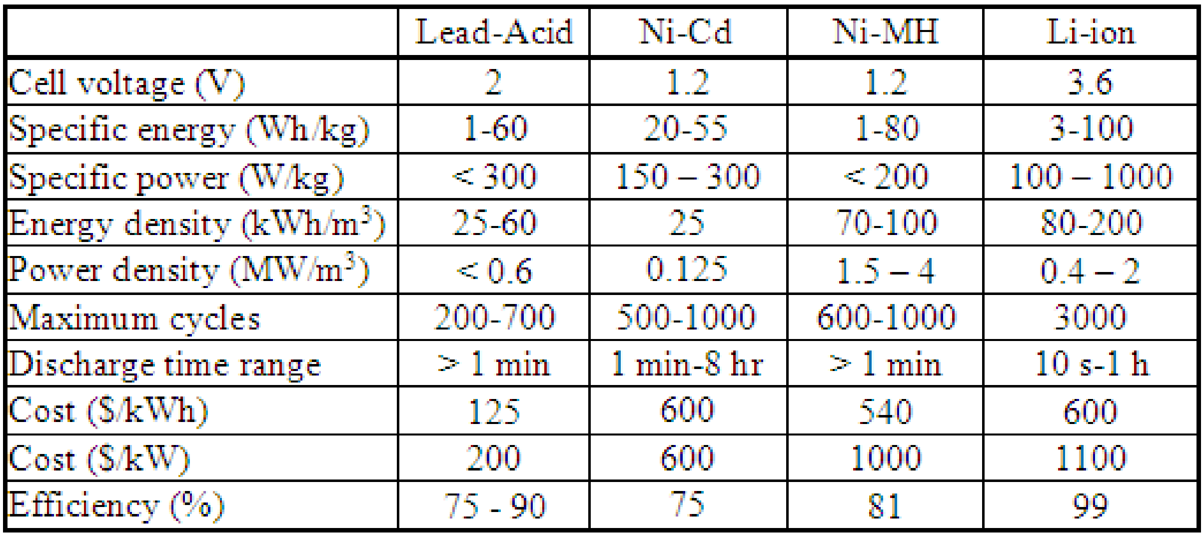
VRB – Vanadium Redox Battery; ETES – Electro Thermal Energy Storage
Technology Risks: Cnt - Contamination, Mech - Mechanical, Leak - Leakage

Levelized Cost of Storage
Lower █ ▓ ░ Higher

		Power				**Energy**	**Technology Risks**	**Comments**
		Levelized Cost of Storage						
		1 min	15 min	1 h	10 h	1 month		
	Flywheel	█	▓	NA	NA	NA	Mech	Low maintenance, no big changes anticipated
	Supercapacitor	█	░	NA	NA	NA	Fire	Mature, asymmetric caps R&D is ramping up
Power	**Li-ion**	▓	█	█	░	NA	Fire Cnt	Rapid tech & cost improvement driven by automotive industry
	Lead-acid	▓	█	█	░	NA	Fire Cnt	Widely available at moderate cost Limited cycle life
	Na-NiCl	░	▓	▓	░	NA	Fire Cnt	Limited field experience, only 2 OEM supplier
	NaS	░	░	▓	█	NA	Fire Cnt	Large installed base, single supplier, can be wiped by Li-ion
	Pumped Hydro	NA	░	▓	█	░	Visual Mech	Technically proven and lowest energy cost, limited geography
	Flow battery (VRB)	NA	░	░	▓	░	Leak Cnt	Can be fully discharged, still under development
Energy	**H_2 & Fuel Cell**	NA	NA	░	▓	█	Leak Mech Fire	Can be used as transportation fuel, low round trip eff, scalability
	ETES	NA	NA	░	▓	▓	Mech	Scalability must be proven

Figure 2. Energy storage technologies.

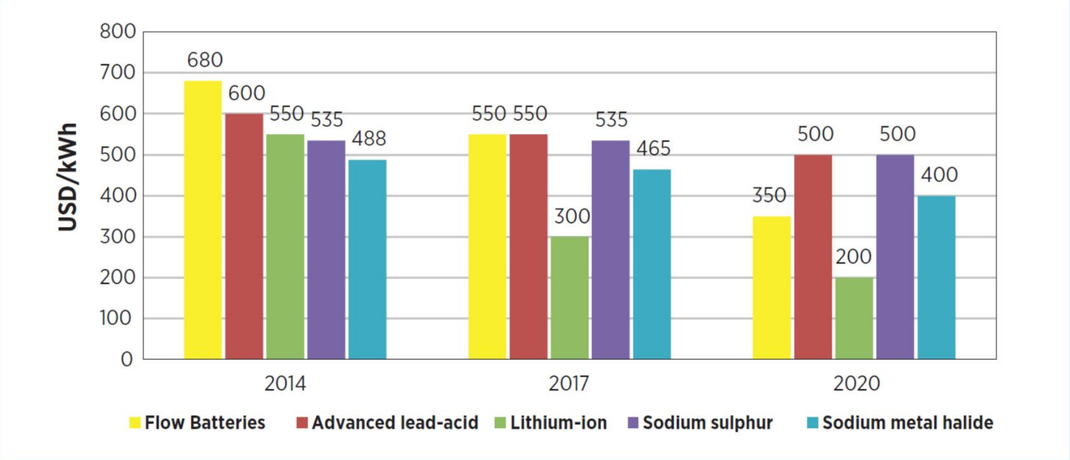
Figure 3 provides a summary of the various technologies that have improved since 2012 to the more favorable Li-Ion. Figure 4 and Figure 5 provide an overview of the price evolution for various BESS chemistries.



	Lead-Acid	Ni-Cd	Ni-MH	Li-ion
Cell voltage (V)	2	1.2	1.2	3.6
Specific energy (Wh/kg)	1-60	20-55	1-80	3-100
Specific power (W/kg)	< 300	150 – 300	< 200	100 – 1000
Energy density (kWh/m^3)	25-60	25	70-100	80-200
Power density (MW/m^3)	< 0.6	0.125	1.5 – 4	0.4 – 2
Maximum cycles	200-700	500-1000	600-1000	3000
Discharge time range	> 1 min	1 min-8 hr	> 1 min	10 s-1 h
Cost ($/kWh)	125	600	540	600
Cost ($/kW)	200	600	1000	1100
Efficiency (%)	75 - 90	75	81	99

Figure 3. Energy storage technologies review [22].

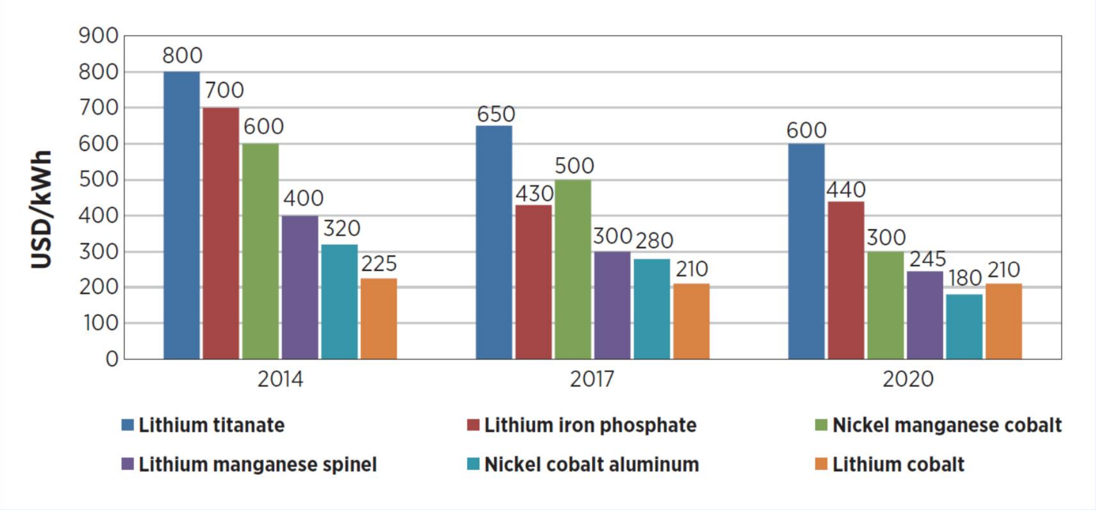
Figure 20: Lowest current and projected battery cell price by type for utility-scale applications



Source: Navigant Research (Jaffe and Adamson, 2014)

Figure 4. Lowest current and projected battery cell price by type for utility-scale applications [2].

Figure 21: Lowest cell price of lithium-ion chemistries for utility-scale applications



Source: Navigant Research (Jaffe and Adamson, 2014)

Figure 5. Overview of price development for Li-ion chemistries [2].

The current analysis focuses on a lithium-ion BESS. Li-ion technology is a name for a large family of materials used for positive (lithium nickel manganese cobalt oxide, lithium manganese oxide, lithium iron phosphate, etc.) and negative (graphite, lithium titanate, hard carbon, tin/cobalt alloy, etc.) electrodes. The technology we consider in the analysis is LMO-based (lithium manganese oxide) since it has good properties in terms of thermal stability; i.e. safety, aging and costs. Furthermore it has proven to be the technology of choice for grid-connected BESS where the main application has been frequency regulation. The properties of this battery technology have been studied by the working group and form the basis of the detailed state-of-charge simulations in section 2.2.2. It may be considered that at a project realization stage, other battery technologies could be considered if characteristics, such as efficiency, discharge time, number of cycles, aging are sufficiently well characterized.

Figure 6 [3] shows a reduction in the lithium-ion battery module cost in the period 2005-2015, and projections of future cost reductions to 2025-2030.

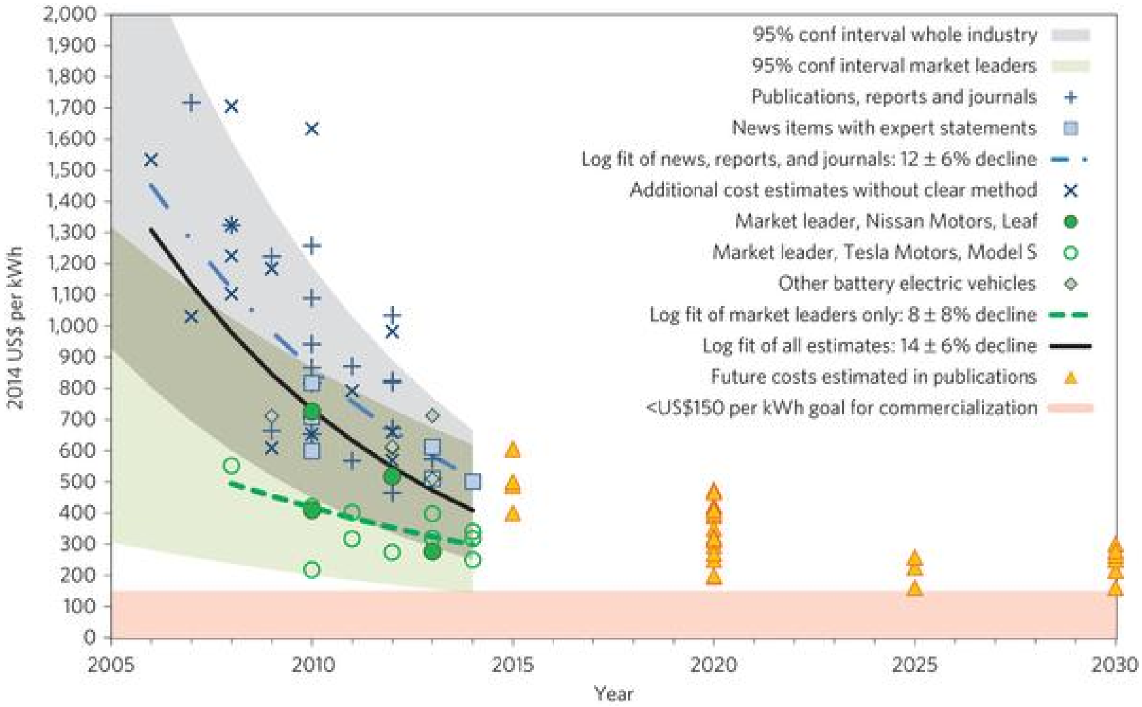


Figure 6. Cost of Li-ion battery packs in battery electric vehicles. Data from multiple types of sources, trace reported cost for the industry and costs for market-leading manufacturers [3].

The economics of the BESS have continuously improved over the last few years due to a significant cost reduction of the battery cells. This reduction is mainly driven by mass production to fulfill the demands of the automotive industry. Companies are building large new factories, such as Tesla’s Gigafactory with an annual output capacity of 50 GWh of the battery packs.

2. Techno-economic analysis

2.1. Applications

2.1.1. Primary frequency control

A transmission system operator (TSO) has the task of keeping the equilibrium between electricity generation and demand at all times. To do so, it needs different types of frequency control reserves that differ according to volume, speed of activation, and duration. Primary frequency control (PRL) is the automatically called, fast and proportional response of an energy source to a frequency deviation from the reference range. Any prequalified unit can provide frequency support. For a BESS providing a multitude of ancillary services, it is favorable if the grid connection is unconstrained and highly reliable, such as a connection to the 220kV transmission grid. Figure 7 demonstrated principles of frequency control in power systems following an outage of a power plant.

Technical requirements

As the fastest reserve, PRL is automatically called immediately after a frequency deviation detection. In the CE ENTSO-E zone, a primary reserve must be activated immediately after detection of a frequency deviation and must reach a level of 100% in 30 seconds (50% in 15 seconds). One of the specific requirements is that the qualified supplier of reserve capacity must be capable of providing a full contracted positive or negative power over 15 minutes. Currently, the total requirement for the PRL in Switzerland is 70 MW.

Remuneration

The qualified supplier of PRL reserve may submit bids on a weekly basis today and possibly on a daily basis in the future (with capacity specified for the 24 hours of a day). The PRL reserves are symmetric and are paid as bid based on provided capacity in MW.

Received remuneration is based on acceptance of the bid by the market; i.e. whether the offered bid price is below or above the market clearing price. In the following, we assume that the BESS bids are close to the market price; however, the acceptance rate of its bids is 90%.

Swissgrid predicts PRL prices to decrease in the period 2016-2030 (Figure 8, blue line). For the period beyond 2030 (e.g. with 30 years' system life, 2045), we consider a flat price of 18 CHF/MWh/h.

Since PRL prices in real CHF are expected to decrease due to growing competition, the annual earnings in real CHF (Figure 8, red bars) are expected to go down as well from about 150 kCHF for ±1 MW of PRL in 2016 to about 142 kCHF for the same amount of regulation power in 2030.

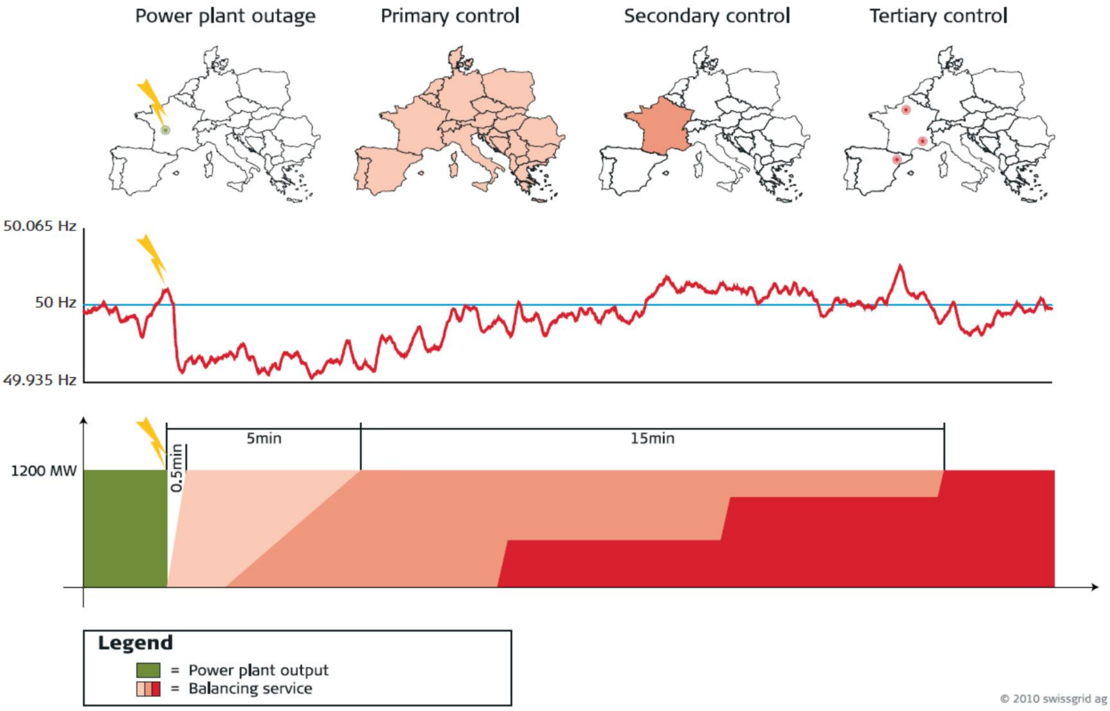


Figure 7. Example of a power plant outage in France [14].

2.1.2. Secondary and tertiary frequency control

Secondary and tertiary frequency control was excluded from the further detailed consideration based on the simplified analysis and discussion in the working group due to the following reasons:

- Secondary control reserves might be required for a much longer period than primary control – i.e. one hour – while tertiary control may be needed for periods of a few hours.
- Cycles are likely to be much deeper compared with primary control, resulting in worse aging.
- Remuneration for the secondary control reserves is conducted for the capacity and energy provided; however, energy would also need to be procured from the market. Knowing the efficiency of the charging cycle, this would be close to zero profit/loss. Capacity payments for the secondary control reserves are slightly higher than for the primary. Combined with the requirement for much larger battery capacity, this is a worse option than a primary control reserves provision.
- The picture is even clearer (more negative) for tertiary control.

This conclusion is also in line with broadly conducted studies, the results of which are available in technical and scientific literature [1],[16],[18],[20],[21].

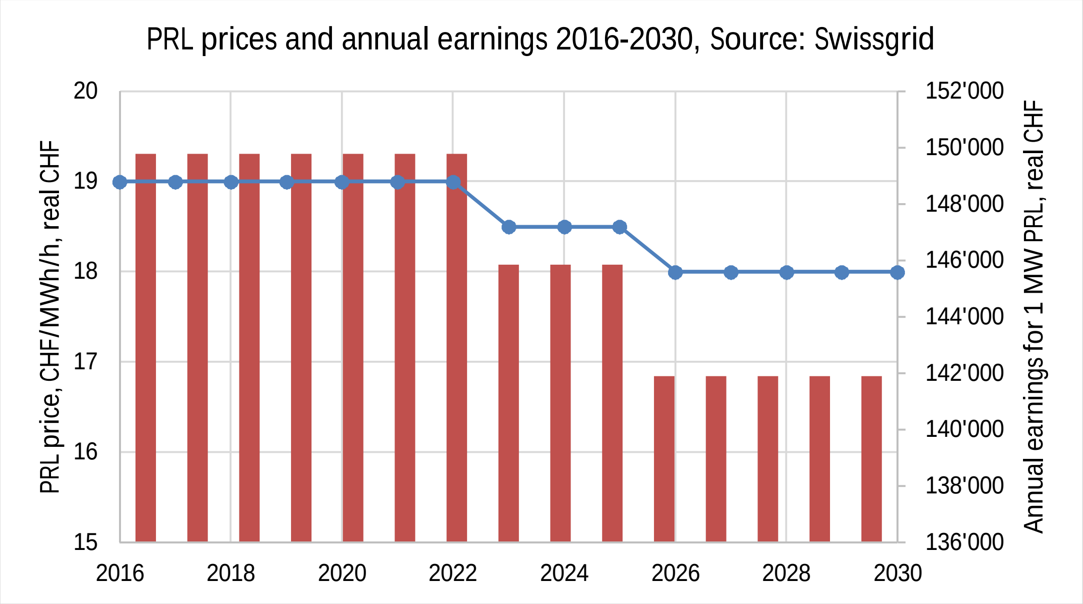


Figure 8. Future PRL prices (in blue) and annual benefit of supply of PRL (in red).

2.1.3. Voltage control

Voltage support and reactive power provision principles, technical requirements and remuneration are described in the corresponding Swissgrid documents [4] page 9, [5]. Swissgrid defines hourly voltage set points in advance and distributes these to participants.

In order to evaluate the potential of the reactive power provision in the particular node in detail, one would need to obtain a series of state-estimation snapshots from Swissgrid and apply voltage scheduling principles; however, these may not represent future situations correctly. Based on expert evaluation, in the calculations below a participation factor of 50% is assumed for the reactive power provision capability; i.e. remuneration covers 50% of the reactive energy that a specific BESS can potentially produce. Simultaneously, we estimate, based on the expert opinion, that half the converter capacity will be available for reactive power provision. Thus, the assumption can be made that the system needs reactive power half the time and the BESS responds with reactive power compensation at half the nominal converter power.

Technical requirements

Participants connected to the transmission level can choose between an active and passive role in voltage support. Passive grid users do not take on any responsibilities or obligations with regard to active voltage support in the transmission system. In the event that they exceed the cost-free range, they are billed for the cost of the reactive energy. Active participants must fulfill the reactive energy provision for 80% of time, otherwise they can be disqualified. In addition, a supra-mandatory role can be chosen; i.e. provision of the reactive power beyond mandatory. Active participants provide only available reactive power; i.e. that which does not require change of the operating point. The studied BESS can participate actively to voltage support and get remunerated for this service.

Remuneration

Both active and passive [7] participants are penalized for noncompliant reactive power. Active participants are remunerated for reactive power provision if it is compliant more than 80% of the month; i.e. absorption of reactive power during high voltage conditions and conversely injection of reactive power during low voltage conditions. The current Swissgrid remuneration tariff is 0.3 cents/kvarh [8]. We assume that this price will not change and use it in this study for a quantification of the benefit.

2.1.4. Black start

Black start is the process of restoration of an electric power station or part of an electric grid to operation. Normally, the electric power used within the plant is provided from the station's emergency power supply generators (diesel). At the initial phase of the restoration process, generation and load come in steps that can cause large frequency deviations due to low system inertia. The BESS can help to start a remote power plant in the event local sources are not available, and can help to balance the restoration process before the system gains a certain level of inertia.

Technical requirements

Black start capability is evaluated in connection with the specific system restoration plan. Clearly, the BESS would be a valuable and technically feasible support source capable of fast load balancing and voltage support. It should be considered that under black start conditions, lines are unloaded and generate large volumes of the reactive power, which should be compensated in order to transfer active power from the BESS to remote locations. With appropriate compensation, the BESS can provide sufficient reactive power compensation and additional reactive power.

For example, a 220 kV transmission line with zero loading may generate about 25-30 MVAr per 100 km. Therefore, a 10 MVA converter used at power factor 0.9 may reach about 15-20 km without the need for additional compensation (e.g. shunt reactor). A 30 MVA converter used at power factor 0.9 will triple the distance and can potentially reach a remote plant located 45-60 km away.

Remuneration

Swissgrid spends about CHF 1 million per year to ensure sufficient black start capacity [13]. In this study, based on the expert assessment, 10% of the present total black start capacity cost is assumed as a payment to the BESS facility to provide black start power and support the grid restoration process. Therefore, we consider 0.1 MCHF additional annual benefit independent of the actual BESS size.

2.1.5. Transmission line outage, system integrity support, system reliability

The specific location of Laufenburg, as considered in this study, is one of the electrically strongest nodes in Europe with a large number of connected lines. Therefore, there is little potential for a BESS to contribute to system integrity support, transmission network reliability enhancement or support of ’n-1’ security. Such contributions are usually tailored to location- and system specific outage scenarios and involves detailed network studies. Results of such simulations are not publicly available hence such an analysis was omitted from the current study by the Steco.

Technical requirements

Technical requirements will depend on the particular limitation and problem addressed.

Remuneration

Currently, similar services to relieve congestion are not remunerated.

2.2. Technical requirements of a battery energy storage system

2.2.1. Factors to consider

Several parameters have significant impact on BESS costs, even for the same BESS technology, namely:

- Maximum power P (active power in MW) of the battery
- Apparent power ratings of the converter, transformer, switchgear
- Maximum capacity E (energy in MWh) of the battery

In order to proceed with a CBA, we have to estimate the proper BESS dimensions, i.e. power and energy, to allow fulfillment of the application requirements as mentioned in the previous section. These requirements must be satisfied during the targeted life-time, despite deterioration of the battery capacity over time and the usage impact.

Active and apparent power

In the event the BESS is used exclusively to deliver active power, the interface to the grid (converter, transformer, switchgear) will have the same rating as the battery (P=S, where S is apparent power).

Should the BESS be used for both frequency control (active power exchange) and voltage control (reactive power exchange), a corresponding reactive power Q in MVAr could be added, so that the rating of the grid interface S is higher than P of the battery. As discussed, the BESS can fulfill reactive power provision obligations in an active role also without additional over-dimensioning of the converter; however, the contribution and revenues may be smaller.

In addition, no additional power needs to be reserved for black start operation, since in these conditions system control and ancillary services are structured differently. The overall control scheme should be developed separately for such emergency operation and the BESS technology.

Thus, we assume that a lithium-ion battery dimension depends exclusively on the PRL application.

Maximum capacity

Let us first consider the required capacity rating, while ignoring the impact of operational and calendar aging.

Based on the frequency control regulation principle in ENTSO-E, in the worst-case requirement, the full PRL reserve must be provided over 15 minutes in a low frequency event (frequency ≤ 49.8 Hz).

Therefore, in the case of ±X MW of PRL, the BESS must have at least 0.25*X MWh of a 'fully' charged capacity and 0.25*X MWh of an 'empty' capacity in order to respond to the system disturbances. More commonly in the operational practice, PRL steadily responds to the system's frequency deviations and does not have continuous positive or negative contribution for the longer time periods in the range of minutes. Simultaneously, it might be beneficial to increase the capacity of the BESS to avoid deep discharges, and thus prolong its life-time. Yet, this consideration depends on both statistics of the required operation and the approach to state of charge maintenance, or on the statistics of the charge-discharge cycles, as considered in the calculations below. Details of the lithium battery capacity aging model can be found in [7].

We also consider that this 'locked' capacity will also be available in the event of a black start, since two applications will not be physically needed at the same time and will share the same capacity. Indeed, PRL contributes to the frequency support continuously; even during stressed operation resulting in a blackout, hence one can expect that primary control would not be used constantly in one direction only. Instead, it would contribute (fluctuate) to frequency corrections and compensate the effect of other control means (e.g. secondary control). Besides, blackout development might not be linked to frequency problems or may evolve much faster than 15 minutes.

Thus, we consider that no additional capacity is envisaged for a black start application. This principle has been agreed and accepted for this study by Steco and Swissgrid. Should it not be accepted in practice, the economic indicators and figures will change correspondingly.

2.2.2. Impact of state of charge maintenance

State of charge (SoC) control, i.e. maintaining the SoC near its reference value or within the operating range in parallel to performing the frequency control application, plays an important role in the definition of the required battery capacity and the battery life-time. The BESS may not see a zero-mean control signal (having a net zero energy exchange with the connected grid) over a short period of time (few hours). This may result in the

BESS being fully charged or fully discharged without the possibility of providing contracted PRL or other services. In addition, the BESS full-cycle efficiency is less than 100%. Therefore, the SoC has to be corrected over time in order to keep it within the 'comfort zone' to allow provision of contracted services and minimize the battery capacity aging over time. For other applications, the loss of active power in the converter for the reactive power regulation was ignored in the simulations. A black start service can not be simulated in a regular system operation; furthermore, it is a rare event and the losses can be ignored. Thus, in the following we discuss a PRL application only.

Several well-known strategies exist for the SoC control proposed by the industry and academia [4],[9],[10],[11]. Their main difference is in a mechanism for procurement of the off-set power for battery recharging/discharging. This power comes on top of the power exchange with the grid required by the frequency control application. In some situations, these two power signals may add up and the total power exchange between the BESS and the grid may exceed the contracted capacity of PRL. It would seem that it requires an over-dimensioning of power conversion and grid interconnection equipment. Our assumption is that at the moment when the full reserve activation is required for 15 minutes, the SoC control should not be activated and in this case the battery will be allowed to discharge fully or charged to 100%; thus, no converter over-dimensioning is required for the PRL function. We address and quantify consider this aspect in the computations below.

The total capacity (energy) is computed via simulation of a performance of the BESS with an annual frequency profile (1Hz sampling) provided by Swissgrid as in Figure 9. The profile is repeated 't' number of years and the remaining BESS capacity (aging) is estimated for each year. The input parameters for the simulation are listed in Table 1. There, the BESS capacity is determined empirically to comply with the operational and end-of-life aging requirements. The SoC minimum and maximum are the settings for the control strategy, which are chosen empirically and verified by the simulations as shown in Table 2. We analyze the links among these parameters based on the example of strategy A i.e. the battery must able to provide 10 MW for 15 minutes, which results in 2.5 MWh minimum charged energy; for a battery of 9.2 MWh, this corresponds to 28%. The parameters in Table 1 demonstrate that several solutions are possible, depending on the charging strategy and agreement with the balancing group, trends and the influences of these parameters on the BESS capacity and therefore costs.

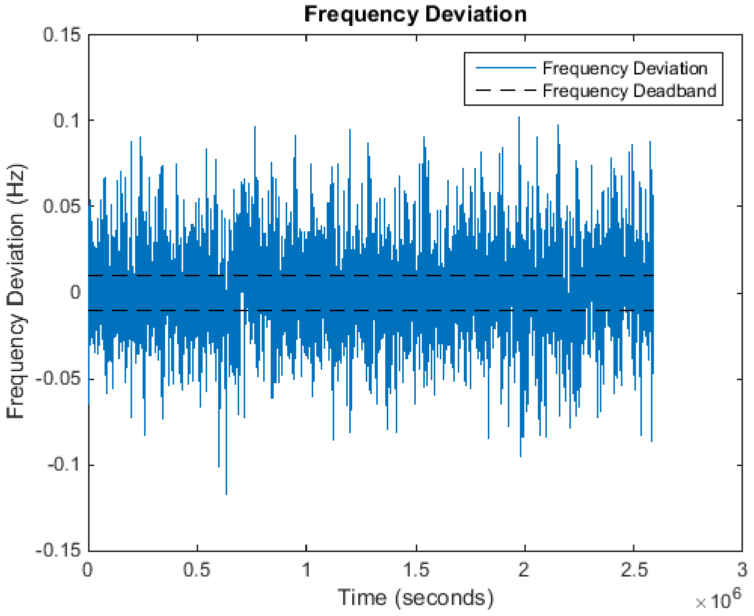


Figure 9. Frequency deviation profile; i.e. zero frequency deviation implies that system frequency is 50.00 Hz. A regulation dead-band is ±10 mHz. Source: Swissgrid internal data.

Table 1. Input parameters for a battery capacity aging simulation (BESS of 10 MW only).

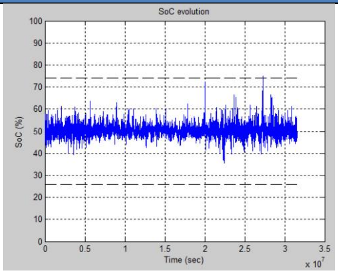
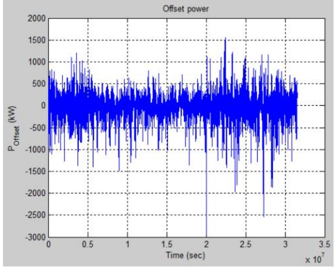
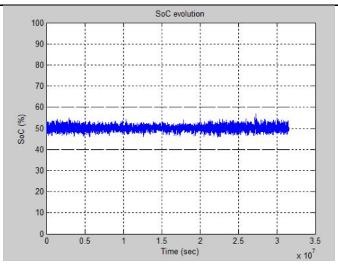
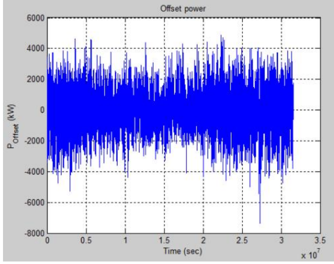
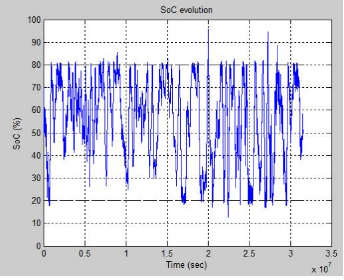
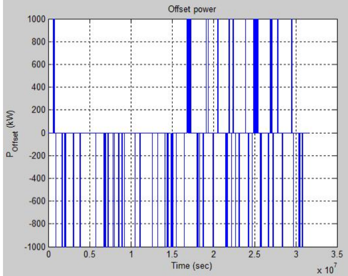
Strategy	**Power, MW**	**Energy, MWh**	**SoC min**	**SoC max**	**Avg period, sec**	**Dispatch delay, sec**	**Ramp, sec**	**Offset duration, sec**	**Offset to power ratio**	**Cell temp, C**
A	10	9.2	0.28	0.72	3600	900	-	-	-	25
A*	10	6.3	0.40	0.60	300	60	-	-	-	25
B	10	12.5	0.20	0.80	-	-	300	600	0.1	25

We used the following SoC control strategies:

Strategy A [8] – An off-set power is acquired continuously via a calculation of moving average. The control parameters comprise past time window duration and a time delay in the offset implementation. The energy should be compensated by a balance group. In case A*, the correction is implemented almost immediately (one-minute delay).

Strategy B [9] – An off-set power is acquired on request from other energy sources, which ramp up or down on a signal issued by the BESS control system. The control parameters comprise fixed levels of off-set power, ramp of fixed slope and fixed duration of one call for providing off-set power. The control action is active when the SoC exceeds predefined minimum or maximum thresholds. The energy used for charging/discharging the battery is assumed to be compensated by a balancing group.

Table 2. Simulation results of the battery end of life.

Strategy	EoL 80%, years	Annual SoC profile	Annual power off-set profile	Annual off-set power
A	~17-17.5			Buy: 516 MWh Sell: 565 MWh
A*	~17.5-18			Buy: 1245 MWh Sell: 1656 MWh
B	~18			Buy: 87 MWh Sell: 136 MWh

Strategy A allows handling of a PRL obligation with a smaller size battery due to a fast, unscheduled correction of SoC. Case A* results in a practically flat SoC profile <3% variation, as it assumes that used energy is recharged almost immediately from the balancing group, which results in a small variation in the SoC.

Simultaneously, strategy A and A* need a larger amount of off-set power, which increases as the averaging period and dispatch delay decrease. Indeed, in a longer time horizon at least part of the energy would be recharged by the contribution to the frequency regulation, while in the short period frequency deviation tends to be asymmetric. If SoC is permanently corrected instead of being corrected by natural frequency variations, more energy will be used in both a positive and negative direction. This may make charging cycle losses more marked. The annual off-set power is shown in Table 2, both for the positive and negative direction, and differs to the total energy fluctuation of the battery, as part of the energy is received/given to the grid and is not considered.

2.2.3. Verification of the end of life requirement

In all the simulated cases, the system showed relatively similar end of life (EoL) results. We considered the EoL criterion as 80% of the initial BESS capacity and we calculated the time before this condition is reached by repetitively feeding our model with the frequency profile shown in Figure 9.

The result in Table 2 shows an expected life of 17 to 18 years, depending on the system size and operating strategy. The capacity aging is mainly due to a calendar aging effect.

Since the benefits are calculated for 15 and 30 years of operation, we set 15 years as a targeted life of the battery. The results show that for each control direction i.e. provision of positive or negative regulation, almost no incidents occur in which the BESS cannot fulfill the requirements, due to the SoC that guarantees a discharge/charge of the contracted power over 15 minutes.

Therefore, for the final cost-benefit analysis, we consider three different discharge times for each power option: 40 (variant A), 55 (variant B) and 75 minutes (variant C), which define the total battery capacity.

2.3. Cost-benefit analysis

The goal of the cost-benefit analysis (CBA) is to obtain an indication of whether a reviewed BESS system could be an interesting business case under current market conditions.

2.3.1. Evaluation of costs

The price estimate was conducted based on the collected market price estimates for the following equipment that would constitute the total BESS installation. Schematic visualization of the BESS is shown in Figure 10.

Included items:

- Converters
- Batteries
- Step-up transformer (to MV level)
- MV switchgear
- Controller
- Auxiliary systems
- Installation of the described items above.
- Containers, HVAC, firefighting

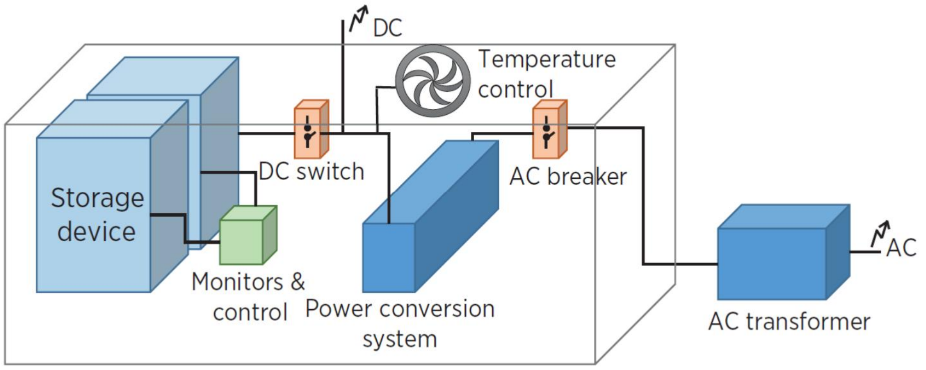
The BESS is assumed to be connected to an existing 220 kV GIS substation. Connection cost estimates included electrical equipment, such as substation and transformer extensions, and installation and civil works.

It is clear from the numbers that the BESS with a larger MVA rating will cost less per MVA, since the connection costs are not significantly lower for smaller BESS sizes.

Excluded items:

- Integration at existing controls
- Cabling outside the containers

Figure 3: Battery storage system and primary power components



Source: Based on EPRI and DOE, 2013

Figure 10. Schematic visualization of BESS components [2].

In addition, operational and maintenance costs should be considered. Due to the fully automated operations of the installed BESS facility, operational and maintenance costs are assumed to be zero and were excluded from the study. In [3], maintenance costs were assumed to be 1% per year.

2.3.2. Evaluation of the total benefit

The business case has been evaluated for several BESS power ratings, namely 10, 20 and 30 MW. Larger storage sizes are limited both by the space at the considered facility and the technical need for the reserves. The capacity of the BESS (energy) was determined based on the historical frequency profile and the requirement of PRL provision over 15 minutes in the previous sections.

The capacity of the BESS converter determines reactive power provision capability. The converter can operate at various power factors, yet apparent power must not exceed the converter rating. If we assume that we target provision of PRL up to 10 MW (or 10 MW BESS), then all the converter capacity that is not employed at that particular instance by the activated frequency control can be used for reactive power support. Since contribution to the reactive power control is required only within the limits of the device, even if the converter is fully used for the frequency reserve provision, the BESS remains compliant with the reactive power provision requirement.

The total benefit aggregates remunerations from all three services and can be expressed as follows:

$$Annual\ Benefit = B_{PRL} * P_{BESS} * 8760 * \alpha + B_V * Q_{BESS} * 8760 * \beta + B_{BS}$$

where: B_{PRL}, $P_{BESS}, \alpha, B_V, Q_{BESS}, \beta, B_{BS}$ are as specified in Table 4.

We used a conversion of real prices for provision of all three services into nominal 2015 prices using the inflation rate. In addition, future annual benefits are discounted in order to calculate a present value in 2015.

Thus,

$$Nominal\ price = Real\ price * (1 - r_i)^t$$

$$PV\ Benefit_t = \frac{Benefit_t}{(1 + r_d)^t}$$

where t is a considered year, r_i, r_d are specified in Table 3.

Table 5 provides an estimated present value of the benefit for 15 and 30 years of provision of above-mentioned services for three sizes of BESS (10, 20 and 30 MW) using parameters in Table 3 and Table 4.

Figure 11 graphically illustrates the contribution of each application to a total system benefit after 15 years of operation for a 10 MW BESS. It is dominated by benefits of provision of PRL, while voltage control and black start together cover only 6%.

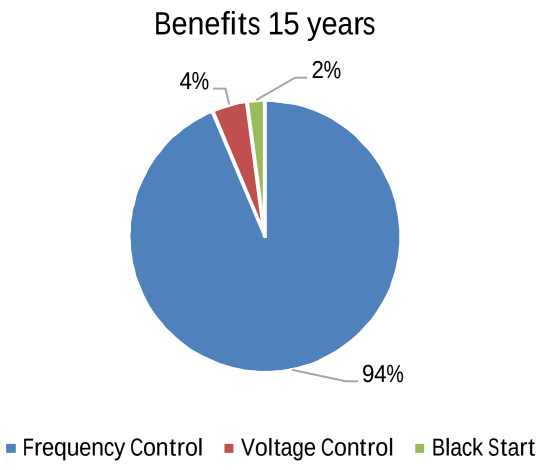


Figure 11. Summary of BESS benefits after 15 years of operation.

Table 3. Inflation and discount rate parameters for a quantification of the benefits.

Parameter	Description	Values
r_i	Annual inflation rate	1%
r_d	Annual discount rate	2%

Table 4. Input parameters for quantification of benefits.

Parameter	Description	Values
B_{PRL} **(CHF/MW/h)**	real market price of the primary reserve, per hour	shown in Figure 5
P_{BESS} **(MW)**	BESS-rated power; we assume positive (and negative) reserve as P_{BESS}	10, 20 and 30 MW
α	Success rate of bidding or system utilization factor	90%
B_V **(CHF/MVAr/h)**	compensation tariff for provision of reactive energy	current Swissgrid tariff for active participation = CHF 0.30/kvarh (used for the whole lifetime)
Q_{BESS} **(MVAr)**	available reactive power of the BESS	5, 10, 15 MVAr for corresponding P_{BESS} (per Steco and expert decision)
β	utilization factor of the maximum available reactive power compensation Q_{BESS}	50% (per Steco and expert decision)
B_{BS}	black start benefit	CHF 100,000 per year independent of P_{BESS}

Table 5. Results of a quantification of benefits.

P_{BESS} Q_{BESS}	Duration, years	Primary frequency control, MCHF	Voltage control, MCHF	Black start, MCHF	Total benefit, MCHF
10 MW **5 MVAr**	15	17	0.8	1.2	19
	30	28	1.3	2.0	32
20 MW **10 MVAr**	15	35	1.6	1.2	38
	30	57	2.6	2.0	61
30 MW **15 MVAr**	15	52	2.3	1.2	56
	30	85	3.8	2.0	91

Table 6. Detailed calculations of revenues from different services and total present value, BESS 10 MW.

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Real tariffs															
PCR tariff, CHF /MW	19	19	19	19	19	19	19	18.5	18.5	18.5	18	18	18	18	18
Voltage control, CHF/MVARh	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Black start, kCHF	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Nominal tariffs															
PCR tariff, CHF/MW	18.81	18.62	18.44	18.25	18.07	17.89	17.71	17.07	16.90	16.73	16.12	15.95	15.80	15.64	15.48
Voltage control, CHF/MVARh	2.97	2.94	2.91	2.88	2.85	2.82	2.80	2.77	2.74	2.71	2.69	2.66	2.63	2.61	2.58
Black start, kCHF	99.00	98.01	97.03	96.06	95.10	94.15	93.21	92.27	91.35	90.44	89.53	88.64	87.75	86.87	86.01
Nominal revenues, MCHF															
PCR	1.483	1.468	1.453	1.439	1.425	1.410	1.396	1.346	1.332	1.319	1.271	1.258	1.245	1.233	1.221
Voltage control	0.065	0.064	0.064	0.063	0.062	0.062	0.061	0.061	0.060	0.059	0.059	0.058	0.058	0.057	0.057
Black start	0.099	0.098	0.097	0.096	0.095	0.094	0.093	0.092	0.091	0.090	0.090	0.089	0.088	0.087	0.086
Total	1.65	1.63	1.61	1.60	1.58	1.57	1.55	1.50	1.48	1.47	1.42	1.40	1.39	1.38	1.36
Present value, MCHF															
PCR	1.45	1.41	1.37	1.33	1.29	1.25	1.22	1.15	1.11	1.08	1.02	0.99	0.96	0.93	0.91
Voltage control	0.064	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04
Black start	0.10	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.06
Annual total present value	1.61	1.57	1.52	1.48	1.43	1.39	1.35	1.28	1.24	1.21	1.14	1.11	1.08	1.04	1.01
Total present value	1.61	3.18	4.70	6.18	7.61	9.00	10.35	11.63	12.87	14.08	15.22	16.33	17.40	18.45	19.46

2.3.3. Net present value calculations

By combining estimated costs (as described in 2.3.1) and benefits in an equation, we calculate a net present value (NPV), payback time and return on investment (ROI) for variants A to C (discharge times in the approximate range of 30 to 80 minutes) of the BESS, as shown in Table 7.

Table 7. NPV, payback time and ROI results.

Discharge time, variant	**System lifetime, years**	**Installed power, MW**								
		10			**20**			**30**		
		NPV, MCHF	Payback time, years	ROI, %	NPV, MCHF	Payback time, years	ROI, %	NPV, MCHF	Payback time, years	ROI, %
A	15	3.9	12+	125	11.7	10+	145	19.7	9+	154%
	30	15		191	33.6		222	52.2		236%
B	15	1.5	14+	108	7.3	12+	124	12.9	11+	130%
	30	12.5		165	28.9		190	45.1		199%
C	15	-1.3	18+	94	2.2	14+	106	4.9	14+	110%
	30	9.5		143	23.5		163	36.6		168%

Table 7 illustrates a variation of NPV and a payback time as a function of the BESS discharge time; i.e. BESS energy for a fixed maximum power rating of 10, 20, 30 MW. The fixed power rating determines benefits, while the BESS costs are also influenced by the size (capacity) of the system. It naturally follows that for the smaller energy/discharge time, the BESS provides the highest economic figures. As mentioned before, the BESS size varies due to the SoC control strategy, and further discussions and studies should be made in order to define which control strategies are feasible from a system security point of view.

Figure 12 shows NPV over time for a system of 30 MW and various capacities. A step change after 15 years is due to replacement of the battery cells.

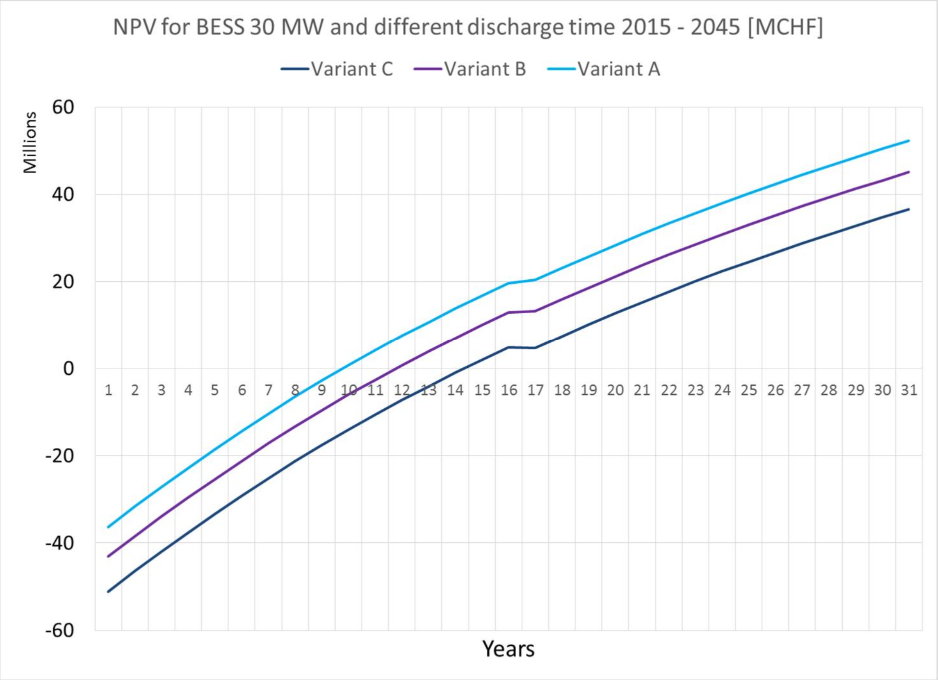


Figure 12. NPV for 30 MW BESS with differing discharge times.

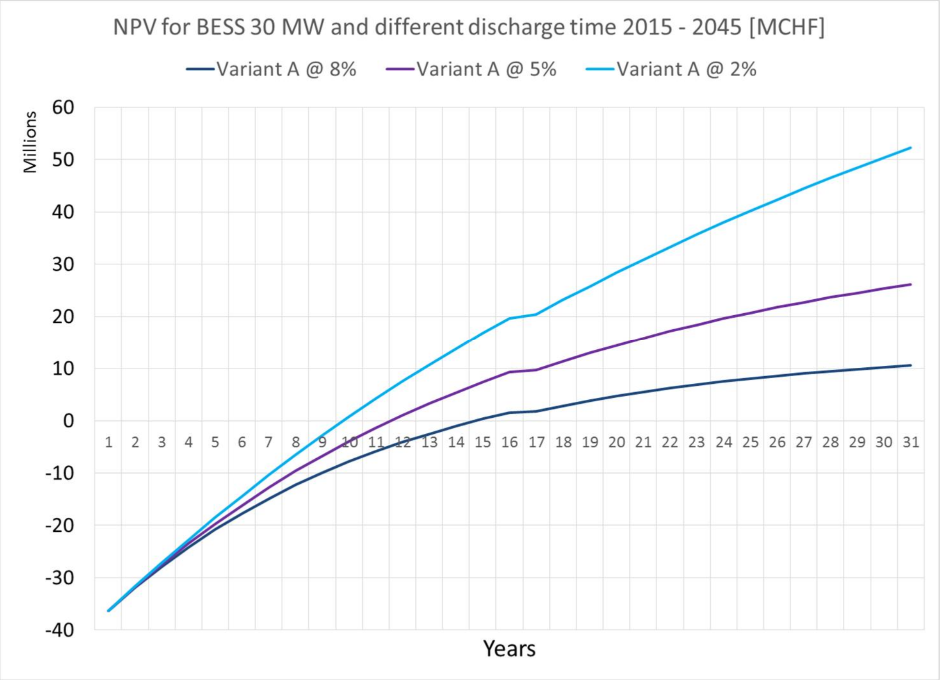


Figure 13. NPV for 30 MW BESS with differing discount rates.

2.3.4. Sensitivity analysis

Figure 13 shows the effect of discount rate value on the system NPV. As mentioned previously, we use a discount rate of 2%. It is clear that higher discount rates will reduce the system NPV, which however remains positive for the 30 MW BESS variant A. The question of which discount rate should be used is very important and further in-depth risk assessment should be made in order to select a realistic value. It is also possible to use a dynamic value, which will grow in the more distant future to address service price uncertainty.

On the other hand, we completely ignore the possibility of changes in the range of ancillary service products; for example, a fast response similar to inertial response of rotating machines (virtual inertia) or introduction of performance payment schemes, where a provider receives extra remuneration for speed and accuracy of response to a control signal, thus potentially increasing revenues for BESS owners.

Summary and outlook

This report summarizes the results of a preliminary technical and economic feasibility assessment of using a large-scale battery energy storage at a transmission substation in Switzerland.

The main targeted applications include primary frequency control, voltage control and support of system restoration after a major blackout – black start. An estimated forecast of future prices for these services was provided by Swissgrid. The primary frequency control benefit dominates the total benefit, but future prices for this service are expected to decrease due to the growing market competition. Voltage control and black start prices are considered to remain constant and they make a minor contribution to the total benefit.

When sizing and evaluating a BESS, it is important to take into account the effect of capacity aging. We dimension the BESS in such a way that it provides the same amount of reserve power over the whole life period. Our simulations have shown that 15 years is an achievable battery life. Grid interfacing equipment, such as converters and transformers, have a longer life span; therefore, we assume two cases of 15 and 30 years. In the case of 30 years' system life, the battery is replaced after 15 years.

SoC control strategy is another important factor that can significantly influence the system size in terms of required discharge time. A strategy where the off-set power, needed to keep a SoC close to the reference value, can be taken with the shortest delay results in a smaller size and lower price.

Grid connection prices to the 220 kV level are practically independent from the BESS rating in MW. Therefore, a BESS with a larger MW rating shows better economic results.

Several further steps can be taken to improve the analysis and make a more accurate CBA (potential cost reduction) in the event of interest and support from the major stakeholders:

- Model the surrounding grid and run numerical analysis in order to better understand the potential voltage control and system requirements (reactive compensation) for a black start.
- Investigate whether the grid connection cost can be reduced by connection of the BESS to an autotransformer without installation of a dedicated power transformer.
- Investigate possible improvements in SoC control strategy using SoC prediction techniques and risk management.
- Apply CBA to different types of Li-ion batteries.
- Investigate potential and conduct CBA for the BESS at several other substations.
- Investigate the possibility of use of the BESS for other system level applications; e.g. harmonics mitigation, system protection schemes, etc. The overall system integrity protection scheme should be developed separately for emergency operation and

BESS technology. This could also include use of multiple large-scale BESS in Switzerland and coordination for voltage control, and use in system protection and restoration schemes.

- Examine potential benefits of use of the ‘pay for performance’ mechanism used in the US (FERC Order 755) for a system operator and owner of the BESS in frequency control provision.

It would be desirable to further explore the benefits of using BESS for ancillary services and control structures of power systems.

A BESS is able to provide faster and more accurate response characteristics than other providers of ancillary services i.e. rotating machines. However, a long activation time leading to a large energy capacity of the battery makes a BESS less economic. Should the technical requirements consider energy limitations and the merits of each technology and a new performance-based reward structure be introduced, the economic value of a BESS would be further improved.

References

[1] A.Oudalov, Microgrid Storage Integration: Battery modeling and advanced control, 10th Microgrid Symposium, Beijing, November 13-14, 2014.

[2] IRENA, Battery storage for renewables: Market status and technology outlook, Report, 2015.

[3] Sandia National Lab. DOE/EPRI in Collaboration with NRECA, Electricity Storage Handbook, 2015. Available at: http://www.sandia.gov/ess/tools/doeepri-electricity-storage-handbook/, accessed 16.06.2016

[4] Ch. Hewicker et al, KEMA Consulting GMBH under assignment of Bundesamt für Energie, Energiespeicher in der Schweiz: Bedarf, Wirtschaftlichkeit und Rahmenbedingungen im Kontext der Energiestrategie 2050, December 2013. Available at: http://www.bfe.admin.ch/forschungenergiespeicher/index.html?lang=de&dossier_id=06230, accessed: 16.06.2016.

[5] Oudalov, D. Chartouni, C. Ohler, Optimizing a Battery Energy Storage System for Primary Frequency Control. IEEE Transactions on Power Systems, Vol 22, No 3, pp. 1259-1266, 2007.

[6] Nykvist, M. Nilsson. Rapidly falling costs of battery packs for electric vehicles, Nature Climate Change, no. 5, pp. 329-332, 2015.

[7] Swissgrid, Basic principles of ancillary service products, Product description, online: https://www.swissgrid.ch/dam/swissgrid/experts/ancillary_services/Dokumente/D160111_AS-Products_V9R1_en.pdf, accessed 16.06.2016;

[8] Swissgrid, Voltage support concept for the Swiss transmission system from 2011, online: https://www.swissgrid.ch/swissgrid/en/home/experts/topics/ancillary_services/voltage_support.html, accessed 16.06.2016.

[9] Published tariffs of Swissgrid, online: https://www.swissgrid.ch/swissgrid/en/home/experts/topics/grid_usage.html, accessed on 16.06.2016

[10] B. Xu. Degradation-limiting optimization of BESS operation. Master thesis report. ETH-PSL-316. Available at: https://www.eeh.ee.ethz.ch/uploads/tx_eth-publications/Xu_MA_2013.pdf accessed 17.11.2015

[11] T. Borsche, A. Ulbig, M. Koller, G. Andersson. Power and energy capacity requirements of storages providing frequency control reserves. IEEE Power and Energy Society General Meeting, 2013

[12] O. Megel, J. L. Mathieu, G. Andersson. Maximizing the potential of energy storage to provide fast frequency control, 4th IEEE Innovative Smart Grid Technologies Europe, 2013.

[13] Thackeray, Michael M. "Manganese oxides for lithium batteries." Progress in Solid State Chemistry 25.1, 1997.

[14] Swissgrid, Annual Report 2015, Available at: https://www.swissgrid.ch/dam/swissgrid/company/publications/en/Swissgrid_GB15_en.pdf accessed 1.06.2016

[15] Martin Beck, Marc Scherer, Overview of ancillary services, online: https://www.swissgrid.ch/dam/swissgrid/experts/ancillary_services/Dokumente/D100412_AS-concept_V1R0_en.pdf, accessed: 16.06.2016.

[16] ENTSO-E, Supporting Document for the Network Code on Load-Frequency Control and Reserves, 2013

[17] Consentec, Description of load-frequency control concept and market for control reserves, 27 February 2014

[18] National Grid, Enhanced Frequency Control Capability (EFCC), online: http://www.nationalgridconnecting.com/The_balance_of_power/EFCC%20Battery_Storage_Investigation_Report.pdf, June 2015. Accessed: 16.06.2016.

[19] Bolun Xu, Yury Dvorkin, Daniel S. Kirschen, A Comparison of Policies on the Participation of Storage in U.S. Frequency Regulation Markets - IEEE PES General Meeting, 2016.

[20] Fraunhofer Institute for Systems and Innovation Research ISI, Technology Roadmap Energy storage for Electric mobility 2030, 2015

[21] IEC, Electrical Energy Storage, White Paper, 2011

[22] EPRI, Electricity Energy Storage Technology Options, A White Paper Primer on Applications, Costs, and Benefits, 1020676, December 2010

[23] Alexis Kwasinski, Distributed Generation Technologies, Course documentation, University of Texas at Austin, EE394J10, Fall 2012