BESS Techno-economic Challenges to Support Wind Energy: Mind Mapping and Correlation Matrix

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***Abstract*— This paper proposes a compact approach to perform a preliminary techno-economic feasibility study to decide the technology and size of Battery Energy Storage System (BESS) that is suitable to particular application(s). A detailed mind matrix is proposed to provide a high-level vision of the incorporated techno-economic challenges and questions within the process, where 38 issues are expansively considered. Afterwards, a prioritization scheme is presented to evaluate the benefits and required capacity of BESS integration aiming to mitigate the complexity of such study. A simplified costing model is also discussed to highlight the main factors that judge the financial value of the BESS. This paper provides spotlight on the key knowledge gaps and research areas that could be of interest to industry and academic stakeholders.**

***Index Terms*—battery storage, wind power, Li-ion, power systems, ancillary services.**

I. Introduction

Energy strong candidate to support renewable energy sources mainly solar and wind. BESS can play a key role as either provider of ancillary services (AS) or balancing/smoothing stochastic renewable power [1-4]. Literature exploits several types of energy storage mediums, some of them are still in early stage of development while others stand on a solid ground of mature technologies [5]. This paper focuses on BESS as it is widely applied in power systems and intensively investigated in many R&D projects. Energy storage mediums could be integrated to flatten wind power intermittency, thus mitigate system transient stability issues, and aid wind farms (WFs) to supply their forecasted production i.e. defined time-interval bidding. The literature investigates several methods of providing AS to assist wind turbines' generators (WTGs) and/or provide such services on their behalf. Particularly, wide range of frequency support direct methods are vulnerable to wind power conditions just before, during and shortly after the frequency event [6]. Moreover, the majority of these control methods make the WTG deviates from Maximum Power Tracking (MPT), implying negative economic influences on WFs' investors. BESS can overcome such obstacles as an auxiliary source of energy, which is more stable, ultra-responsive and highly controllable to provide the required power support to curtail frequency events, and other AS. A sizing simulation tool was presented in [7], which focused on wind power forecasting to alleviate the burdens on System Operators (SOs). Three main aspects supervised the forecasting process of WF power i.e. forecasts of wind power, not wind speed (WS), through an agreed-on look-ahead interval up to 48 hours, availability of both single WFs and WFs' clusters; maintain associated level of confidence i.e. defined error thresholds. The offered algorithm aimed to mitigate the error between *hourly* forecasted power and the actual power so that the deviation is below 50% of scheduled output within 95% of forecasting interval according to the Hungarian code requirements. The BESS sizing could also rely on its impact on system frequency excursions [8], where wind power penetration to generation capacity is limited by the allowed threshold of frequency deviations. A composite mathematical method was applied to convert the actual WS data into equally time-sized samples of wind power, where each sample has average and static stochastic fluctuations reflecting turbulences. Thereupon, wind power was regularly integrated into a detailed model of the examined system to obtain system frequency within the required time interval i.e. several samples. The penetration level was monitored and increased unless frequency deviation limit was violated. The next step was integrating a BESS to improve the frequency response of the system, where the BESS acted as a band-stop filter to avoid frequency drops of a certain rate of occurrence.

BESS control is a major challenge where the controller design, tuning and its supplementary role in the holistic control is widely investigated. A self-adaptive control method was proposed in [9], where a Fuzzy controller was applied based on a produced the array of set-points not only of the battery bank but also the coordinated power plants. The acceptable operational range of SoC was divided into favourable, avoided and forbidden regions, this approach should extend lifetime of batteries, where the charging and discharging power was adjusted according to the reference SoC i.e. not set by default to rated power, which is common in conventional operation. Each of the charging and discharging process had its own fuzzification model. The state machine control was used in [10] to coordinate between active power set-points of WFs, battery banks and conventional plants, where the AGC increments, and economic dispatch set-points were considered. Similar to [9], a multi-level SoC control model was proposed to extend the lifetime of batteries. The provision of frequency support by an onshore co-located BESS to complement an offshore WF was developed and investigated in [11]. The BESS was assumed to be 5% of the rated capacity of the offshore WF, and was connected to the onshore point of common coupling

(PCC), where the WF was connected via a high voltage dc link. A supplementary controller was proposed to enable the WF to mimic the response of the BESS during frequency excursions to avoid communicating frequency measurement at PCC to WF controllers. A new controller was developed in [12] to coordinate between the production/consumption of a BESS with the holistic controller of a multi-terminal HVDC grid. This control managed the exchange of frequency support between the ac areas [13], while the BESS controller was able to manipulate the charging/discharging process according to set-points of dc grid controller; frequency conditions at the interconnected ac grids; and the output power of the offshore WFs. The coordinated control of wind energy conversion system with BESS was also investigated in [14], where the active power of permanent magnet synchronous generator was controlled to provide frequency support. The aspect of novelty was simplifying the connection topology of the BESS, where the inverter is replaced by a dc-chopper since the battery bank is connected in parallel with dc – link of the Type 4 WTG. However, this could lead to oversizing the grid side converter to accommodate the additional power fed to the grid from both the WTG and the BESS. Throughout the previous work, several types of batteries were implemented however, the most popular types in the field of balancing and supporting renewable energies' intermittency are NaS, Li-ion, and the new technology of Redox-Vanadium. This technology shows clear merit in lifetime and environmental impact. However, being an immature technology makes it very costly.

II. INTERDEPENDENCIES IN PLANNING AND OPERATION

This section discusses best practices on planning and integration of BESS, starting with a general overview on the major technical, economic and environmental challenges and aspects taking into consideration potential correlations and mutual impacts. Additionally, it presents a comprehensive approach to determine the suitable size of BESS in a specific wind turbine/wind farm application.

A. Expanded overview

The planning and operation of BESS in wind energy applications is a complex process, as various parameters need to be taken into account not only from the BESS and WTG/WF, but also from the hosting power grid. The complexity is caused by the strong to weak correlation between different factors and parameters, where the aimed application(s) is the main driver of both planning and operation where the key R&D topics are classified into these two groups in Table I. The broad mind maps shown in Figure 1 and Figure 2 focus on the main perspectives and factors to be considered to plan, decide and evaluate integration of BESSs to carry out certain applications. The correlation matrix shown in Figure 3 relies on the investigated literature, acquired lessons from running projects worldwide [15-18] through the author's experience. The matrix categorises the interdependencies between the 38 issues listed in the two mind maps to three levels: 1) critical and clear correlation, 2) moderate and most probable, 3) mild and weak relation.

TABLE I. KEY TOPICS OF BESS PLANNING AND INTEGRATION

Planning topics	Operation topics
Location Single/hybrid technology Sizing Environmental Cost/benefit	Application Safety Integration Monitoring

The matrix applies a simplified approach to visualise the different relations where the horizontal headlines are the main topics of Operation, while the number before the arrow indicates the issues related to that topic. The letter after the arrow is the topic identifier from the second mind map and the number is an issue related to that topic. For example, in the Application column, there is a moderate interdependency between Power quality (number before the arrow: issue 3, in Topic A of Operation mind map), and Energy/Power ratio of the integrated BESS, which is issue 5 in Topic C (Sizing) of the Planning mind map, hence it is written as 3 → C5. The main driver is always the target application(s), which determines the BESS physical location, connection hierarchy level, size and adopted approach. The connection hierarchy in this context means the connection point of the BESS i.e. WTG, WTGs ring station, WF substation, PCC, etc. Connection and coordination levels influence significantly the control design. For example, *lower coordination and lower connection hierarchy reduce control complicity and facilitate the optimisation of control parameters.* Higher energy/power ratio (E/P) could extend the allowed flexibility of the controllers' parameters and expand the range of services provided. The applied control method could raise the incorporated operation hazards, mainly if the parameters are set to push the system to its limits. These hazards include overheating (fire hazard) for some technologies such as Li-ion. Moreover, poorly tuned control parameters, in addition to inaccurate monitoring of SOC and temperature, may lead to reduction in the lifetime of the BESS. Conversely, well-designed controllers provide accurate and smart tracking of network requirements and energy markets schemes without violating the secure operation of BESS. As an example, accurate controls adopt sophisticated e.g. sectionalised, SOC models. *Coordination levels between BESS, renewable and conventional power plants, and other grid assets could be a branch of the control issue*, however, it is emphasised according to the connection level, where higher hierarchy leads to complex coordination. *The level of coordination slightly relates to E/P ratio*, where small sized BESS are not capable of providing a wide spectrum of coordination with other power system assets. This returns to the limited rated power and energy capacity compared to other power sources in addition to narrow control margins i.e. SOC. *The ownership aspect plays a moderate role to decide the level of coordination*, where BESS owned by SOs could be more flexible with extended permissions and facilitated operation to react according to system dynamics.

Temperature regulation is a critical aspect on both the environmental and economic aspects. It relies on the location [19] of the BESS, which determines some key factors including moisture levels, average ambient temperature and allowed 'breathing' space inside the compartments. Hence, the presence of co-located BESS at each WTG offshore will be a major challenge. Apart from the unique ZEBRA technology, most common battery technologies can operate at normal ambient temperature, however cooling requirements might differ according to heating rates, which are decided by the selected technology and dominant charging/discharging rates. It is worth noting that optimum *temperature regulation* has pros and cons from the economic point of view, where *optimisation leads to increased infrastructure costs i.e. additional equipment and more hours of operation of such equipment,* but will extend the battery lifetime, hence a compromise is required, which is typically case-dependent.

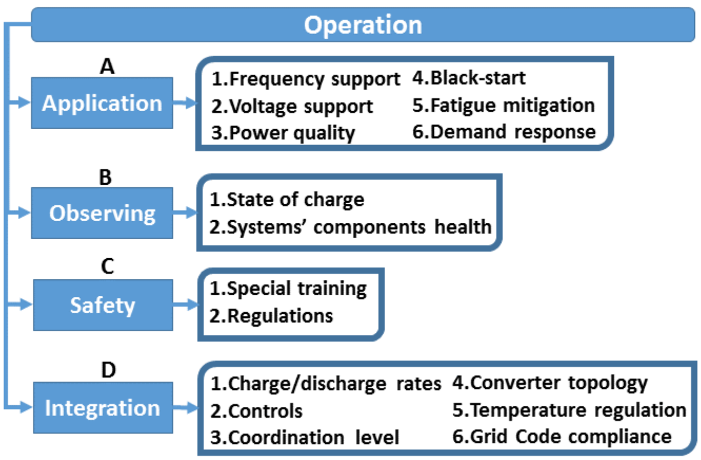

Figure 1. Mind map of Operation related challenges.

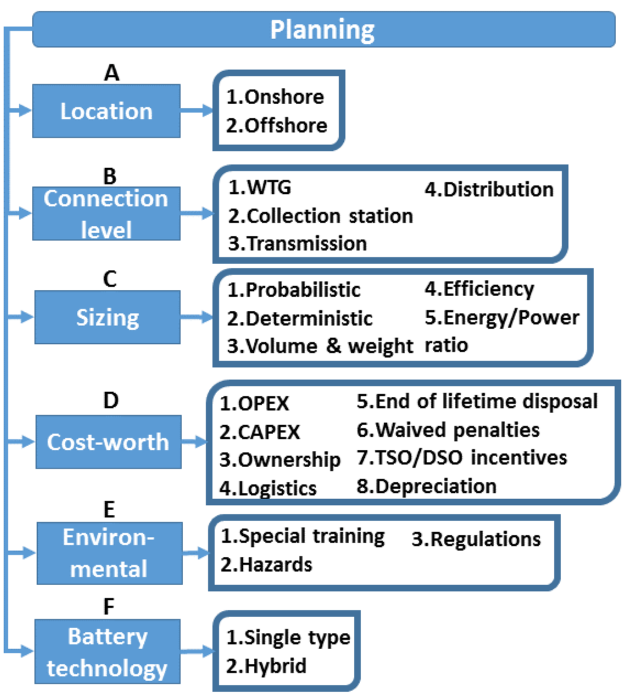

Figure 2. Mind map of Planning related challenges.

	Application	Observing	Safety	Integration
Critical	1→A1; B2, 3, 4; C1, 5; D3, 6 2→ A1; B1, 2, 3, 4; C5; D5, 6 3→A1; B2, 3, 4; D5, 6 4→A1, 2; B2, 3, 4; D6 5→A1, 2; B2, 3, 4; D6 6→A1, 2; B2, 3, 4; D6	1→ D8; F1, 2 2→ D7	1→A1, 2 2→ B1, 2, 3, 4	1→ F1, 2 2→ B1, 2, 3, 4; D7 4→ A1, 2; F2 5→ B1 6→ A1; B1, 2, 3, 4; C5; D6, 7
Moderate	3→ C5; D8 4→ C2, 5; D1, 2, 3 6→ C1, 5; D1, 8	1→ C4; D1, 2 2→ A1, 5; C4; D1; F1, 2	1→ D3, 4 2→ D3, 4	1→ C4, 5; D8 2→ D8; E2 3→ B2, 3, 4; D3, 7 4→ B3; C5; D2 5→ D2; F1 6→ D3, 8
Mild	1→ D6 3→ D3 4→ C1, 3, 4; D8 5→ C1, 2, 4; D1 6→ D2, 6, 7	1→ B1; C3, 5; 2→ B2, 3, 4; C3, 5; D4	1→ C3, D2 2→ C3, D2	1→ D6 3→ D6, 7 4→ B4; 5→ B1; D1;

Figure 3. Correlation matrix between Operation and Planning topics and issues.

III. WIND POWER INSTALLERS FOCUSED VIEW

According to the previous section, it is very challenging to consider all the emphasised aspects to design and operate a BESS. Hence, it is subject to the agreement of stakeholders to focus on certain applications, which are more relevant to WF investors. The cost/benefit dimension is pivotal in such analysis. The process flow triangle in Figure 4 visualises a comprehensive and reasonably complex approach to estimate the size of BESS and perform a simplified 2-stage cost/benefit assessment. In the first stage, *the main application should be decided in the light of the WF owners' requirements and the foreseen issues and performance of the WF*. Afterwards, the connection level is decided in relation to the available/desired converter topology. As an illustration, a small BESS (preferably a technology without liquids) can be integrated inside the WTG nacelle to smooth power fluctuations, and mitigate stress on the mechanical components of the WTG i.e. absorbs surplus energy instead of accelerating the WTG or extended activation of pitching. The converters of the WTG, Type 4 for example, can be utilised to accommodate the BESS input/output dc power and reduce the costs of the additional power electronics interface. It is expected that the connection level will be limited to WTG or within the WF collection network, while for higher connection hierarchy the WF owners should be aiming to wider range of applications e.g.AS that are incentivised by SOs. The second stage develops an initial cost assessment taking on board the required capital expenditure (CAPEX) only to provide a first estimate of the required budget to build, commission and terminate (at the end of its life) such project, and to confirm its financial feasibility. At this stage, *for simplicity authentic data of the BESS is not essential, however, the authentic data of the WTG/WF should be already available* as it is assumed that the WF is fully designed or in operation prior to the BESS integration. According to some of the present cost figures, the key element is the equipment, including the battery cells, and their compartments that are equipped with necessary cooling facilities. The power electronics converters are the second element and represent about 5-25% of the equipment cost relying on the applied technology e.g. 6-8% in case of Vanadium Redox.

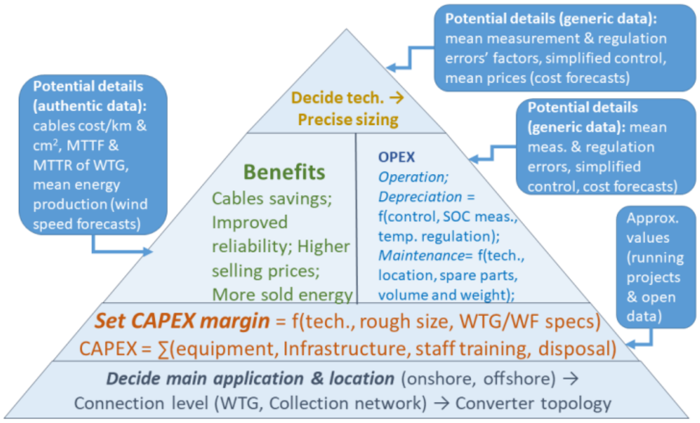

Figure 4. Generic assessment and sizing process of BESS.

However, its actual cost is almost constant regardless of the storage technology but highly dependent on the size and E/P ratio. Infrastructure includes landscape and compartments to accommodate the BESS and *additional civil structure, e.g. steel offshore platforms*. Staff training is an important aspect, where *WFs operator might have to hire special teams to deal with the BESS, and it will be significant extra cost if the BESS is located offshore*. The worst case if it the BESS is in the nacelle due to extreme heights and confined space constraints.

Third stage estimates the OPEX and financial benefit of the BESS according to the decided provisional size and technology in stage two. The benefits enumerated in Figure 4 rely on the available data about the WF/WTG, which should be authentic to achieve high accuracy. *However, it would be challenging to quantify precisely some factors like the impact of BESS on the enhanced reliability of the WTG/WF components, hence the improved Mean Time To Fail and Mean Time To Repair (MTTF and MTTR) of each major component could be obtained through a probabilistic study.* The improvements would concentrate on the failure rates of cables and mechanical parts of the WTG (although this aspect is also influenced by the BESS application). Likewise, energy prices will be simply forecasted within the expected lifetime of the BESS to estimate the additional income when the BESS is tracking higher prices (Arbitrage). In contrary to the quantification of benefits, OPEX estimation relies on generic data or careful assumptions to consider the negative impact of erroneous SOC measurements and temperature regulation, where a simplified control could be applied to simulate the BESS response under such adverse conditions. The maintenance cost is challenging and related to the applied technology and size. The final stage should provide a final decision on the selected technology, where a detailed size assessment is carried out based on authentic data and a certain main application without violating the CAPEX margin that is determined in stage 2.

IV. EXPANDED TECHNOLOGIES COMPARISON

The average power cost in \$/kW between (2012-2050) [20] for several types of battery technologies are compared in Figure 5.

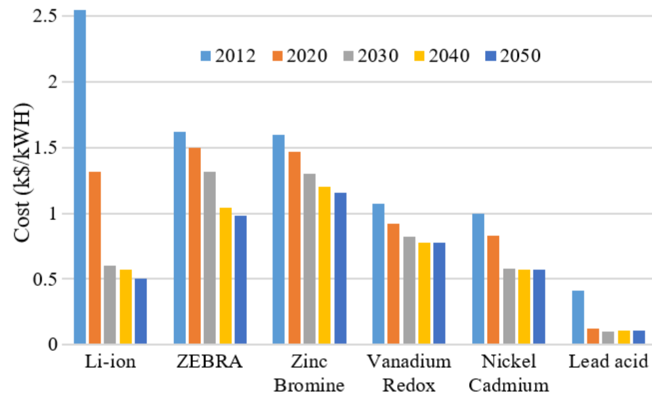

Figure 5. Cost comparison between various BESS technologies.

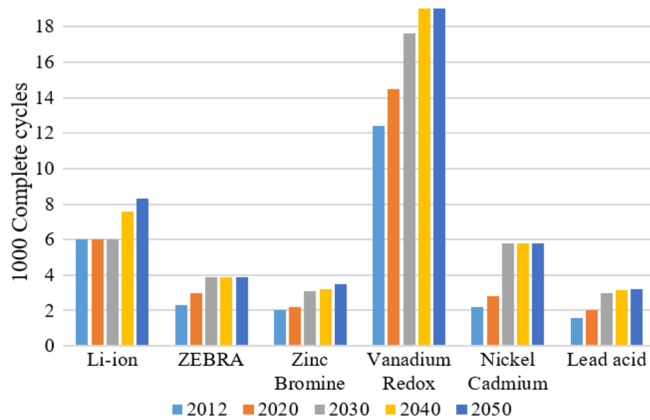

Figure 6. Forecast of average number of cycles of various BESS technologies.

TABLE II. EVALUATION GROUPS AND AVREAGE BASES

Group A: Technical	Group B: Echo-economic
Power density (W/kg) (average base = 232)	Lifetime (Years) (average base = 15)
Energy density (kWh/kg) (average base = 137)	Life cycles (Cycles) (average base = 12500)
Efficiency (%) (average base = 90)	Power cost (\$/kW) (Average base = 2600)
Responsiveness (S) (average base =1.003)	Energy cost (\$/kWh) (average base = 1550)
Self-discharge (%/day) (average base = 0.4)	Environmental friendly (average base = 0.8)

It shows that the average power cost for different battery technologies would continue dropping during the full period. However, the Lithium-Ion battery shows a very significant drop in the average cost. In 2040, the Lithium-Ion average cost is expected to continue falling to be the second cheapest technology after the lead acid. The average number of cycles of various battery technologies for the period 2012-2050 are shown in Figure 6. It indicates that the Vanadium redox battery would have a continuous improvement in the number of cycles for the full period of study. However, the Lithium-Ion battery would have a steady growth in the number of the cycles but with an extra 25%

increase for the last decade of the study period. The following paragraphs compare four BESS technologies that are commonly integrated in power networks worldwide: Lead Acid, Nickel Cadmium, Lithium Ion, and Vanadium Redox against two groups of factors that are presented in Table II. The fast-changing process of BESS development ensures the need to the regular update of the used data to match the very recent developments. A comparison is depicted in Figure 7 and Figure 8, where the per unit value of each parameter/technology is referred to the base values in Table II. The graphs are normalised with respect to a factor of 5 hence, the values on the centre axis are per unit values multiplied by 5 using (1).

$$Higher\ is\ better\ (parameter\ scaling) = \frac{actual\ value}{base} \times 5 \qquad (1)$$

For some parameters, the lower is the better; energy investment cost; power investment cost; and self-discharge, hence the approach in (2) is applied to scale its score.

$$Lower\ is\ better\ (parameter\ scaling) = (1 - \frac{actual\ value}{base}) \times 5 \qquad (2)$$

The selected BESS technologies are benchmarked against ten different aspects of comparison. Although, the average total score determines the technology that is aligned to more requirements, however, certain applications could require high score in specific area(s) regardless of the average total score. The Lithium-Ion technology, compared to the other technologies, offers the best performance in Group A criterion. Meanwhile, Vanadium Redox technology is the lowest performer and requires further development. Regarding Group B, Vanadium Redox technology shows the best performance, however, the Lithium Ion technology is the lowest under the same criterion after the Lead Acid, and Nickel Cadmium respectively. Following technology comparison, it is a complex process to identify the overall best technology to use, as each one has its own characteristics and it shows more strength in some areas and weakness in others. However, the Lithium Ion and the Vanadium Redox technologies show high potential to be widely integrated in the future. It is of note that in practice Lead-Acid is dominating battery market worldwide. The high potential of the Vanadium Redox technology encouraged the authors to include a real and up-to-date quotation from a leading vendor to elaborate the high costs of such cutting-edge technology. The data given in Table III describe a single module of a Vanadium-Redox flow battery of 300 kWH energy capacity. It can be seen that the costs of the associated power electronics converter are very low compared to the total cost of the module.

TABLE III. ACTUAL DATA OF A VANADIUM REDOX MODULE

Electrical specifications		Dimensions and weights	
Rated Power	60 kW	LxWxH	6x2.4x2.9 m
Nominal Voltage	48/96 V	Weight (Dry)	10450 kg
Rated Current	1250/625 A	Weight (Filled)	31450 kg
Energy Capacity	300 kWH	Converter Cost	1.15 k€
Depth of Charge	100%	Modules Cost	1.91 M€
DC/DC Efficiency	70%-80%	Annual maintenance	2% of cost
System Life	25 years		

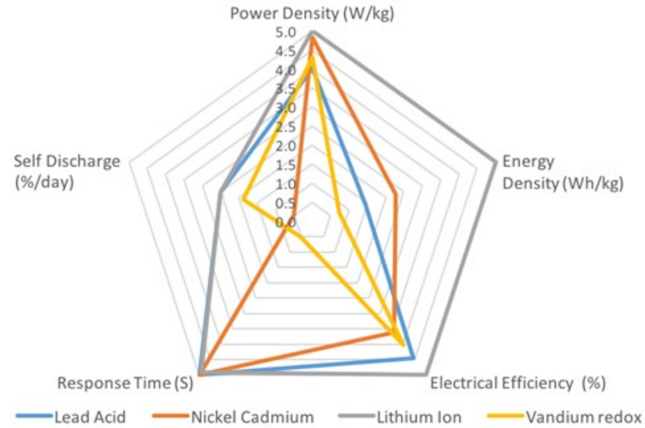

Figure 7. Group A assessment criterion.

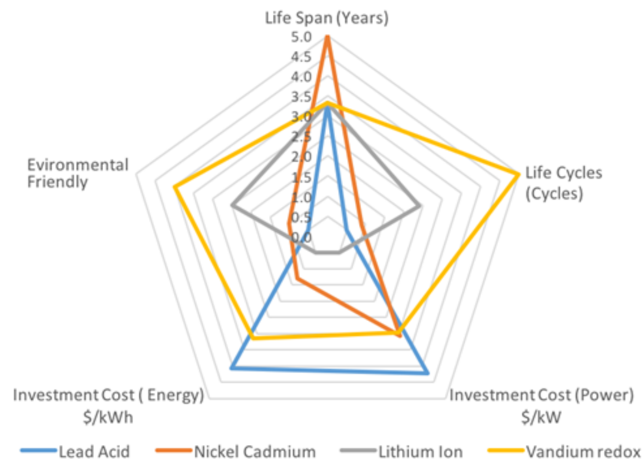

Figure 8. Group B assessment criterion.

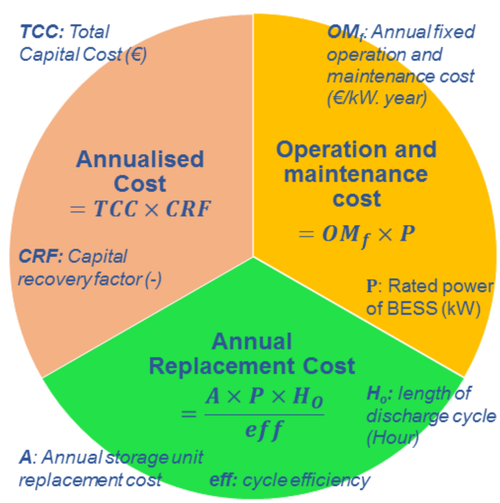

Figure 9. Simplified business model of the total costs of BESS.

The BESS cost considers two elements. Firstly, the energy cost which is the cost of the battery cells. Second, the power conversion cost that is cost of power electronics. The total cost of BESS has the three key elements: 1) annualised capital cost (AC),

2) the operation and maintenance cost (OMC), and 3) the annualised replacement cost (ARC) as shown in Figure 9.

V. Conclusions

This paper conducts an extended analysis of all aspects that are related to the integration of BESS to different hierarchy levels of power and wind energy systems in coordinative approaches. It could be concluded that sizing and operation are the bold headlines of BESS integration with the intended application as the main driver. Different technologies are evaluated against several factors, and simplified cost model is described. This revealed the high cost of Vanadium Redox with strong potential to be mitigated within the next 20 years; however, the Lead-acid technology is still in pole position. Operational and under-development projects, predict the domination of Lithium-Ion and Vanadium Redox batteries, which would be a key enabler to the foreseen high penetration of renewables. A comprehensive breakdown for the key elements of planning i.e. location, technology, sizing, environmental impact and cost/benefit) and operation (application, safety, integration, monitoring) of BESS provides wide scope of inter-disciplinary research and innovation avenues. The health and condition monitoring with mutual impact of BESS states' measurements and temperature regulation accuracy are among the promising topics.

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