Technology Management Tools for Assessing Emerging Technologies: The Case of Grid-Scale Storage

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Abstract--**We apply business and technology management concepts to describe a new framework for valuation and adopting grid-scale emerging storage technologies. The main challenge of adopting emerging storage technologies among utilities is how to match the right energy storage technology to appropriate business-operation strategy for a site-specific grid configuration. With exclusive application in electricity storage market, our analysis approach integrates the technology road map, storage performance matrix, and storage valuation models into business opportunity assessment with additional features that enable fast screening of the emerging storage technologies. The results from this phenomenological study can form the basis of a unique management methodology that assesses alternative technology solutions. It can also provide unbiased information upon which reliable management decisions can be made for adopting new technologies.**

I. INTRODUCTION

The electricity grid is an essential regional asset that provides infrastructure for local electrical energy demand or export markets. In recent years, electricity distribution networks are encountered considerable challenges such as aging network assets, the installation of new distributed generators, carbon reduction obligations, implementing regulatory incentives, and the capability of adopting new technologies for electricity generation, transmission, and distribution [1, 2]. There is a recent trend in which the energy industry is transformed towards producing a more sustainable production of electricity. In many countries, including Canada, grid capital assets are coming close to the end of life as they are not able to satisfy increasing demand conditions. In particular, increasing use of intermittent renewable energy generation can create new challenges for grid stability and reliability. By 2035, renewable sources such as wind and PhotoVoltaics (PV) will account for nearly half of the increase in global power generation [3]. The increasing share of renewable sources in the global power market can also create challenges in the power sector such as investment risks and supply reliability [3].

Energy storage (ES) technologies with their capabilities to control power intermittency, can provide various services along the electricity value chain at generation, transmission and distribution (T&D), retail, and end user consumption. Examples of these services are energy or power arbitrage, backup power, frequency regulation, peak shaving, and power reliability. The role of storage technologies is to transform electricity into a different form of energy (e.g., chemical, potential, or mechanical), store the energy for certain periods of time (from seconds to days), and recover electrical energy in case of needs [4]. Despite the fact that by focusing on the only one application, energy storage systems increase the operational cost of the distributed electricity system [5, 6, 7, 8], energy storage technologies can play a vital role in reducing the overall upgrade cost of the electricity grids in the presence of renewable sources.

The main challenge of adopting ES technologies is how to match the right technology to appropriate grid service for a site-specific configuration. There are numerous technical assessment and engineering tools that provide substantial information around technical value of storage technologies. The tools are usually built around electricity production or transmission reliability models, with no or little market and financial driven information [6]. The majority of the tools thus suffer from lacking technology management and business information, making them difficult to be used by managers for decision making purposes. In order to address the gaps, we introduce relevant frameworks from business and technology management discipliners that can be used for valuation and early adoption of grid-scale emerging storage technologies. Such analysis approaches integrate the technical data-base into business opportunity assessment with additional features that enable fast screening of the emerging technologies. On a general basis, these concepts form the basis of a unique management methodology to assess alternative technology solutions and provide unbiased reliable information upon which reliable management decisions for adopting new technologies can be made.

II. METHODOLOGY

Customized for grid-scale storage technologies, our analysis methodology stays on the basis that any storage deployment is identified by key characteristics that include location, grid application or services (e.g., backup, grid reliability, frequency regulation, arbitrage), type of electricity market (e.g., regulated vs. de-regulated), type of ownership (utility owned vs. privately owned) and type of ES technology to be deployed (e.g., performance, time of discharge, response time). The business strategy is defined on a separate layer and identifies how revenue stream and profit maximization strategies are connected and can determine who would receive the benefit/risk and how long-term profit is distributed among stakeholders. A major difference between our approach to that of others is where business strategies and models are added as key characteristics of the benefit in addition to market and type of storage asset ownership [6]. Moreover, we utilize several standard technology management tools, such as technology roadmap and technology development matrix that are primarily utilized for generating inputs and introducing new analysis frameworks. ES-select tool [36] was utilized as a framework to quantify the feasibility and reliability of the energy storage systems.

III. TECHNOLOGY MANAGEMENT FRAMEWORKS

Technology management tools help managers to implement solutions for adoption of new technologies. Phaal et al. have extensively studied the typology of technology management tools and applications therein [9,10]. Several generic tools have already been employed from matrix management techniques such as Technology Development Matrix, Technology Landscape Road Mapping, Innovation Matrix, and Linkage Grid [11]. According to Phaal et al. [11], technology management tools should be theoretically robust and reliable, be practical for implementation, integrated (i.e., integrate perfectly and can work with other processes or resources within organization or business/management process), and flexible (adapt easily in various business ecosystems). On the other hand, improving short term performance and long term sustainability of the technology-driven firms depends on fast and accurate strategic decisions. These tools should be practical to support and evaluate management decisions and strategic actions. Appropriate techniques and tools should be developed and combined in order to address a specific business or management problem [12,13,14,15,16,17,18]. There is a distinct difference between generic “management tools” and “technology management tools” [11]. While the latter is referred to as practical tools, models, the framework, and techniques to conceptually understand business processes for adoption or development of technologies, the former includes devices for supporting management action and conception in a general sense. A “meta-framework” was proposed by Shehabuddeen [19] and later by Phaal et al. [9], which provides description of terms and interrelation between approaches. In the context of grid-scale storage, the latter implies that an appropriate framework should provide a solution for adopting ES technologies by incorporating assessment of risks & opportunities, technology development planning (prioritizing key technology attributes through the use of road mapping and development matrix), Economic Viability Analysis (technology and life-cycle cost & environmental assessment) and project portfolio management.

In order to fully assess value proposition of ES technologies, formulate their risk & opportunity profile, and develop implementation plan, a number of analyses frameworks need to be developed and utilized from techno-economics and business operation perspectives. The underlying idea is to focus on a specific storage technology, and compare it to other similar technologies for grid applications by mapping its technological advantages/ disadvantages, and innovation capacity. Here, we particularly focus on technology road mapping, technology development matrix, and technology valuation grid.

IV. TECHNOLOGY ROAD MAPPING

A roadmap is a layered, structured and connected view of the future development of business or market needs, the products or services that address them, and the technologies that allow the products or services to be delivered [18]. Roadmaps are primarily a communication tool [20]. They conveniently bring together the information at these various levels and present it in such a way as to be useful to multiple stakeholders. They help with the identification of gaps in technology provision, help indicate where investment of effort and funding is needed and help various stakeholders to understand where their contribution fits with that of others in helping to realize the overall vision.

For grid-scale storage, roadmap can be structured for technology vendors, technology enablers (e.g., policy makers, integrators), and end users (e.g. utilities or residential). The organizational roadmap may contain market, business, products, services, system, technology, science, and resource themes. The technology based roadmap which is the focus of this paper includes industry, market, product, service, system, technology, and enablers. Each theme may contain one or more technical relevant attributes such as power density, life cycle, round trip efficiency, levelized cost of electricity, and response time. The roadmap is generally built through a series of workshops, consultations and desk based research, including research publications, journals, magazines, newspapers, industry reports, other roadmaps, strategy documents, and conferences. The roadmap is presented in two forms – a brief descriptive version and a diagram or graphical version. The descriptive version is useful for understanding the content. The graphical version is a summary form that makes clear how the challenge of describing the evolution to the vision is achieved i.e. by breaking it down into a number of interrelated layers, Figure 1.

A. Vision

The first step to design the grid-scale storage roadmap is to identify the vision and technical targets for each item. Essentially, the vision and technical targets define the ’why’ and ‘what” questions of the roadmap, respectively. This layer is driven by a demand to develop specific storage performance, cost, discharge rate, following extensive consultations with stakeholders. The vision and targets are essential part of the roadmap, in which the monetary value of a specific storage technology (or a group of technologies) for a given grid service application (or a group of multiple services) is estimated based on input financial information and storage technology attributes. Several databases are required in this layer to determine which storage technology can fulfill the technical requirement of certain applications on the grid. The output of this layer is a feasible subset (binary) of applications for a given storage technology or a subset of storage technologies which are feasible for a given grid service.

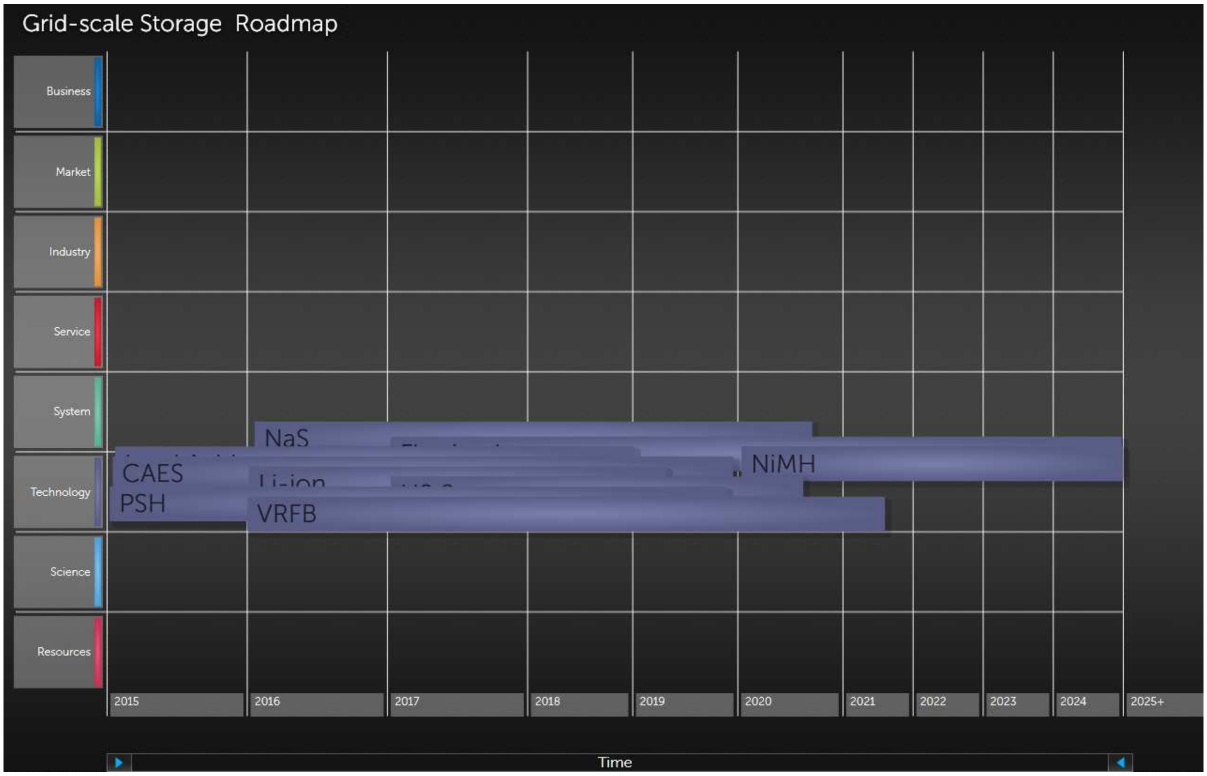

Fig 1. A typical framework for grid-scale storage technology road map, visualized using sharpecloud software [21]. Various storage technologies are mapped on "technology" layer. NaS: Sodium Sulfur battery; VRFB: Vanadium Redox Flow battery, NiCd: Nickle Cadmium battery; Li-ion: Lithium Ion battery; CAES: Compressed Air Energy Storage; PSH: Pump Storage Hydroelectricity; NiMH; Nickle Metal Hydride.

B. Business layer

A number of factors are driving or constraining the realization of the vision described above. A potential market is to evaluate or complement deployment of grid-scale storage. Moreover, an emerging storage technology competes in that market with other potential solutions. For instance, large scale backup storage using lithium ion batteries consists of long term and expensive demonstration that a common mechanical storage (pumped hydro or compress air) can do in a cheaper and faster fashion. The renewed interest and a sound business case is driven by environmental and economic factors such as the consistently high cost of fossil-based electricity sources.

C. Market and industry

The second and third layers of the roadmap utilizes industry type and market structure to determine which business strategy can fulfill the monetary value of the benefits calculated within the first layer for each binary choice of [storage, application]. Each market and industry is described by a series of characteristics related to market structure, industry needs, asset ownership, and range of risk profile, benefit, and asset location. The market demand is associated to a renewed interest in alternative energy systems, including renewable sources for electricity generation. While the power industry represents a large market opportunity for emerging storage technologies, further technological improvements are required to make them competitive with incumbent technologies.

D. Storage service layer

Services are an essential component of the roadmap as they provide a repeatable and consistent set of outcomes for organizations seeking the storage solutions. The key target is to identify and enable storage technologies for various grid services. The particular services are linked to electricity market structure and storage technical attributes. Despite considerable improvements, there is no consensus in the definition of services that can be given by various storage technologies [6]. A few services are considered that include energy time-shift (arbitrage), power quality, frequency regulations, backup, and supply capacity.

E. Storage system and technology layers

The products layer describes distinct storage technology attributes that can be offered to the market either as standalone storage technology or a full system. Different technologies are mapped over the roadmap timeline that shows the improvement in those technical attributes over time. Long term scientific advances can be captured in technology layer or being placed in a separate layer. Scientific research are strongly linked to the system and

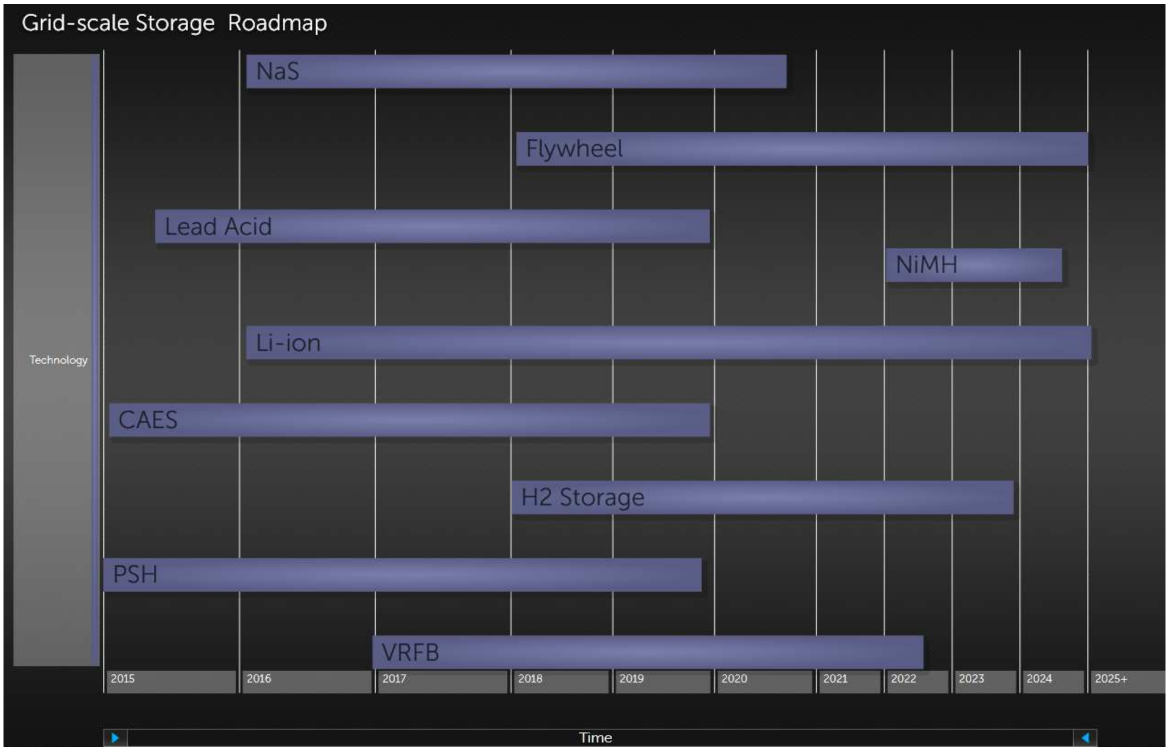

Fig 2. Example of storage technologies mapped on the technology layer and spanned over 10 years based on their technical maturity for a given grid service application. NaS: Sodium Sulfur battery; VRFB: Vanadium Redox Flow Battery, NiCd: Nickle Cadmium Battery; Li-ion: Lithium Ion Battery; CAES: Compressed Air Energy Storage; PSH: Pump Storage Hydroelectircity; NiMH; Nickle Metal Hydride.

technical layers. Some storage technologies, such as pumped-hydro, are more mature than the other emerging storage technologies. For instance, Compressed Air Energy Storage (CAES) has already been used for decades. The new generation of energy storage technologies such as lithium-ion batteries, flow batteries, flywheels, and sodium-sulfur batteries (NaS) has been emerged in recent years and are in the early market adoption stage. The main advantage of the new generation of storage technologies to the old ones is in their "operational flexibility, improved charge/discharge cycle life, and longer duration or fast response capabilities" [5].

F. Resources (enablers, policy) layer

Public support programs and policies in all major electricity markets in North America and Europe will continue to play a key role in supporting storage R&D and as part of that specific work on grid-scale storage. Several policy instruments have recently been utilized by regional and federal authorities to stimulate deployment of renewable energies for their electricity production. Power authorities and policy makers employ Renewable Portfolio Standard (RPS) to enforce utilities replace a fraction of their electricity production by renewable energy sources [22]. Feed in Tariff (FIT), on the other hand, focuses on generating revenue and niche market for emerging technologies that supply electricity from renewable resources. FIT is "technology specific" and puts in place a fixed payment (tariff) for each energy unit (kWh) that is loaded to the electricity grid [23]. Notice that FIT is exclusively intended for a small volume electricity supply that is produced from the emerging renewable sources and for that reason it can not be utilized as an instrument for electricity export, according to [24]. Pay For Performance (PFP) and Diffuse Benefits (DB) versus Concentrated Benefits (CB) are the other form of policy instruments that have been proposed for adopting energy storage technologies by utilities [25]. PFP is a pricing policy. Some studies indicated that PFP may double the utility's revenue from use of storage in regulation service while it may reduce the revenue from spinning reserves [25].

V. TECHNOLOGY DEVELOPMENT MATRIX

Technology Development Matrix (TDM) is linking market needs to technology attributes to key technical parameters. TDM is another form of technology management framework that can help technology managers and system integrators identify the technical R&D gaps and target suitable market opportunities for adopting their technologies. It translates what consumer wants into technical goals for a given market. When constructed carefully, it forms the technology plan and R&D projects portfolio. When used as a collaborative tool, it brings technical team together in a common goal to address commercialization gaps. However, market needs change, so as the state-of-the-art (SoTA) performance and key underlying assumptions. TDM should be a live document and updated regularly. In reality, the *stage-gate* process that are developed internally in many firms, are normally a workable version of TDM. They serve the initial purpose of understanding the landscape, technology priorities and making a decision of project's portfolio mix.

Storage performance matrix is an integral part of TDM for energy storage technologies that describes the acceptable range of technical attributes for a given grid service. A brief description of storage performance matrix is provided here by concentrating on the application of technology development matrix for technology mapping of the grid-scale energy storage technologies. Based on the types of services and installed capacity, energy storage technologies in electrical energy systems can be grouped into chemical storage (batteries or hydrogen), potential energy (pumped hydro or compressed air), electrical energy (supercapacitor), mechanical energy (flywheels), and magnetic energy (supermagnetic energy storage). Storage systems include a number of technologies in different Technology Readiness Levels (TRLs). The performance matrix that characterizes and compares different technologies are separated from the location and services that they can provide. Other categorizations are based on the time of use (TOU), short-term, long-term, and distributed storage, or level of maturity and technology advancement.

The cost and reliability of an energy storage technology are function of several key factors. Among those factors are round-trip efficiency (the ratio of the released electrical energy to the stored energy), cycle life (the number of times that the device can get discharged and charged while maintaining a minimum required efficiency), power rating ($/kW), and energy rating ($/kWh). Moreover, capital and operating costs determine economic viability and service profitability, Figure 3 illustrates required power and response time for different grid-scale storage services.

The real benefit of energy storage technologies have been studied extensively in different markets (e.g., arbitrage, regulation services, and T&D) [26,27,28,29]. By focusing on only one single application, storage technologies has not shown significant value and service profitability [3]. The reason is that the actual choice of appropriate storage technology for a specific grid application is the interplay between time of usage, charge/discharge time, and cost that may not collectively lead to a profitable operation for a single storage technology or in a single application. Commercial viability requirements and cost effectiveness of storage solutions for grid applications is still under debates in academic and business-management literature [30]. Figure 3 captures the characteristic time and cost benefit data for specific application and maps some storage technologies. As indicated in various studies, no single energy storage system can provide multiple grid application requirements [28]. Moreover, some storage technologies may complement each other for multiple services, where combining services could lead to cost recovery and profitability in the long run [3, 6]. A performance matrix is the basis of the energy storage valuation which characterizes a storage technology for various applications in electricity grid systems. The most common attributes in the metrics are provided in Table 1. This is an example of TDM in which elements of storage performance matrix and system attributes are described for different storage technologies, both at system and standalone technology levels.

Fig 3. Required power and response time for different grid-scale storage services.

TABLE 1. AN EXAMPLE OF TECHNOLOGY DEVELOPMENT MATRIX WITH SELECTED ELEMENTS FROM PERFORMANCE MATRIX AND THE LINKAGES THEREIN.

TDM level of attribute	Category of element/attribute	Performance matrix element	Brief description of the element
Technology	Operation	Energy Storage Capacity [kWh or Ah] SoTA vs. Target	The amount of energy that can be recovered at a given time.
	Operation	Charge and Discharge Rates [kW or A] SoTA vs. Target	The rate at which energy is consumed or stored in a storage system.
	Performance	Energy and Power Density [kWh/m3 or kWh/ton] SoTA vs. Target	Energy per weight [kWh/ton] or energy per volume [kWh/m3] are considered as energy and power factors.
System	Performance	Round-trip Efficiency [%] SoTA vs. Target	The percentage of the additional required energy during charging is expressed as round-trip efficiency [%].
	Cost	Levelized Cost of Storage [$/kW] SoTA vs. Target	The Levelized Cost of Energy Storage (LCOES) is defined as the overall cost of ownership of storage over the investment period divided to the total delivered energy in that period
	Durability	Lifetime [cycles, years, kWh_{life}] SoTA vs. Target	The lifetime of a storage system can be measured by the number of charge/discharge cycles at given energy capacity.

VI. TECHNOLOGY VALUATION GRID

The complexity of adopting energy storage is attributed to the wide variety of technology choices and diverse applications along the electricity value chain which makes the choice of appropriate storage technology difficult [31,32]. As pointed out by Southern California Edison (SCE), another “roadblock”, particularly for utilities is the lack of storage project parameters in the context of existing infrastructure [33]. The lack of clarity around value proposition and technical needs from buyers (i.e. utilities) make it difficult for the manufacturer to improve cost effectiveness and performance. An application-focused valuation methodology was introduced by SCE [33]. Among the most common valuation approaches and tools that have been widely utilized by utilities and independent consultant are National Renewable Energy Lab (NREL) valuation (an analysis tool to evaluate the operational benefit of commercial storage, including load-leveling, spinning reserves, and regulation reserves) [34]; Energy Storage Valuation Tool (ESVT) developed by Electric Power Research Institute (EPRI) [35] has proposed a methodology for separating and clarifying analytical stages for storage valuation. ESVT calculates the value of energy storage by considering the full scope of the electricity system, including system/market, transmission, distribution, and customer services; and ES-Select™ developed by DLV-GL [36]. In ES-select, the user needs to choose where energy storage is connected to an electric grid [36].

Key characteristics of storage systems for particular markets in the electricity energy system were illustrated in Table 1, where typical energy storage applications are characterized in view of different performance attributes. Energy storage market and its associated applications span on a variety of locations along the electricity value chain [29], Figure 4. For instance, on the generation side, the addressable market for energy storage is improving power quality or usage of existing generation sources.

A. Cost-benefit calculations

Several key steps are involved in creating and utilizing valuation tools. From various academic and business sources, detailed data-sets are gathered for several electrochemical energy storage solutions with potential applications in power grids. Each data-set contains technology description and technology targets for various grid applications, Table 1. TDMs were developed on system and component levels, including prioritized technical parameters and market attributes. The data sets are updated on an ongoing basis and are used for storage valuation analysis.

The benefit of storage is ultimately described by return on the total cost of capital for a specific period of time (asset life time) based on several financial outputs that include Net Present Value (NPV), Internal Rate of Return (IRR), the Total Cost of Ownership (TCO), and Cash Flow.

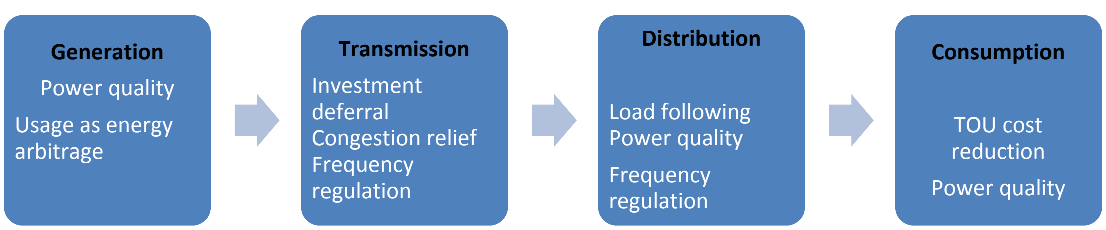

Fig 4. Energy storages market and their potential applications along electricity value chain.

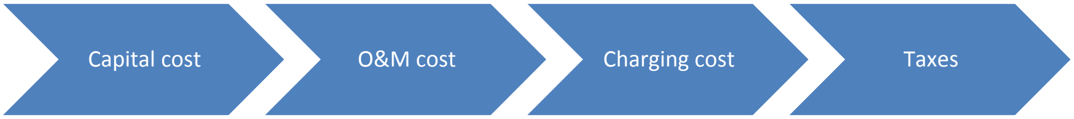

Fig 5. Overview of cost components for a storage asset.

Figure 5 provides an overview of the cost components for storage asset. The expected (annual) benefits ($/kW) are simply defined as default and are qualitatively ranked as regulation services> system capacity>arbitrage>backup [36]. The annual cost of expenses ($/yr/kW) are calculated from the annual cost of operation (C_{ops}) and maintenance (C_m):

$$\boldsymbol{C_{exp} = (C_{ops} + C_m)} \quad (1)$$

The annual cost of operation is calculated by:

$$\boldsymbol{C_{ops} = \frac{C_{charge} \times L_{ops}}{1000}} \quad (2)$$

where L_{ops} represents the annual operation loss of the storage storage performance and is defined as kWh/yr/kW. C_{charge} represents the cost of battery charge and C_m is an input parameter in the storage technology database.

The cost of storage installation, C_{SI} is the sum of installation cost C_I and capital cost of storage C_S in $/kW:

$$\boldsymbol{C_{SI} = (C_I + C_S)} \quad (3)$$

By factoring in the discount rate over asset life time (n) and calculating Present Value (PV) of the annual cost of expense, one can calculate the Total Cost of Ownership (TCO) as:

$$\boldsymbol{TCO = [PV(C_{exp}) + C_{SI} + PV(C_R)\,]} \quad (4)$$

where C_R is the replacement cost. The present value of the annual benefits or PV(B) are calculated by using the discounted (interest) rate from the financial database and the annual benefits defined in the application database. The annual net present value of benefits or annual Cash Flow is calculated by:

$$\boldsymbol{Cash\ Flow = CF = [PV(B) - PV(C_{exp})\,]} \quad (5)$$

The payback year is defined as the year (n) in which the cumulative cash flow at that year is equal to C_{SI}.

$$\boldsymbol{\sum_1^n CF = C_{SI}} \quad (6)$$

Tax rates (τ) will be included in all cost and benefit terms. One should notice that a single revenue stream (from a single application service) usually does not lead to a short (<10 years) payback time. Only multiple revenue streams could lead to net benefits in a reasonable payback period as illustrated by many studies [37]. Note that the effect of electricity price increase is captured by electricity price escalation factor as an input parameter within the financial database in ES-Select [36]. Finally, internal rate of return (IRR) is calculated as the discounted rate under the assumption that the net cash flow is zero.

B. Valuation analysis

The primary step in valuation of ES technologies for a specific service application is to identify technical parameters (power/energy density, life time, life cycle, cycle ability, cost) using a ranking strategy for each storage technology based on the various attributes. Figure 6 shows an example of the attributes (L: location; M: Maturity level; A: meeting Application requirement; C: Cost requirement) for NaS, lithium-ion (LIB-e) and Vanadium Redox Flow (VRFB) batteries, mapped on spider charts for arbitrage as a potential service application. Ranking feasibility scores for this application were obtained for different batteries for a given application area. The charts are obtained from ES-select ™ tool [36]. The results have also indicated feasibility order for the above configuration as: NaS > Li-ion > A-VRFB, where A-VRFB stands for the advanced Vanadium Redox Flow Battery. The financial indicators such as NPV and TCO determine the economic feasibility of the storage technologies over their lifetime, as illustrated in Figure 7. Calculations suggest that none of the battery solutions fulfill the 20 years payback period requirements. In terms of discharge duration, the calculation has shown advantage of A-VRFB for the greatest range where peak demand is steady for 3 to 6 hours (NaS > A-VRFB > VRFB > Li-ion).

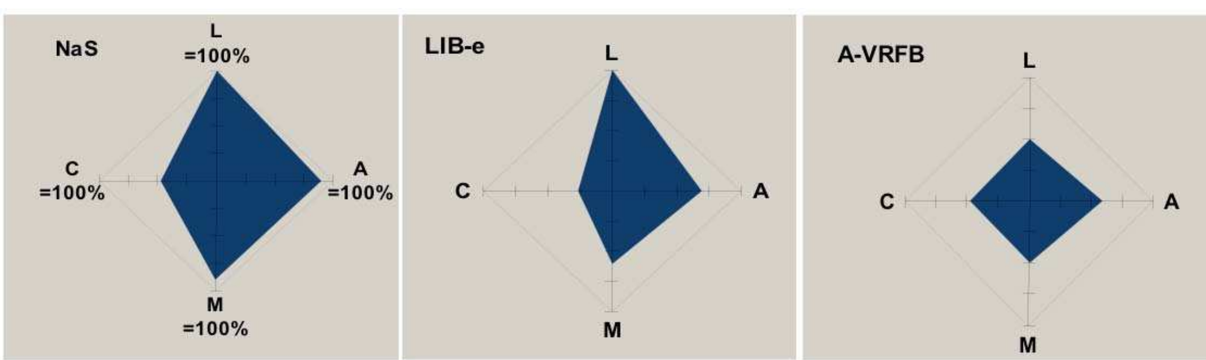

Fig 6. Ranking feasibility scores for different batteries for a given application. The charts are obtained from ES-select [36]. L: location; M: Maturity level; A: meeting Application requirement; C: Cost requirement.

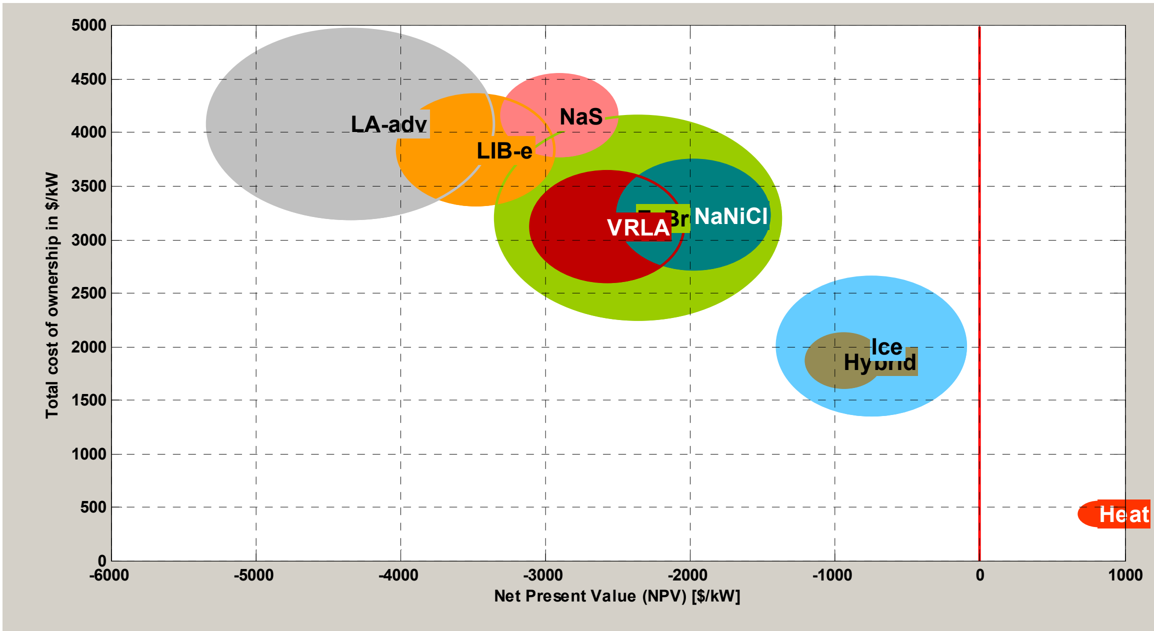

Fig 7. Total cost of ownership vs. NPV ($/kW) for selected storage solutions. The charts are obtained from ES-select [36]. NaNiCl: Sodium Nickel Chloride; LIB-e: Lithium Ion Battery; LA-adv: advanced Lead Acid; VRLA: Valve Regulated Lead Acid; NaS: Sodium Sulfur; Ice/Heat represents the charge/discharge cycles of a thermal battery.

VII. SUMMARY AND CONCLUSION

Current valuation and technical assessment tools provide substantial information around technology readiness and maturity level of emerging technologies, however, only few of the existing approaches use market driven and business-management information. Technology management tools can help managers evaluate market readiness of new technologies to support new investment decisions and strategic business actions. Technology management tools are essentially different from traditional management and business intelligence in which they provide practical guideline, framework, and modeling techniques to understand and implement business processes for early stage technologies.

We have discussed a bottom-up approach that employs a set of technology management frameworks to support business-management decision of adopting grid-scale storage technologies for grid services and variable electricity generation. Among those technology management tools, severals are employed from matrix management techniques such as Technology Development Matrix, Technology Road Mapping, and Technology Valuation Grid. For industry looking to adapt new energy storage technologies, such analysis frameworks can provide multi-dimension considerations (cost, efficiency, reliability, best practice business operation model, and policy instruments), which can potentially lead to complete view for strategic decision making purposes.

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