Typology of Business Models for Emerging Grid-scale Energy Storage Technologies

By

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to public.

Statement of Contributions

Chapter 3 is based on the published book chapter, (Malek, Kourosh and Nathwani, Jatin, Cost Modeling and Valuation of Grid-Scale Electrochemical Energy Storage Technologies, in Physical Multiscale Modeling and Numerical Simulation of Electrochemical Devices for Energy Conversion and Storage pp 235-249) co-authored with my thesis supervisor Dr. Jatin Nathwani

Chapter 4 is based on two published articles, (Malek, Kourosh and Nathwani, Jatin, Technology management tools for assessing emerging technologies: The case of grid-scale storage, 2015 Portland International Conference on Management of Engineering and Technology (PICMET), January 2015, 2346 - 2354) co-authored with my thesis supervisors Dr. Jatin Nathwani and (Kompis, Costa and Malek, Kourosh, Fuel Cell Modeling Strategic Roadmap: A Systematic Approach, Fuel Cells, Volume16, Issue 6, Pages 760-770) co-authored with C. Kompis

Chapter 5 is based on a published article (Malek, Kourosh and Nathwani, Jatin, Typology of Business Models for Adopting Grid-Scale Emerging Storage Technologies, Portland International Conference on Management of Engineering and Technology (PICMET), December 2017, 978-1-890843-36-6 ©2017 PICMET, IEEE *DOI:* 10.23919/PICMET.2017.8125281) co-authored with Dr. Nathwani

Chapter 7 is based on a manuscript which is submitted for publication (Business Model Analysis and Cost valuation for Power-to-Gas Systems in a Regulated Market), co-authored with Dr. Nathwani, J. Yang, Q. Wang

Chapter 8 is based on a manuscript which is currently in preparation, co-authored with Dr. Nathwani, J. Yang, Q. Wang, R. Baker

Other major contributions include industry white papers and contributions to several publicly available tools and analysis models (EPRI, DNV GL)

“Energy Storage Cost Template and Tool: Guidelines Developed by the Energy Storage Integration Council for Distribution-Connected Systems” 2016, (ESIC Cost Tool) v1.0
https://www.epri.com/#/pages/product/3002006072/?lang=en

“Hydrogen Energy Storage: Grid and Transportation Services” 2015, NREL, Technical Report NREL/TP-5400-62518

“New Energy Storage Technology Selection Tool: ES-Select™ Canada”

“Your storage mix: can Power-to-Gas (P2G) fit in?”

Abstract

The main goals of this thesis are to develop, validate, and analyze emerging business models to ensure near-term market success of the grid-scale Energy Storage (ES) technologies. The main research contributions are a typology (i.e. classification according to general type) of emerging business models for investment and operational viability of grid–scale storage, validation of business models for valuation analysis of diverse grid-scale storage, and a unique technology management framework for value analysis of emerging technologies.

It is widely accepted that the intermittency of primary renewable energy sources is a limiting factor for inclusion of these technologies in autonomous power applications. ES technologies can be seen as valuable flexibility assets with their capabilities to control grid power intermittency or power quality services in generation, transmission, and distribution, as well as in end-user consumption side. When combined with sophisticated and reliable business models, grid-scale storage technologies can contribute significantly to enhance asset utilization rate and reliability of the power systems. The latter is particularly critical for deployment of regional and national energy policies of implementing renewable sources. Despite the fact that energy storage systems increase operational cost of the distributed electricity system, energy storage technologies can play a vital role in reducing overall upgrade cost of the electricity grids when renewable sources need to be integrated locally. The main challenge of adopting ES technologies among utilities is how to match the right energy storage technology to appropriate business-operation models for a site-specific grid configuration. Current know-how and assessment tools provide substantial information around technical specifications and requirements for adopting ES technologies for various grid configurations. However, only few of the existing approaches use market driven information. The majority of the tools also suffer from a lack of detailed information relevant for business managers for decision making purposes. Currently, none of the existing tools and investment methodologies evaluate the benefits of electricity storage from the perspective of a detailed techno-economic and business-operation models. The choice of appropriate business model, complexity of regulatory and policy environment, ownership and governance structure of storage asset, financing strategies, managing revenue streams, and associated operational risks are critical for providing an accurate assessment of the viability of the emerging ES technologies.

In order to fully assess the value proposition of ES technologies, formulate their risks and opportunities profile, and develop implementation plans, a comprehensive analysis framework is needed to support integration of technical, economic and business operation perspectives. This research aims to develop a typology of different business models in the context of grid-scale ES technologies. A bottom-up approach is proposed, demonstrated, and validated to identify a generalized business model framework. The business model framework is tailored to provide a customized analysis platform for adopting emerging energy storage technologies. Several case studies are carried out based on the proposed business model framework and energy storage valuation analysis therein. Each business model, combined with thorough valuation analysis, provides insights on when deployment of individual storage technologies can be economically and technically viable. For industry looking to adapt new energy storage technologies, such analysis can provide multi-dimension considerations (cost, efficiency, reliability, best practice business operation model, and policy instruments), which can potentially lead to complete insights for strategic decision-making purposes.

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This work would not have been possible without the help, encouragement, and collaboration with many individuals and organizations. I am extremely privileged to have such a supportive network of colleagues, friends, and collaborators.

I am profoundly grateful to my thesis supervisor, Dr. Jatin Nathwani for his tremendous support and encouragement throughout my journey. From Jatin I learned critical thinking, goal settings, and the power of multidisciplinary view that can accompany research findings and lead to personal success.

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Finally, I would like to dedicate this thesis to my wife and my daughter. Thank you for your unconditional love and support.

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List of Acronyms

AESO: Alberta Electric System Operator
BC: British Columbia
BCTC: Transmission Corporation
BCUC: British Columbia Utilities Commission
BoS: Balance of System
CAES: Compressed Air Energy Storage
CB: Concentrated Benefits
CPAEX: Capital Expenditure
DB: Diffuse Benefits
DNO: Distributed Network Operator
DOE: Department of Energy
DSO: Distributed System Operator
EA: Energy Arbitrage
ESVT: Energy Storage Valuation Tool
ESSO: Energy Storage System Operators
FIT: Feed-In-Tariff
GHG: Green House Gas
GW: Gigawatt
GWh: Gigawatts hour
KW: Kilowatt
KWh: Kilowatts hour
IESO: Independent Electricity System Operator
IPP: Independent Power Producer
IM: Innovation Matrix
LCOE: Levelized Cost of Energy or Electricity
LCOES: Levelized Cost of Energy Storage
LCOS: Levelized Cost of Storage
LG: Linkage Grid
Li-ion: Lithium ion

MRL: Manufacturing Readiness Level

NaS: Na-Sulfide

NPV: Net Present Value

NPC: Net Present Cost

NEB: National Energy Board

OEB : Ontario Energy Board

OECD: Organization for Economic Co-operation and Development

OPA: Ontario Power Authority

OPG: Ontario Power Generation

PFP: Pay For Performance

P2G: Power to Gas

PPP: Public Private Partnership

PV: photo voltaic

PSH: Pumped Storage Hydroelectricity

PQ: Power Quality

PEM: Polymer Electrolyte Membrane

PEMFC: Polymer Electrolyte Membrane Fuel Cell

QFD: Quality Function Deployment

R&D: Research and Development

RPS: Renewable Portfolio Standard

SCE: Southern California Edison

SOFC: Solid Oxide Fuel Cell

T&D: Transmission and Distribution

TCES: Total Cost of Energy Storage

TCO: Total Cost of Ownership

TRL: Technology Readiness Level

TRM: Technology Road Mapping

TW: Terra Watt

TWh: Terra Watt hour

UPS: Uninterrupted Power Supply

VRFB: Vanadium Redox Flow Battery

List of Nomenclature

ISC_t: Invested storage capital in year (t),

SOM_t: Storage O&M cost in year (t),

EC_t : Charging energy cost

r: Annual discount rate

EO_t: Total released energy in year

$\mathrm{L_{ops}}$: Annual operation loss of the storage

$\mathrm{C_{charge}}$: Cost of battery charge

$\mathrm{C_m}$: An input parameter in the storage technology database

$\mathrm{C_{SI}}$: Sum of installation cost $\mathrm{C_I}$ and capital cost of storage $\mathrm{C_S}$

$\mathrm{C_R}$: Replacement cost

τ': Tax rate

$\mathrm{C_{Score}}$: Feasibility score of cost

$\bar{\mathrm{S}}$: Combined feasibility score

P_{dis}: Power capacity

t_{dis}: Discharge time per day

E_{dis}: Energy discharge capacity per day

C_{FC}: Capital cost of hydrogen fuel cell system

UC_{FC}: Unit capital cost of hydrogen fuel cell

$C_{Gbuy,FC}^{ann}$: Annualized cost of energy bought from grid

$\mathrm{n_p}$: Number of operational years

C_{Gbuy}: Energy purchase price from grid

$r_{aux,FC}$: Ratio of the power consumption of the auxiliary subsystems to the power output fuel cell

$C_{FC,OM}^{ann}$: Annualized O&M cost of fuel cell system

$UC_{FC,OM}$: O&M unit cost per kW-year

C_{Stor}: Capital cost of the hydrogen storage

UC_{Stor}: Unit capital cost of hydrogen storage

$C_{Stor,OM}^{ann}$: Annual O&M cost of hydrogen storage

$r_{Stor,OM}$: Ratio of the annual O&M cost to capital cost of hydrogen storage

$C_{Comp}^{uninst}(\$)$: Uninstallation cost of larger compressors

$C_{Comp}^{inst}(\$)$: Installation cost of larger compressors

f_{Comp}^{inst}: Installation cost factor of larger compressors

$C_{Gbuy,Comp}^{ann}$: Annualized cost of energy bought from grid for compressors

r_{EComp}: Electricity consumption of compressors per unit of H_2

$C_{comp,OM}^{ann}$: Annualized O&M cost of compressor

$C_{Elec}^{uninst}(\$)$: Uninstallation cost of the electrolyzer

f_{Elec}^{inst}: Installation cost factor of the electrolyzer

C_{elec}: Capital cost of the electrolyzer

UC_{elec}: Unit capital cost of the electrolyzer

$C_{WFbuy,Elec}^{ann,stack}(\$)$: Annual cost of electricity for the electrolyzer stack

$C_{Gbuy,Elec}^{ann,stack}(\$)$: Annual cost of electricity for the electrolyzer stack

$C_{Gbuy,Elec}^{ann,BOP}(\$)$: Annual cost of electricity for the electrolyzer BOP

$EWF\%$: Ratio of electricity purchased from wind farm to the electricity from grid

$C_{Elec,OM}^{ann}$: Annualized O&M cost of the electrolyzer

C_{cap}^{tot}: Total capital cost of the hydrogen fuel cell storage system

CRF: Capital recovery factor

i_r: Annual interest rate in fraction

n_y: System lifetime in years

C_{Ebuy}^{tot}: Total annual electricity cost of the hydrogen fuel cell storage system

C_{OM}^{ann} : Total annual operation and maintenance cost of the hydrogen fuel cell storage system

$P_{\text{Supply capacity}}$: Supply capacity benefit

C_{payment} : Capacity Payment ($/kW-yr)

C_q: Storage Qualifying Capacity

C_d: Capacity derate

$P_{\text{time shift}}$: Energy Time-Shift benefit

E_{sales}: Energy sales

E_{Scost}: Energy Cost)

R: Round trip efficiency

1 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 have encountered considerable challenges such as aging network assets, installation of new distributed generation, carbon reduction obligations, regulatory incentives, and adoption of new technologies for electricity generation, transmission, and distribution [1,2]. There is a recent trend in the energy industry towards more sustainable energy production. In many countries, including Canada, grid capital assets are nearing the end of life and are not able to satisfy increasing demand conditions. Increasing the percentage of intermittent renewable energy generation creates new challenges for grid stability and reliability. By 2035, renewable sources such as wind and Photovoltaics (PV) could account for nearly half of the increase in global power generation [3]. The increasing share of renewable sources in the global power market will likely also create challenges in the power sector such as increasing investment risks and decreasing supply reliability [3].

Energy storage (ES) technologies have the ability to mitigate power intermittency and also provide various services along the electricity value chain at generation, transmission and distribution (T&D), retail, and end user consumption. 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 generate electrical energy (depending on specific needs). Distributed "smart" grids may require wide-scale ES in order to achieve their full potential [4]. Despite the fact that by focusing on the only one application, ES systems increase the operational cost of the distributed electricity system [5,6,7], ES technologies can play a vital role in reducing the overall upgrade costs of the electricity grids in the presence of renewable sources.

The main challenge of adopting ES technologies among utilities is matching the right ES technology to the appropriate business-operation models for a specific grid configuration. The enormous number of academic and market studies have been carried out in recent years to evaluate and justify the benefits of electricity storage for various grid applications from generation to T&D and consumption side [2, 8, 9, 10, 11, 12, 13, 14, 15]. The end-user side of application, often referred to as "distributed energy storage system", has also been investigated extensively in the literature [16, 17, 18, 19, 20]. While technology development activities are still focused on reducing capital cost and enhancing cycle life of the electricity storage technologies, the utilities and independent Power / System Operators (IPO/ISO) have begun to realize the need for business-operation models that increase the revenue and the economic value of the storage technologies [15]. Despite existing "blueprints" of utility-side business models for adopting renewable sources of electricity [21, 22], little academic work and business-management studies has been undertaken towards applicability of those models, particularly at consumer-side [22]. For the most part, the primary reason for such a literature gap is based on the fact that business models for adopting storage technologies in power grids are multi-facet and more complicated than those for renewable energy sources (e.g., wind, solar). In other words, in contrast to renewables, suitable business models for storage technologies depend on several temporal (size and maturity of the storage technology) and spatial factors (the type of service, location, application and market or electricity pricing structure). The latter implies that value generation and appropriate business-operation models for adopting storage technologies cannot be trivially inferred from those in the case of renewables. Therefore, there is a need to analyze existing business models and develop practical frameworks that ensure accurate assessment of profitability and value created by electricity storage technologies.

This research work thus delves into innovative business models to provide several practical business-management frameworks for the techno-economic valuation of storage technologies. Energy storage can create new fundamental economic value by providing a range of services to the transmission and distribution systems; the current regulatory models do not recognize the value of differentiated services and hence the need for a more sophisticated typology of business models to help shape investment patterns in the energy system. The proposed typology framework in this thesis contains multi-dimensional considerations (cost, efficiency, reliability, best practice business operation model, and policy instruments), which can potentially lead to a complete view for strategic decision making and policy purposes.

1.1 Background Review

There is an evolution in the global energy sector as a result of new energy policies and advancements in traditional and emerging energy technologies. The increase of unconventional oil and gas and transformation of the electric power sector towards more sustainable form of energy production from renewable sources have re-written the long-standing principle of the world's energy resources [3,23,24]. With the increasing share of renewable energies in the electricity supply mix, the exclusive ownership of utilities in the electricity generation and distribution is dramatically changing [22]. This section provides a summary of the global and Canadian electricity market, an overview of energy storage market, and value of grid-scale energy storage in those markets. Understanding energy storage markets and performance metrics of various energy storage technologies are vital for choosing appropriate business models based on specific storage capabilities, performance, location, and the market or pricing of electricity. The former is directly relevant to the objective of this research work, where the electricity pricing and energy storage market determines the choice of the appropriate business model.

1.1.1 Global Electricity Market and Role of Renewables

The increasing use of unconventional energy sources is changing the blueprint of the world's energy resources; yet, a secure and reliable energy supply is of vital importance for today's modern societies [3,22]**.** Electricity security, in particular, has been a matter of high priority in energy policies for countries throughout the world. In the majority of those policies, development and adopting more efficient, environmentally benign forms of power sources with reliable and secure services are seen as key challenges in the next two decades [3,25]. An analysis by the International Energy Agency (IEA) has indicated that the large-scale deployment of renewables is feasible from a technical point of view; however, the inherent variability and intermittency nature of these power sources will lead to less reliable power flows [3]. In order to ensure electricity security, IEA suggests that a greater level of power flexibility is required for large-scale deployment of renewables (e.g., photovoltaic, wind and tidal energy) [25].

Emerging markets in Asia and the Middle East have significantly contributed to the growth of global energy demand [3]. It is projected that by 2020, China and India could become the largest importers of oil and coal, respectively [26]. China and India combined, according to IEA [26], cover close to 40% of the increase in world electricity power capacity, whereas the remaining 60% of the increase within Organization for Economic Co-operation and Development (OECD) has replaced the retired capacity, Figure 1-1. The United States has shown significant effort in shifting towards self-supported energy needs from domestic resources [3]. Growth in electricity generation from renewable sources plays a significant role for the success of such policy.

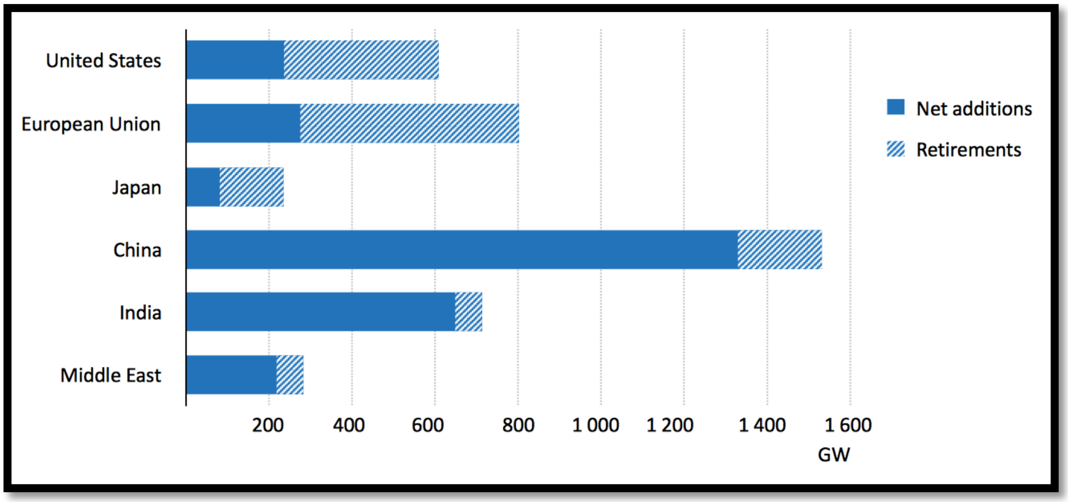


Figure 1-1 Additions and retirements of power generation capacity, 2013-2035, reprinted from [3], with permission.

As illustrated in Figure 1-2, increase in share of the non-hydro renewables in the electricity supply mix depends on the level of national subsidies for renewables [3]. Moreover, the increasing role of renewables in generation capacity requires innovation in market structure [3]. The latter implies that uncertainty about climate regulations and renewable energy policies affects public and private short-term needs and investment appetite in the long run [26].

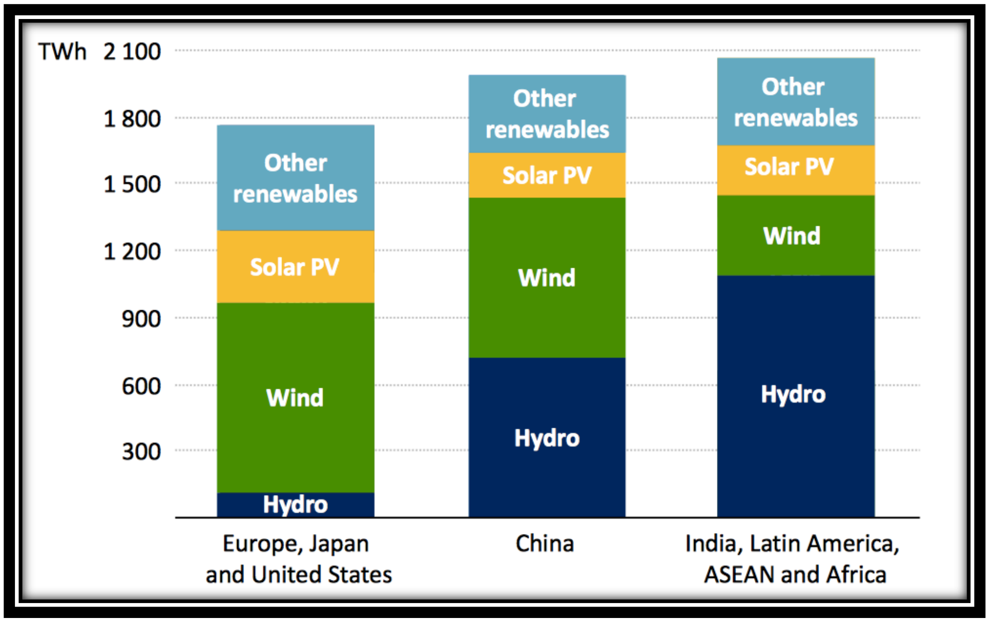


Figure 1-2 Predicated growth in the electricity generation from renewable sources, 2011-2035, reprinted from [3], with permission.

Notwithstanding, the overall clean energy market continued to grow and indeed expanded [27]. According to the "Clean Energy Trends 2011-2013" reports by CleanEdge [28,29,30], total revenue for PV solar, wind energy, and biofuels has collectively increased in 2013 by 35.2% compared to 2010. While we have witnessed a steady growth in biofuels and solar PV installations, the wind power sector has suffered from smaller market size and lower installation capacity [30]. The new installation cost of wind power has gone up since 2011 and is expected to reach $124.7 billion in 2022 [30]. Global capacity of wind power expanded by 44.7 gigawatts (GW) in 2012, 13 GW of which has attributed to U.S. and China. Europe has added 12.4 GW of new capacity in 2012 [30]. Noticeably, only 35.3 GW capacities were installed in 2013, which indicates the 44.7GW decrease from its level in the previous year [30]. According to a 2012 CleanEdge report, the major clean energy sectors growth by 2020 is estimated as follows [29]:

- The capital cost of the wind power installation is projected to double in 2020 up from $60.5 billion in 2010. China has been leading the wind installations from 2009-2014 with 27% growth. The U.S. capacity, as the second-largest market in the world, has shrunk 50%.
- The solar PV industry consists of module development, system components, and installation. This industry is expected to grow 60% to become a $110 billion industry in 2020.
- Both sectors (solar PV, wind) have increased in total deployment of their technologies with increased revenue, especially wind power.

1.1.2 Overview of Canadian Electric Power Sector

The electricity sector in Canada is a major economic driver of the country. This sector varies along different provinces and territories, from large government-owned integrated public utilities to Independent Power Producers (IPPs). These public or private entities play a significant role in generation, transmission and distribution of electricity in the regional electricity market.

Canada is “the world's third largest producer” of hydroelectricity, which accounted for 57% of total world capacity in 2012 [31]. The energy mix varies substantially from the hydroelectric system (British Columbia, Manitoba, Quebec and Newfoundland and Labrador) to fossil fuels (Alberta, Saskatchewan, Nova Scotia and New Brunswick) [31]. The fluctuation of the electricity supply mix among the provinces and the territories reflects variations in available source of energy, economic considerations, and policy choices. According to a recent report by National Energy Board (NEB), the value of the Canadian electricity market is exceeding $47 billion, where Hydro-Quebec is leading the market by generating 37.6% share of the market's volume. As shown in Figure 1-3, BC Hydro and Toronto Hydro contribute to 10% and 5% of the market, respectively [32].

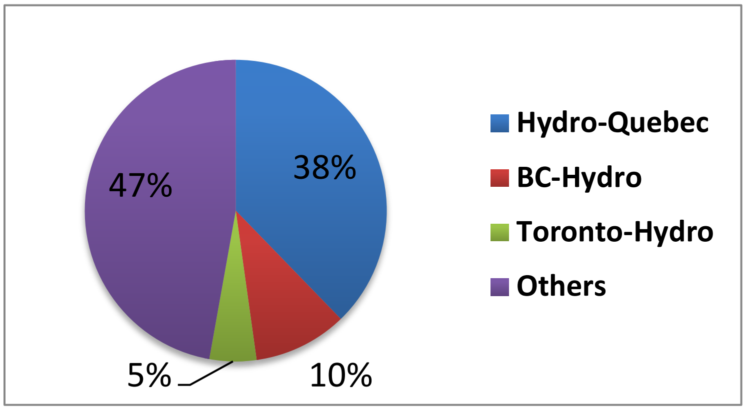


Figure 1-3 The Canadian electricity market; data is compiled from [31].

Similar to types of available energy sources, the electricity market structure varies among different provinces and territories [32].

Alberta Electric System Operator (AESO) manages and operates the Power Pool in Alberta’s wholesale competitive electricity market [31]. Alberta Utilities Commission (AUC) regulates utilities (gas, electricity) with the aim to protect social, economic and environmental interest of the province. The competitive wholesale electricity market in Alberta consists of 170 participants and the total value of energy transactions $6.4 billion annually [32]. The Alberta electricity market is open to various buyers and sellers of electrical energy.

BC Hydro is the main electricity generator, purchaser and distributor in British Columbia (BC), which accounts for 80% of the BC market. British Columbia Transmission Corporation (BCTC) provides and monitors access to BC Hydro’s transmission system. BC utilities Commission (BCUC) is responsible for regulation of electricity and natural gas utilities in BC. Powerex

Corporation, a subsidiary of BC Hydro, is a key player in the electricity trade in the wholesale market, earning significant revenues for BC Hydro and BC [33].

In Ontario, the Independent Electricity System Operator (IESO) administers the electricity markets and governs the operation of Ontario's transmission grid [31]. The Ontario Power Generation (OPG) is in charge of electricity generation. Hydro One owns and operates 97% of transmission and distribution assets in Ontario [31]. IESO is operating deregulated wholesale and retail electric market, where electricity prices are set by the Ontario Energy Board through the "regulated price plan" [32].

The Quebec electricity is dominated by provincial government-owned Hydro-Quebec (the largest utility in Canada). Hydro-Quebec controls and operates generation, distribution and transmission of the electricity in Quebec. The transmission and distribution of electricity is regulated by the Regie de l'energie [32].

According to the Conference Board of Canada, the total electrical energy generated in Canada has been 595 TWh (terra watt hour) in 2012 [31]. The breakdown of electricity generated in Canada as of 2012 is illustrated in Figure 1-4, indicating hydroelectricity as the leading type of power generation followed by nuclear, coal, and small share of natural gas (5%) and wind (2%). By 2030, the forecasted power generation supply mix in Canada is expected to be hydro (46%), wind (16%), natural gas (15%), nuclear (9%), and coal (9%). In return, average residential electricity price per kilowatt-hour is expected to rise more than 50% by 2020 compared to its 2012 level [31].

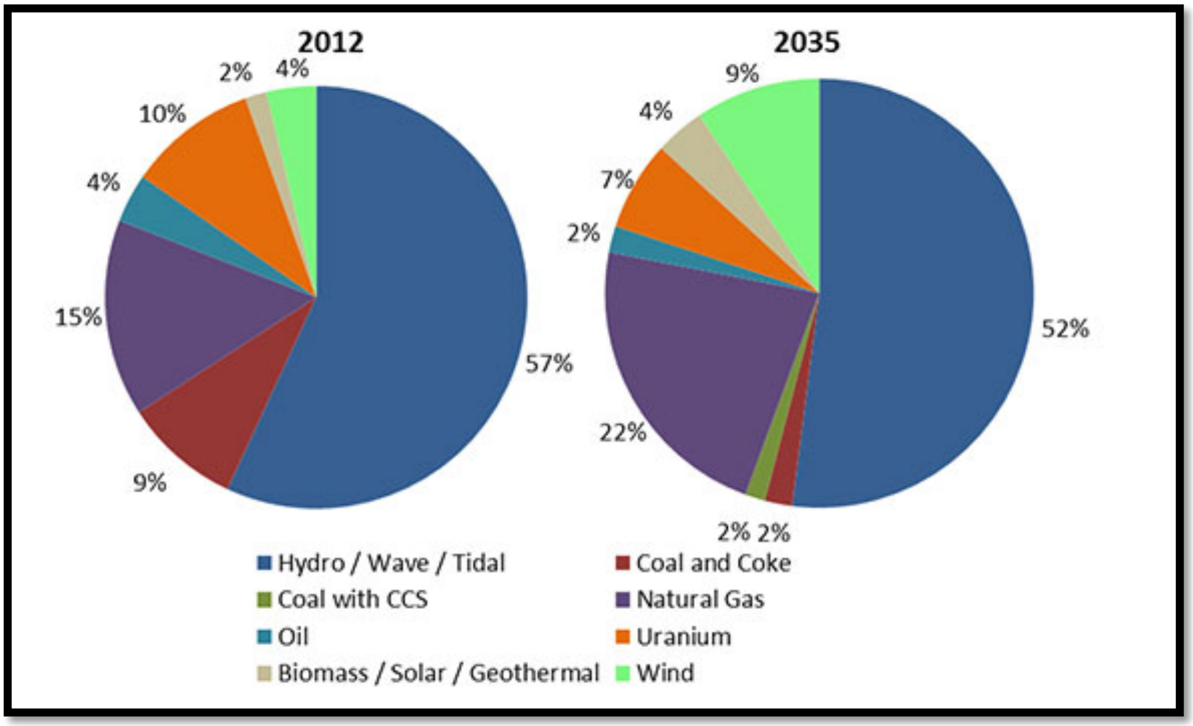


Figure 1-4 The breakdown of the electricity generation capacity in Canada between 2012-2035, adapted from [32] with permission.

1.2 Energy Storage as a Grid Asset

The electricity grid is an important national and regional infrastructure for domestic use and export purposes [31]. Electricity grids, however, are facing various market and technological challenges that influence their reliability and profitability [34]. One challenge is that under increasing electricity demand conditions, the grid capital assets are coming to the end of life. Another challenge is related to the grid stability that is associated with increasing use of intermittent renewable energy generation. Finally, in order to achieve their full potential, distributed “smart” grids require efficient, stable, durable, and cheap energy storage solutions. The main interest in stationary energy storage technologies in the past two decades is in their use for the deployment of renewable energy sources, such as solar and wind energy [25,35].

Energy storage technologies provide multiple service delivery along the electricity grid value chain, including electricity generation, T&D, and end-user consumption, Figure 1-5 [36]. In addition to their role for penetration of renewables in future of electricity grid, electricity storage technologies possess a number of environmental benefits, such as reducing carbon footprint and securing regional electricity demand to avoid long-time service interruptions [36].

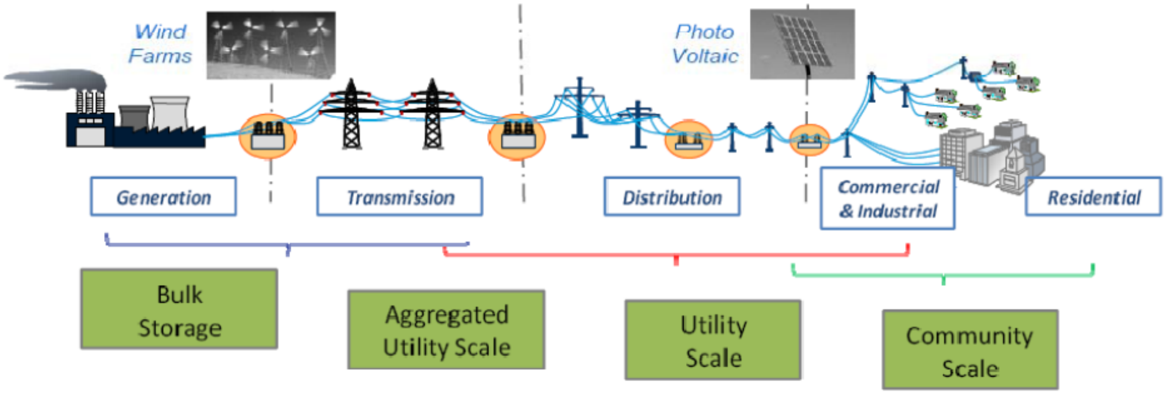


Figure 1-5 The role of energy storage technologies along electricity value chain, reprinted from [36].

Energy storage is an established technology concept in electricity power grid [36]. Some storage technologies, such as pumped-hydro, are more mature than the other emerging storage technologies [25,36]. 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) have 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” [36].

The cost and reliability of an energy storage technology are function of several key factors. Among those factors are roundtrip 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) [36]. Moreover, capital and operating costs determine economic viability and service profitability. Chapter 2 provides a detailed description of storage performance parameters and elements of Storage Performance Metrics for different storage technologies.

The real benefit of energy storage technologies have been studied extensively in different grid service applications (e.g., arbitrage, regulation services, and T&D) [9, 10,12,13,15,37,38,39,40]. By focusing on only one single application, storage technologies have not shown significant value and service profitability [15,34]. 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 debate in academic and business-management literature [41]. Figure 1-6 captures the characteristic time and cost benefit data for specific application and maps some storage technologies [34]. As indicated in various studies, no single energy storage system can provide multiple grid application requirements. 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 [16].

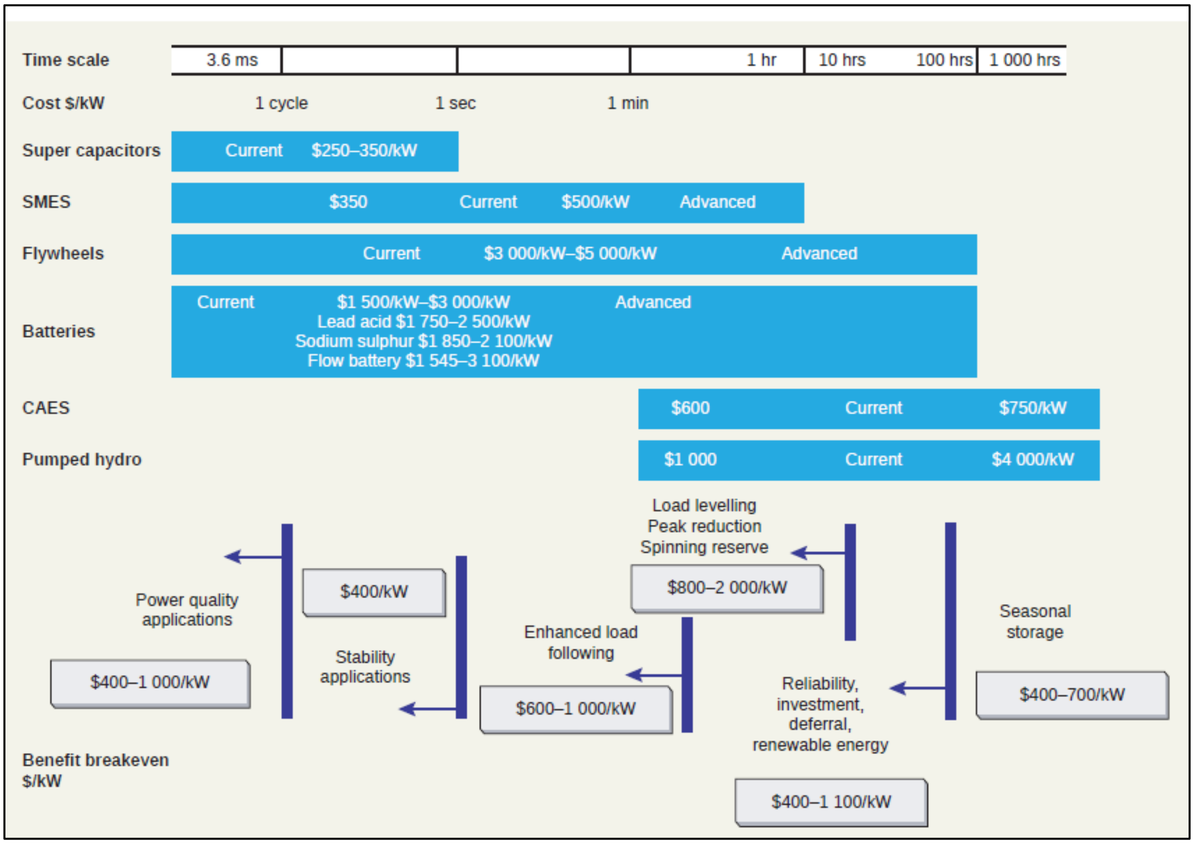


Figure 1-6 Characteristic time and cost data for various storage technologies and grid applications, reprinted from [34] with permission.

The challenge of "aggregating" the value of energy storage technologies [16], often referred to as "benefits-stacking" [25], is related to how the market attributes (regulated vs. deregulated) and electricity system owners or operators can share the cost and revenue streams. It also depends on how the usage of storage can be decentralized by different grid "actors" [16]. A practical business model framework can allow systematic stacking of the value and benefits of multiple technologies.

According to Pike research [35], the key market drivers for energy storage include the price of electricity, grid instability due to renewable integration, high T&D cost, power quality obligations, and moderated feed-in-tariffs (FITs). These are collectively considered among the most important market drivers for the installation of advanced energy storage technologies in electricity grids, according to Electric Power Research Institute (EPRI) and recent Pike research report [13,35]. New data for the large-scale grid-connected electricity storage system, which was compiled by IEA [25] has shown that close to 140 gigawatts (GW) of large-scale energy storage was installed in electricity grids worldwide, with the largest contribution (99%) from Pumped Storage Hydroelectricity (PSH) and the other 1% from the mix of batteries, CAES, flywheels, and hydrogen storage [25, 42], Figure 1-7.

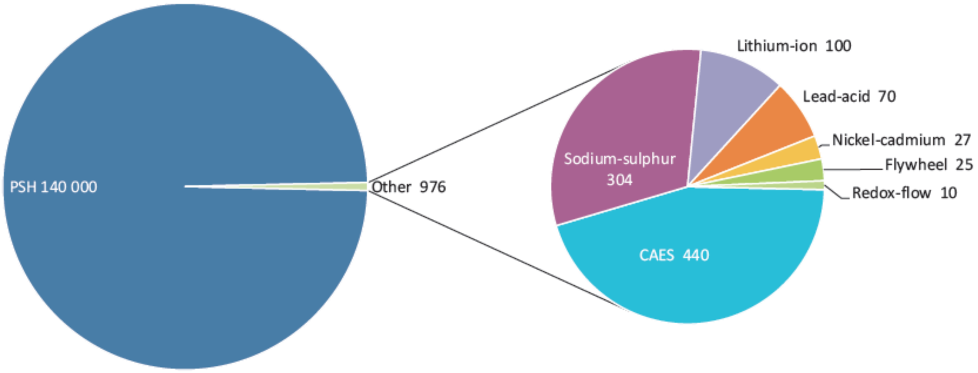


Figure 1-7 Global installed grid-connected electricity. Reprinted from [25] with data compiled from [41,42].

In Canada, renewable energy integration is not the only main driver for unraveling the value of energy storage [31]. Except in rural areas and remote communities, PV solar and wind constitute of a small fraction of electricity production in Canada [31]. By 2012, only 3,819 and 33 GWh of electricity was generated in Canada from the wind and PV solar, respectively [32]. The grid stability, on the other hand, is yet a great concern in major Canadian cities, where the benefit of energy storage technologies is better recognized [31]. As indicated by the Ontario Smart Grid Forum report [43], the biggest commercialization challenge for energy storage technologies is the lack of a benefit structure that works fairly for utility and consumers. The majority of utilities and power producers across Canada have indicated that storage technology is strategic to balance the economics of grid electricity [25]. Ontario, in particular, substantially contributed to put Canada as the preferred market entry point for emerging technologies for new grid storage technologies [25,44]. Finally, storage technologies can expand the wholesale and retail markets of electricity. Some storage technologies are suited for small-scale applications, whereas others are more appropriate for bulk electric systems [45]. The appropriate strategic business models need to realize and develop the potential market for all of these market segments.

In summary, the limitations of adopting emerging energy storage technologies for future grid structure are [25]:

- Electricity market structure is not flexible enough to adopt the new operation/technology
- Ambiguity between cost takers (undertaken by utilities only) and benefit (shared between utilities and consumers) and a lack of appropriate service-based business models.
- High Capital expenditure (CAPEX) and a low rate of return
- Power management cost
- Siting and permitting cost
- Complexity and cost of managing energy storage projects

1.2.1 Energy Storage Market and Use Cases

The real benefit of energy storage technologies depends on the location and form of services that they provide in the distributed or off-grid electricity system [25]. With supply and demand variability at different load scenarios, storage technologies can provide infrastructure support services to system operators. The latter is particularly critical when renewable sources are integrated across the generation or demand portion of the energy system [25].

Overall, the application of energy storage technologies in the electricity market can be divided into two general categories of Power Quality (PQ) and Energy Arbitrage [25]. There are many potential services available for adopting energy storage technologies at the generation side or directly on the grid. In this thesis, we develop business models that cover some of these potential service applications [25,46]. Thus, in this sub-section, we provide definitions for the most common energy market terms and introduce applications that are relevant to the ES market and this research work.

Power Quality

Power quality includes a range of application from frequency and voltage regulation to backup power in case of power outage as well as Uninterrupted Power Supply (UPS). Frequency and voltage regulations refer to the balancing of shifting supply and demand within a central control area, which is done automatically on a short time interval (e.g., minutes or seconds). Energy storage systems can be utilized for improving power quality for short-duration events that affect the quality of power delivered to the customer's loads. The lack of power reliability usually cause service disruption, where the economic losses can be significant. Energy storage technologies can be used to offer auxiliary power when there is a loss of power from the utility grid.

Energy Arbitrage

This market involves the storage of energy when the price or demand or both is low, and discharges or sells the energy when the price and/or demand are high [46]. In economic term, arbitrage or “storage trade” also refers to as energy trade between two energy markets, given price elasticity and supply-demand function in each market [25]. Under a de-regulated electricity market regime, a “uniform pricing auction style is used as all generation assets participating in the market get paid the same price as the last dispatched generation asset’s bidding price”. ES systems can facilitate access to an inexpensive electrical energy when electricity prices are low and sell it back to the grid when prices are rising.

Seasonal storage

This application refers to storage of (electrical) energy for a limited period of time from days-months to “compensate” for a longer-term disruption in supply or other “seasonal” supply or demand variability [25]. An example of such application is storing heat in summer via underground thermal energy storage systems to be re-used in the winter [25].

Frequency regulation

In this service application, power producers or network operators use energy storage to maintain the frequency within the fluctuation limits of the generator. This is usually the case when the frequency drops faster than a new generation can come online [25,46]. Because ES systems can rapidly ramp the power output up and down, they are well suited to play a role as a regulating asset.

Load-Following

This application uses storage technologies to match the generation profile of the grid to the rapidly fluctuating demand on the end-user side [46]. Load following is a continuous form of electricity balancing which manages system fluctuations in longer time periods than frequency regulations (the fraction of hours to days) [46]. For this application, the energy storage device can be used as an automatic or manually controlled generation source.

Voltage Support

This application uses storage technologies to inject power in order to maintain the voltage levels in T&D systems under normal conditions [25]. This service ensures both real and reactive power generation and demand are matched continuously. Energy storage system can provide distributed voltage support at the point in the power system where it is actually needed.

Black Start and System Restoration

Black-start capability allows the electricity resource to self-start in the rare event of the collapsing power system and failure with other ancillary service mechanisms, which implies transferring electricity from the seller to the buyer and ensures that electricity can be transmitted with the high level of reliability, efficiently and securely across transmission system [25]. In the event of a black out, generation facilities, when co-located with energy storage systems, can self-start and re-generate power back to the grid, thus potentially avoid load loss.

Transmission and Distribution (T&D) Deferral

By increasing the peak-capacity (maximum supplied energy) of the transmission line, this application involves the short-term usage of a storage device to allow the existing transmission line to operate for a longer time without being upgraded or replaced. Also refers to as “congestion relief” or “investment deferral”, this application defers the need of a major investment for upgrading T&D infrastructure [25]. The use of energy storage systems can delay or avoid the utility investments in transmission and distribution system entirely. In addition, energy storage systems can defer the distribution upgrades if the reason of upgrading is excess peak demands on the distribution system. Transmission and distribution upgrade deferral is highly depending upon location and its operational value varies, depending upon the condition and age of the facilities.

Time of Use (TOU) Cost Reduction

This is a form of energy arbitrage on the user side in which the consumption from periods of high electricity rates is shifted to those of lower cost. This application is also referred to as "end user energy arbitrage" [45,46].

Demand Shifting and Peak Reduction

This application is particularly important in the integration of variable supply sources such as renewables. It shifts the energy demand by changing the time of certain loads and reduces the maximum (peak) energy demand level [25,46].

1.3 Off-grid and Renewable Integration

In order to improve reliability of off-grid energy supplies (mainly fossil fuels with variable renewable sources), energy storage is used to fill the gap between variable supply resources and demand [25]. The fast-growing renewable energy markets continue to be solar PV and wind. These variable forms of generation present challenges to the power system, which was designed using a centralized model with predictable power flows. As the total amount of solar PV and wind generation in a control area increases, this highly variable generation source puts power system reliability at risk. However, this growing variable generation source also presents opportunities for an energy storage system. An energy storage system's ability to "smooth" the damping effect of renewable to the power system could potentially reduce the system operators' challenge on renewable integration.

Key characteristics of storage systems for particular markets in the electricity energy system were illustrated in Figure 1-6, where typical energy storage applications are characterized in view of different performance attributes. As mentioned in the beginning of this section, this thesis mainly focuses on energy arbitrage and power quality market while developing a typological framework for business models. Energy storage market and its associated applications span on a variety of locations along the electricity value chain [40], Figure 1-8. For instance, on the generation side, the addressable market for energy storage is improving power quality or usage of existing generation source.

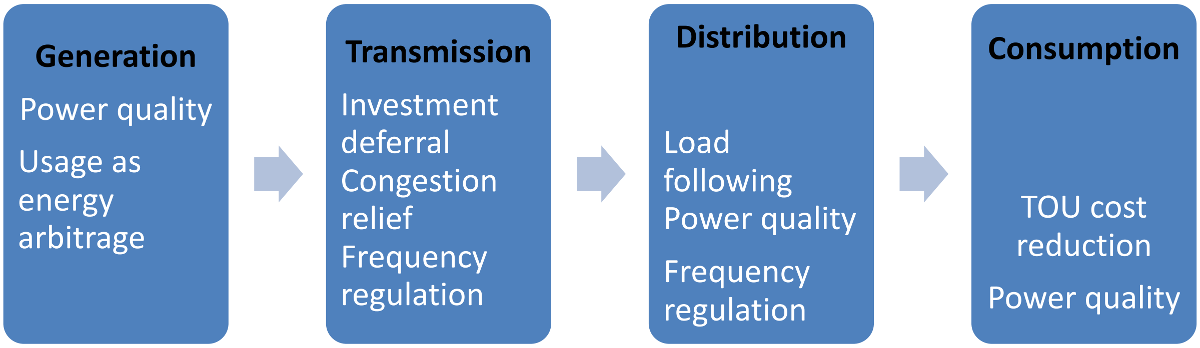


Figure 1-8 Energy storages market and their potential applications along electricity value chain**.**

In addition to economic benefits, storage technologies can also provide environmental benefits along the electricity value chain by utilizing cleaner generators in the arbitrage market that offsets the emission from oil- and coal-based electricity sources [46,47]. Notably, a purely environmental benefit from energy storage may lead to significant revenue losses in a real-time pricing market [16]. Moreover, a single energy storage solution may not generate revenue from various services along the value chain [16,48]. We will discuss this topic in the next section in view of policy framework and regulatory barriers.

1.4 Regulatory Barriers and Business Models

With the medium to long term goal of developed countries for lowering the cost of clean energy and reducing Green House Gas (GHG) emissions, electrical storage technologies should be seen as a "mechanism to protect and extend public investments" [25]. As such, development of electrical storage is seen to directly contribute to improve economic production of electricity and plays an important role in maintaining competitiveness of Canada in global energy market [25]. Chapter 2 provides a literature review and detailed analysis of existing and emerging business models for energy storage systems. For the sake of discussion, a brief overview is provided here as well.

1.4.1 Policy Instruments for Renewables

As indicated in IEA 2014 roadmap, several socio-economic factors determine the deployment of energy storage technologies, in addition to the cost of technology development and performance [25].

"Current policy environments and market conditions often cloud the cost of energy services, creating significant price distortions (e.g. by requiring generators to also supply power services without additional compensation, obscuring the cost of these additional services). In liberalised electricity markets, energy storage cannot receive direct payments for many of the benefits it provides (e.g. transmission investment deferral)."

Although many nations, including Canada, actively support development and deployment of energy storage technologies by providing grants to support large to medium size demonstration projects [25], continuous effort is still required for the radical market transformation towards widespread adoption of energy storage technologies in the electricity grid market.

In a recent market analysis performed by Pike research, several key market conditions were identified for energy storage technologies related to technical needs, and market signals for capturing revenue from storage. Those signals include market structures, regulatory environment, cost-competitiveness of storage system, and business models, both at utility or consumer sides. The report also emphasizes on two key industry issues which include business models and the strength of supply chain [35], which mainly impact scalability of the storage services at commercialization stage than technological innovation during technology development.

“Business models that focus on integrating storage with existing products, delivering services instead of selling technology, and packaging grid-scale energy storage with other, less speculative technologies will be more successful. Currently, sustainable business models are not possible in the energy storage industry unless specific pieces of the supply chain are fleshed out. In some cases, technology vendors are struggling to balance the inherent technology and financial risks within the storage industry. Energy storage does not have enough intermediaries in the storage industry to scale up and fully commercialize.”

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 force utilities to replace a fraction of their electricity production by renewable energy sources [49]. 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 [50]. 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 [51].

1.4.2 Policy Instruments for Energy Storage Technologies

Two basic installation formats are generally considered for storage systems. In the first format, the storage system is installed as a stand-alone unit, whereas in the other format, the storage technology is installed together with the other component of the system and as part of a hybrid format design [52]. In practice, each of these two different formats provides their own advantages and disadvantages, depending on the “location, plants size, and required efficiency” [53].

In an attempt to introduce self-consumption tariffs to replace FITs for energy storage systems, Drizard suggested that FITs are unnecessary and are “*dis-incentivizing*” deployment of ES technologies on the grid [50]. The argument is based on a lack of interest in storing the energy if it is possible to receive payment for delivering it directly to the grid [54].

Couture and Gagnon has put FIT policies into two broad categories: fixed FITs or varying with the electricity market price [55]. A stepped FIT, introduced by Gonzalez and Gual, suggests that FIT is an appropriate policy instrument for energy storage as it advocates for various types of technology options on the market, which are available in different Technology Readiness Levels (TRLs) [56]. The latter is clearly the case for energy storage technologies. Countries or states with a policy on the installation of energy storage systems are scarce. Those countries with a policy in place (UK, Greece, Germany, and Denmark) employ multiple tariff schemes. The first level of tariff can apply to a renewable source that is directly connected to the grid, whereas the others are applicable to electricity generated by storage units only or by Combined Heat and Power (CHP) units [25].

Pay For Performance (PFP) and Diffuse Benefits (DB) versus Concentrated Benefits (CB) are the other form of policy instruments that has been proposed for adopting energy storage technologies by utilities [39,57]. 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 [39].

Investment by Canadian utilities over the past 10 years and the next 20 years has been mainly devoted to upgrading electricity infrastructure [31]. This provides vast opportunities to develop and integrate energy storage technologies to create significant economic benefits for Canada. Ontario is well positioned to take advantage of this opportunity, by leveraging early-adopter traction in the Canadian electrical utility market with existing expertise and resources to co-develop, validate and prove energy storage technologies for grid applications.

Since 2006, Ontario has had a rigorous and focused policy around energy storage technologies for grid applications [58]. However, in 2006, Ontario Power Authority (OPA) did not recommend an immediate need for energy storage technologies. The assessment has been reviewed later from 2006 to 2011, while Ontario energy supply mix and system conditions have been changing [59]. In particular, the Ontario Smart Grid Forum Working Group has mainly recommended pumped generation storage to be considered in the future as the most competitive technology since it can import electricity from nearby utilities that possesses storage capacity or capability to adopt emerging storage technologies such as flow batteries [59]. In May 2011, the OPA, Ontario Energy Board (OEB) and IESO have worked with utilities and relevant industries and decided to promote the integration of cost–effective distributed energy storage systems for the grid application [59]. The forum has particularly developed a smart home roadmap that demonstrates how consumers will utilize existing and future energy storage technologies in the next 5, 10, and 20 years [59]. The report also states that a significant part of the policy development during the period of 2012-2030 should focus on developing and using standards and regulations for defining smart grid specifications, with a close interaction with smart grid Task force and Standard Council of Canada as a monitoring agent [60].

In view of innovation and actual economic development, the policy of Ontario is to foster smart grid innovation, energy storage technology commercialization, and related economic development opportunities [59]. In the form of Public Private Partnership (PPP), Ontario plans to boost export opportunities of technologies and innovations related to the smart grid over long term, particularly those related to energy storage technologies [60]. The recent call for "Energy Storage Procurement Framework" is an example of such efforts, which is currently executed by IESO [44].

Ontario's current FIT schemes are only applicable to a short list of technologies that are lagging behind the potential of innovation for new energy storage systems [61]. The FIT program also prevents a multi-level scheme for FIT implementation as it will raise electricity prices, independent of level of storage capacity. The storage capacity is an important factor that determines the viability of multi-level FIT schemes. Further review and studies are required to enhance opportunities in Ontario to transform FIT program with a new arrangement that delivers more cost-effective benefits to electricity customers [61].

1.5 Complexity of Adopting Storage Technologies

In summary, the lack of practical and service-based business models, complexity of regulatory and policy environments, ambiguity of ownership and governance structures of storage assets, profit and financing strategies, difficulties in managing revenue streams, and associated operational risks are among the critical road-blocks for providing an accurate assessment of the viability of the emerging ES technologies. The storage market structure is complex due to the wide variety of technology solutions and diverse application services that each technology can offer along the electricity value chain.

1.6 Research Objectives

The review of the current technical and business-management literature reveals the need for developing practical business models for grid-scale electricity storage technologies. The characterization of various business models should be able to address temporal (size and maturity of the storage technology) and spatial contingencies (the type of service, location, application and market or electricity pricing structure). There is a need to analyze existing business models and develop practical frameworks that ensure accurate assessment of profitability and value created by adopting electricity storage technologies in electricity power grids. This research work proposes new business models and assess the value proposition of storage technologies by formulating their risks and opportunity profile. Thus, the main objectives of this research are as follows:

- Develop a typology of business models for grid-scale storage technologies that can be used as a practical framework for management decision-making purposes. The framework tackles some of the issues discussed in Sections 1.2-1.4 for accurate screening of storage technologies to capture the value and unique benefits of an energy storage medium. For industry looking to adapt new energy storage technologies, such analysis framework of various business models 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.
- Develop a bottom-up approach to identify remaining R&D priorities necessary to ensure near-term (3-5 years) market success of grid-scale energy storage technologies. The resulting platform employs a set of technology management frameworks in the context of storage technologies to support grid services and variable electricity generation. Among those technology management tools, several are employed from matrix management techniques such as Technology Development Matrix (TDM), Technology Landscape Road Mapping (TRM), Innovation Matrix (IM), and Linkage Grid (LG). The idea is to focus on a specific storage technology and compare it to other similar

technologies for grid applications by mapping their technological advantages/ disadvantages, economic value, and innovation capacity.

- Develop a comprehensive study to identify policy and regulatory priorities at the interface of business models that drive the future storage market and analyze policies and regulations that may change the competitive environment.

1.7 Research Motivation

The motivation behind this work was to answer several important research questions:

How can a single ES technology, or a group of ES technologies, be matched to appropriate business-operation models for a site-specific grid configuration under certain grid service applications?

- With increasing penetration of renewable energy resources in the overall energy system, is there a need for new business models to address the role of storage technologies and pathways for investment of storage within the power grid? In particular, do the business models already in use for renewable energy applications suffice to address storage challenges?
- It is of vital importance to develop practical frameworks that ensure accurate assessment of profitability and value created for the electricity power grid by ES technologies. Given the diverse characteristics of ES technologies and unique requirements (temporal and spatial) of the power grid, there is a compelling need for sophisticated business models that can provide insights into the parameters for which deployments of individual storage technologies can be economically, operationally and technologically viable.
- A thorough analysis requires multi-dimensional considerations such as regional electricity market structure, opportunities for bundling grid services to aggregate revenue streams, electricity and technology costs, system efficiency and reliability, best practice business operation models, and alignment with local or national policies. Including all of these parameters in the analysis leads to a complete and comprehensive view for strategic decision-making purposes. This thesis is primarily focused on the application of a proposed typology of business models to specific grid-scale use cases to ultimately assess the value proposition of storage technologies.
- In order to ensure proper deployment of the proposed typology of business models, continued refinement, and vast adoption by key stakeholders along the ES value chain, this thesis intends to offer a proof of concept for a practical analysis tool, Storage Monetization Analysis and Reliability (SMART). This tool is intended to evaluate overall economic value and monetization strategies for adoption of ES systems. In order to ensure a consensus on the valuation methodology and a validated user interface, the valuation model is based upon an existing screening tool, ES-select™.

1.8 Thesis Outline

The rest of this document is organized as follows: Chapter 2 provides a background review and detailed description of storage performance metrics together with an overview of storage technologies. A general discussion and literature review is also presented in this chapter on applications of technology management tools for technology mapping of the grid-scale energy storage technologies. This chapter also provides literature review on the value of energy storage technologies and state-of-the-art business models for integrating energy storage systems. Chapter 3 describes the analytics framework, underlying databases and cost assessment models that are used throughout this thesis. In Chapter 4, series of technology management tools are introduced for assessing the value of grid-scale storage technologies. A typical technology development matrix is also introduced and complex relationships among electricity generation, storage and costs are explored. The detailed phenomenological analysis of selected configuration and typology of proposed business models are provided in Chapter 5. Estimation of storage market opportunity is provided in Chapter 6 where the overall market size, key grid services, and deployment timing of ES systems are quantified. In Chapter 7, business models and valuation analysis for grid-scale power-to-gas systems are discussed in great details. Chapter 8 studies cost-effectiveness of several energy storage use cases, building upon cost-benefit analysis and the typology of business models that are developed throughout this thesis. Finally, Chapter 9 outlines the main findings and key contributions of this research work.

2 Review of Relevant Concepts

This chapter presents a literature review of the concepts, models and tools that are going to be used in this research work. A detailed description of storage performance metrics together with an overview of storage technologies are provided in this chapter. A general discussion and literature review is presented, by concentrating on the application of technology management tools for technology mapping of the grid-scale energy storage technologies. An overview of valuation tools is also presented, outlining different types of tools and methodologies from screening to in-depth analysis of the storage technologies. Finally, state-of-the-art business models for integrating energy storage systems are discussed.

2.1 Storage Performance Metrics

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 (super-capacitor), mechanical energy (flywheels), and magnetic energy (super-magnetic energy storage). Storage systems include a number of technologies in different TRLs, Figure 2-1. The performance metrics that characterize and compare different technologies are separated from the location and services that they can provide [45]. Other categorizations are based on the TOU, short-term, long-term, and distributed storage, or level of maturity and technology advancement [25,45].

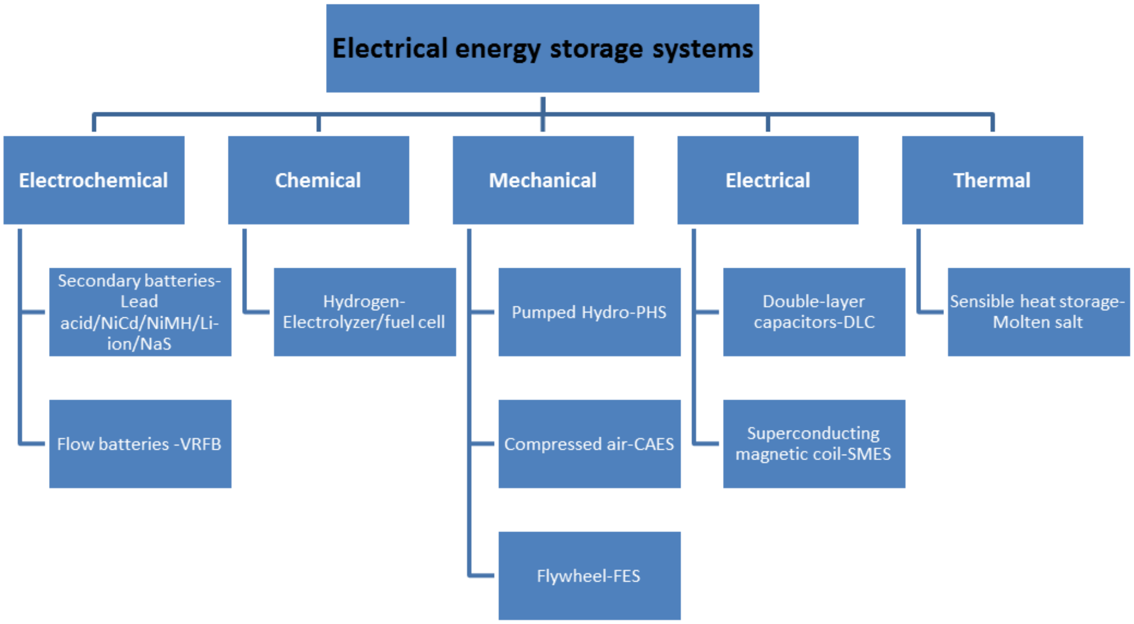


Figure 2-1 Classification of storage technologies according to form of energy, adapted from [45].

In this section, performance metrics for storage technologies are introduced. Later in the next section, we also provide an overview of few storage technologies with a focus on those that are at the early commercialization stage or those that are currently used in energy storage demonstration projects. In this research work, the attempt is to develop and analyze generic business models that apply to a range of storage technologies. Particular consideration, however, is given to those technologies that appear to have considerable challenges for technology adoption and business model innovation.

Performance metrics that form the basis for the ES valuation characterize a storage technology for various applications in electricity grid systems. The most common metrics are the following:

- Energy storage capacity [kWh or Ah];
- Charge and discharge rates [kW or A];
- Lifetime [cycles, years, kWh_{life}];
- Round-trip efficiency [%];
- Initial capital costs[$/kW, $/$\text{kWh}_{\text{cap}}$, and $/$\text{kWh}_{\text{life}}$];
- Operating costs [$/MWh, $/kW x yr]
- Energy density [Wh/kg and Wh/m^3] and power density [W/kg and W/m^3].

2.1.1 ES Capacity [kWh or Ah]

Applications for electricity storage technologies can be specified in terms of power applications or energy applications. Power applications are those with high power output for a short period of time (i.e, seconds to minutes), whereas energy applications generally requires discharges over a longer period of time (i.e., minutes to several hours) near its nominal power rating [25]. Energy storage capacity, in kWh, is the amount of energy that can be recovered at a given time. If the operating voltage of the storage is considered as the key performance characteristics, the energy storage capacity is defined in Ah [where kWh = V × Ah / 1,000]. The actual energy capacity depends on several factors such as the rate of charge/discharge and over-discharging which shorten the lifetime.

2.1.2 Charge and Discharge Rates [kW or A]

The rate of charging or discharging is the rate at which energy is consumed or stored in a storage system. For those systems with assuming an operating voltage, the rates are measured by Amperes (A), however, kW is a more common unit. The rate is not constant and depends on the amount of energy stored and how long power has been taken from the system. Generally, the rate of charging is lower than discharging for most storage technologies.

2.1.3 Lifetime [cycles, years, kWh_{life}]

The lifetime of a storage system can be measured by the number of charge/discharge cycles at given energy capacity. The lifetime of batteries is depending on how much their storage capacity is deviated from its initial capacity after each charge/discharge cycle. This is generally known as the “Depth of Discharge” (DoD) or “Stage of Charge” (SoC). Usually, higher cycles shorten expected lifetime of the battery [45].

Due to the mechanical, chemical, or electrochemical degradation of components, the performance is decayed slightly during each charge/discharge cycle. Some storage technologies, particularly those already commercialized, use an average time (e.g., year) as the lifetime, while others describe the lifetime by actual total energy (kWh_{life} or Ah_{life}) at full charge state.

Figure 2-2 maps major storage technologies based on power output (charge/discharge rate) and energy capacity/stored for different rate of applications [62]. The grayed region indicates several storage technologies that are not appropriate for arbitrage, which include superconducting SMES, flywheels, and super-capacitors. The remaining storage technologies that could potentially perform arbitrage services are electrochemical batteries, flow batteries, CAES, and PHS. Hydrogen storage is another technology which is not listed in this figure but is considered in this work. Each technology is described briefly in the following sections.

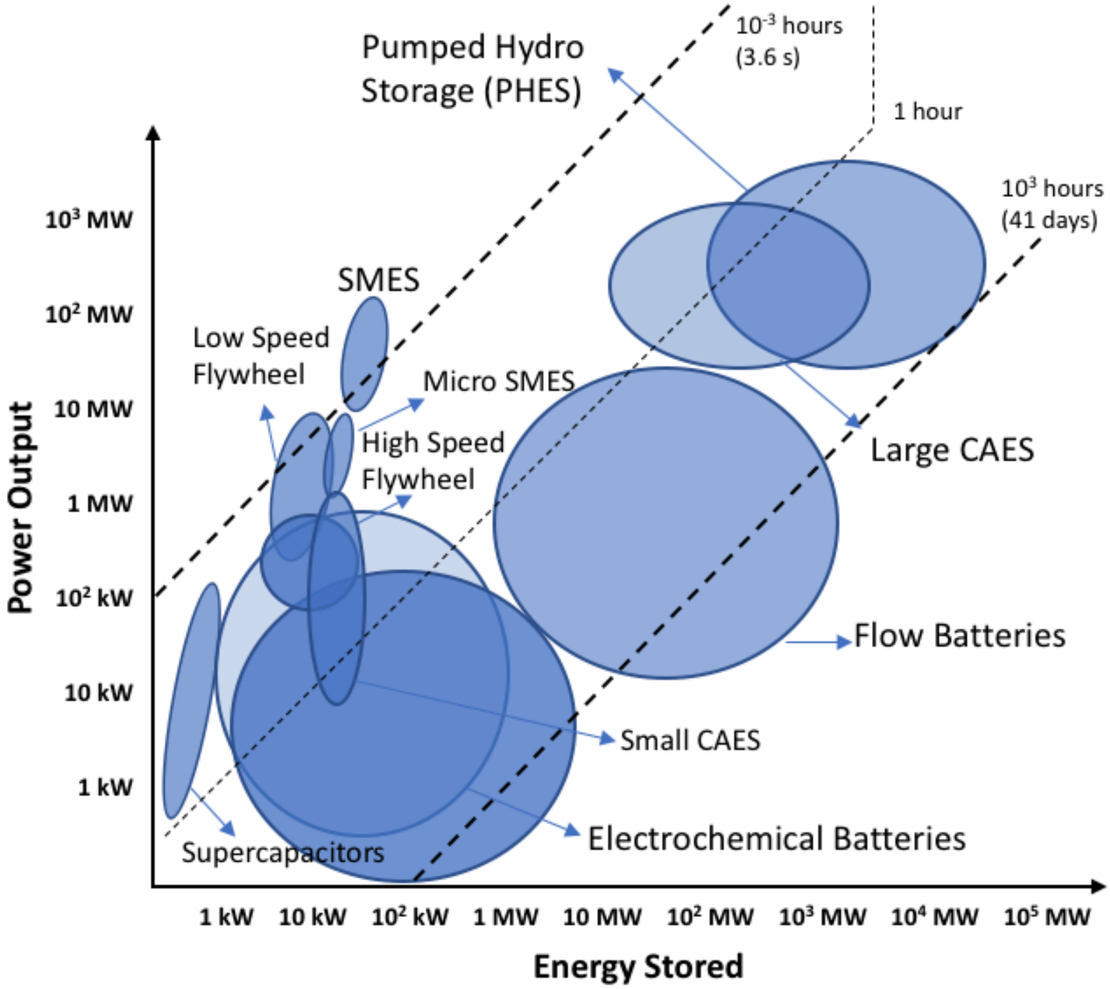


Figure 2-2 Storage technologies based on power output (charge/discharge rate) and energy capacity/stored for different rate of applications, adopted from [62]. The size of each circle represents the range of low-high value for energy stored vs power output.

2.1.4 Round-trip Efficiency [%]

The percentage of the additional required energy during charging is expressed as round-trip efficiency [%]. It is an energy loss and is calculated as the ratio of energy released from storage system to the energy input during charging. Notice that energy loss exists during both storing energy and converting chemical or mechanical energies to electricity; both contribute to round-trip efficiency. Round-trip efficiency has a direct cost implication, where less efficient storage systems (e.g., hydrogen storage) are more costly to charge than more efficient storage systems [45].

2.1.5 Capital Cost [$/kW]

Total capital cost for a specific storage system includes system acquisition cost and system installation cost. While the former depends on storage size, the latter depends on various factors such as location, labor rates, climate and environmental considerations, and logistics issues [45]. In addition to these costs, the full installation imposes additional costs, known as Balance of System (BoS) costs, which are mainly related to safety, inverters, data monitoring, and sensor installations. The BoS cost often exceeds the cost of storage device, and therefore must be considered carefully during planning stage. The capital cost is usually described based on the power that the storage can deliver [$/kW] or costs per total energy capacity [$/kWhcap] [45]. The lifetime cost or Cost of Ownership, often used in valuation studies, is the cost associated with the entire life of the storage. It is the total capital cost divided by the lifetime energy throughput [$/kWh$_{\text{life}}$].

2.1.6 Operating Costs [$/kW]

Storage technologies require various operation and maintenance (O&M) activities to stay on a reliable level of performance and power output [45]. The frequency of usage, type of application, climate control, the equipment handling, and the quality of storage services are among important factors that affect the O&M cost.

2.1.7 Levelized Cost of Energy [$/kW]

The Levelized Cost of Energy (LCOE) for grid storage is defined as the overall cost of ownership of storage over the investment period divided to the total delivered energy in that period [63]. In economics term, LCOES is defined as the internal price of energy sold at which the Net Present Value (NPV) is zero [63]. LCOE indicates that for comparing the value of different storage technologies, the total cost of ownership over the project lifetime is more important than the cost of capital [63]. The equation below expresses the LC,

$$LC = \frac{\sum_{t=1}^{n} \frac{ISC_t + SOM_t + EC_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{EO_t}{(1+r)^t}} \qquad (1)$$

where ISC_t is the invested storage capital per year (t), SOM_t is the storage O&M cost per year (t), EC_t is the charging energy cost, r is the annual discount rate and EO_t is the total released energy in year (t) [64]. For a specific storage technology, the more energy is produced over storage lifetime, a lower LCOE is determined by the maximum energy turnover during lifetime.

Figure 2-3 shows the variation of LCOE as a function of utilized storage capacity at different charging electricity price. Lazard provides a comprehensive technology assessment framework based on levelized cost of storage (LCOS) [65,66] instead of LCOE. In a recent study, lithium-ion is shown as the most economical solution across all use cases. The only exception is related to flow battery technologies that can offer lower cost solution for longer duration services. LCOS only analyzes observed costs and revenue streams from the project and is generally an empirical indication for equipment costs and associated revenues. LCOS reported by Lazard is based on aggregating cost and operational data from original equipment manufacturers and technology developers, and is only applicable to a selected subset of identified use cases.

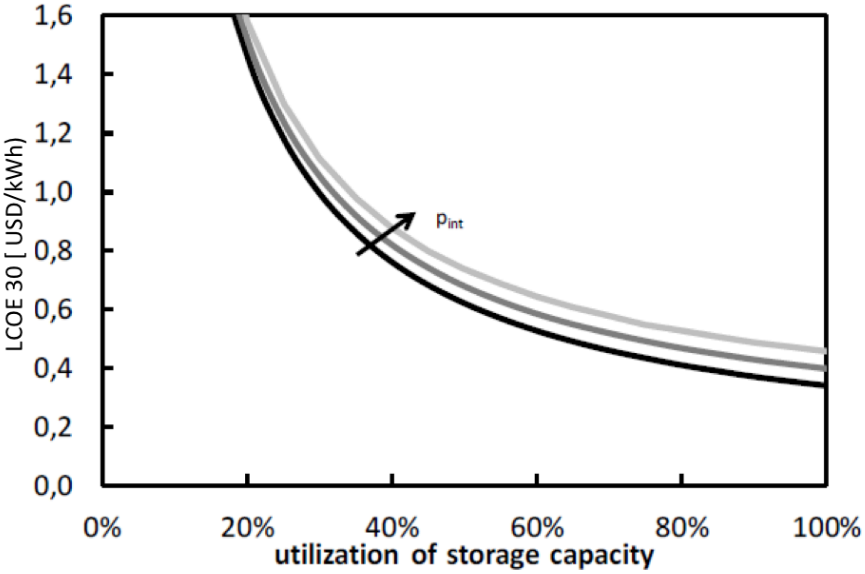


Figure 2-3 LCOE as a function of used storage capacity per cycle with varying electricity price of charging [63].

The cost of implementing energy storage is a combination of cost of installation, cost of operation and the level that storage performs over its service life time. In other words, the efficiency of storage technology and optimal service lifetime are major factors in lowering total cost of ownership. As stated in Chapter 9, Levelized Cost of Storage (LCOS) is a method to benchmark the actual cost of storage by taking into account all aspects of storage including cost of installation, and all limitations including service life time. The effect of State of Charge (SoC) of batteries can only be addressed by estimating LCOS, which is an entirely different descriptor compared to LCOE.

2.1.8 Energy and Power Density [kWh/m3 or kWh/ton]

The energy and power density are generally more important in mobile and site specific applications than stationary applications, in which case energy per weight [kWh/ton] or energy per volume [kWh/m3] are considered as energy and power factors [45].

2.2 Overview of Choices for Storage Technologies

This section provides an overview of energy storage technologies considered in this work. The technologies are grouped in the literature with different features such as performance, round trip efficiency, charge/discharge rate, response time, LCOE or LCS, the application, and industry readiness level. Technical and cost parameters for most of the storage technologies are summarized in Chapter 3.

2.2.1 Commercially Available Storage Technologies

Commercially available storage technologies are those with multiple venders and readily available for purchase [25,45]. Lead-acid battery is the most commercially available technology at small scale power output (up to 10 MW). Albeit with better gravimetric and volumetric energy density, Lithium ion batteries are also significantly more expensive than Lead-acid batteries and are available commercially.

For larger electrical grids (>10 MW), PHS is a mature technology and has been widely commercialized. CAES and NaS batteries have gained small market share. Both CAES and PHS are location specific and their installation requires particular geological considerations. Flywheels, lithium-ion batteries and the Vanadium Redox Flow Battery (VRFB) are gaining market potentials, but still are not commercially available for large scale applications.

2.2.2 Emerging and Under Development Technologies

Emerging storage technologies are those that are still under extensive Research and Development (R&D) with no or few demonstrations worldwide. They require significant improvement in performance and cost. Hydrogen storage in an emerging storage technology with low round trip efficiency (20-30%) [25] that is still too expensive for grid-scale applications. Hydrogen is better suited for off-grid and remote applications. Hydrogen storage, as a storage technology solution, consists of an electrolyzer, the hydrogen storage tank, and a fuel cell or other sort of electricity generator that uses hydrogen. VRFB, Lithium ion, and Zinc-Bromide are also at an emerging stage, particularly for large scale (>10 MW) applications.

2.3 Storage technologies: Summary

There is a consensus among technology developers, storage technology integrators, and utilities that there is not a single winning storage technology, despite enormous technological and cost advancement in recent years [16,39]. Table 2-1 summarizes the advantages and constraints with different storage technologies [45]. Relevant to this research work and for the sake of case studies, few emerging technologies such as Li-ion batteries, VRFB and Hydrogen Storage are considered and compared to one or two mature storage technologies (e.g., CAES). These technologies possess different market structure and industry readiness level. They impose different technology and financial risks to the grid, thus are of interest for testing the business model frameworks developed in this thesis.

Table 2-1 Advantages and constraints of storage technologies, adapted from [45].

Storage Technology	**Advantages**	**Constraints**
Lead-acid batteries	Widely available, moderate costs, modular	Limited lifetime, must be disposed & maintained properly
Li-Ion batteries	Rapid technological improvement, compact in size	Rupture risk, little experience in electric grids
Na-S batteries	ancillary services high round-trip efficiency	Suitable for larger electricity systems, corrosive chemicals
Flow batteries	Can be fully discharged, some- what modular	Still under development, higher capital costs
Flywheels	Modular, low maintenance	Expensive
Pumped Hydro	Technically proven, low costs	Very large scale, significant environmental impacts of construction
CAES	Moderate costs	Very large scale, uses natural gas
Hydrogen	Transportation fuel, compatible with fuel cells	Low round-trip efficiency, expensive

2.4 Maturity of ES Technologies

ES technologies possess values at many levels of development, from the early stages R&D to mature, deployed technologies [42,67]. The maturity of energy storage technologies can be assessed by using TRL and Manufacturing Readiness Levels (MRL) [68]. TRL1 refers to an innovation activity at the very basic research, while TRL9 represents the technology at the commercial stage. Most of the energy storages considered in this work are at the prototype stage (TRL6). The highest TRL9 is assigned to Pumped hydro systems as the most deployed storage technology, whereas VRFBs are at TRL6. The MRL is similarly assigned to each of the storage systems [68]. IEA 2014 Technology Roadmap has provided a development spectrum for maturity of energy storage technologies which is closely equivalent to the TRL and MPL levels defined by [68]. Key technologies are mapped with respect to their associated initial capital investment requirements and technology risk versus their current phase of development (i.e. R&D, demonstration and deployment, or commercialization phases) [25,69,70].

2.5 Technological Innovation

TRL and the risk associated with the maturity of energy storage systems have been used by U.S. Department of Energy (DOE) for providing support for scientific, R&D and commercialization activities related to grid-scale energy storage systems. In a recent report, DOE [71] has evaluated the risk and technology readiness of energy storage technologies. In energy storage, similar to many other technologies, the roles and responsibilities of private and public sector increase as risk is reduced. Government role changes from that of "*providing scientific and technology advances during the early stages of technology development to one of independent analyst, convener, and facilitator addressing common issues affecting technology adoption*" [71].

2.6 Technology Management Tools

Technology management tools help managers to implement solutions for adoption of new technologies [72]. These tools should be practical to support and evaluate management decisions and strategic actions. Moreover, appropriate techniques and tools should be developed and combined in order to address a specific business or management problem [73,74,75,76,77, 78,79]. According to Phaal et al [80], the tools should be theoretically robust and reliable, be practical for implementation, integrated (integrate perfectly and can work with other processes or resources within organization or business/management process), and flexible (adapt easily in various business ecosystems). One should notice the difference between generic "management tools" and "technology management tools" [81] and later by Phaal et al. [80]. The following framework provides description of terms and interrelation between these approaches, **Figure 2-4**.

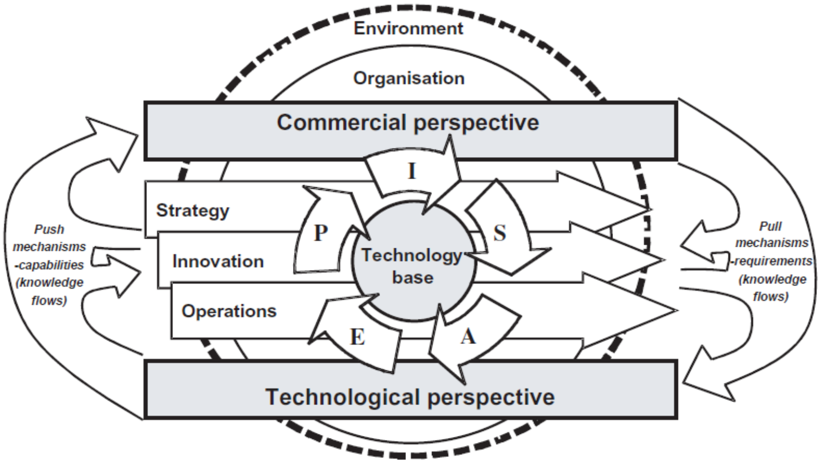


Figure 2-4 Technology management framework representing management approaches and methodologies for technology development and adoption process, reprinted from [80].

This platform can provide 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 (techno-economic cost modeling and life-cycle cost & environmental assessment) and project portfolio management.

Among various technology management tools [77,78], several tools have already been employed including matrix management techniques such as Technology Development Matrix, Technology Landscape Road Mapping, Innovation Matrix, and Linkage Grid. A common objective of these tools 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. The following technology management tools and methodologies will be utilized in this project.

2.6.1 Technology Road Mapping

The most general form of Technology Roadmap (TRM) is comprised of a "*multi-layer time-based chart, within which the development of themes can be mapped*" [75, 82]. TRM can be structured for firms or for technologies. The firm-based TRM contains market, business, products, services, technology, and resource themes. The technology based TRM which is the focus of this research work includes industry, market, and other technical relevant attributes [80].

2.6.2 Link Analysis Grid

Analysis grid poses orthogonal structures and is used to link one set of Themes (technical, market, business, product) to another [80]. There are many forms of such tools [83,84,85,86]. We will employ the one suggested by [87], in which the market attributes are related to current products and future technologies. The most widely used form of this class, Quality Function

Deployment (QFD) grid or "House of Quality" can be used to support the choice of grid-scale energy storage, linking user requirements to technology solutions [88].

2.6.3 Technology Development Matrix

Technology development matrix (TDM) is linking market needs to technology attributes to key technical parameters [80]. 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 [80]. 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 truth, TDMs developed internally in many firms were normally a workable version of TDM. It serves the initial purpose of understanding the landscape, technology priorities and making a decision of project's portfolio mix.

2.7 Energy Storage Valuation

Despite considerable benefits that storage technologies provide, storage deployment projects worldwide are still scarce [89,90]. For the most part, the low volume of the demonstration project and early commercialization cases are attributed to the lack of appropriate valuation frameworks or benchmarks to quantify their techno-economic value. Some of the economic benefits cannot be fully captured within the existing electricity market, albeit with significant stability and quality that storage can add to the power grid system. Adoption of energy storage is a complex process due to the wide variety of technology choices and potential grid service applications which makes the choice of a reliable, affordable, and sustainable storage technology extremely difficult [91,92]. An overview of various valuation techniques and approached are provided in this section.

There exists a great level of ambiguity among end user (i.e. utilities), transferred to manufacturer, to improve cost effectiveness and performance [93]. Chapters 3 and 4 provide detailed review and analysis of valuation approaches and tools that have been widely utilized by utilities, technology vendors, independent consultant, and research institutes [91, 92,94,94].

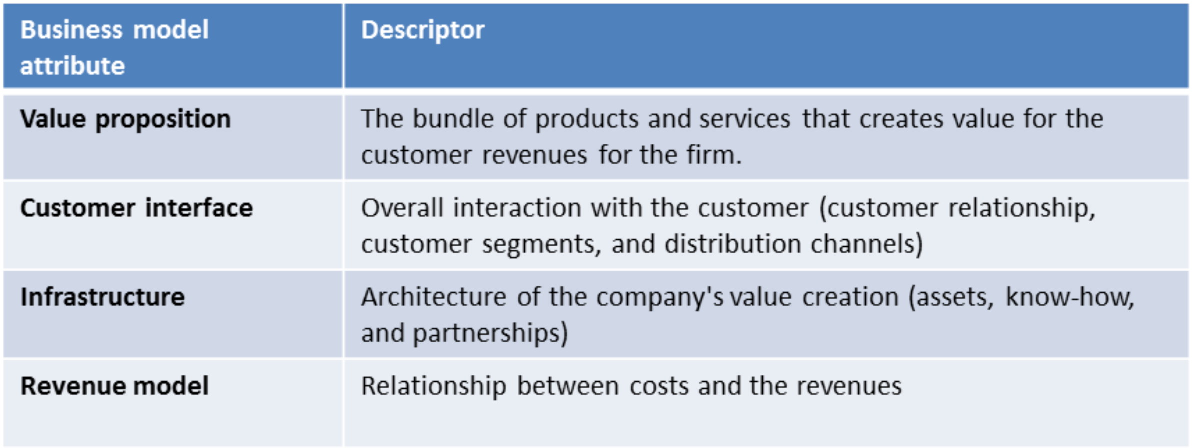
2.8 Overview of Business Models

The purpose of this section is to document all available sources on possible business models for distributed and connected storage systems. This section also emphasizes that all significant cost and revenue streams should be accounted for in the design of the appropriate market and business models. Business models are evaluated in terms of scale and storage type [22]. A recent review by Richter [21] has provided extensive analysis of how utilities need to revamp their business models to overcome new challenges related to grid security and integration of renewables. Richter [21] identified two basic choices as "utility-side business models" and "customer-side business models". Although utility-side business models are preferred by utilities for which a blueprint exists; the business models for customer-side has not been developed extensively [21]. In the following section, we highlight the insights into each of these choices and discuss the applicability of such models for storage technologies in power grid.

2.8.1 Business Model Innovation

The business model is defined as a strategies guideline that constructs the "organizational and financial architecture of the firm" [21, 22,95]. For the purpose of this work, business model is the way that firms deliver value to their customers, make customers purchase that value, and create profit from those purchases [96,97]. The latter concept of business models has been extensively tested [98] in the real world and is fully applicable to renewable energies (Table 2-2). Business model innovation is a strategic alternative taken by firms to respond to externalities [22,99,100,101]. Richter defined business model innovation as "*development of new organizational forms for the creation, delivery, and capture of value*" [22]. The opportunities and barriers of business model innovation are of vital importance for clean energy industry due to the extensive presence of disruptive innovations [22,102] and "organizational ambidexterity" (103,104,105).

Table 2-2 Business model conceptualization, adapted from [22].



Business model attribute	Descriptor
Value proposition	The bundle of products and services that creates value for the customer revenues for the firm.
Customer interface	Overall interaction with the customer (customer relationship, customer segments, and distribution channels)
Infrastructure	Architecture of the company's value creation (assets, know-how, and partnerships)
Revenue model	Relationship between costs and the revenues

2.8.2 Business Models for Renewable Energy

The choice of business models for renewable energies has been addressed by a number of recent studies [106, 107, 108,109, 110]. Several generic, utility-focused business models for renewable sources are proposed in literature, Figure 2-5 [21,22]. On- and off-shore wind energy, large-scale photovoltaic systems, biomass, and large-scale solar thermal energy are few examples of technologies that may adopt a utility-side business model [21]. The value proposition in this business model is in "*bulk generation of electricity*" [111]. The customer-side business model is best described by energy generation in small-scale systems close to the point of consumption, often referred to as "distributed generation" [21]. A detailed review and analysis of existing and proposed business models is provided in Chapter 5.

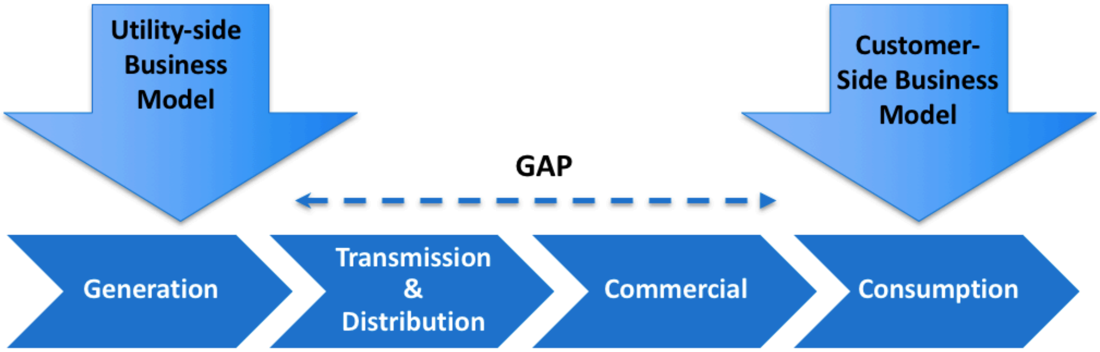


Figure 2-5 Two generic utility business models and their position along value chain, adapted from [21].

2.9 Business Models for Energy Storage Systems

In a recent study [16], He et al. proposed a new business model that aggregates multiple revenue streams of storage. The model, also referred to as “Benefits-stacking” [25], consists of multiple ways to utilize the storage unit at different time intervals. The results from [16] show that under aggregating revenue streams, a storage unit can reach to a higher rate of return and profitability [16]. A set of consumer-side business models are proposed and communicated to a group of utility and power system operators for a particular installation of energy storage systems in UK [112]. The business models were designed and analyzed from an investor or “controlling entity” perspective [112]. The suitability of the business models for projects of a similar distribution-scale and of similar technology-type was discussed as well**.** Such studies could complement previous work on the macro-economic benefit of storage, similar to those introduced for the valuation of storage technologies in the previous sections. The business model framework in [112] contains three main attributes, based on which each business model is characterized. The attributes include:

- Ownership: This attribute describes who takes the risk of construction and operation for the installation of large-scale storage systems.
- Commercial operation: This attribute identifies the entity who is managing the risk of monetizing and capturing the value of storage
- Market: This attribute describes the relevant market structure to which the operator or owner provides storage services.

The following sections provide a brief description of each business model introduced in [112].

2.9.1 Network Operator Merchant Model

In this business model, the power network operator owns and operates the energy storage asset. The Distributed Network Operator (DNO) also generates revenue directly from the asset with no third-party involvement. Under such circumstance, the network operator plans, finances and executes the development and construction of the storage asset. Thus, the network operator accepts risk, cost, and security of supply, but shares the benefit of the storage with the customers. The market structure of electricity power (publicly or privately owned vs. regulated or de-regulated) may impact the suitability of such model [112].

2.9.2 Distributed System Operator Model

According to [112], a Distributed System Operator (DSO) establishes a "centralized control mechanism" to manage and coordinate the distribution and benefit of the storage system. DSO may actively manage the distributed network through "curtailing" electrical energy at different locations [112]. The DSO business model needs specific regulatory environment, in which the distributed network operator can own, operate and maintain an electrical energy storage asset in addition to "electric Network management" role. In this case, DSO develops, operates and commercializes the storage system, yet, with no third-party involvement. This model is very similar to above DNO merchant model, except for a need of new regulatory environment to adsorb the asset risk management [112].

2.9.3 Network Operator Contracted Model

This business model involves a third party who manages (except for security purposes) the storage asset for ancillary services, in contrast to the DNO merchant model. According to this mode, DNO is still in control of operation, finance and long-term maintenance of the asset. DNO contracts the third party (until the operation life of the storage asset) and receives fixed annual payments in the form of revenue sharing as additional value [112]. A characteristic of such model is that the monetizing risk of storage asset is partially or fully transferred to the third party. To avoid the risk associated with the long-term revenue, the third party has to "bid at a discount" to accept the viability risk of the investment by DNO. A schematic of the model is provided in Figure 2-6.

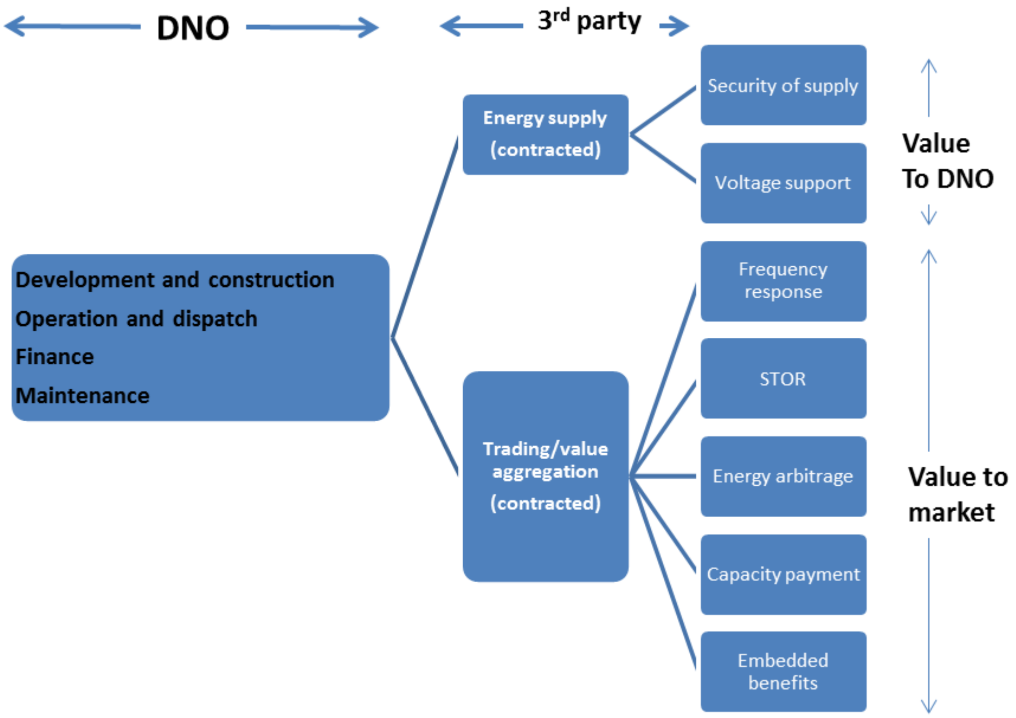


Figure 2-6 Schematic of network operator contracted model, reproduced from [112].

2.9.4 Service-Contracted Model

This business model is the most common for Independent System Operators (ISOs) and is very similar to the business model that is currently adopted by Ontario Independent System (IESO). In this model, first DNO selects the installation site of the storage asset and evaluates security and network limitations. A third party is then selected through an open tender process to build and operate storage. All the technical requirements, including capacity and lifetime are set by DNO. In this model, the third party finances and thus owns the storage asset. It also leads the planning, development and construction process and operates the storage facilities upon completion. There is a guaranteed annual fixed payment for the services provided by the third party in return for meeting "DNO security requirements". A schematic of this business model is provided in Figure 2-7.

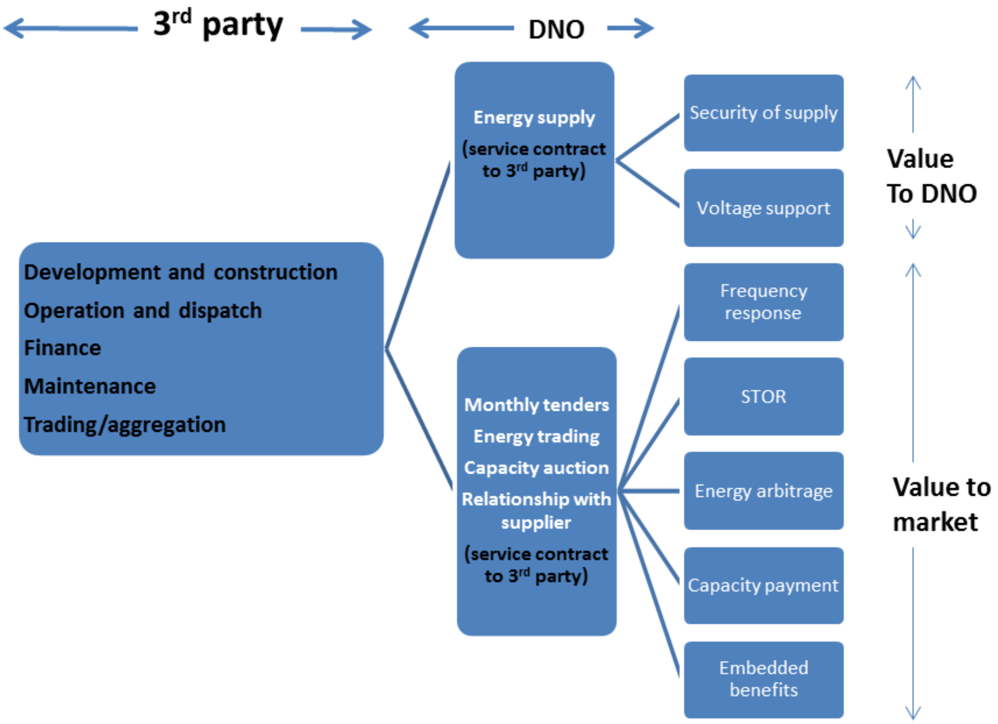


Figure 2-7 Schematic of network contracted business model, reproduced from [112].

2.9.5 Summary of Business Models

The above models consist of two classes of the business models in creating profits from storage assets:

- Those which are adopted from general business models for utility, the smart grid, or renewables
- Those which are specific to storage systems with particular considerations for operation, ownership and revenue streams.

The proposed business models in the literature are mainly "technology-centric" or "service – centric" meaning that the storage business model is not chosen based on maturity and suitability of the technology for a specific market. There is a gap in the literature on a clear pathway for understanding how the choice of an energy storage system coupled with optimal cost-benefit analysis would meet the practical rest of business model that delivers profitability and economic value. We elaborate further on this issue in Chapter 5 where the proposed business model framework is introduced.

3 Methodology

This chapter describes a business model-focused valuation methodology for calculating the benefits of grid-scale energy storage (ES) technologies. The background, methodology, assumptions, and detailed necessary steps are provided in order to build a computational tool for assessing the value of certain business models which maximize the benefits of a given ES asset. The resulting computational tool (Storage Monetization Analysis and Reliability Tool: SMART) will address the current gap in existing energy storage valuation tools in view of defining and evaluating suitable business models for location specific storage solutions. This chapter is based on Ref. [113].

3.1 Introduction

Despite a broad acceptance of the view that grid-scale storage technologies provide considerable benefits [114,115], there is a lack of appropriate valuation frameworks to quantify their benefits at each stage in the planning, installation, demonstration and full commercial operation of the system. The complexity of adopting energy storage is attributed to the wide variety of technology choices, diverse application services along the electricity value chain, lack of understanding business models at utility and end user side, and complicated ownership or revenue structure which make the choice of appropriate storage technology difficult [91,92].

For utilities, the poor understanding of storage project parameters in the context of existing infrastructure is the main constraint. The ambiguity around economics (cost-benefit structure) and technical barriers from buyers (i.e. utilities) make it difficult for the manufacturer and system integrators to improve the cost and technical performance of their products and services [93].

Several valuation tools have been developed to analyze the value of distributed or bulk storage technologies for various grid applications [116]. The underlying assumption in the majority of those tools is that the storage system will not significantly influence market conditions and therefore existing market prices are used as the input market parameters [116]. There is a fundamental difference between such valuation tools and those of electricity production cost models, where an extensive system operation and knowledge of economic dispatch is required for the latter. The focus in this work is, however, entirely on the former class of valuation tools.

Among the most common valuation approaches and tools that have been widely utilized by utilities and independent consultant are National Renewable Energy Laboratory (NREL) valuation (an analysis tool to evaluate the operational benefit of commercial storage, including load-leveling, spinning reserves, and regulation reserves) [91,117]; Energy Storage Valuation Tool (ESVT) developed by Electricity Power Research Institute (EPRI) [92] 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™ designed and developed by DNV-KEMA [94]. In ES-Select™, the user needs to choose where energy storage is connected to an electric grid [94] and the emphasis is more on "simplicity" and user friendly functionalities for screening and educational purposes than ultimate "accuracy" [94]. Therefore, inputs are assumed by default or entered by the user in a certain range of accuracy.

According to a recent report by Navigant [118], among the main shortcomings with existing energy storage valuation tools is a lack of standardization among valuation model and limits on the data available for storage technologies. To the best of our knowledge, none of the existing valuation tools compile or utilize information about business models. Storage ownership or a specific service application is often referred to as a mean to identify the business model and has been used to define the group of stakeholders that retain the profit or losses of storage asset. Ownership can be with private individuals, utilities, or "Gentailers". The latter is a new type of ownership in which the retailer has the option to install a storage system and therefore reduces the supply cost of the customers [119].

The main goal in this thesis is to develop a technology management framework for *technology screening* and *decision-making* purposes. The particular focus is on technology and business model screenings for a given grid service application with the choice of asset ownership and electricity market structure. Building upon previously developed ES benefit frameworks [48,94,118], we intend to customize an existing valuation tool, i.e. ES-Select™ for base-line case studies where business models are defined separately and employed independently from the tool's embedded functionalities. We ultimately intend to develop a new tool, built with a similar user interface as ES-Select™ that connects ownership and revenue structure to business models, cost, and benefit of a site-specific grid service. The new platform (APPENDIX) can potentially help a number of stakeholders along electricity value chain (utilities, technology vendors, system integrators, and end users) to identify and quantify benefit and shortcomings of a specific business model over certain operation periods. The primary purpose of such a tool is to address the gap in storage valuation analysis that can connect operational attributes to business models and market/location constrains for an operating project or for a proposed/plausible distributed storage scenario.

3.2 Analytics Framework

This section explains the overall methodology and a flow chart used for analysis of a given business model to maximize the benefit of deploying a specific ES system. In our valuation, each deployment is identified by key characteristics that include location, type of market, and ownership type of ES technology to be deployed (see Section 3.2.2). The business model is defined on a separate layer and is chosen from several choices, as discussed in Section 3.2.2. The business model will identify 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 main difference between our valuation methodologies to that of other valuation tools is where business models are added as a key characteristic of the benefit in addition to market and type of storage asset ownership. The database in ES-Select™ [94] are initially utilized for the majority of technical attributes, applications, and cost data, including installation costs. However, we partially updated these data bases and replaced them with most recent information. We have particularly updated some of the technical and market attributes that will be added to the data tables. The scoring criteria in our valuation methodology follow the same logic as that in ES-Select™ methodology, whereas a new scoring scheme is introduced for business models.

Figure 3-1 illustrates our logic model for determining the value of a specific business model for storage deployment. The first layer of the diagram is common among exiting valuation tools, 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 calculated 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. Finally, using input financial and asset ownership information, one can calculate the economic value of each benefit. Section 3.2.1 provides the basic equations and relationships used to calculate the asset benefits.

The second layer of the logic model utilizes ownership type and market structure to determine which business model can fulfill the monetary value of the benefits calculated within the first layer for each binary choice of [storage, application]. Each business model is described by a series of characteristics related to market structure, asset ownership, and range of risk profile, benefit, and asset location. The algorithm in the second layer will utilize the feasibility score of a given business model for a given storage-application combination.

For the sake of simplicity, only primary applications are considered in our model. Thus, we do not consider the benefit of a given storage technology for a bundled set of applications same as that considered in ES-Select™ and other valuation tools such as ESVT [94,118]. However, the benefit stacking for multiple applications can be determined separately from each [storage, application] binaries. Four types of business models are also considered, details of which are provided in Section 3.2.2.

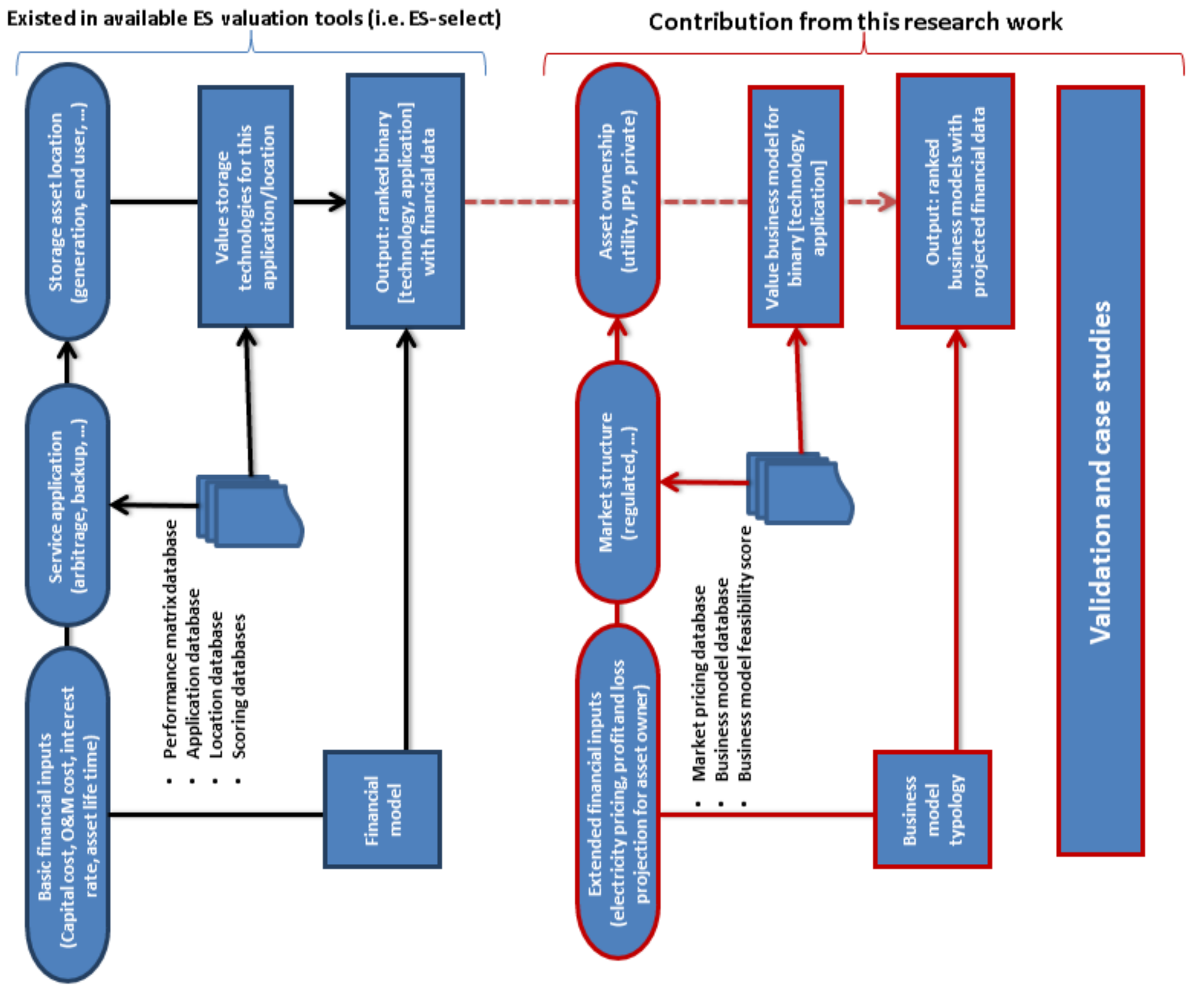


Figure 3-1 Logic diagram and overall methodology for determining the value of business models for grid-scale ES deployment.

3.2.1 Determining Storage Benefits

In order to evaluate the financial benefit of a given storage technology, one needs to determine the type of storage asset, the application (grid service) that storage asset provides, owner of the storage asset, the type of market that storage asset will be deployed in, and location of the asset in the electricity grid. The feasibility of the applications and suitability of a specific business model are determined by a combination of other characteristics (storage technology, location, ownership, and electricity market structure and pricing). A grid application describes how the storage system can be utilized for a specific grid service and business model describes how the asset owner can monetize that service to gain certain value or benefit.

Table 3-1 provides the primary list of grid locations (Generation, Transmission and Distribution-T&D, and End-user), technologies, applications, ownership, and market structures that are considered in this thesis. The choice of storage technologies is based on two distinct factors: Technology Readiness (maturity) Level or TRL of the storage technology and the extent of demonstration projects or available real-time data that have utilized those technologies. Based on these factors, Lithium Ion Battery (LiB), Redox Flow Battery (RFB), Sodium Sulfur (NaS) Battery, Hydrogen Storage, Advanced Lead Acid Battery (LAB), and Compressed Air Energy Storage (CAES) are chosen as the primary storage technologies.

The focus of this analysis is on selected application services, most important of which are Energy time shift (arbitrage), Supply capacity, Utility backup (Service reliability), Power quality, and Frequency regulations (firming renewables). Although there is no clear consensus and standard for defining storage services, we refer to the definition in ES-Select™ [94] and those explained in this thesis and elsewhere [92].

Three types of market structures are considered in our work, including highly regulated, deregulated and mix of regulated and deregulated markets (i.e. mix-regulated). In a regulated electricity market, utilities incorporate all or most of the services and electricity deliveries are vertically integrated. In a deregulated market, on the other hand, the services are not vertically integrated by utilities. Instead, other Independent Power Producers (IPPs), distributes or other merchant generators are allowed to participate in the electricity market. In the case of mixed regulated-deregulated market structure, the generation side is highly regulated and is managed by utilities, whereas distribution and end user sides are de-regulated. The market structures are chosen in a manner that represents various jurisdictions across Canada (e.g., Ontario, British Columbia, and Alberta).

Owners of the storage asset are divided into utilities, a non-utility merchant or an independent Power Producer (IPP), and private individuals (end users). As storage asset owner, utilities maintain and operate the transmission line, whereas IPPs deploy the ES asset independently in whole-sale electricity market. Private owners are end users of electricity.

Four types of business models are considered (utility-side, service-contracted, IPP-side, end-user-side), details of which are provided in Section 3.2.2 and Chapter 5. Although we have limited our research to the attributes discussed in Section 3.2.3, the concepts and methodologies are scalable and can be extended to a wider range of application services and technologies. In general, one is able to define his or her own technology or application by adjusting these default values.

Table 3-1 List of grid locations, technologies, applications, ownerships, and market structures that are considered in this research work.

Attributes	**Types**	**Definition**	**Comments**
Location	Generation, Transmission and Distribution (T&D) and end-user	Determines on what part of the grid the storage is located.	End user can be further categorized to residential and commercial users
Technology	Lithium Ion Batteries, (Vanadium) Redox Flow, Sodium Sulfur (NaS), Hydrogen Storage, Advanced Lead Acid, and Compress Air Energy Storage	Determines the type of energy storage technology	Only those with high TRL and available demonstration data are considered here.
Application	Arbitrage, Supply capacity, Backup Power quality, Frequency regulations	Indicates how the storage asset will be used and what kind of service will be provided by the storage	The most common services are considered.
Ownership	**Utility,** Independent Power Producers including non-utility merchant (**IPPs**), Private individuals and end users (**End User**)	Identify the entity who owns the asset and therefore accept the capital cost, benefit/loss and risk of capital	For the sake of simplicity, only three levels of ownership are considered.
Market	Regulated, De-regulated, Mixed	Specify the jurisdictions and electricity market for deploying the asset and electricity pricing structure	Each type represents a jurisdiction in Canadian electricity market.
Business models	BM1: Utility side; BM2: Service contracted; BM3: IPP side; BM4: End-user side	Determines the manner that storage asset is creating value and being monetized for generating benefit	The typology will be further improved in course of this research work.

The benefit of storage is ultimately described by the 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.

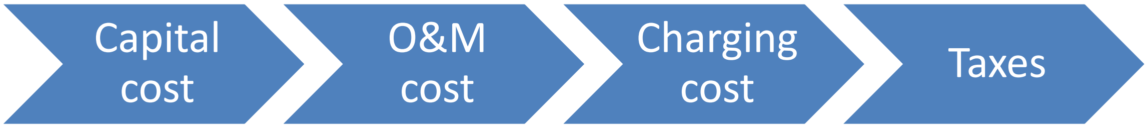


Figure 3-2 Overview of cost components for a storage asset.

Figure 3-2 provides an overview of the cost components for storage asset. The expected (annual) benefits ($/kW) are simply defined as default in the Application database for each application type. Qualitatively, the benefits are ranked as regulation services> system capacity>arbitrage>backup. The annual cost of expenses ($/yr/kW) are calculated from the annual cost of operation (C_{ops}) and maintenance (C_m):

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

The annual cost of operation is calculated by:

$$\boldsymbol{C_{ops}} = \frac{\boldsymbol{C_{charge}} \times \boldsymbol{L_{ops}}}{\mathbf{1000}} \tag{2}$$

where L_{ops} represents the annual operation loss of the storage is the loss of storage performance and is defined as kWh/yr/kW and C_{charge} represents the cost of battery charge. 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:

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

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:

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

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:

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

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

$$\sum_1^n \boldsymbol{CF} = \boldsymbol{C_{SI}} \tag{6}$$

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 [14,41]. Our approach is simplified compared to a more statistical basis that has previously employed in the literature [94]. Note that the effect of electricity price increase is captured by electricity price escalation factor as an input parameter within the financial database. Finally, IRR is calculated as the discounted rate under the assumption that the net cash flow is zero. Table 3-2 provides the list of essential input parameters. All other parameters not listed in this table are taken as default in the databases but can be adjusted if necessary.

Table 3-2 List of essential input parameters.

Input parameter	Unit	Definition	Source
Cost of maintenance per year	$/yr/kW	Includes Balance of System (BOS)	[94]
Required application discharge duration	Cycles	Technical requirements for specific application	[14,94]
Annual benefit	$/kW		[94]
Cost of energy used for charging	$/MWh		This work
Cycle life at 10% DoD	Cycles		This work
Cycle life at 80% DoD	Cycles		This work
Discount rate	%/yr	Also referred to as interest rate	User input
Escalation of benefits	%/yr	Projected annual increase of benefits	User input
10-year total benefits	$B		[94]
AC round-trip efficiency	%		[94]
Feasibility score for fulfilling application requirement	%	Scores based on power, energy, frequency of use	[94, this work]
Feasibility score for selected location	%	Scores are different for selected locations on grid	[14,94]
Feasibility score for maturity	%	lab-scale, prototype, pre-commercial or fully commercial (TRL level)	[14,94] This work
Feasibility score for selected ownership	%		This work
Electricity price escalation	%/yr		User input
AC storage cost	$/kW		[94] This work
Storage discharge duration	Cycles	From Technology Matrix	[94]

3.2.2 Determining Business Models

For the purposes of this analysis, a business model defines the terms under which storage asset owners or operators (on behalf of the owners) deliver value to their storage customers, make customers purchase that value, and create profit from those purchases [96,97]. The growth and success with the storage industry is relying on innovative business models. As being discussed in Chapter 5 of this thesis, the most viable business model for adopting storage technologies at utility side is based on *Service Contracted* model, which include both *technology enabling* and *operation* services. This core business model consists of contracts with private and public partners. The technology developer and enabler such as storage integrators can contribute to the planning and construction phase and can cover a variety of services from technology evaluation and assessment to project planning, coordination, resource management, implementation, execution, and managing operation from generation side to distribution. This type of business model does not target emerging storage technologies at low TRLs. The commercial viability of storage technologies lies on short- to long-term testing, demonstration, and integration by publicly owned utilities, independent power producers, power distributer, power authorities or operators, and end users. Some models are generally more capital intensive than others but can attract clients among service recipients from communities (e.g. remote communities). As one the main objectives of this research work, systematic approach is placed on exploring better typologies of the business models and improving the classification criteria.

Business models are divided into four groups that have distinct characteristics to be met by ownership, commercial operation, application, revenue value stream, market structure, and asset maturity (TRL) level. The flexibility of business models to adapt to various location or market structures is another factor that is considered. Chapter 5 presents the four models with a few examples in each group. These groups can be determined as the four quadrants of two axes, asset maturity level and risk profile. The feasibility score for a given business model (between 0 and 1) is determined by geometric average of scores for each of the attributes.

3.2.3 Relation Between Key Attributes and Scenario Creation

Several scenarios are built “as default” in the module, but the user is allowed to create new scenarios. For each scenario, the configuration of energy source, scale of operation and operating strategy, the ownership model, business model, and revenue and profit streams are selected as per existing functionalities within the tool. As depicted in Figure 3-3, the module consists of four building blocks of decision variables (includes cost and financial information, market, the ownership structure and business model), physical model (configuration, size, location), performance model and performance indicators. The physical model will define the storage system under consideration. The performance model is formed of financial and emission foot print (taken from ES-select data base) components that are connected to physical models via subset of variables. This configuration is consistent with the current modular architecture of other existing valuation tools. The modules are initially built and validated in EXCEL as a stand-alone tool. The major relationships are quantified based on scoring factors (between 0 and 1) as per valuation model requirement (APPENDIX). The major relationships are:

- Ownership score of the business model
- Market structure score of the business model
- Application score of the business model
- Technology maturity score of the business model
- Location score of the storage technology
- Cost score of storage technology
- Technology maturity score of the storage technology
- Application score of storage technology

The process flow chart shows the scenario building process and examples of five initial scenarios are presented in Table 3-3.

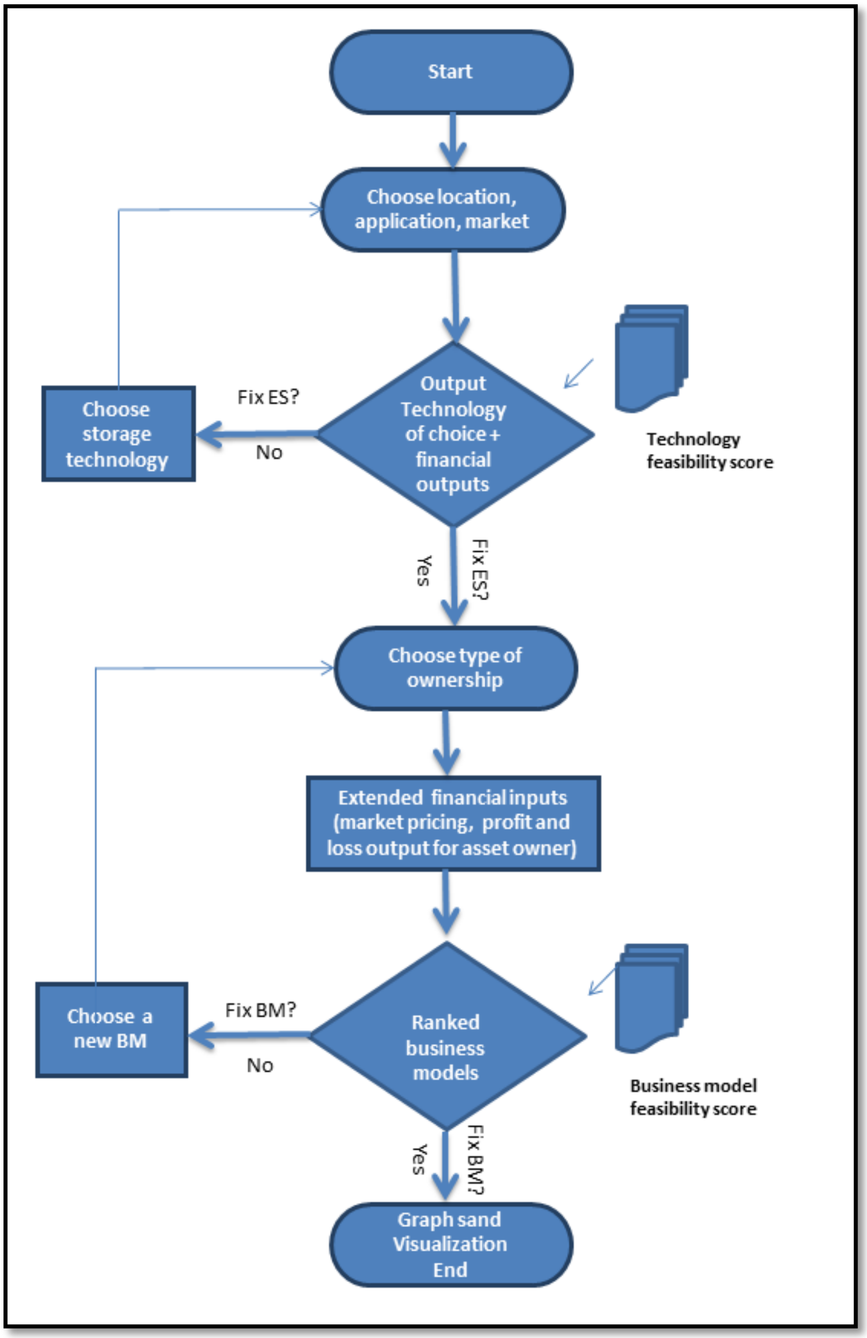


Figure 3-3 The flow chart for creating scenarios.

Table 3-3 The preliminary list of baseline scenarios that are considered in this research project.

Scenario ID	Location	Market	Application	Asset Ownership	Example of Case studies
1a	T&D	Regulated	Supply Capacity	Utility	NaS demo in BC
1b	T&D	Deregulated	Power Quality	ISO	NaS or CAES demo in AB
2	Generation	Deregulated	Frequency regulations	IPP	LiB-Wind power in AB
3	End user	Regulated	Backup	End user	Industrial or commercial LiB in BC
4	Generation	Mix	Supply Capacity	ISO	H2 Storage in ON

3.3 Databases

Several databases were generated for this analysis by collecting data from existing valuation tools and updating those databases for various ES technologies and application services. For storage technology databases, we utilize the database developed internally (using Technology Development Matrix developed for each technology) and adapt those to ES-select database. The storage database includes detailed information for different energy storage technology or types (Performance Metrics). This data has been obtained from several surveys and RFP processes in various jurisdictions. In contrast to a range of accuracy used in ES-select, here we mainly utilize a single, average value for the parameters.

Table 3-4 List of essential parameters in storage technology database.

Storage Technology	Discharge Duration (hrs)	Specific Energy (kWh/ton)	Energy Density (kWh/m3)	Round Trip Efficiency (at 80% DoD)	Cycle life at 80% DoD	Response time
LiB	2.5	100	110	0.885	8000	ms
Advanced Lead Acid	3.5	24	50	0.85	240	ms
RFB	4	9.5	18	0.63	8000	ms
Sodium Sulfur	6.5	110	135	0.765	6000	ms
H2 Storage (PtP)	6.5	155	120	0.545	10000	sec
CAES	4	100	4	0.65	20000	sec

3.3.1 Database of Storage Applications

Despite considerable improvements, there is no consensus in the definition of services that can be given by various storage technologies [94]. At least five services will be considered in our study that includes energy time-shift (arbitrage), power quality, frequency regulations, backup, and supply capacity. The database table includes application name, discharge time, annual benefits, market potential, and the minimum required deep (80% depth of discharge) cycles.

Table 3-5 List of selected attributes for Application database

Applications Name	**Discharge Duration (hrs)**	**Annual Benefit ($/kW)**	**Total 10-Year Market Potential ($B)**	**Required Response time**	**Required Deep Cycles (80% DoD) (cycles/yr)**	**Market Potential 10 years (GW)**
Arbitrage	7	100	11	hrs	190	21.34
Supply Capacity	6	101	12.1	hrs	190	22.85
Frequency regulations	0.5	560	1.96	sec	4000	3.31
Utility Backup	2	330	9.01	sec	100	9.53
Power Quality	0.02	150	8.3	ms	500	11.95

3.3.2 Financial Database

The following financial parameters are used in calculating cash flow, Internal Rate of Return (IRR), and storage payback time.

- Escalation of benefits (%)
- Interest rate (%)
- Electricity price escalation (%/yr)
- Cost of energy for storage charge ($/MWh)
- Project life time (yr)

3.3.3 Feasibility Scores

The feasibility scores are the most uncertain parameters in the database and are subject to further refinement and validation by user. The scoring system in ES-Select™ will be utilized initially for the feasibility of storage technologies (see APPENDIX). Scores are varied between 0 and 1. The key feasibility scores for a given technology for a specific grid-scale application are broken down into scores for location, maturity, application, cost and business model. The feasibility scores are determined by a combination of user input and surveys as well as industry-accepted technical targets (see APPENDIX). For instance, the total installed cost is required for calculating a cost score for each storage technology. The installed cost $\boldsymbol{C_{SI}}$ and technical cost target $\boldsymbol{C_{target}}$ (currently assumed at 500 or 1500 $/kWh) are required for each application in order to estimate the cost score of $\boldsymbol{C_{Score}}$:

$$\boldsymbol{C_{score}} = \boldsymbol{C_{target}}/(\boldsymbol{C_{target}} + \boldsymbol{C_{SI}}) \qquad \textbf{(7)}$$

A geometric averaging is applied to five scores to calculate a combined feasibility score of $\bar{S}$: Location (S1), readiness level or maturity (S2), application (S3), cost (S4), and business model (S5):

$$\overline{\boldsymbol{S}} = (\boldsymbol{S1} \times \boldsymbol{S2} \times \boldsymbol{S3} \times \boldsymbol{S4} \times \boldsymbol{S5})^{1/5} \qquad \textbf{(8)}$$

The same methodology is applied to calculate a combined business model feasibility score for each scenario based on ownership, technology readiness or maturity, application, and market structure.

3.4 Case studies

The results of the baseline scenarios described in Table 3-3 will be used for several case studies. We first perform analysis of a baseline scenario and then adapt the results of analysis in a case study, which represents the installation of the ES system in a relevant Canadian electricity market. Thereafter, we examine and analyse changes to the market structure. In order to define a case study for each scenario, we consider a realistic demonstration project, where a storage system has been built and installed (or is in the process of installation) for certain grid services in a specific Canadian jurisdiction. The information from existing demonstration projects in the US and Canada is compiled and will be used to further validate and demonstrate the undertaken assumptions in case studies. For each scenario in Table 3-3, at least two projects are considered, one in a mix-regulated market (e.g. Ontario), one in a de-regulated market (e.g. Alberta) or in a regulated market (e.g. British Columbia). The list of major case studies includes:

- Residential, commercial and industrial LiB, CAES and VRFB in regulated and de-regulated markets
- Grid-scale LiB-Wind turbine in a regulated market
- H2 storage deployment in a mixed- or regulated market

3.5 Tool Development

The ultimate goal of this research project is to develop and validate a user-friendly tool, in which the feasibility of certain business models is assessed for maximizing the benefit of grid-scale energy storage (ES) technologies. In course of this research project, several stand-alone analysis modules were developed in close collaboration with Electric Power Research Institute (EPRI) [92] and DNV GL [94]. The resulting computational tool (Storage Monetization Analysis and Reliability Tool: SMART) is built collectively on various modules and databases with the new business-model features therein. The detailed workflow, the tool requirements, features and functions, and the source of databases are provided in APPENDIX. Such technology management functionalities are not currently available in the existing energy storage valuation tools. Built on ES-select user interface and leveraging databases developed jointly with a significant contribution from the author to Energy Storage Integration Council (ESIC), the user is able to select or enter information about the physical location of the storage asset, market type, ownership, and target grid application services. The user will then navigate through this front-end page to accept default technology or the financial database and perform further analysis to choose a suitable business model. The ESIC Energy Storage Cost Tool [120] in particular lists the full set of cost items for a distributed-connected energy storage project from initial project development through decommissioning. The cost template includes one-time, upfront project costs, recurring annual or periodic costs, and endo-of-life costs. The users also have the ability to enter individual cost line items or sub-categories of a group of cost line items. The ESIC Cost Tool can clarify the scope of the cost components, simplify the Request for Project (RFP) and create a transparent template of cost components and TCES (Total Cost of Energy Storage) that can be used as input data bases to other existing valuation tools such as ESVT and SMART.

Currently in beta testing, the SMART allows users to compare and rank feasible technologies in selected jurisdictions for a range of grid services, at any given location on the electricity grid. The tool allows users to screen technologies and business models by calculating financial outputs that include cash flow, cumulative costs and benefits, and net present values. It can then be used to generate a variety of plots and charts for comparing technology options and final rankings based on total feasibility scores. Drawing on a Canadian database, the tool can perform specific evaluations for grid locations in Alberta, BC and Ontario, and provide average values for any other location in Canada.

4 Technology Management Tools for Assessing Emerging Grid-scale Storage Technologies

In this chapter, we apply business and technology management concepts to describe a new framework for valuation and adopting grid-scale emerging storage technologies. Grid-scale adoption of emerging storage technologies among utilities hinges decisively on matching 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. This chapter is based on Ref. [121].

4.1 Introduction to Technology Management Tools

The electricity grid provides essential infrastructures for local electrical energy demand or electricity trade purposes. 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 [122, 123]. 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. Intermittency of renewable sources create operational challenges for grid stability and reliability of the power sector which can cause substantial investment risks and potential destruction in electricity supply and reliability [3].

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], energy storage technologies can play a vital role in reducing the overall upgrade cost of the electricity grids in the presence of renewable sources.

In order to overcome challenges of adopting ES technologies to the right technology and grid service application, numerous technical assessment and engineering have been developed. These tools provide substantial information around technical and economic value of storage technologies. They are, however, 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 a lack of 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. 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 investment in adopting new technologies can be made.

4.2 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 approaches 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 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 [94] is utilized as a framework to quantify the feasibility and reliability of the energy storage systems.

4.3 Technology Management Frameworks

Technology management tools help managers implement solutions for adoption of new technologies. Phaal et al. have extensively studied the typology of technology management tools and applications therein [80,73]. 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 [124]. According to Phaal et al. [124], 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 [125,74,75,76,77,78,79]. There is a distinct difference between generic *management tools* and *technology management tools* [124]. 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 [81] and later by Phaal et al. [80], 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 the value proposition of ES technologies, formulate their risk & opportunity profile, and develop an implementation plan, a number of analyses frameworks are needed to support business operations. 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 [126]. Here, we focus on technology road mapping, technology development matrix, and technology valuation grid.

4.4 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 [80]. Roadmaps are primarily a communication tool [82]. 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 4-1.

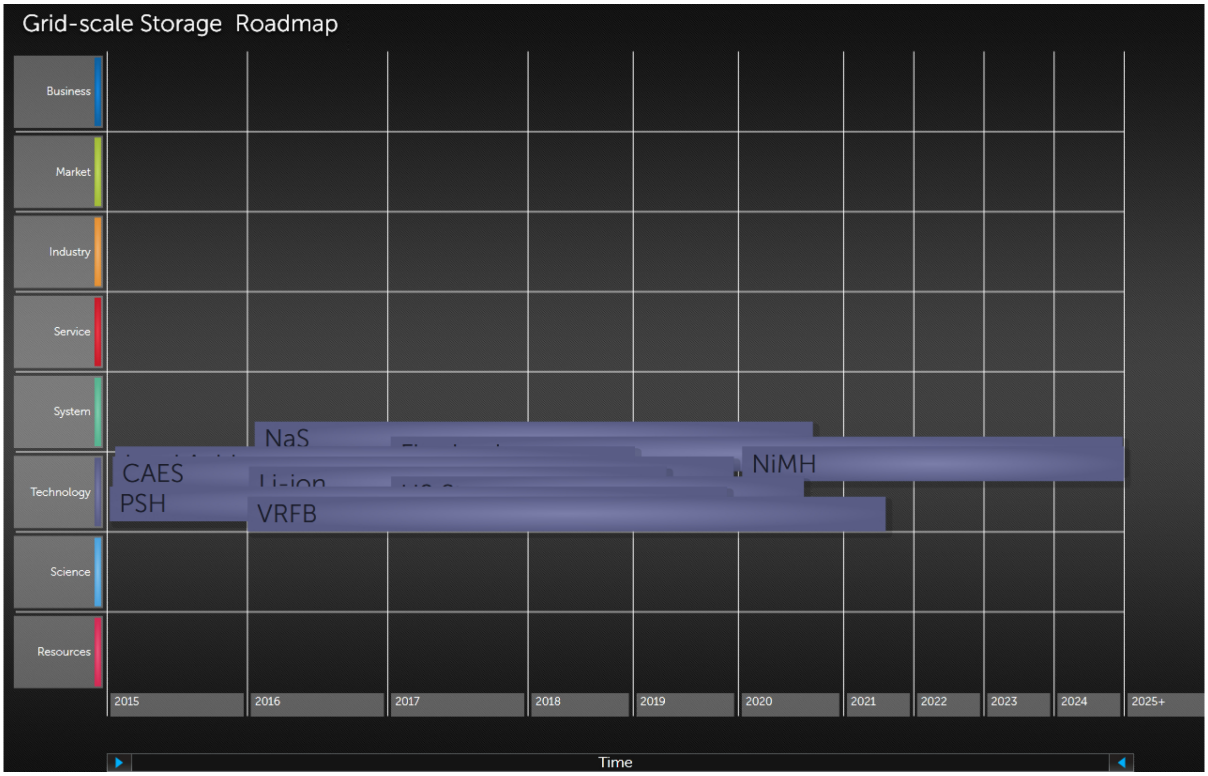


Figure 4-1 A typical framework for grid-scale storage technology road map, visualized using sharpecloud software [127]. Various storage technologies are mapped on "technology" layer. NaS: Sodium Sulfur battery; VRFB: Vanadium Redox Flow battery, NiCd: Nickle Cadmium battery; Li-ion: Lithium Ion battery; CAES: Compressed Air Energy Storage; PSH: Pump Storage Hydroelectricity; NiMH; Nickle Metal Hydride.

4.4.1 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.

4.4.2 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.

4.4.3 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.

4.4.4 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.

4.4.5 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, Figure 4-2. Long term scientific advances can be captured in technology layer or being placed in a separate layer. Scientific research is strongly linked to the system and 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” [4].

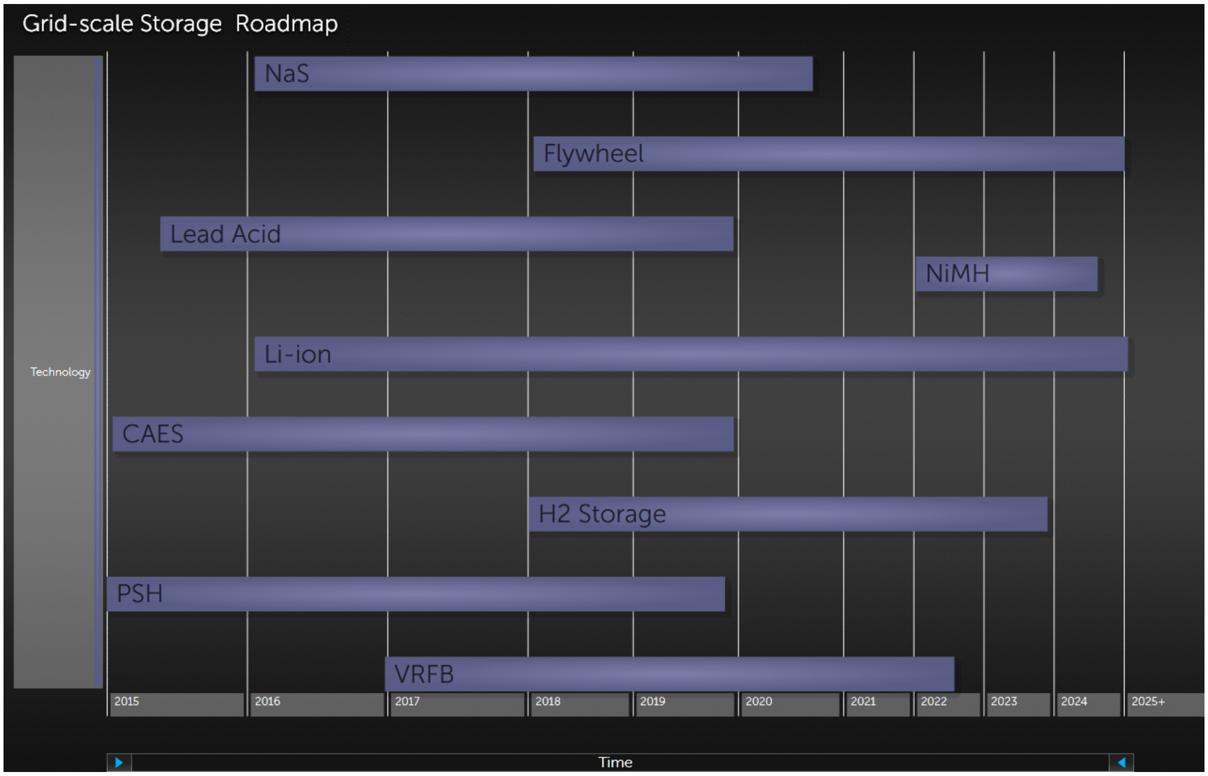


Figure 4-2 Example of storage technologies mapped on the technology layer and spanned over 10 years based on their technical maturity for a given grid service application. NaS: Sodium Sulfur battery; VRFB: Vanadium Redox Flow Battery, NiCd: Nickle Cadmium Battery; Li-ion: Lithium Ion Battery; CAES: Compressed Air Energy Storage; PSH: Pump Storage Hydroelectircity; NiMH; Nickle Metal Hydride. This figure only indicates the roadmap (i.e. timing) of relative level of maturity for each technology from its current maturity level (TRL<5) to the commercial maturity (TRL>9). Technology key performance indicators, cost, and life time are considered in a separate layer.

4.4.6 Resource (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 [49]. 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 [50]. 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 cannot be utilized as an instrument for electricity export, according to [51]. 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 [55]. 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 [39].

4.5 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 (super-magnetic energy storage). Storage systems include a number of technologies at 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 ES 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 4-3 illustrates required power and response time for different grid-scale storage services.

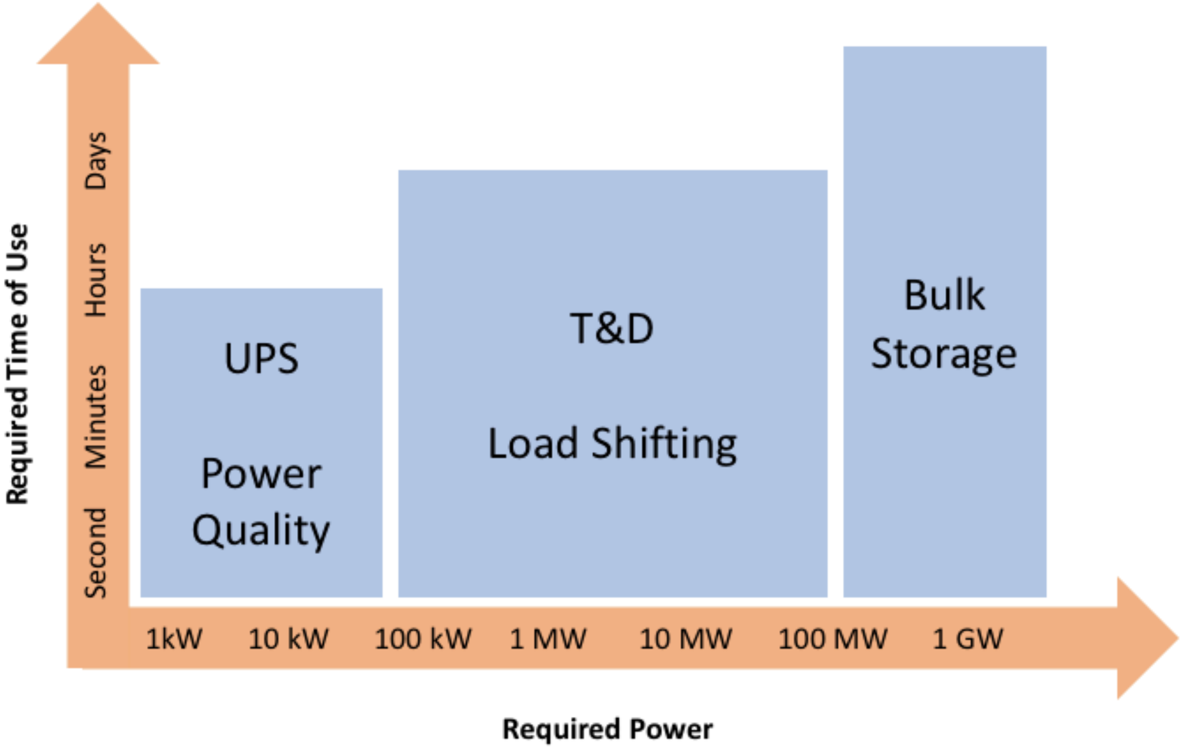


Figure 4-3 Required power and response time for different grid-scale storage services.

The real benefit of energy storage technologies have been studied extensively for different grid services (e.g., arbitrage, regulation services, and T&D) [37,38,39,40]. By focusing on only one single application, storage technologies have 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 [41]. As indicated in various studies, no single energy storage system can provide multiple grid application requirements [39]. 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 4-1. 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.

Table 4-1 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] State-of-The-Art 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, kWhlife] SoTA vs. Target	The lifetime of a storage system can be measured by the number of charge/discharge cycles at given energy capacity.

4.6 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 [91,92,93]. 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. The most common valuation tools have been introduced in Chapter 3. These tools and methodologies have been widely employed by utilities and independent consultant. To emphasize, Energy Storage Valuation Tool (ESVT) developed by Electric Power Research Institute (EPRI) [92] 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 [94]. In ES-select, the user needs to choose where energy storage is connected to an electric grid [94].

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 [40]. For instance, on the generation side, the addressable market for energy storage is improving power quality or usage of existing generation sources.

4.6.1 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 4-1. 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), IRR, the Total Cost of Ownership (TCO), and Cash Flow. Full detailed description of the cost model is provided in Chapter 3. To clarify, 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 [128]. 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 [94]. Finally, IRR is calculated as the discounted rate under the assumption that the net cash flow is zero.

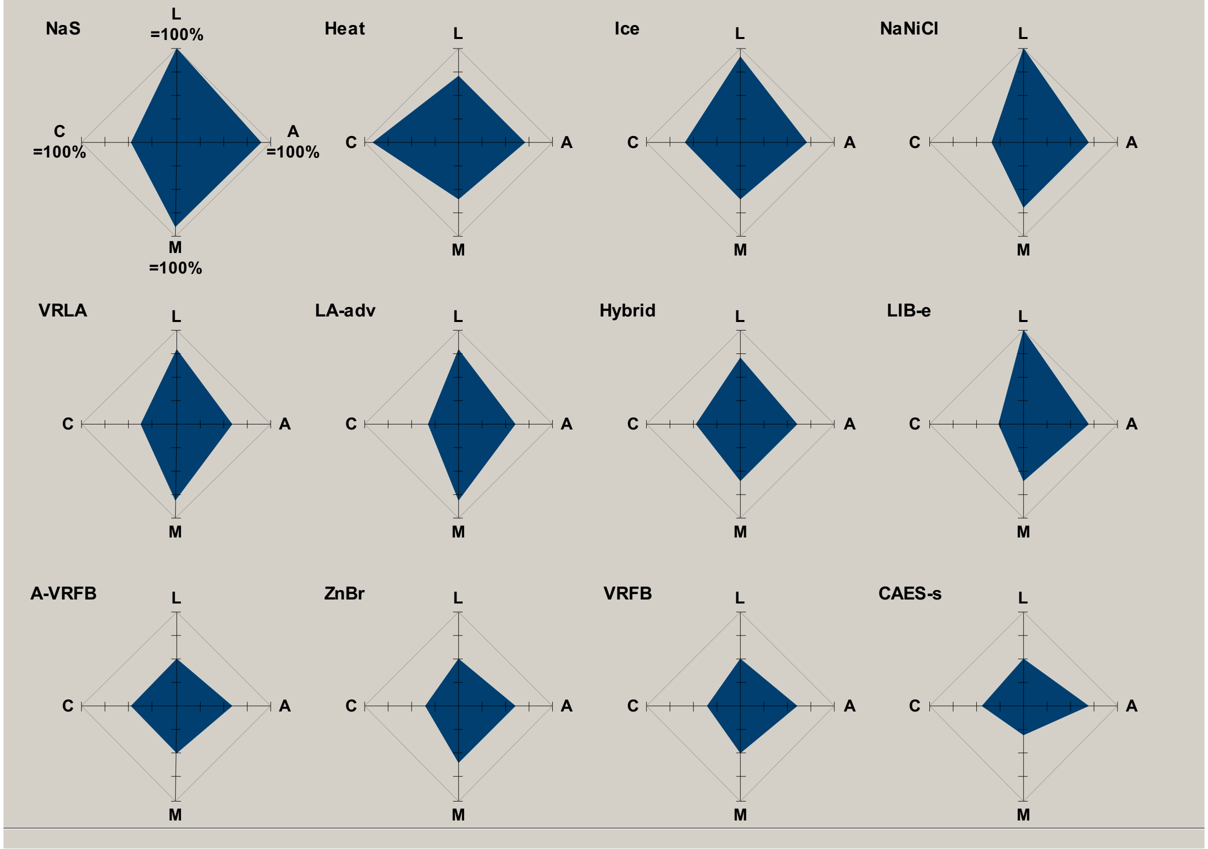


Figure 4-4 Feasibility ranking for different batteries for a given application. The charts are obtained from ES-select [94]. L: location; M: Maturity level; A: meeting Application requirement; C: Cost requirement.

4.6.2 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 4-4 shows an example of the attributes (L: location; M: Maturity level; A: meeting Application requirement; C: Cost requirement) for several ES technologies including 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 [94]. 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 4-5. 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).

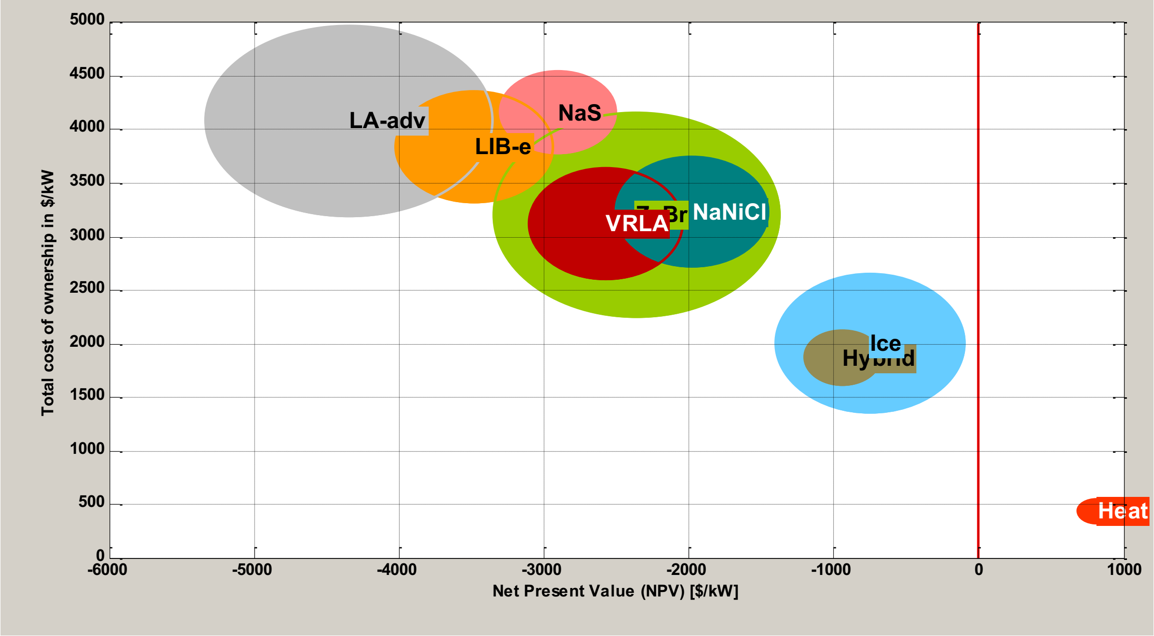


Figure 4-5 Total cost of ownership vs. NPV ($/kW) for selected storage solutions. The charts are obtained from ES-select [36]. NaNiCl: Sodium Nickel Chloride; LIB-e: Lithium Ion Battery; LA-adv: advanced Lead Acid; VRLA: Valve Regulated Lead Acid; NaS: Sodium Sulfur; Ice/Heat represents the charge/discharge cycles of a thermal battery.

4.7 Summary

Current valuation and technical assessment tools provide substantial information around technology readiness and maturity level of emerging technologies, however, only a 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, several 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.

5 Typology of Business Models

Electricity grids are subject to various market and technological challenges that influence their reliability and cost-effective performance. As a potential viable solution to meet these challenges, energy storage technologies can be adopted to provide multiple services along the electricity grid value chain. In addition to their role in enabling increased penetration of renewables in future electricity grids, energy storage (ES) technologies create a number of societal and environmental benefits, such as reducing carbon emissions and securing regional energy infrastructure. The primary challenge for utilities and regulators, however, is to find favorable business models that align with ES technologies, applications, and regional electricity markets. We propose a typology of different business models for the adoption of ES technologies by utilities. The business model framework provides a customized analysis platform for adopting emerging ES technologies. For industrial stakeholders looking to adapt new ES technologies, such analyses can generate multi-dimensional parameters (cost, efficiency, reliability, best practice business operation model, and policy instruments), which form a complete view for strategic decision-making purposes. This chapter is based on Ref. [129].

5.1 Introduction

The increasing use of alternative and renewable energy sources is changing the blueprint of the world's energy resources; yet, a secure and reliable energy supply is of vital importance for today's modern societies. In particular, Energy security has been a high priority in national energy policies throughout the world. In the majority of these policies, the development and adoption of more efficient and environmentally-benign energy sources that are reliable and secure are seen as key challenges in the next two decades [25]. The electricity grid is the most critical national and regional infrastructure for domestic energy use and export [31]. Electricity grids, however, are facing various market and technological challenges that have the potential to negatively influence their reliability and profitability [34]. One major challenge is that, due to increasing electricity demand conditions, many major capital grid assets are nearing their end of life. Another challenge is maintaining grid stability while increasing the penetration of renewable energy generation. Finally, in order to achieve their full potential, distributed "smart" grids require efficient, stable, durable, and cheap ES solutions. The main interest in stationary ES technologies over the past two decades has been their ability to effectively store and dispatch the intermittent power from renewable energy sources, such as solar and wind energy [35].

ES technologies provide multiple services along the electricity grid value chain, including electricity generation, transmission and distribution (T&D), and end-user consumption. In addition to their role in enabling increased penetration of renewables in future electrical grids, ES technologies possess a number of environmental benefits, such as reducing carbon emissions and securing regional energy infrastructure to avoid long service interruptions [**36**]. The use of ES in electrical grids is an established technology concept [**36**]. Some storage technologies, such as pumped hydro, are more mature than other emerging storage technologies [**25**,**36**]. For example, Compressed Air Energy Storage (CAES) has been used for decades. The new generation of storage technologies such as lithium-ion batteries, flow batteries, flywheels, and sodium-sulfur batteries (NaS) has emerged in recent years and is in the early market adoption stage. The main advantages of the new generation of storage technologies are their "operational flexibility, improved charge/discharge cycle life, and longer duration or fast response capabilities" [**36**]. The cost and reliability of ES technologies are functions 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 charges and discharges of a device while maintaining a minimum required efficiency), power rating ($/kW), and energy rating ($/kWh) [**36**]. Moreover, capital and operating costs determine economic viability and service profitability, as shown in Figure 5-1.

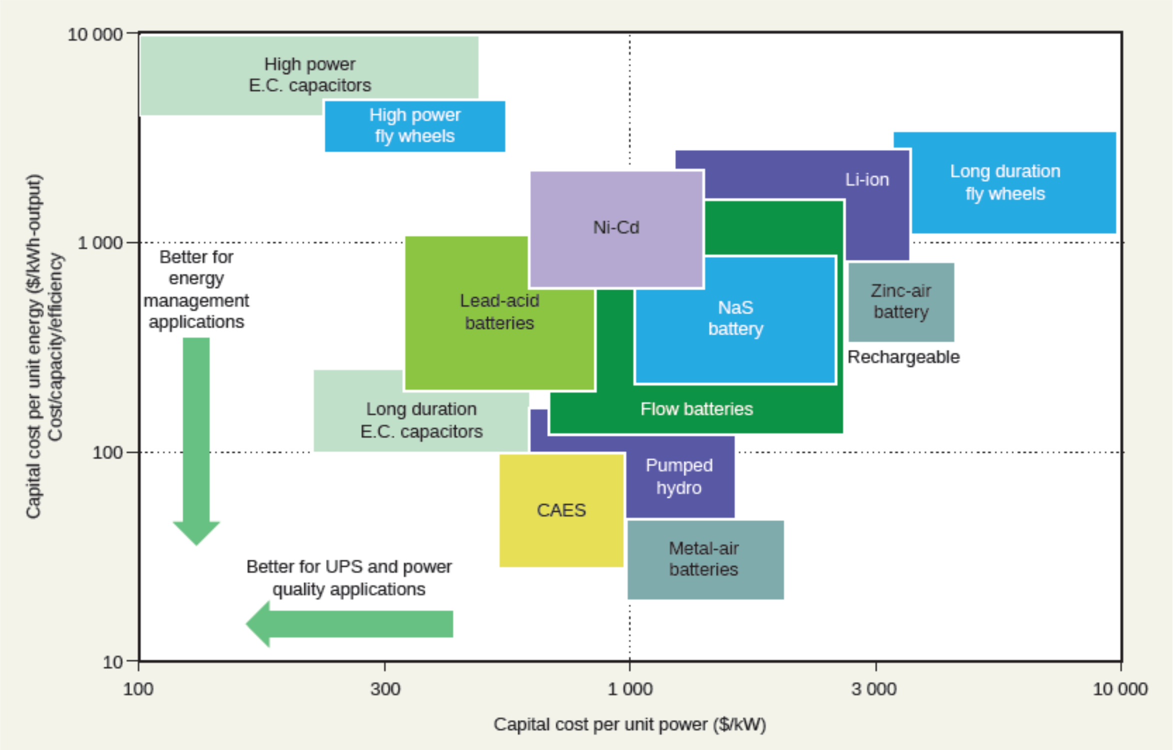


Figure 5-1 Commercial characteristics for different ES technologies, reprinted from [34] with permission.

The real and quantifiable benefits of ES technologies have been studied extensively in different energy markets (e.g., arbitrage, regulation services, and T&D). As indicated in various studies, no single ES system can meet the requirements of all grid service applications. 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 [16]. It is challenging to "aggregate" the value of ES technologies [16], often referred to as "Benefits-stacking" [25], because of varying market attributes (regulated vs. deregulated) and in determining how electricity system owners or operators can share the costs and revenue streams. It also depends on how the usage of storage can be decentralized by different grid "actors" [**16**]. A sophisticated business model framework can allow systematic stacking of the value and benefits of multiple technologies. The appropriate strategic business models need to realize and develop the potential market for all of these market segments. In summary, the limitations of adopting emerging ES technologies for future electricity grid are the following: (i) Existing electricity market structures are not flexible enough to adopt the new operation/technology; (ii) Ambiguity between cost-takers (utilities only) and those sharing benefits (utilities and consumers) and a lack of appropriate service-based business models; (iii) High capital expenditure (CAPEX) and a low rate of return; (iv) High power management costs; (v) High siting and permitting costs; (vi) Complexity and costs of managing ES projects [1].

There is a need for developing practical business models for grid-scale ES technologies from a business-management point of view. Current grid services can be acquired through several common business models ranging from contracting for services without storage ownership to upfront purchasing of storage technologies. It is currently unclear how the specific technology solution depends upon the financial or technical preferences of the asset owner [48]. Effective business models should be able to account for temporal (size and maturity of the storage technology) and spatial contingencies (the type of service, location, application and market or electricity pricing structure). There is a need to analyze existing business models and develop practical frameworks that ensure accurate assessment of profitability and value created by adopting ES technologies in electrical grids. Here we attempt to benchmark and analyze business models and assess the value proposition of storage technologies by formulating their risks and opportunity profile. We demonstrate a typology of business models for grid-scale storage technologies that can be used as a practical framework for management decision-making purposes. The framework tackles some of the existing issues for accurate screening of storage technologies to capture the value and unique benefits of an ES system.

5.2 Business Models

A business model is defined as a strategic guideline that constructs the "organizational and financial architecture of the firm" [97]. It serves as a roadmap for firms to follow to deliver value to their customers, attract customers to purchase their products or services, and create profit from those purchases [96,97]. Business models have been extensively evaluated [98] in the real-world and are fully applicable to renewable energies [22].An innovative business model is a strategic alternative to explore new market opportunities or respond to externalities [99,100,101]. The opportunities and barriers of business model innovation are of vital importance to the clean energy sector due to the extensive presence of disruptive innovations [102] and "organizational ambidexterity" [103,104,105].

A recent review by Richter [21,22] provided an extensive analysis of utilities and their need to revamp their business models to overcome new challenges related to grid security and integration of renewables. Richter [21] identified two basic choices as "utility-side business models" and "customer-side business models". Utility-side business models are preferred by utilities and blueprints for them exist. Customer-side business models, however, have not been developed extensively [21]. In the following sections, we unravel more insights into each of these choices and discuss the applicability of such models for storage technologies in electrical grids.

The choice of business models for renewable energies has been addressed by several recent studies [106,107,108,109]. Of Richter's two generic business models discussed above, the *utility-side business model has been utilized for renewable energy* on a few large-scale projects with a capacity between 1-100 megawatts [22]. On- and offshore wind energy, large-scale photovoltaic systems, biomass, and large-scale solar thermal energy are examples of technologies that may adopt a *utility-side business model*. The value proposition in this business model is in "*bulk generation of electricity*" [111]. *The customer-side business model is best described by* energy generation in small-scale systems close to the point of consumption, often referred to as "distributed generation" [21].

5.3 Business Models for Electricity Storage

In order to evaluate the financial benefit of a given storage technology, one needs to determine the type of storage asset, the application (grid service) that the storage asset provides, the owner of the storage asset, the type of market that storage asset will be deployed in, and the location of the asset in the electrical grid. In a recent study [**16**], He et al. proposed a new business model that aggregates multiple revenue streams of storage. The model, also referred to as "Benefits-stacking" [**25**], consists of multiple methods to utilize the storage unit at different time intervals. The results from [**16**] show that by aggregating revenue streams, a storage unit can achieve a higher rate of return and profitability [**16**]. A set of consumer-side business models were proposed and communicated to a group of utility and power system operators for a particular installation of energy storage systems in the UK [112]. The business models were designed and analyzed from an investor or "controlling entity" perspective [**112**]. The suitability of the business models for projects of a similar distribution-scale and of similar technology-type was discussed as well**.** Such studies complement previous work on the macro-economic benefits of storage, similar to those introduced for the valuation of storage technologies in the previous sections. The business model framework in [**112**] contains three main attributes, based on which business model is characterized. The attributes include (i) Ownership: This attribute describes the entity that accepts the risk of construction and operation for the installation of large-scale storage systems; (ii) Commercial operation: This attribute identifies the entity that manages the risk of monetizing and capturing the value of storage; and (iii) Market: This attribute describes the relevant market structure to which the operator or owner provides storage services.

5.4 Proposed Typology of Business Models

Previous studies indicated that many utilities have already developed and implemented viable business models for large-scale utility-size renewable energy generation. Thus, there are existing examples of business models for those large-scale storage technologies on the generation side. However, small-scale customer-side ES technologies suffer from a lack of existing business models adopted or tested by utilities. An appropriate business model framework should be able to combine the business model concept with technological innovation of the storage technologies to provide recommendations for utility managers and policy makers.

The feasibility of the applications and suitability of a specific business model are determined by a combination of characteristics (storage technology, location, ownership, and electricity market structure and pricing). The grid application of an ES system defines how the storage system can be utilized for a specific grid service and the business model defines how the asset owner can monetize that service to gain value or benefits. The choice of storage technologies is based on two distinct factors: Technology and Market Readiness (maturity) Level (TRL/MRL) of the storage technology, and the number of demonstration projects or available real-time data that have utilized that technology. Based on these factors, Lithium Ion Battery (LiB), Redox Flow Battery (RFB), Sodium Sulfur (NaS) Battery, Hydrogen Storage, Advanced Lead Acid Battery (LAB), and Compressed Air Energy Storage (CAES) are considered the primary storage technologies. As for applications, our focus is on selected application services, most important of which are energy time shift (arbitrage), supply capacity, utility backup (service reliability), power quality, and frequency regulation (firming renewable generation).

Three types of market structures are considered in this analysis: Highly regulated, de-regulated, and a mix between regulated and deregulated markets. In a regulated electricity market, utilities incorporate all or most of the services and electricity deliveries are vertically integrated. In a deregulated market, on the other hand, the services are not vertically integrated by utilities. Instead, Independent Power Producers (IPPs) distributors, and other merchant generators are allowed to participate in the electricity market. In the case of a mixed regulated-deregulated market structure, the generation side is highly regulated and is managed by utilities, whereas distribution and end-user sides are de-regulated. The market structures are chosen in a manner that represents various jurisdictions across Canada (e.g., Ontario, British Columbia, and Alberta).

Finally, owners of the storage asset are divided into utilities, non-utility merchants, IPPs, and private individuals (end-users). As storage asset owners, utilities maintain and operate the transmission line, whereas IPPs deploy the ES asset independently in whole-sale electricity market. Private owners are end-users of electricity.

Based on the above conditions, four types of business models are proposed (utility-side, service contracted, IPP-side, end-user side), details of which are provided in Figure 5-2 and Table 5-1.

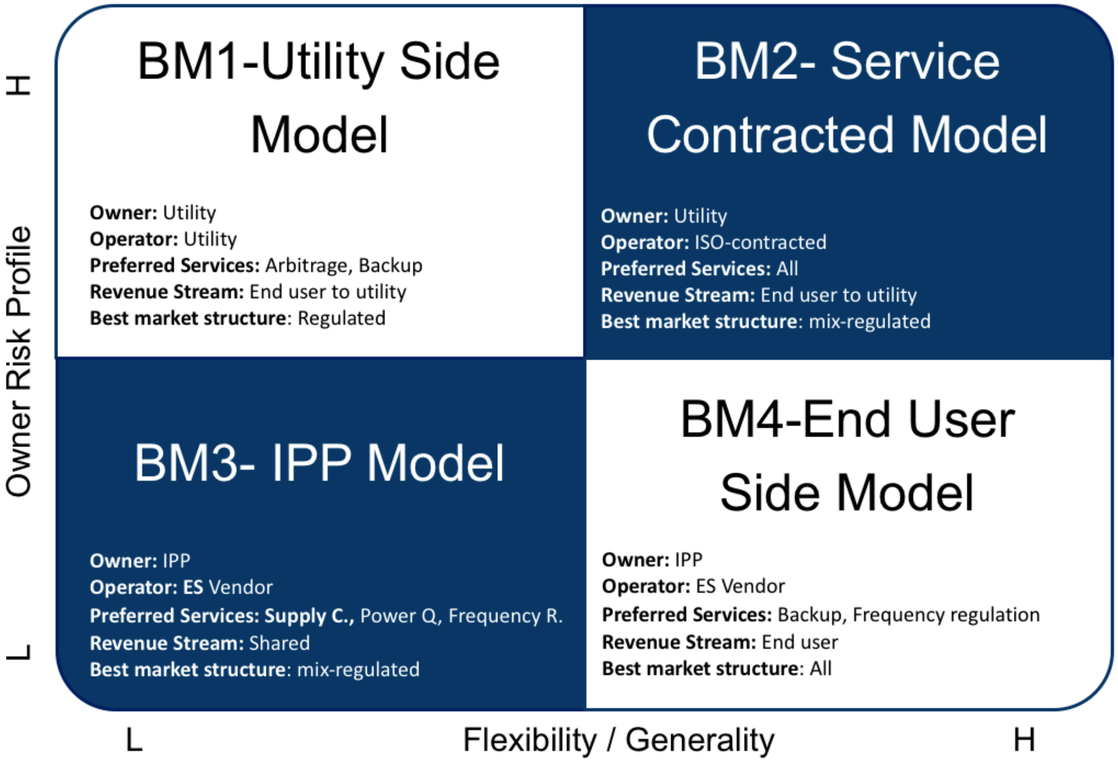


Figure 5-2 The business model (BM) grid diagram, representing four distinct categories and their characteristics; BM1: Utility side model; BM2: Service contracted model; BM3: IPP model; BM4: End user side model.

The growth and success of the storage industry are due in large part to innovative business models. Traditionally, the most viable business model for adopting storage technologies on the utility-side has been the “Service Contract” model. This core business model consists of contracts with private and public partners, where the technology developers and enablers such as storage integrators can contribute to the planning and construction phases of the project. The enablers can also provide a variety of services from technology evaluation and assessment to project planning, coordination, resource management, implementation, execution, and operations management from generation to distribution. This type of business model is not usually applied to emerging storage technologies at low MRLs. The commercial viability of storage technologies requires short- to long-term testing, demonstration, and integration by publicly owned utilities, independent power producers, power distributers, power authorities and operators, and end users. Some models are generally more capital intensive than others, but can attract clients among service recipients from communities (e.g. remote communities). As one the main areas of focus of this analysis, continuous effort will be made to explore better typologies of the business models and improve the classification criteria.

Here, the business models are divided into four groups that have distinct characteristics that are impacted by ownership, commercial operation, application, revenue value stream, market structure, and asset maturity (TRL/MRL) level. The flexibility of business models to adapt to various locations or market structures is another factor that should be considered. Table 5-1 and Figure 5-2 describe the four models with a few examples in each group. These groups are characterized by the four quadrants created by the intersection of two axes, asset maturity level and risk profile.

Table 5-1 The typology of business models and their relationships to other attributes. ISO: Independent System Operators. BM: Business Model.

Type	**Asset Owner**	**Asset operator**	**Application**	**Revenue Stream**	**Market Structure**	**Asset Maturity (MRL)**
BM1	Utility	Utility	• Arbitrage • Backup	End User to Utility	Regulated	High (MRL>7)
BM2	Utility	ISO (contracted)	All	End User to Utility	Mix-regulated	High (MRL>7)
BM3	IPP	Asset Vendor	• Supply capacity • Backup • Power quality • Frequency regulation	Shared	De-regulated	Medium to high (MRL>5)
BM4	End user	Asset Vendor	• Backup • Frequency regulation	End user	All	Medium to high (MRL>5)

5.5 Case study

One strategic business model for adopting high risk, emerging technologies relates to large-scale projects and leverages relationships with strategic partners such as government and technology suppliers (strategic partner engagement model). Their financial position often prohibits the technology vendors from being directly involved in capital-intensive, large-scale projects. These projects can have high impacts on communities and have the potential to generate substantial payoffs to the technology developer or Energy Storage System Operators (ESSOs). By employing a strategic partner model, ESSOs or IPPs can develop projects mainly based on public-private partnerships. The services can follow different “revenue sharing” strategies among the end-users, asset owners and the technology suppliers. Power authorities can play a role as a project evaluator, addressing the feasibility and capability of a specific storage solution in fulfilling needs. Other operational services depend upon available resources and capabilities to directly participate in project execution as project manager or monitor the project as per the ISO or IPP request. The latter can cover technical and marketing services for developing adequate policy and regulation. In such circumstances, the public or private partner may finance and therefore own the storage facility [113,130]. By financing the asset, the public entity accepts the risk of being responsible for the capital investment. Similarly, the private party may fully or partially finance the asset in return for a long-term service contract to operate the facility and generate revenue from the storage asset. Examples of business models are provided below in which services that system operators or storage technology vendors can provide to utilities within this framework are described in detail.

If the private technology vendor has the ability to fund and run the project independently, the role of ESSO/IPP and the public partner (ISO) is limited to a predefined period to monitor and evaluate the viability and framework of the project. In this case, the business model suggests a "Service Level Agreement" with the public sector or private vendor. ESSO, often referred to as ES integrators, can provide an independent and effective evaluation of the framework to the public sector and a technical/market evaluation to the private partner, Figure 5-3. The model is particularly suitable to scenarios in which several private vendors can participate, decreasing the amount of capital investment needed from each vendor. The vendor(s) accept(s) the overall financial risk of the project, whereas the public utility or power authority shares the risk of administrative control (which can also be transferred to ESSO). The latter could lead to end-user and end-customer dissatisfaction; thus, ESSO has to ensure that its contribution will lead to improvements in power services. Either fixed or variable payoffs by the vendor to the Independent System Operator (ISO) are expected. Several early stage technologies and market structures can fall into this model.

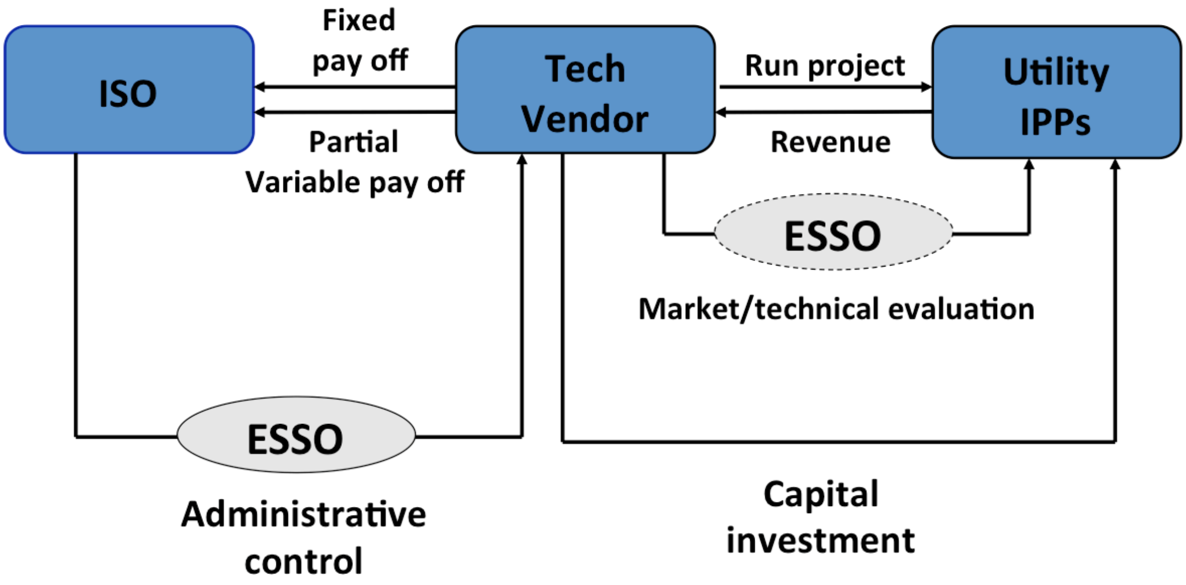


Figure 5-3 A business activity in which ESSO plays a role as project evaluator.

5.6 Summary

In general, existing business models for adopting renewable sources to electricity grids can be classified in one of two categories for creating profits from storage assets: (i) Those which are adopted from general business models for utilities, smart grids, or renewables; and (ii) those which are specific to storage systems with particular considerations for operation, ownership and revenue streams. The existing business models are mainly “technology-centric” meaning that the storage system is chosen based on maturity and suitability of the technology for specific market and use case. There is a gap in the literature related to the grid-scale ES systems where the choice of the ES technology and an appropriate business model would meet. The typology of business models presented in our analysis is divided into four groups that have distinct characteristics impacted by factors such as ownership, commercial operation, application, revenue value stream, market structure, and asset maturity (TRL) level. The business model framework and a test case study indicated that the most viable business model for adopting storage technologies on the utility-side could be based on a “service contracted” model, which include both “technology enabling” and “operation” services. The core business model consists of contracts with private and public partners. The technology developers and enablers, such as storage integrators, can contribute to the planning and construction phases and can cover a variety of services from technology evaluation and assessment to project planning, coordination, resource management, implementation, execution, and managing operations from the generation side to distribution. These types of business model usually do not target emerging storage technologies at low TRLs. An innovation analysis based on technology management tools will be required in order to unravel the relationship between industry readiness level and innovation of the technology and the choice of appropriate business model on the other hand. This requires demonstration and certification or regulation of the facility together with required policy instruments, which need to be analyzed in parallel. Finally, the commercial viability of storage technologies requires short- and long-term testing, demonstration, and integration by publicly owned utilities, IPPs, power distributers, power authorities or operators, and end-users.

6 Estimation of Storage Market Opportunity

This chapter describes basic assumptions for estimating the total ES capacity for each of regulated, de-regulated and mixed-regulated market. ES technologies in theory are able to provide various benefits to an electricity market structure. The objective of this chapter is to quantify the overall market size, key grid services, and deployment timing of ES systems that can add maximum benefit to the asset owners and operators over a minimum of 10 years. The estimated values are the key parameters or cost-benefit and business model analysis in the following chapters.

There are several methodologies based on electricity production cost models that can estimate the overall capacity of the electrical grid for adopting storage technologies. In order to build a model that simulates various scenarios of ES deployment in each market structure, pricing data have been collected from publicly available sources such as governmental (federal, provincial) and available data from provincial utilities. Technology costs data are based on a combination of available data in the ES-select tool as well as internationally accepted industrial data when no local/national data were available.

6.1 Electricity Market Structures

There are different electricity market structures to balance electricity supply and demand. Those market structures generally fall into three categories: regulated, deregulated, and some combination thereof. A deregulated electricity market is one where the price of electricity is set by the intersection of electricity supply and demand curves. In a dergulated market, the price is determined by market participants adhering to market rules set by an Independent System Operator or Regional Transmission Operator (ISO/RTO) [131]. In a deregulated market, the market is open for competition from IPPs. At present, the only two provinces or territories with some form of a deregulated electricity market are Alberta and Ontario. Specifically, in Alberta the generation market is deregulated, whereas the transmission and distribution sides of the market are regulated. In contrast, a regulated electricity market, such as BC, is a market in which the price is determined by regulator, usually on yearly basis. A regulated electricity market is a vertically integrated monopoly that can oversee the pricing in the entire electricity value chain, including generation and distribution.

6.2 Methodology

In order to determine the size of the distributed ES deployment in each market structure, an accurate database from provinces across Canada was utilized with additional industry-recognized data. This was done for each of the evaluation sites and included the following parameters: Energy, power, location and timing. A full-range stacked services benefit assessment, including the potential operational benefits, financial savings and additional revenue opportunities that can be realized through the deployment of the energy storage, was also utilized. In order to simplify the estimation, two different methodologies were taken into account based on extracting hourly pool prices for a selected year as an input to a detailed production cost model and direct data extracted from existing annual reports from available industry reports. Finally, the numbers were tabulated and estimated with the most viable grid services for each market structure that keep the total opportunity for ES at certain level for each regulated, de-regulated and mixed-market structure.

6.2.1 Comparing Existing Models and Tools

Navigant recently compared the capabilities of the various models impacting ES systems and relevant software packages [132]. The categorization isbased on stakeholder types in the electricity industry that include technology providers, project developers, utilities, generators/ independent power producers (IPPs), regulators, end-users, independent system operators (ISOs) and regional transmission organizations (RTOs), research and development (R&D) and consulting firms, and the finance community. These software packages or analysis tools were split into three major categories of (i) System planning, (ii) Real-time grid operation; and (iii) ES systems analysis. For portfolio and system planning, ES systems are modeled based on an energy production cost simulation, bulk transmission or in the context of a real-time grid operation. In contrast to all other tools and analysis platform, the tool developed in this effort is specifically geared toward the financial community to provide reliable characterizations of ES systems. Appendix provides details of the analysis model, and the source, and type of underlying databases.

6.2.2 Production Cost Analysis

The approach for the grid-level optimization of ES storage is largely based on production cost analysis which is generally used to estimate how much energy could be available in the proposed locations and to evaluate the performance of the grid through the hourly and sub hourly demand points along the grid network. The capacity optimization phase uses inputs of capital costs and operational costs of current and future assets to run the grid as well as new technologies and performs a least cost minimization analysis. In the capacity optimization phase the MW size and location of the ES system are determined. The objective function of the capacity optimization modeling is to minimize the production cost and the capital cost of the system.

The hourly production cost phase simulates day-ahead dispatch schedules and optimizes the system variable costs of current assets along with future assets and optimizes the MWh of energy storage from the capacity optimization phase. The hourly production cost is a nodal model that enforces contingency criteria. The sub-hourly production cost phase simulates real-time dispatch schedules and optimizes the system variable costs of the current assets along with future assets and refines the sizing of the ES system in terms of MW and MWh [133].

6.3 Base-line Application Databases

Baseline assumptions are provided in APPENDIX that were used evaluate the market size for ES in various market structures. A detailed grid-level production cost model, together with historical pricing and network data, is generally required for an accurate estimation of overall available capacity for ES. APPENDIX details the key storage market size databases used in this thesis. The methodology is designed to allow an ES technology-agnostic approach for estimating total market size and storage capacity in each market.

For a de-regulated market structure, the market potential is estimated based on a sample annual price depicted in Figure 11-5, extracted from available historical data for AB. Here, we evaluate the effect of the addition of ES in the electrical grid on electricity prices. As a result, the total service opportunity in a de-regulated market is calculated to be \$1.7 - \$2.7B. In a deregulated market structure, similar services are shown in APPENDIX from the possible grid services similar to those in the mix-regulated market.

Overall, the comparison of electricity prices in each market structure exhibits less price volatility when ES is deployed. In terms of ES market potential, the majority (> 70%) of the optimized storage capacity will be long-duration storage technologies. In addition, most of the ES capacity will be optimally deployed in the next 10 years based on anticipated decreases in technology prices, as well as overall mandates for carbon pricing and coal asset retirements. No sensitivity analyses were performed as they are beyond the scope of this thesis. They are generally focused on fuel prices, electricity prices, energy and electricity mix, and technology prices.

6.4 Summary

The main findings of this chapter are shown in Table 6-1. For simplicity, no specific ES technology is targeted, although each application may apply to none, one, or few ES technologies. ES technologies are categorized in four groups corresponding to the ratio of the stored energy volume to the deliverability rate and expressed as duration of time (APPENDIX).

Table 6-1 ES technologies grouping and total market size attributed in each group.

Service applications Category	Duration at Full Power	ES Market Size (GW or $B)	Example of Relevant ES Technologies
Long Duration	4+ Hours	Regulated: $1.7 B or 213 GW De-regulated: $1.7 B Mixed-regulated: $1.7 B	CAES, Flow Battery, NaS Battery
Medium Duration	1-2 Hours	Regulated: $ 1.7B or 213 GW De-regulated: $1.7B Mixed-regulated: $3.25B or 396 GW	Lithium Ion, Flow Battery, NaS Battery, NaNiCL2 Battery, Advanced Lead Acid Lead Acid, Lithium Ion, NiCd, NiMH
Short Duration	30 Minutes	Regulated: $1.7 B De-regulated: $2.7B Mixed-regulated: $3.25B	Lithium ion, Flywheel, High Power Super Capacitors, Thermal Storage
Very Short Duration	>1-15 Minutes	Regulated: $1.7 B De-regulated: $2.7B Mixed-regulated: $3.25B	Lithium ion, Flywheel, High Power Super Capacitors

This chapter considers all technologies, i.e. long duration (e.g. CAES, flow battery, sodium–sulfur [NaS] battery), medium duration (e.g. NaS battery, flow battery, Lithium Ion battery, lead acid battery, nickel–cadmium (NiCd) battery, Lithium Ion battery), and short or very short duration (e.g. Lithium Ion battery, flywheel, supercapacitors).

To evaluate the benefits ES can provide to the grid, simulations of the stacked services offered by the storage will be performed using our ES valuation framework for each suitable business model.

7 Business Model Analysis for Power-to-Gas Systems In A Regulated Market

This chapter is focused on business models and valuation analysis for power-to-gas (P2G) systems primarily utilized for grid-scale ES purposes. The objective is to explore the potential for using P2G to help integrate renewable sources into the grid (grid applications) and the gas pipeline or the hydrogen network (gas applications). The focus of this chapter will be on grid applications. The methodology involves performing process design, a component physical model, and a detailed cost analysis for the production of hydrogen from renewable energy sources such as solar and wind, hydrogen storage, and the delivery of the produced power back to the grid by either fuel cells or gas turbines. The required input parameters are capital and operating costs for the hydrogen/power production processes, parameters for hydrogen storage and delivery, financial parameters such as the type of financing, and plant life. Three case studies and analyses were performed for grid applications, all carried out in the context of utility-side and service contracted business models within a regulated market structure. The three cases for the grid application are load shifting, rapid reserve, and the combination of the two services.

7.1 Introduction

P2G technology links the power grid with the gas grid by converting surplus power into a pipeline via a two-step process: hydrogen production by water electrolysis and hydrogen conversion to CH4 via a methanation process [134, 135,136]. Power to Hydrogen, in particular, is a technology for P2G that uses Polymer Electrolyte Membrane (PEM) or alkaline electrolyzer technology to convert electrical energy to chemical energy in the form of hydrogen, injecting the hydrogen produced along with natural gas into existing gas storage facilities, and recovering the stored energy as hydrogen for industrial and transportation applications (Power to Hydrogen), as electricity to serve power demand (Power to Power), or as hydrogen-enriched natural gas to serve gas demand (Power to Gas). Underground Storage of Hydrogen with Natural Gas (UHNG) is an ES solution for utility scale applications. The resulting CH4 can be injected into the existing gas distribution grid or gas storage infrastructure, or it can easily be utilized in other well-established natural gas facilities [137,138, 139].

The main drawbacks of P2G are a relatively low efficiency and high costs. Recent interest in Power-to-Gas is mainly attributed to the increased presence of wind and solar power on the electricity grid [140,141]. Publicly available P2G studies to date can be separated into either an EU or a North American (NA) market focus. For the EU market such reports focused on firming offshore wind power [142]. Canadian P2G studies to date have focused on installation sites in Alberta. To clarify, this chapter will focus on the North American market and specifically P2G opportunities (with or without the fuel cell) in a broader range of grid-service applications in a regulated market.

To our knowledge no studies to date have systematically studied the interplay between suitable business models and the grid-value of the P2G connected to existing wind, solar, natural gas pipeline and storage infrastructure in North America.

It is critical to evaluate both the profitability and technical viability of P2G systems. A P2G system shifts the burden between existing natural gas and electricity grid infrastructures using an electrolyzer, as well as H_2 storage and an injection system. The configuration can also include renewable electricity that may or may not be tied to the grid. Depending on demand or price, H_2 can be injected into pipelines and then converted downstream to heat and or power. Although P2G subcomponents are commercially available, effective integration of the subcomponents in real-world applications is still unproven. Furthermore, next-generation P2G subcomponent technologies, specifically pressurized PEM electrolyzers, are relatively new to the commercial market and also need to be evaluated.

There is a gap in the systematic study of suitable business models and techno-economic valuation analysis to understand which grid-service applications are the most viable option for each regulated and de-regulated electricity market structure. This study aims to develop and implement a detailed model that analyzes high-level dynamic behavior, financial and environmental performance through a scenario-based approach. This model, for the first time, offers a P2G module analysis as a standalone tool for techno-economic valuation purposes under various business models. Although our primary focus in this chapter is on regulated market structures, our module is general enough to be integrated into other existing tools for fast screening or planning purposes under other business models and pricing regulations beyond the utility and service contracted models considered here.

7.2 Methodology

The detailed PEM and alkaline electrolyzer physical models are derived from previously developed models [143,144]. The output of the P2G model includes the net present cost, the cost of hydrogen, GHG emissions, the dynamic response of the input parameters, and the market pricing. Several default scenarios are built into the module, but the user is allowed to create new scenarios. For each scenario, the configuration of energy source, scale of operation and operating strategy, ownership model, and revenue and profit streams can be selected as per existing functionalities within our developed valuation tool. All new scenarios are compared to the base-case scenario of a conventional underground gas storage facility. The module consists of four building blocks of decision variables (including cost and financial information), physical model (configuration, size, and location), performance model, and performance indicators. The physical model defines the system under consideration and the production and delivery of electricity, hydrogen and natural gas (enriched or pure). The performance model utilizes financial, business model, market structure and emission (if required) components that are connected to the physical model via subset of variables. This configuration is consistent with our current modular valuation architecture. The electricity pricing and levelized cost of storage or electricity are based on annualized pricing. Our methodology can be expanded to a de-regulated market structure where 8760 hourly load data are provided as inputs and are analyzed dynamically over time. The latter, however, is beyond the scope of this chapter. The modules are initially built and validated in Excel as a stand-alone tool. **Figure 7-1** shows the architecture of the logic model.

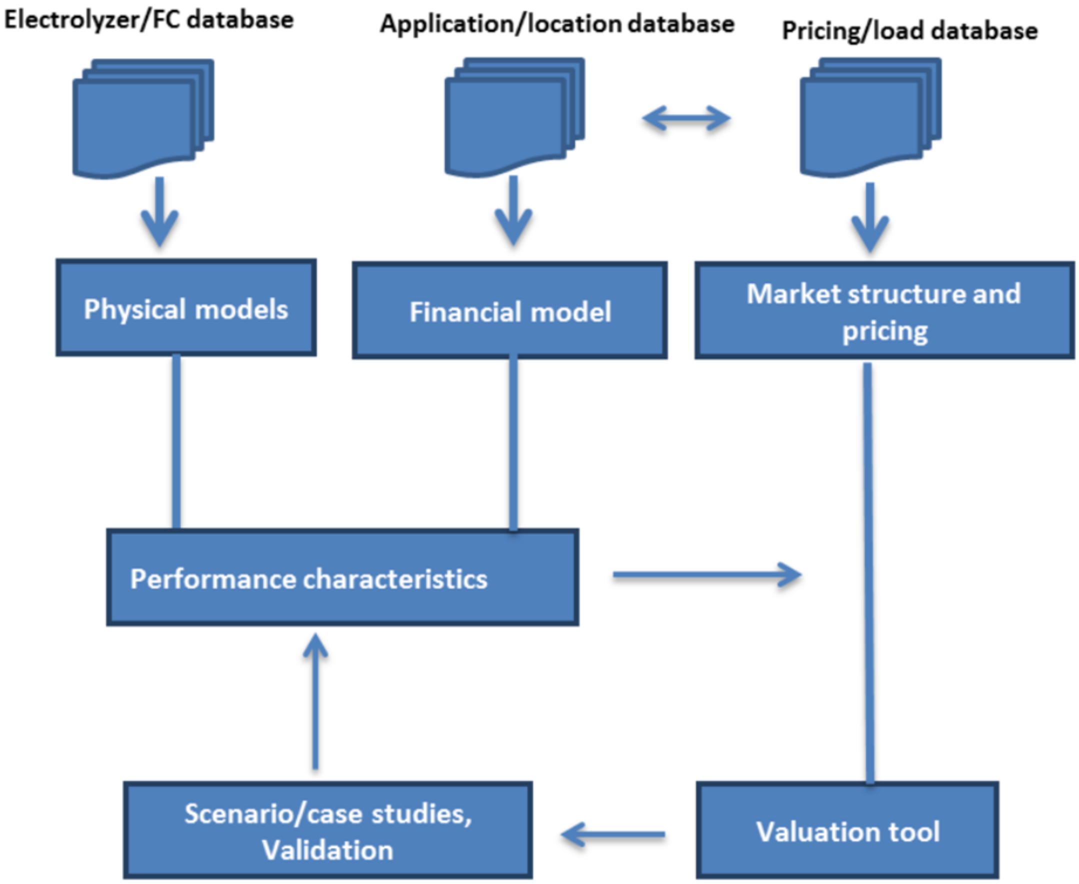


Figure 7-1. The overall model architecture.

There are two distinct applications; P2G for the gas application and Power to Power (PtP) for the grid application. Electrolyzer, fuel cell and hydrogen storage are the key components in the system.

This analysis module includes process design assumptions, a component physical model, and a cost analysis methodology for the production, storage, and delivery of hydrogen from renewable energy such as solar and wind. The power delivered to the grid is produced by either fuel cells or gas turbines. Model inputs include capital and operating costs for the hydrogen/power production process, type of business model (to identify asset ownership and profit structure), market structure (to identify pricing), method of hydrogen storage and delivery, and financial parameters such as the type of financing and plant life. The output of the standalone tool includes the system net present cost, the cost of hydrogen and electricity, GHG emissions, the dynamic response of input parameters, and the market pricing.

7.2.1 Model Description

We have designed three cases for grid applications: Load shifting, rapid reserve, and a combination of the two. The results provide an indication of the potential value of ES and demonstrate the unique capability and financial performance of the configuration given the specific business model.

7.2.2 System Configuration

The PtP system consists of bi-directional inverters, electrolyzers, compressors, hydrogen storage systems, and PEM fuel cell systems, as shown in Figure 7-2.

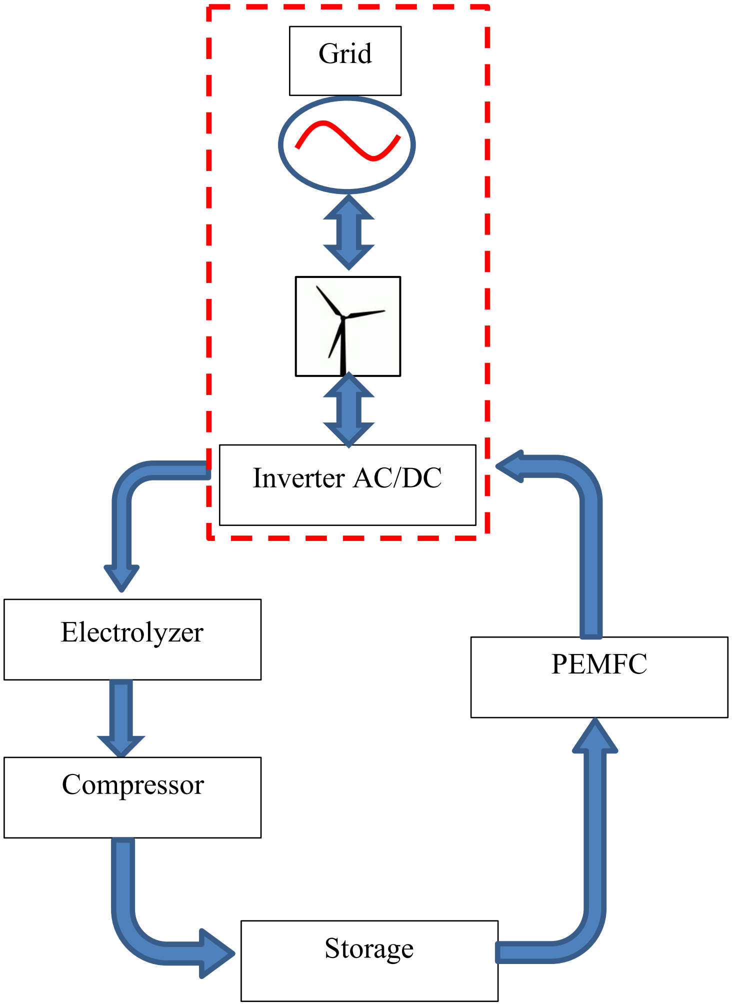


Figure 7-2 System configuration for a P2P grid application

In the above system, excess energy from the solar or a wind farm is used to produce hydrogen which is compressed and stored in either ground storage systems (such as steel tanks, pipelines, etc.) or underground systems, such as depleted oil fields, or excavated rock caverns.

When power is needed, the stored hydrogen can be converted to electricity by the PEM fuel cell subsystem to meet the required grid applications.

7.2.3 PtP Grid Applications

The baseline power and energy requirement for the three grid applications (load shifting, rapid reserve, and combined application) are given in Table 7-1. The basic financial parameter and technology cost inputs are shown in Table 7-2.

Table 7-1 Requirements of fuel cell system for grid applications

Application	Power capacity, P_{dis} (kW)	Discharge time per day, t_{dis} (h)	Energy discharge capacity per day, E_{dis} (kWh)
Load shifting	5,000	5	25,000
Rapid reserve	10,000	0.25	2,500
Combined App.	10,000	2.5	25,000

Table 7-2 Input parameters for annualized cost calculation

Parameters	value	unit
Annual interest rate, i_r	15	%
Total lifetime, n_y	20	year
Number of operation days per year, n_{op}	365	Day/year
Electricity price purchased from wind farm, C_{WFbuy}	0.01	\$/kWh
Electricity price purchased from grid, C_{Gbuy}	0.06	\$/kWh
Electricity price sell to grid, C_{Gsell}	0.15	\$/kWh

Both the PEM fuel cell efficiency and hydrogen consumption rate depend on the fuel cell performance parameters that are estimated in Ref. [145].

Table 7-3 Calculation of the PEM fuel cell efficiency [137] and hydrogen consumption

Parameter	value	unit	Assumption and method
Maximum fuel cell efficiency, η_{LHV}^{max}	94.5%		$\eta_{LHV}^{max} = -\frac{\Delta G}{-\Delta H_{LHV}}$ Gibbs free energy of hydrogen, $\Delta G = -228.74\text{kJmol}^{-1}$; lower heating value of hydrogen, $\Delta H_{LHV} = -241.98\text{kJmol}^{-1}\ or\ -120.1\text{MJ}kg^{-1}$
Maximum fuel cell efficiency, η_{HHV}^{max}	83%		$\eta_{HHV}^{max} = -\frac{\Delta G}{-\Delta H_{HHV}}$ Gibbs free energy of hydrogen, $\Delta G = -237.34\text{kJmol}^{-1}$; higher heating value of hydrogen, $\Delta H_{HHV} = -286.02\text{kJmol}^{-1}\ or\ -141.9\text{MJ}kg^{-1}$
Real fuel cell efficiency, η_{LHV}	56%		$\eta_{LHV} = \frac{V_{FC}}{1.254}$ V_{FC} is generated voltage, which is related to the fuel cell current through its polarization curve. Here we assume $V_{FC} = 0.7V$, at $I_{FC} = 1A/cm^2$.
Real fuel cell efficiency, η_{HHV}	47%		$\eta_{HHV} = \frac{V_{FC}}{1.482}$ V_{FC} is generated voltage, which is related to the fuel cell current through its polarization curve. Here we assume $V_{FC} = 0.7V$, at $I_{FC} = 1A/cm^2$.
Power consumption for auxiliary systems, $r_{aux,FC}$	5.6%	kW	The auxiliary subsystems include air compressors, humidifiers, and etc. The power consumption of the auxiliary subsystem is assumed to be a percentage of the output power from the fuel cell, $r_{aux,FC} = \frac{P_{aux}}{P_{FC}}$.
Fuel cell system efficiency, η_{FC}	44.4%		$\eta_{FC} = \eta_{HHV} * \frac{P_{FC} - r_{aux,FC} \times P_{FC}}{P_{FC}}$
Hydrogen consumption per kWh electricity production, $r_{H_2E_{dis}}$	0.054	Kg H_2 /kWh	$r_{H_2E_{dis}} = \frac{1}{39.4 \times \eta_{HHV}}$ Based on the value of 39.4 kWh/KgH_2 at HHV
Electricity consumption for auxiliary systems per Kg H_2, $r_{E_{aux}H_2}$	1.04	kWh /Kg H_2	$r_{E_{aux}H_2} = \frac{1}{39.4 \times \eta_{HHV}}$ Based on the value of 39.4 kWh/KgH_2 at HHV

The capacity and power rating of the PEM fuel cell system are estimated from the requirements of the grid application. The design parameters for a regulated market structure are listed in Table 7-3.

Table 7-4 Design parameters for a PEM fuel cell system

parameter	Expression	unit
Power rating	$P_{FC}^{rating} = \frac{P_{dis}}{\eta_{HHV}}$	kW
Net power output	$P_{FC} = P_{dis}$	kW
Discharge time	t_{dis}	h/day
Discharged electricity	$E_{dis} = P_{dis} \times t_{dis}$	kWh/day
H_2 flow rate to fuel cell system	$f_{H_2toFC} = E_{dis} \times r_{H_2E_{dis}}$	Kg H_2/day

The capital cost of a PEM fuel cell system is calculated by [146]:

$$C_{FC}(\$) = UC_{FC}(\frac{\$}{kW}) \times P_{dis}(kW) \tag{1}$$

Where

C_{FC}: capital cost of hydrogen fuel cell system, \$

UC_{FC}: unit capital cost of hydrogen fuel cell per kW, \$/kW

Here we assume that the energy consumption by the auxiliary unit attached to the PEM fuel cell system is provided by the grid only. The cost of this electricity consumption is calculated by

$$C_{Gbuy,FC}^{ann}(\$) = C_{Gbuy} \times \left(E_{dis} \times r_{aux,FC}\right) \times n_{op} \tag{2}$$

where

$C_{Gbuy,FC}^{ann}$: Annualized cost of energy bought from grid for auxiliary subsystems of the PEM fuel cell system.

n_p : number of operational years

C_{Gbuy}: Energy purchase price from grid, \$/kWh.

$r_{aux,FC}$: Ratio of the power consumption of the auxiliary subsystems to the power output of the whole PEM fuel cell system.

Operation and maintenance (O&M) costs of the P2P system include annualized cost of the fuel cell system and unit cost per year and exclude the cost of the electricity to power the auxiliary subsystem. Note that the type of business model and therefore ownership structure determines the flow of operational cost and benefit structure to the overall financial parameters.

$$C_{FC,OM}^{ann}(\$) = UC_{FC,OM}\left(\frac{\$}{kW - yr}\right) \times P_{dis}(kW) \tag{3}$$

Where

$C_{FC,OM}^{ann}$: Annualized O&M cost of fuel cell system, $.

$UC_{FC,OM}$: O&M unit cost per kW-year, $/kW-yr

The values of the parameters for the fuel cell system cost calculation are given in Table 7-5. As a comparison, for automotive applications, the PEM fuel cell cost is much cheaper and is estimated at 47$/kW-yr [138,140].

Table 7-5 Input parameters for PEM fuel cell system cost calculations

parameter	Baseline value	unit
UC_{FC}	2500[1, 3]	$/kW
$UC_{FC,OM}$	27	$/kW-yr

7.2.4 Hydrogen Storage System

The design parameters for a hydrogen storage system are listed in Table 7-6.

Table 7-6 Design parameters for the hydrogen storage system

parameter	Value/expression	unit
H_2 mass efficiency	$\eta_{stor}^{mass} = \frac{m_{in}}{m_{out}} = 100\%$	
H_2 flow rate to storage	$f_{H_2toStor} = \frac{f_{H_2toFC}}{\eta_{Stor}^{m}}$	Kg H_2/day
Inlet pressure	$p_{Stor,in} = 175$	bar
Number of days for storage	$n_{Stor} = 2$	day
Storage capacity	$m_{Stor} = f_{H_2toStor} \times n_{Stor}$	Kg

The capital cost for a hydrogen storage system is calculated from

$$C_{Stor}(\$) = UC_{Stor}(\frac{\$}{KgH_2}) \times m_{Stor}(KgH_2) \tag{4}$$

Where

C_{Stor}: Capital cost of the hydrogen storage, $

UC_{Stor}: Unit capital cost of hydrogen storage, $/KgH$_2$

Assuming no electricity consumption for the hydrogen storage system,

$$C_{Gbuy,Stor}^{ann} = 0 \tag{5}$$

the annual O&M cost of hydrogen storage is proportional to its total capital cost

$$C_{Stor,OM}^{ann}(\$) = r_{Stor,OM}(\% / yr) \times C_{Stor}(\$) \tag{6}$$

$C_{Stor,OM}^{ann}$: Annual O&M cost of hydrogen storage

$r_{Stor,OM}$: Ratio of the annual O&M cost to capital cost of hydrogen storage

The values needed for the cost calculation of hydrogen storage are given in Table 7-6. The specifications for the compressor for a hydrogen storage system are listed Table 7-7. The capital cost of the compressor is then calculated by

$$C_{Comp}(\$) = C_{Comp}^{uninst}(\$) + C_{Comp}^{inst}(\$) \tag{7}$$

Where

$C_{Comp}^{uninst}(\$)$ is the uninstallation cost of larger compressors with two or three stage compression stages and can be estimated as:

$$C_{Comp}^{uninst}(\$) = 6893 \times \left(P_{Comp}^{rating}\right)^{0.7464} \times n_{Comp} \tag{8}$$

And $C_{Comp}^{inst}(\$)$ is the installation cost and proportional to its uninstallation cost,

$$C_{Comp}^{inst}(\$) = f_{Comp}^{inst} \times C_{Comp}^{uninst}(\$) \tag{9}$$

f_{Comp}^{inst} refers to the installation cost factor and is proportional to the uninstallation cost. Here, we assume that the energy by the compressors is provided by the grid only. The cost of this electricity consumption is calculated as

$$C_{Gbuy,Comp}^{ann}(\$) = C_{Gbuy} \times \left(f_{H_2toComp} \times r_{EComp}\right) \times n_{Comp} \times n_{op} \tag{10}$$

$C^{ann}_{Gbuy,Comp}$: Annualized cost of energy bought from grid for compressors.

r_{EComp}: Electricity consumption of compressors per unit of H_2, kWh/Kg H_2

Finally, the annual O&M cost of hydrogen storage is assumed to be proportional to its total capital cost:

$$C^{ann}_{comp,OM}(\$) = r_{comp,OM}(\%/yr) \times C_{comp}(\$) \quad (11)$$

$C^{ann}_{comp,OM}$: Annualized O&M cost of compressor.

The financial parameters used for the calculation of compressor cost are given in Table 7-7.

Table 7-7 Specifications of the compressor

Parameter	Value/expression	unit
Hydrogen mass efficiency	$\eta^{m}_{Comp} = 99.5\%$	
Hydrogen flow rate to compressor	$f_{H_2toComp} = \dfrac{f_{H_2toStor}}{\eta^{m}_{Comp}}$	Kg H_2/day
Inlet pressure	$p_{Comp,in} = 20$	bar
Outlet pressure	$p_{Comp,out} = 175$	bar
Compression ratio per stage	$r_{Comp,stag} = 2.1$	
Number of compression stages	$n_{Comp,stag} = 3$	
Compressor efficiency	$\eta_{Comp} = 88\%$	
Mean compressibility factor	$f_{Comp,fact} = 1.161$	
Compressor rating power	$P^{rating}_{Comp} = 0.06$	MW
Number of compressors needed	$n_{Comp} = 2$	

Table 7-8 Parameters for compressor cost calculation

Parameter	value	unit
f_{Comp}^{inst}	100%	
r_{EComp}	1.05	kWh/Kg H_2
$r_{Comp,OM}$	2%	

7.2.5 Electrolyzer

The key parameters of energy efficiency and electricity consumption of the electrolyzer are provided in Ref [143].

Table 7-9 Energy efficiency and electricity consumption of the electrolyzer

	parameter	Value/expression	unit
Stack electrical usage	Voltage supply	$V_{Elec}^{stack} = 4.974.97$	Volt/stack
	Stack voltage efficiency (LHV)	$\eta_{LHV}^{stack} = 60.6\%$	
	Dryer loss	$l_{Dryer}^{stack} = 1.0\%$	% of gross H_2
	Permeation loss	$l_{Perm}^{stack} = 0.1\%$	% of gross H_2
	Total stack efficiency	$\eta_{Elec}^{stack} = \eta_{LHV}^{stack} \times (1 - l_{Dryer}^{stack}) \times \left(1 - l_{Perm}^{stack}\right) = 60.0\%$	
	Total stack energy usage per mass net H_2	$C_{EH_2}^{stack} = \frac{1}{\eta_{Elec}^{stack}} \times 33.33 = 55.9$	$kWh_{elec}/Kg_{net}H_2$
Balance of Plant (BOP) loads	Power inverter efficiency	$\eta_{Elec}^{inve} = 95\%$	
	Inverter electrical load	$L_{EH_2}^{inve} = \frac{C_{EH_2}^{stack}}{\eta_{Elec}^{inve}} - C_{EH_2}^{stack} = 2.93$	$kWh_{elec}/Kg_{net}H_2$
	Dryer thermal load	$L_{Dryer,therm}^{BOP} = 0.10$	$kWh_{therm}/Kg_{net}H_2$
	Dryer efficiency	$\eta_{Dryer}^{BOP} = 0.8$	kWh_{elec}/ kWh_{therm}

	Dryer electrical load	$L_{E,Dryer}^{BOP} = L_{Dryer,therm}^{BOP} \times \eta_{Dryer}^{BOP} = 0.08$	kWh$_{elec}$/Kg$_{net}$H$_2$
	Misc electrical load	$L_{E,misc}^{BOP} = 0.01$	kWh$_{elec}$/Kg$_{net}$H$_2$
	Total BOP electrical load	$L_{EH_2}^{BOP} = L_{EH_2}^{inve} + L_{E,Dryer}^{BOP} + L_{E,misc}^{BOP} = 3.02$	kWh$_{elec}$/Kg$_{net}$H$_2$
Total electrolyzer system	Total system electrical usage per mass net H$_2$	$C_{EH_2}^{Elec} = C_{EH_2}^{stack} + L_{EH_2}^{BOP} = 58.6$	kWh$_{elec}$/Kg$_{net}$H$_2$
	Effective plant efficiency	$\eta_{Elec} = \frac{33.33}{C_{EH_2}^{Elec}} = 57\%$	

The capital cost of the electrolyzer is calculated from

$$C_{Elec}(\$) = C_{Elec}^{uninst}(\$) + C_{Elec}^{inst}(\$) \tag{12}$$

Where

$C_{Elec}^{uninst}(\$)$ is the uninstallation cost of the electrolyzer and can be estimated as

$$C_{Elec}^{uninst}(\$) = UC_{elec}(\frac{\$}{kW}) \times C_{EH_2}^{Elec} \times f_{H_2,Elec} \times \frac{1}{24} \tag{13}$$

And $C_{Elec}^{inst}(\$)$ is the installation cost and proportional to its uninstallation cost,

$$C_{Elec}^{inst}(\$) = f_{Elec}^{inst} \times C_{Elec}^{uninst}(\$) \tag{14}$$

Here

f_{Elec}^{inst}: installation cost factor and is proportional to the uninstallation cost of the electrolyzer.

C_{elec}: capital cost of the electrolyzer, $

UC_{elec}: unit capital cost of the electrolyzer, $/kW

The input parameters are given in Table 7-10.

Table 7-10 Input parameters for the electrolyzer

parameter	value
UC_{elec}	385 $/kW
f_{Elec}^{inst}	0.12

Here, there are two energy supply sources for the electrolyzer system, the grid and a wind farm. We assume that the electricity supply for the electrolyzer's balance of plant (BOP) is only from the grid; whereas the electricity supply for the electrolyzer stack is provided by both the grid and wind farm. The annual electricity cost for the electrolyzer is then calculated from

$$C_{Ebuy,Elec}^{ann}(\$) = C_{WFbuy,Elec}^{ann,stack}(\$) + C_{Gbuy,Elec}^{ann,stack}(\$) + C_{Gbuy,Elec}^{ann,BOP}(\$) \tag{15}$$

Where $C_{WFbuy,Elec}^{ann,stack}(\$)$ is the annual cost of electricity for the electrolyzer stack purchased from the wind farm,

$$C_{WFbuy,Elec}^{ann,stack}(\$) = \left(C_{EH_2}^{stack} \times f_{H_2,Elec} \times n_{op}\right) \times EWF\% \times C_{WFbuy} \tag{16}$$

$C_{Gbuy,Elec}^{ann,stack}(\$)$ is the annual cost of electricity for the electrolyzer stack purchased from the grid,

$$C_{Gbuy,Elec}^{ann,stack}(\$) = \left(C_{EH_2}^{stack} \times f_{H_2,Elec} \times n_{op}\right) \times \left(1 - EWF\%\right) \times C_{Gbuy} \tag{17}$$

$C_{Gbuy,Elec}^{ann,BOP}(\$)$ is the annual cost of electricity for the electrolyzer BOP purchased from grid,

$$C_{Gbuy,Elec}^{ann,BOP}(\$) = \left(L_{EH_2}^{BOP} \times f_{H_2,Elec} \times n_{op}\right) \times C_{Gbuy} \tag{18}$$

$EWF\%$: Ratio of electricity purchased from wind farm to the electricity from grid for the electrolyzer stack.

The annualized O&M cost of the electrolyzer is assumed to be proportional to its total capital cost. The baseline values are provided in Table 7-11

$$C_{Elec,OM}^{ann}(\$) = r_{Elec,OM}(\%/yr) \times C_{Elec}(\$) \tag{19}$$

$C_{Elec,OM}^{ann}$: Annualized O&M cost of the electrolyzer

Table 7-11 Input parameters for the electrolyzer

parameter	value
$EWF\%$	50%
$r_{Elec,OM}$	2%

Finally, the total capital cost of the hydrogen fuel cell storage system is

$$C_{cap}^{tot}(\$) = C_{FC} + C_{Stor} + C_{Comp} + C_{Elec} \tag{20}$$

Where C_{cap}^{tot} is the total capital cost of the hydrogen fuel cell storage system (\$).

The total annualized capital cost of the hydrogen fuel cell storage system is estimated as

$$C_{cap}^{ann} = C_{cap}^{tot}(\$) \times CRF \tag{21}$$

Where

CRF: Capital recovery factor and given,

$$CRF = \frac{i_r \times (1+i_r)^{n_y}}{(1+i_r)^{n_y} - 1} \tag{22}$$

Here

i_r : Annual interest rate in fraction

n_y : System lifetime in years

The total annual electricity cost of the hydrogen fuel cell storage system is

$$C_{Ebuy}^{ann}(\$) = C_{Gbuy,FC}^{ann} + C_{Gbuy,Stor}^{ann} + C_{Gbuy,Comp}^{ann} + C_{Ebuy,Elec}^{ann} \tag{23}$$

Where C_{Ebuy}^{tot} is the total annual electricity cost of the hydrogen fuel cell storage system.

The total annual operation and maintenance cost of the hydrogen fuel cell storage system can be estimated as

$$C_{OM}^{ann}(\$) = C_{FC,OM}^{ann} + C_{stor,OM}^{ann} + C_{comp,OM}^{ann} + C_{elec,OM}^{ann} \tag{24}$$

Where C_{OM}^{ann} is the total annual operation and maintenance cost of the hydrogen fuel cell storage system, \$.

Therefore, the total annualized cost of the hydrogen fuel cell storage system is

$$C^{ann,tot}(\$) = C_{cap}^{ann} + C_{Ebuy}^{ann} + C_{OM}^{ann} \tag{25}$$

The levelized cost of the electricity from the hydrogen fuel cell storage system is

$$LCOE(\frac{\$}{kWh}) = \frac{C^{ann,tot}(\$/yr)}{AEP(kWh/yr)} \tag{26}$$

Where AEP is the annual energy production. It is the total energy discharged by the hydrogen fuel cell storage system in a year and is proportional to the ES capacity and number of operating days per year of the system.

$$AEP = P_{dis} \times t_{dis} \times n_{op} \tag{27}$$

The net present cost (NPC) of the system includes all costs and revenues that occur within the project life span, with future cash flows discounted to the present. It includes the entire capital cost of the system, all O&M costs, and the cost of purchasing power from grid. The revenue from the sale of power to the grid reduces the total NPC.

$$NPC(\$) = \frac{C^{ann,tot} - C^{ann}_{Esell}}{CRF} \tag{28}$$

Where

$$C^{ann}_{Esell}(\$) = C_{Esell} \times AEP \tag{29}$$

is the total annual revenue of the hydrogen fuel cell storage system.

7.3 Results from Case Studies

For load shifting applications and from Table 7-11, we have

$$\begin{aligned} P_{dis} &= 5000kW \\ t_{dis} &= 5h \\ E_{dis} &= P_{dis} \times t_{dis} = 25000kWh \end{aligned}$$

From Eq(20), the total capital cost for the load shifting grid application is

$$C^{tot}_{cap}(\$) = \$15,716,472$$

The capital cost distribution among the four components is presented in Figure 7-3.

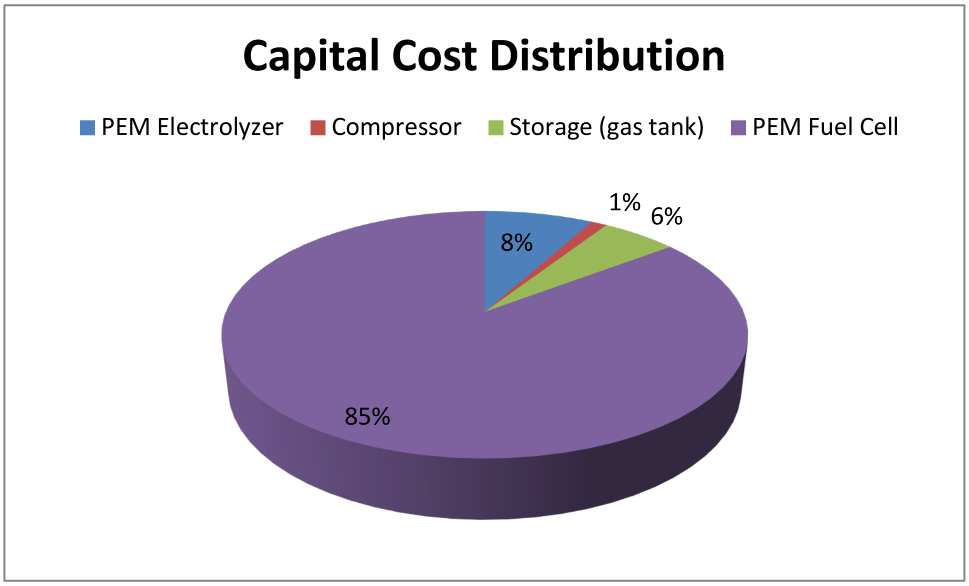


Figure 7-3. Capital cost distribution for the load shifting application

The annual electricity cost for the system is calculated from Eq.(23)

$$C_{Ebuy}^{ann} = 1,201,909\$ / yr$$

The electricity cost distribution among the four components is shown in Figure 7-4.

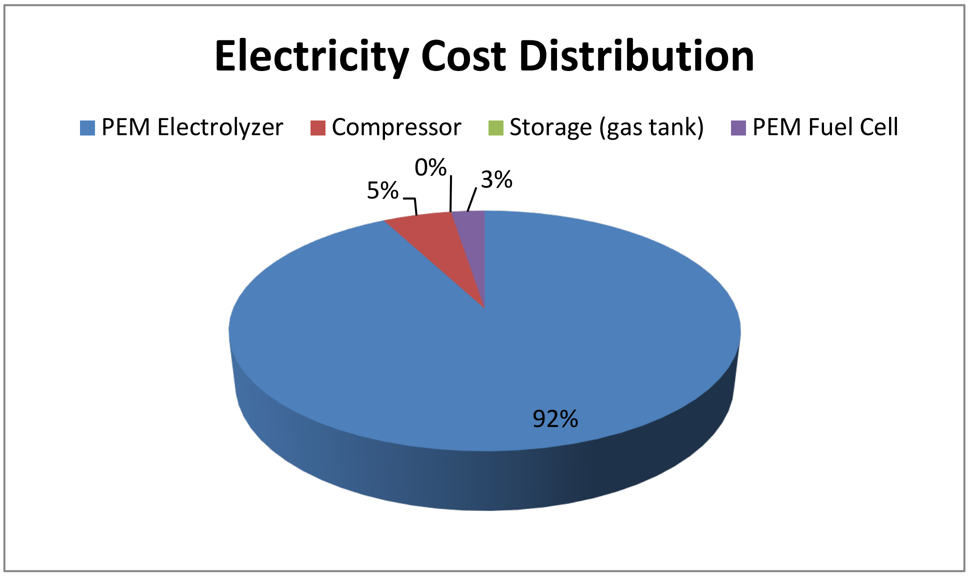


Figure 7-4. Electricity cost distribution for the load shifting application

The annual operation and maintenance cost for the system can be calculated from eq.(24),

$$C_{OM}^{ann} = 199,329\$ / yr$$

And the O&M cost distribution among the four components is shown in Figure 7-5.

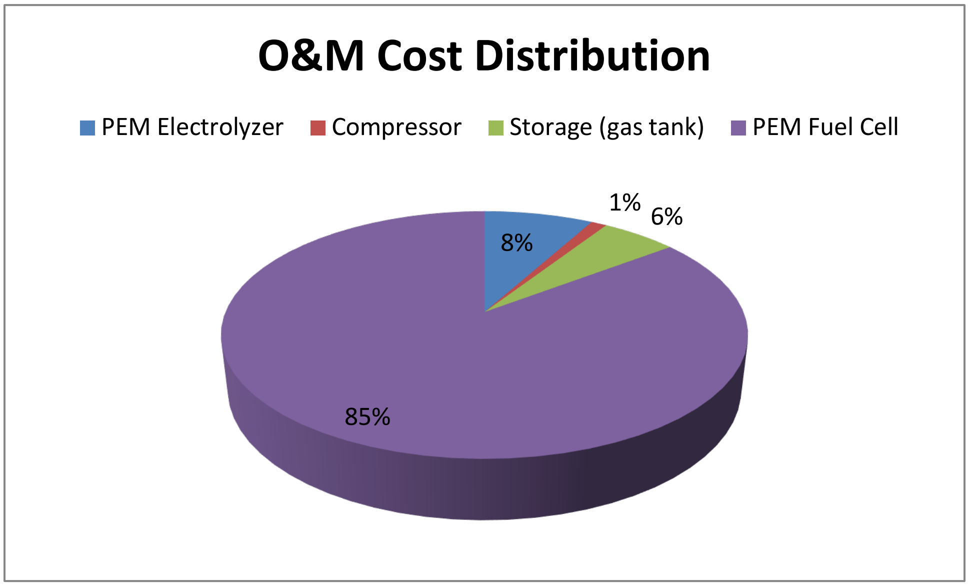


Figure 7-5. O&M cost distribution for the load shifting application

The total annualized cost of the PEM fuel cell storage system from Eq.(25) is

$$C^{ann,tot}(\$) = 3,912,125\$ / yr$$

The annualized cost distribution among the four components is given in Figure 7-6.

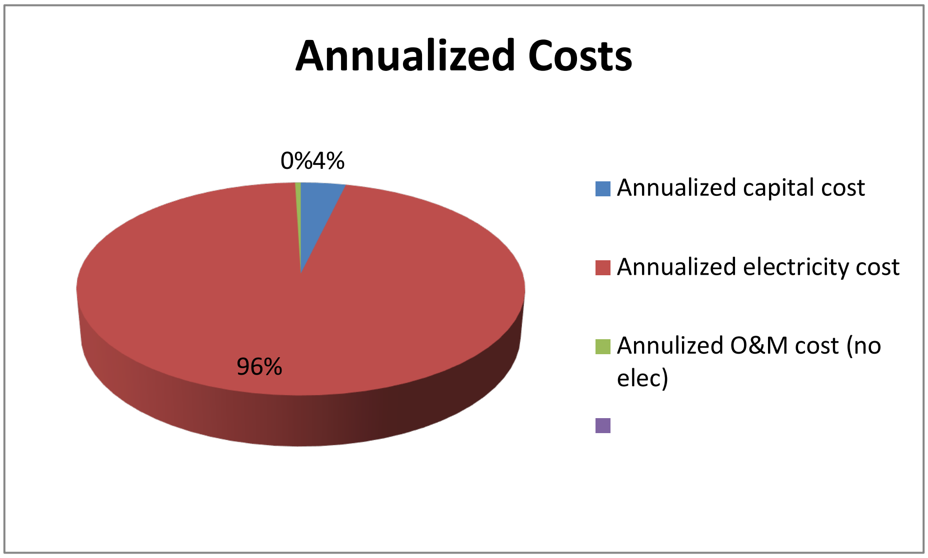


Figure 7-6. Annualized cost distribution for the load shifting application

The levelized cost of electricity is estimated based on Eq.(26) at

$$LCOE = 0.4287 \frac{\$}{kWh}$$

And the net present cost from Eq.(28) is estimated at

$$NPC = \$15,818,827.88$$

Assuming that current energy market price of 0.15$/kWh,

$$LCOE = 0.4287 \frac{\$}{kWh} > C_{Gsell} = 0.15 \frac{\$}{kWh}$$

The above equation clearly indicates that the PtP system is not viable economically for load shifting applications regardless of the selected business model and independent of the market structure in which the P2P system is operating.

For the three applications evaluated in this analysis, we compared the total capital cost, annual electricity cost, annual O&M cost, Levelized cost of electricity (LCOE), and NPC. The results are shown in the following Figure **7-7** to Figure **7-9**. NPC and LCOE comparisons of all three applications are also illustrated in Figure 7-7 where load shifting demonstrates the lowest LCOE and rapid reserve shows the highest NPC.

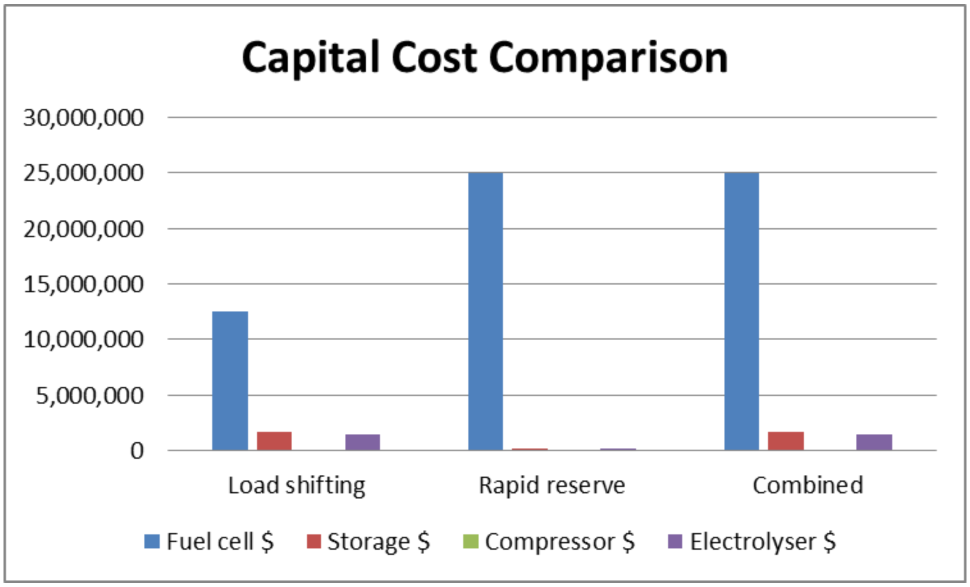


Figure 7-7. Capital cost comparison of all three applications

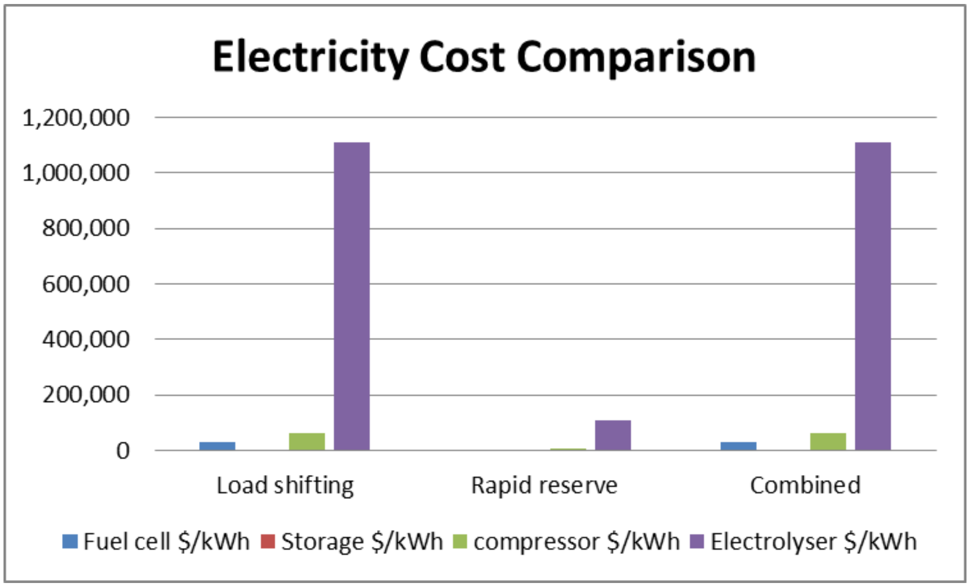


Figure 7-8. Electricity cost comparison of all three applications

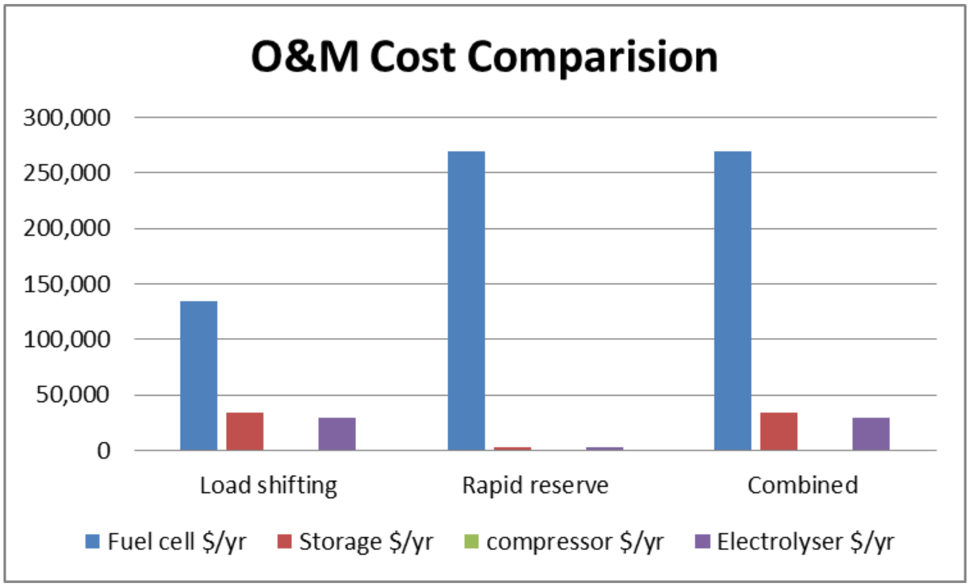


Figure 7-9. O&M cost comparison of all three applications

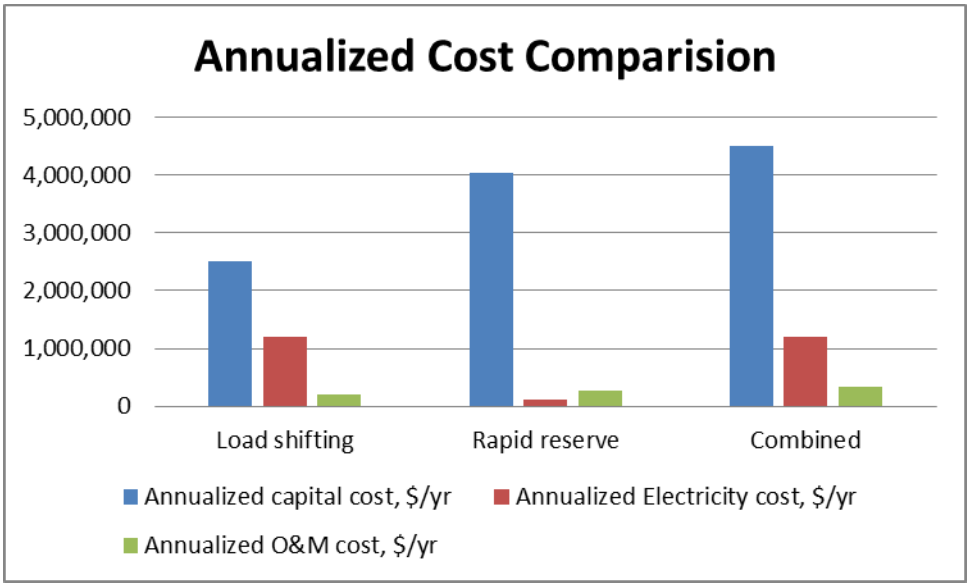


Figure 7-10. Total capital cost and annualized cost comparison of all three applications

A sensitivity analysis was performed for LCOE and NPC. The effects of changing interest rate, wind power penetration ratio, unit capital cost and O&M cost of fuel cell, and unit capital cost of the electrolyzer and hydrogen storage on the LCOE and the NPC of the PtP system are summarized in Table 7-12, where load shifting demonstrates the lowest cost and LCOE among other services. The variation ranges for these parameters are listed in Table 7-13.

Table 7-12 NPC vs. LCOE for all service applications

application	NPC, $	LCOE, $/kWh
Load shifting	15,919,827.88	0.4287
Rapid reserve	26,947,800.64	4.8680
Combined	29,264,837.62	0.6624

Table 7-13 Variation range for parameters to be used in the sensitivity analysis

parameter	range
Interest rate, i_r	[0.05, 0.25]
Wind energy penetration ratio, EWF%	[0, 50]
Unit cost of Fuel Cell, UC_{FC}, in $/kW	[50, 5000]
O&M unit cost per kW-year, $UC_{FC,OM}$ $/kW-yr	[1, 50]
unit capital cost of the electrolyzer, UC_{elec} $/kW	[10, 900]
unit capital cost of hydrogen storage, UC_{Stor} $/KgH$_2$	[6.7, 816]

The sensitivity analysis of the LCOE for the three applications is presented in the following figures (Figure 7-11, Figure 7-12, and Figure 7-13). In all cases unit capital cost of PEM fuel cell and interest rates show the highest response to the sensitivity analysis. Other parameters do not vary significantly except for O&M capital cost in case of rapid reserve application. Finally, the combined service application reduces the sensitivity level to other factors including capital O&M.

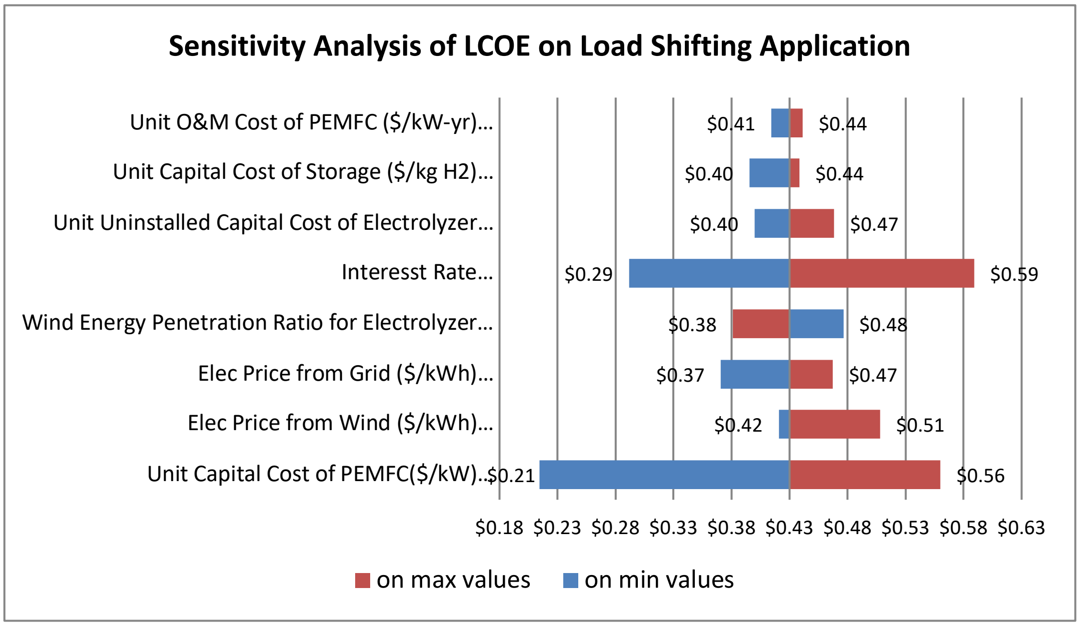


Figure 7-11 Sensitivity analysis of the LCOE for load shifting

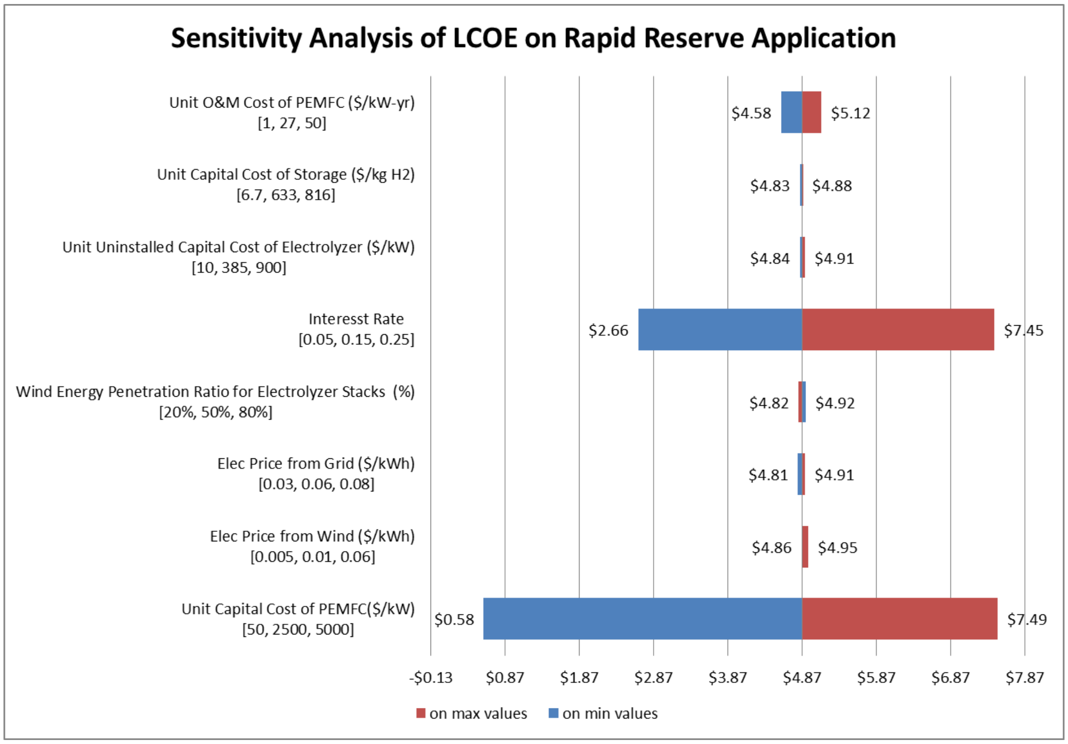


Figure 7-12 Sensitivity analysis of the LCOE for rapid reserve application

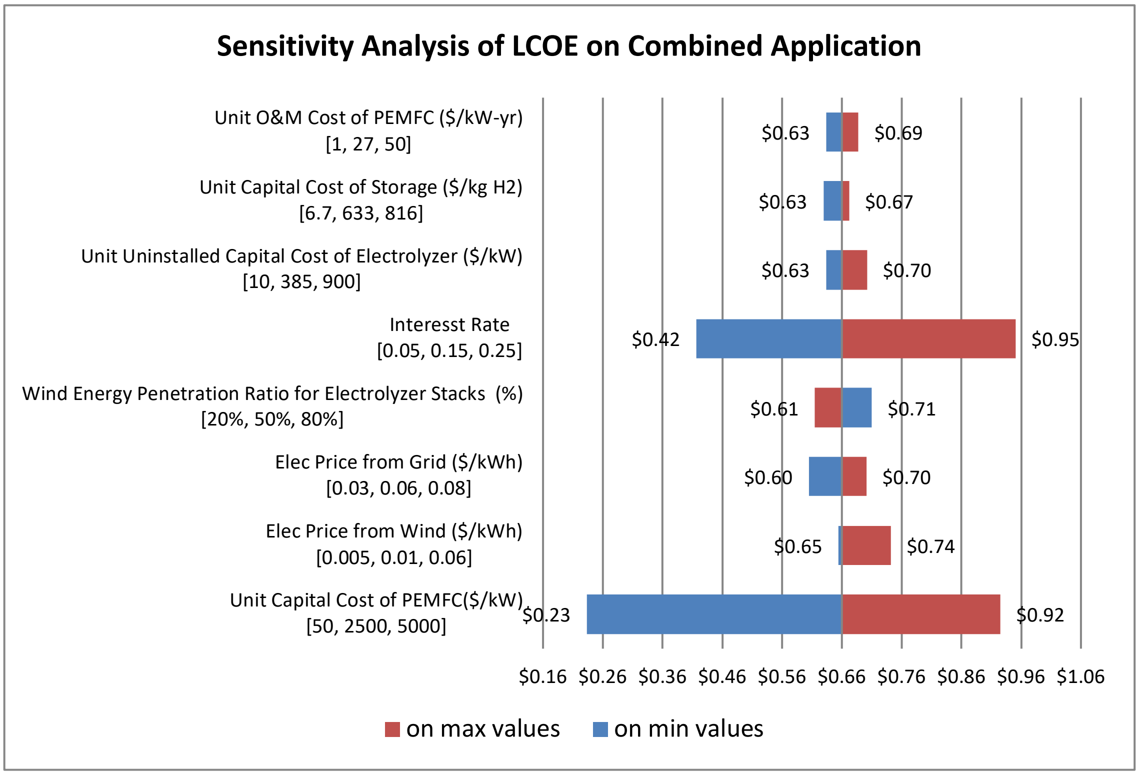


Figure 7-13 Sensitivity analysis of the LCOE for combined application

A comparative study was also performed of the GHG reduction of the proposed PtP system in different market structures with the case of electricity generated entirely from natural gas. The methodology and the results therein will be discussed in detail in the upcoming publication. However, they are only briefly represented here for the sake of discussion. The GHG emission intensity (combined cycle) of electricity from natural gas is taken as 577 g CO2e/kWh. Negative values indicate that there is carbon reduction when using the PtP applications in comparison with the case of the electricity generated from natural gas. In the regulated and mix regulated markets GHG reduction calculations indicated that, regardless of the level of the wind energy penetration ratio for the electrolyzer stack, there is always a carbon reduction. Even in a deregulated market, when the wind energy penetration ratio increases to 25%, the carbon reduction becomes favorable. Based on the electricity consumption from the grid by the PtP system, we can see that the service applications in a regulated market will produce annual GHG emissions of 199 tCO2e/yr. However, in a de-regulated market it will produce significantly higher emissions, 13,019 tCO2e/yr, which is about 65 times higher than in a regulated market. If we apply an average carbon tax rate of $30/tCO2e [147] to all three markets, the carbon cost per unit production of electricity is calculated to be 0.001, 0.043, and 0.006 $/kWh for regulated, de-regulated and mixed-regulated, respectively. The significant dependency of the carbon cost on the jurisdiction in which the system is located will definitely affect the economic evaluation of the grid service application.

The electricity input to the electrolyzer is from renewable sources, which is assumed to have zero GHG emissions. Since GHG emissions are assumed to be dependent on the consumption of grid electricity, the sensitivity analysis of the carbon cost on the wind energy penetration ratio to the electrolyzer stack is also analyzed. It is found that varying the wind energy penetration from 20% to 80% will have an insignificant impact on carbon cost in a regulated market but a substantial impact on carbon cost in a deregulated market. In a typical deregulated market, the carbon cost can be reduced from \$0.064/kWh to \$0.022 /kWh.

The total electricity consumed by the system is

$$C_{Gbuy}^{ann}(\$) = C_{Gbuy,FC}^{ann} + C_{Gbuy,Stor}^{ann} + C_{Gbuy,Comp}^{ann} + C_{Gbuy,Elec}^{ann,stack} + C_{Gbuy,Elec}^{ann,BOP} \tag{30}$$

When the annual energy production, AEP, from the system is larger than its total electricity consumption from grid,

$$AEP > C_{Gbuy}^{ann} \tag{31}$$

Combining with Eqs.(17) and (18), we obtain

$$EWF\% > 1 - \frac{AEP - \left(C_{Gbuy,FC}^{ann} + C_{Gbuy,Stor}^{ann} + C_{Gbuy,Comp}^{ann} + C_{Gbuy,Elec}^{ann,BOP}\right) / C_{Gbuy}}{\left(C_{EH_2}^{stack} \times f_{H_2,Elec} \times n_{op}\right)} \tag{32}$$

This is the minimum electricity percentage from wind farm for the electrolyzer stack in order for the P2P system to produce net green power output compared to its grid power consumption. For the load shifting case,

$$EWF\% > 79.42\%$$

Based on the available technologies and the cost analysis performed here, such a P2P system is not economically viable without significant government incentives. For our baseline and load shifting case, the government incentive for electricity will be as high as

$$LCOE - C_{Gsell} = 0.4287 - 0.15 = 0.28 \frac{\$}{kWh}$$

In the following case:

- The installation cost of the PEM fuel cell → 50\$/kW
- The O&M costs of the PEM fuel cell → 1\$/kW-yr,
- The installation cost of the electrolyzer → 10\$/kW
- The installation cost of hydrogen → 6.0\$/kW

LCOE of the PtP system will be

$$LCOE = 0.1375 \frac{\$}{kWh}$$

which is less than the sale price $C_{Gsell} = 0.15 \frac{\$}{kWh}$. Only in such a case, the P2P system will be profitable.

7.4 Business Model Analysis

The suitability of a specific business model in the context of P2G system can be determined by a combination of asset ownership, electricity market structure, profitability and pricing. A model describes how the asset owner can monetize that service to gain certain value or benefit. We focus specifically on utility-side business models (either direct utility owned facilities or service contracted) to aggregate the values of PtG. Since the current P2G valuation tool is not directly integrated with our business model valuation module and scoring factors, the approach we have taken here is phenomenological in nature. In particular, in the proposed business models below, the cost and pricing information for the use of hydrogen in the three service applications must be considered as the deterministic factors. As shown in the previous sections, the combined services have demonstrated the highest overall cost of P2P, however, utilities are best positioned to bundle two or more services for the best cost-benefit outcomes from the PtP technology.

Previous studies [16,148,149] indicated that utilities who may implement P2G systems in a regulated market have already developed and implemented viable business models for large-scale utility-side renewable energy generation. Thus, there the primary business model for those large-scale PtG commercialization is at generation side. While sub-stations along transmission line, can provide certain services by using PtP systems (Power quality, for example), small scale customer-side PtP, either using a service-contracted model or IPP, can suffer from lack of suitable financial model adopted or tested by utilities. Therefore, the most viable business model for adopting PtP or P2G technologies in a regulated market structure takes place at the utility side either based on “service contracted” or “Utility-side” models. The latter include both “technology enabling” and “operation” services. While utilities manage the grid-connection and actual monetization of the grid-services, the P2G technology vendors can contribute to the planning and construction phases and can cover a variety of services from technology evaluation and assessment to project planning, coordination, resource management, implementation, execution, and managing operation at the generation side. One strategic business model for adopting PtG systems is to engage in large-scale projects by leveraging the partnership with strategic partners such as government and major gas utilities. A poor financial position may limit the technology vendors to be directly involved in capital-intensive, large scale P2G operations. The latter usually have high impacts on communities and could lead to substantial payoffs to the technology developer or Energy Storage System Operators (ESSO). By employing a strategic partner model, ESSOs or IPPs can generate projects mainly based on public-private partnerships. The services can follow different “revenue sharing” strategies among the end users, asset owner and the technology suppliers. Power authorities such as ISO and Regional Transmission Operators (RTOs) can play a role as a project evaluator, in which the feasibility and capability of a specific storage solution in fulfilling needs is evaluated. Other operational services depend upon ESSO available resources and capabilities to directly participate in project execution as project manager or monitor the project as per the ISO’s or IPP’s request. The latter can cover technical and marketing services for developing adequate policy and regulation [149].

7.5 Summary

In the grid application scenario, the capital cost of the fuel cell is critical in order to estimate the LCOE of the system. Based on our analysis, such a PtP system is not economically viable for those grid applications, except with government incentives and under a utility-side business model. Analysis results show there is potential for the P2P system to be profitable for a grid application without government incentives which requires further substantial cost reduction of the system component installation and O&M cost, especially for the PEM fuel cell and the electrolyzer subsystems. For instance, the capital cost of the PEM fuel cell subsystem may be reduced to 50$/kW, approaching that for automotive application. It is also found that the value of wind energy penetration from 20% to 80% for the electricity consumption of the electrolyzer stack will have a slight impact on carbon cost in a regulated market but a substantial impact in a deregulated market. In the latter case, the carbon cost can be reduced from $0.064/kWh to $0.022 /kWh. For the case of the electricity generation from natural gas, a P2P system always helps service providers in all market structures to reduce carbon emission, regardless of the level of wind power penetration in the power supply for the electrolyzer stack. However, in a deregulated market, the carbon cost reduction from using the P2P system becomes favorable only when the wind energy penetration ratio increases reaches 25%.

Therefore, the future direction for the system to survive on the market is to focus on cost reductions of the PEM fuel cell, electrolyzer and storage. It is found that varying the wind energy penetration value from 20% to 80% has a slight impact on carbon cost in a regulated market but a substantial impact on carbon cost in a deregulated market. In such a market structure, the carbon cost can be reduced from $0.064/kWh to $0.022/kWh. In the case in which grid electricity is generated from natural gas, a P2P system always helps to reduce carbon emissions regardless of the level of wind power penetration in the power supply for the electrolyzer stack. In a deregulated market, however, the carbon reduction from the use of a PtP system becomes favorable only when the wind energy penetration ratio increases to 25%.

8 Case studies of Business Model Valuations

Building upon existing valuation tools and methodologies and the typology of business models developed throughout this thesis, the scope of this chapter is to support cost-effectiveness of ES use cases by performing detailed cost-benefit and business model analyses. Specifically, this chapter assesses the value of ES for a range of grid services in different market structures. There is a fundamental difference between storage valuation tools and those of electricity production cost models, where an extensive system operation and knowledge of economic dispatch is required. Our focus in this chapter is entirely on the former class of valuation tools. A generalized cost-benefit approach for evaluating ES technologies is used to assess storage requirements and value originating from the location-specific needs of grid operators and planners. Moreover, the valuation model clearly identifies monetization and cost-benefit ratios of relevant grid services, where various business models (utility-side, service contracted and IPP models) are examined in detail. This chapter excludes the behind-the-meter (end-user side) business model.

8.1 Introduction

Reducing total cost of ownership of ES systems over the past decade has attracted interest from system operators and technology vendors across the transmission- & distribution-connected, and customer-side electric grid. There are significant benefits that grid-scale storage technologies offer [150], however, there is a lack of appropriate valuation frameworks to quantify their benefits from planning, installation, demonstration, and full commercial operation. The complexity of adopting ES can be attributed to the wide variety of technology choices, diverse application services along the electricity value chain, lack of understanding of business models at utility and end user side, and complicated ownership or revenue structures which make the choice of appropriate storage technology difficult (Zhenguo, et al., 2013; Barnhart & Benson, 2013). The actual benefit of storage depends strongly on location, market structure and type of grid services provided by various energy storage technologies [151]. In the context of storage valuation, several valuation tools have been developed to analyze the value of distributed storage technologies for various grid applications [152]. The underlying assumption in the majority of those tools is that the storage system will not significantly influence market conditions and therefore existing market prices are used as the input market parameters [153].

ES technologies possess values at many levels of development, from early stage R&D to mature, deployed technologies (Viswanathan, Kintner-Meyer, Balducci, & Jin, September 2013). The maturity of ES technologies can be assessed by using Technology Readiness Levels (TRL) and Marker or Manufacturing Readiness Levels (MRL) [154]. TRL1 refers to an innovation activity at the very basic research and development stage, while TRL9 represents a technology at a commercial stage. Most of the ES technologies considered in this Chapter are at the commercialization stage (TRL9). The highest TRL is assigned to Pumped hydro systems as they are the most deployed storage technology, whereas, flow batteries are at TRL6. The MRL is similarly assigned to each of the storage systems [121]. The International Energy Agency's (IEA) 2014 Technology Roadmap [25] provided a development spectrum for maturity of ES technologies which closely resembles the TRL and MPL levels defined in Ref. [154]. TRL and the risk associated with the maturity of ES systems have been used by the U.S. Department of Energy (DOE) for providing support for scientific, R&D, and commercialization activities related to grid-scale ES systems. In a recent report, DOE [159] evaluated the risk and technology readiness of ES technologies. Several valuation frameworks have recently been proposed that integrate the technology road map, storage performance matrix, and storage valuation models into a business opportunity assessment [121,113].

The complexity of adopting ES can be attributed to the wide variety of technology choices and diverse applications along the electricity value chain which makes the choice of appropriate ES technology difficult [35,37,41]. An overview of various valuation techniques and approaches is provided in Chapter 2.

8.2 Methodology

We have utilized SMART tool by utilizing customized service application databases in ES-Select™ (for regulated market studies) and ESVT Energy Storage Valuation Tool (for de-regulated market studies) to perform detailed cost-benefit analysis of the selected use cases. The detailed description of the SMART tool and ES-Select™ is provided in Chapter 4. ESVT is a time-series dispatch simulation tool for analyzing the cost-effectiveness of ES. In all of the analyses, the value of ES is calculated for a specific use case and by taking into account the full electricity system, including location-specific load and price data (hourly or yearly), financial and cost information, market structure (i.e., regulated or de-regulated), transmission & distribution capacity, and service applications. ESVT is a financial simulation model that supports ES grid services covering the full scope of the electric system, from generation, transmission and distribution or “front of meter”, down to end-user consumption or “behind the meter”. ESVT is unique among ES cost-effectiveness tools due to its specific focus on ES and its time-series simulation capability [118]. This section is partially based on Ref. [155].

Several steps are used in ESVT for evaluating ES applications. In the first step, the user needs to identify an opportunity or solution that ES offers to the grid. Grid service requirements are defined in the next step. A generic process is then considered to construct a feasible use case after which grid impacts and incidental benefits are evaluated. In the final step, the ES business cases are assessed by focusing on scenarios that can monetize the benefits [92].

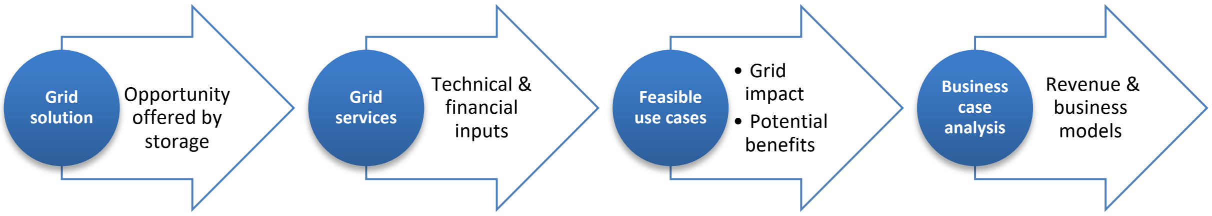


Figure 8-1 Schematic representation of ES valuation methodology and logic

Within a specific use case, each service is modeled by a set of equations. For instance, in the case of electricity supply capacity as a service (where ES replaces a combustion turbine during peak hours), the storage system is charged before capacity hours and is discharged fully during capacity hours. The benefit of this service is calculated by [48].

$$P_{Supply\ Capacity} = C_{Payment} * C_q * C_d \tag{1}$$

Where,

$$P_{Supply\ Capacity} = \text{Supply capacity benefit} \tag{2}$$

$$C_{Payment} = \mathit{Capacity\ Payment\ (\$/kW\text{-}yr)} \tag{3}$$

$$C_q = \mathit{Storage\ Qualifying\ Capacity} \tag{4}$$

$$C_d = \mathit{Capacity\ derate} \tag{5}$$

Capacity payment varies every year. Qualifying capacity is a value in which the storage meets the required duration for capacity services (e.g. 4 hours). Finally, capacity de-rate occurs when a storage system is unable to meet requirements for all the capacity hours. As a comparison, the benefit for energy time shift service (using storage to buy energy at low-price and sell at high price hours) is calculated by:

$$P_{Time\text{-}Shift} = E_{sales} - (E_{cost} / R) - q_{v,O\&M} \tag{6}$$

Where,

$$P_{Time\text{-}Shift} = \mathit{Energy\ Time\text{-}Shift\ benefit} \tag{7}$$

$$E_{sales} = \mathit{Energy\ sales} \tag{8}$$

$$E_{cost} = \mathit{Energy\ Cost)} \tag{9}$$

$$R = \mathit{Round\ trip\ efficiency} \tag{10}$$

$$q_{v,O\&M} = \mathit{Variable\ O\&M} =$$

$$\text{Hourly Discharge(kWh) * Variable O\&M Cost} \tag{11}$$

ESVT requires a technology input with a given capacity [156] (e.g. 40 MW hr). Table 8-1 provides the most important parameters for a typical storage technology application.

Table 8-1 Technology development matrix and key technology input parameters

System level attributes	Capacity (MW)
	Duration (hr)
	Technology Lifetime (yrs)
Performance attributes	Battery Lifetime (yrs)
	Roundtrip Efficiency (%)
	Max Depth of Discharge (DoD)
Cost attributes	Capital Cost ($/kWh) in 2016
	Variable O&M Cost ($/MWh)
	Fixed O&M Cost ($/kW-yr)
	Battery Replacement Cost in 2016 ($/kWh)
	Battery Replacement Cost Reduction

ESVT also uses a baseline of one year of historical hourly price data which creates future-year prices depending upon the price escalation rates derived from natural gas price forecasts. Finally, ESVT uses certain global financial parameters which can vary by business models. For the IPP model, for instance, the main financials assumptions are the discount rate, inflation, and tax, some of which are fixed throughout the analysis [157].

The cost-benefit analysis of storage is ultimately defined by return on the total cost of capital for a specific period of time (asset lifetime) based on several financial outputs that include Net Present Value (NPV), IRR, the Total Cost of Ownership (TCO), and Cash Flow. In general, the ES benefits for various services are ranked as regulation services> system capacity>arbitrage>backup. Such ranking, however, requires extensive quantitative cost model calculations depending upon location, load data and financial inputs. The details of the cost model and input parameters therein is provided in Chapter 4. One should note 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 can lead to net benefits in a reasonable payback period as illustrated by many studies (Kaun, June 2013; Lazard, 2016; Lazard, 2017). It follows that multiple revenue streams can be combined into a location-specific use case to create mutually exclusive stackable benefits (along with stackable costs). ESVT can only approximate profit-maximizing decisions made by a grid asset owner/operator to obtain stackable benefits by participating in multiple electricity markets.

8.3 Case Studies

The ES units that are considered in this chapter are typical commercial scale technologies. ES unit cost, performance and lifetime data include the ES technology, Balance of Plant (BoP) equipment and installation, and operational fixed costs and variable costs, but do not include manufacturing, commissioning, decommissioning, disposal or recycling / repurposing. However, repair and maintenance were taken into account.

8.3.1 Input Data

With respect to technology, the original input data were extracted from the DOE's Energy Storage Handbook [157] as well as those from Lazard's Levelized Cost of Storage (LCOS) [65,66]. In short, we used existing cost data in ES-select™. The cost curve data from Lazard's LCOS 2.0 was used to discount and extrapolate the respective ES costs from either 2010 or 2011 to 2016, when the ES unit would be purchased and installed.

8.4 Treatment of Business Models

The main areas of input for business models are financial or related to the ownership structure. More specifically, the inputs include parameters for project economics, operational details and financial ratios such as debt-to-equity ratios, tax rates, and regulatory incentives that are key to completing the cost benefit analysis. In particular, the Publicly Owned Utility / Municipality owned (POU/Muni), Investor Owned Utility (IOU), IPP, and Residential Customer models defined in ESVT correspond to the defined business models (utility-side, service-contracted, IPP and end-user side) in SMART, respectively.

In a deregulated market, IPP was mainly chosen as the business model, whereas in a regulated market, utility-side (in SMART) or POU/MUBNI (in ESVT) was the model of choice. For a mixed-regulated market, either of the IOU, POU/MUNI and IPP can be selected. In this chapter, however, mixed-regulated market analysis results are not discussed. Financial inputs for the IPP business model are shown in Table 8-2.

Table 8-2 Financial details for an IPP business model [65,66,158]

Financial Inputs	% Debt (20%)
	Debt Interest Rate (8%)
	Return on Equity (12%)
	Income Tax Rate (12-15 %)
	Term (15 Years)
	Fuel Escalation Rate (1.8 %/Year)
Asset Lifetime	Compressed Air or Lithium Ion Battery (15-40 Years)

8.5 Scenarios Analysis of Single Services

This section summarizes the results of the analyses using the valuation tools described above which simulate the operation of ES systems in an ISO/RTO grid with selected grid services, financial and economic constraints, and technological and cost inputs. The cost-benefit valuation of the ES technologies is based on Net Present Value (NPV), LCOE, and IRR among other outputs. Two case studies were defined: A lithium ion battery system providing backup power and potentially peak shaving services (UC1), and a NaS battery system operating in a small residential area mainly providing backup power (UC2).

8.5.1 Input Parameters

For UC1, backup power and reliability, renewables arbitrage, and energy time shift were evaluated as ES grid-scale services. For the UC2 system, the services that were evaluated were power quality, power reliability (backup), and energy time-shift.

For a de-regulated market with hourly price input, ESVT requires all user input data to be in 8760 strings, which is a single column with 8760 rows (hourly data for one year) such that an entire year of operation is used for the simulation. Our initial user data was only for 5 months of operation, and in a format different than required for ESVT. The data were re formatted, filtered and parsed into hour-by-hour data. The 5 months of data (Nov to Mar) output data was extrapolated to 12 months by applying the pattern: Nov, Nov-Mar, Nov-Mar, Mar. The business model type selected for UC1 and UC2 was IPP. The system and market specifications for UC1 and UC2 are summarized in Table 8-3.

Table 8-3 Summary of system and market specifications for UC1 and UC2 scenarios

Location	**Market**	**Ownership**	**Application**	**Payback period**	**Discount rate**	**Cost of energy**
1 MW for small commercial and residential End user	Deregulated / Regulated	Utility IPP	Time shift Energy arbitrage	20 years	6.5-10%	30 - 50 $/MWh

To complete the analysis, several technical specifications as well as operational data were collected such as power requirements, demand duration and LiB specifications from DOE Energy Storage Database based on existing demonstration projects across North America [159].

8.5.2 Analysis of Different Market Structures

Typical profiles of battery power (kW) and Load power (kW) for 24 hours are shown in Figure 8-2 [160]. The longest duration that ES was operational in this scenario was four hours.

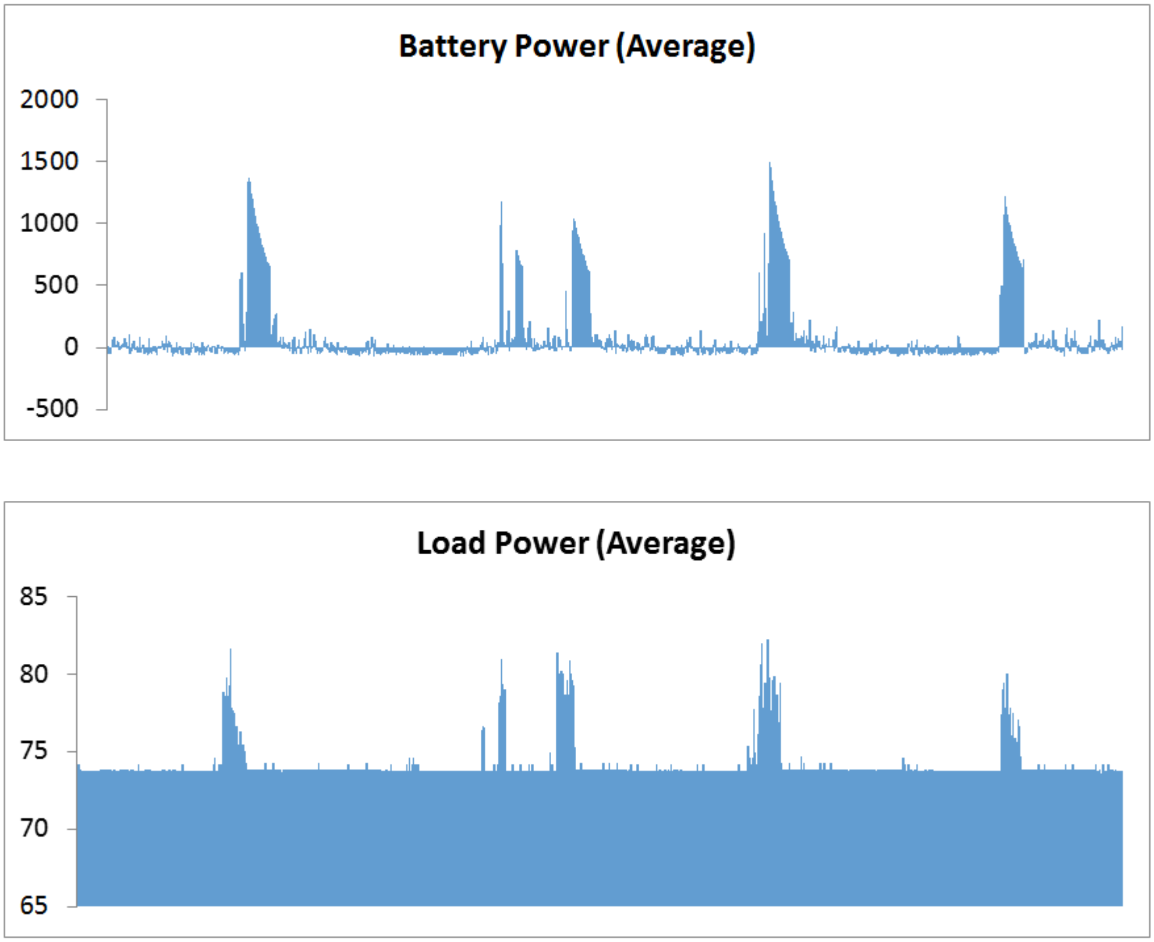


Figure 8-2 Battery power (W) and load power (kW) over 24 hours

ES-select and SMART were initially used to evaluate the feasibility and reliability of the ES systems and assess the choice of Li-ion battery for the above configuration. A feasibility study was performed by using SMART, resulting in a feasibility order for the above configuration as: NaS > LIB-e > VRFB. In terms of discharge duration, the calculation showed an advantage for VRFB because it provided the greatest range where peak demand is steady for 3 to 6 hours (NaS > VRFB > LIB-e). Our calculations showed that none of the battery solutions fulfill the 20 years payback period.

Figure 8-3 shows the cash flow situation over 20 years for UC1 for energy arbitrage as the application and IPP as the business model. As illustrated, annual benefits outweigh annual losses and maintenance costs. Overall, our analysis shows that other grid applications provide better value (in $/kW) than energy arbitrage for such a configuration. With present assumptions VRFB does not show any advantages over LIB-e. In terms of feasibility, discharge duration, and commercial maturity, NaS ranks the highest. It was also concluded that none of the three technologies achieve a payback in the first 20 years. In terms of cash flow, VRFB has the lowest capital costs and the annual benefits outweigh maintenance / losses. NaS is the most expensive where maintenance / losses are far greater than annual benefits. LIB-e is the most expensive in terms of initial capital cost and number of capital outlays for replacements.

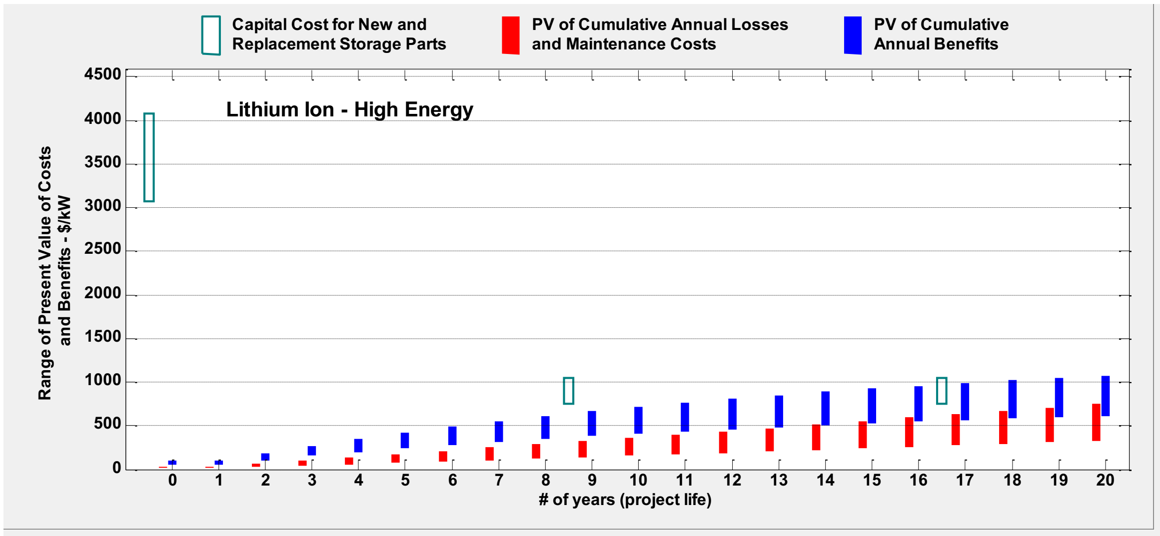
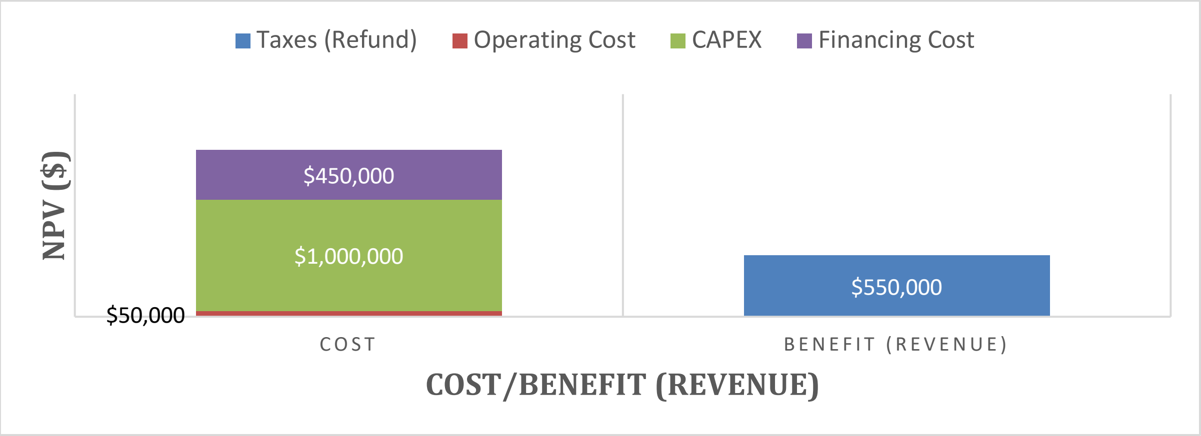


Figure 8-3 Cash flow situation over 20 years for LIB-e in UC1 scenario. Service: Energy arbitrage, business model: IPP

Sensitivity analyses for these scenarios were also performed using ESVT that provide similar cost-benefit analysis in a de-regulated market structure. Case studies below replicated the hypothetical 1MW Li ion system for UC1. Some inputs did not translate from the previous studies using ES Select and SMART. MISO 2010 was chosen as it is the only ESVT option that matched the assumptions related to market structure. All three different ownership types and thus business models were assumed for calculating financial and economic outputs. Cost-benefit analysis is affected by different ownership types but annual services revenue, daily revenue and daily dispatch were not affected. Notably, when utility market rules and pricing as well as technology is held constant, cost benefit ratio changes according to the different possible business models for the hypothetical UC1 case study.

Figure 8-4 provides a comparison of cost and benefit at different discount rates for a Lithium ion battery system (UC1). The financial inputs for this scenario were Debt (100%), Debt rate (6.5%), Equity (0%), Equity rate (0%) and the economic inputs are a yearly inflation rate of 2% and an annual fuel escalation rate of 1%; When single grid-service (energy time shift) was chosen, the utility-side business model shows the best cost-benefit ratio. Under benefit-stacking of all services, the IPP business model demonstrates the best cost-benefit for UC1 scenario.



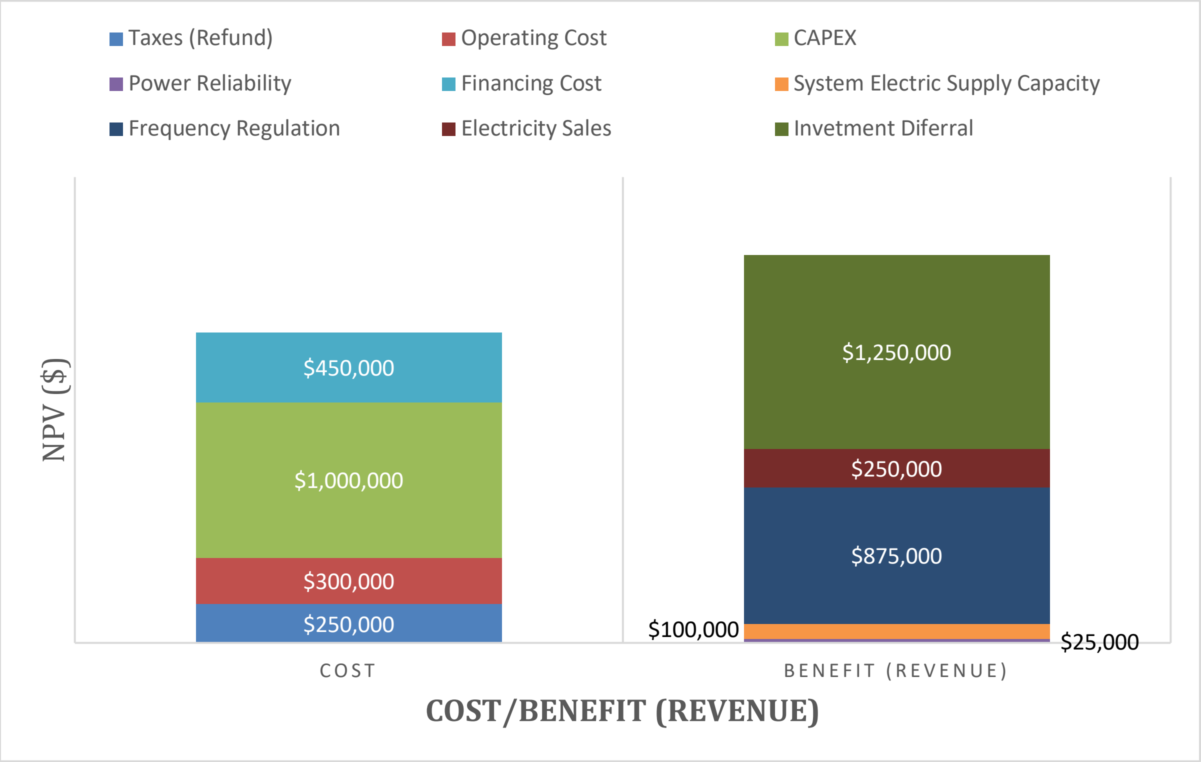


Figure 8-4 Profit and cost sensitivity analysis assuming Utility side business model for a single service of Energy Time Shift (upper chart) and IPP for bundled services (lower chart) for a de-regulated market structure (discount rate at 6.5%)

8.6 Scenario Analysis of Bundled Services

We selected a third case study in which multiple ES technologies were considered for various grid services. The selected technologies were those that are most likely to be competing in a typical market structure. The technologies of choice were Li ion high energy (Li ion), small-scale Compressed Air Energy Storage (CAES-s), and Vanadium Redox Flow Battery (VFRB).

8.6.1 Assumptions

SMART allows the user to define a custom ES technology including technical and financial performance data. The technology specifications were filled in an excel template that included technical and financial data. The final inputs were loaded into the tool and used in the simulations.

For the system configuration, 500 kW power at 4-hour duration (i.e. 2 MWh) were assumed as the base cases, depending upon the selected business models. Three business models were chosen in the analysis - service contracted (~ 100 kW), IPP (~1 MW), and utility-side (~2 MW). The bundled grid service selections under the three selected business models included service reliability (utility backup), energy time shift (arbitrage), and renewable firming. In service reliability (utility backup), the ES technology provides back up power in the event of a grid outage. In case of energy time shift (arbitrage), ES technology stores power from the grid during periods of low electricity prices and low demand, then returns the power to the grid during peak electricity prices and peak demand. Under the renewable firming use case, ES provides continuous electrical power output for renewable power by storing excess capacity when renewable generation is above a pre-defined level, and then returning the excess stored energy when renewable generation is below the same pre-defined level. By doing this, the ES technology serves as a buffer to variable renewable power generation.

The service selections are listed in dispatch priority, so service reliability takes priority over energy time shift, which takes priority over renewable firming. This order also maximizes bundled application value for CAES, listed as a range in $/kW/yr calculated for all business models in Table 8-4.

Table 8-4 Bundle value of business models for all grid services vs. average values from single services

Bundled vs. single Application Value	Single ($/kW/yr)	Bundle ($/kW/yr)
Service contracted business model	248	532
IPP business model	248	532
Utility side business model	227	482

Financial and economic inputs are shown in Table 8-5. The key inputs are the rate of inflation for ES benefits or service applications and annual electricity price, the rate of return or discount rate, cost to charge the ES system, and the total project life. The maximum project life of 20 years was used in all cases. Based on the bundled application values above, the highest valued business model for this case study are the service-contracted and IPP models.

Table 8-5 Financial inputs at 1 MW Commercial / Industrial and 2 MW Distribution Locations.

Escalation of Benefits (%)	Discount Rate (%)	Electricity Price Escalation (%/yr)	Cost of Energy for Charge ($/MWh)		Project Life (yrs)
			Low	**High**	
2.5	10	2.5	30	50	20

8.6.2 Regulated Market

In a regulated market, the analysis shows that energy efficiency vs. discharge duration and specific energy vs. energy density are the same for all business models. On a technology level, however, CAES is set apart from the chosen competing ES technologies with an efficiency lower than that of Li ion, but higher than the other technologies. Minimum and maximum durations are greater than that for Li ion and are on par with the remaining technologies. A comparison of specific energy and energy density indicate that Li ion is by far the best technology of choice, and will be very difficult to match by other technologies given the inherent specifications of Li ion ES technology. The analysis based on feasibility scores and rankings in $/kW for all ES technologies and all business models showed CAES to be the least feasible for the service-contracted business model. Thus, CAES systems under a regulated market and service-contracted model may be less profitable, or not profitable at all compared to other ES technologies under the same or other business models. In addition, NPV and feasibility results show VRFB could also be a competitor to Li ion. However, both of these electrochemical technologies have limited operation under IPP and utility business models due to their technological issues related to response time and low maturity for specific grid services. Figure 8-5 illustrates NPV vs installation cost of all ES technologies for the IPP model at a 4-hour duration. The advantage of small CAES is the moderate installation cost and relatively higher NPV. Advanced VRFB appears to have a slightly higher NPV, but given the range of installation cost, this analysis shows a significant difference between CAES and Adv VRFB. Another key observation is where Li ion dominated previously under UC1 scenario, CAES is clearly more favorable than Li ion on NPV and installation cost, even though CAES may not be competing with Li ion in the given market and for the same grid services.

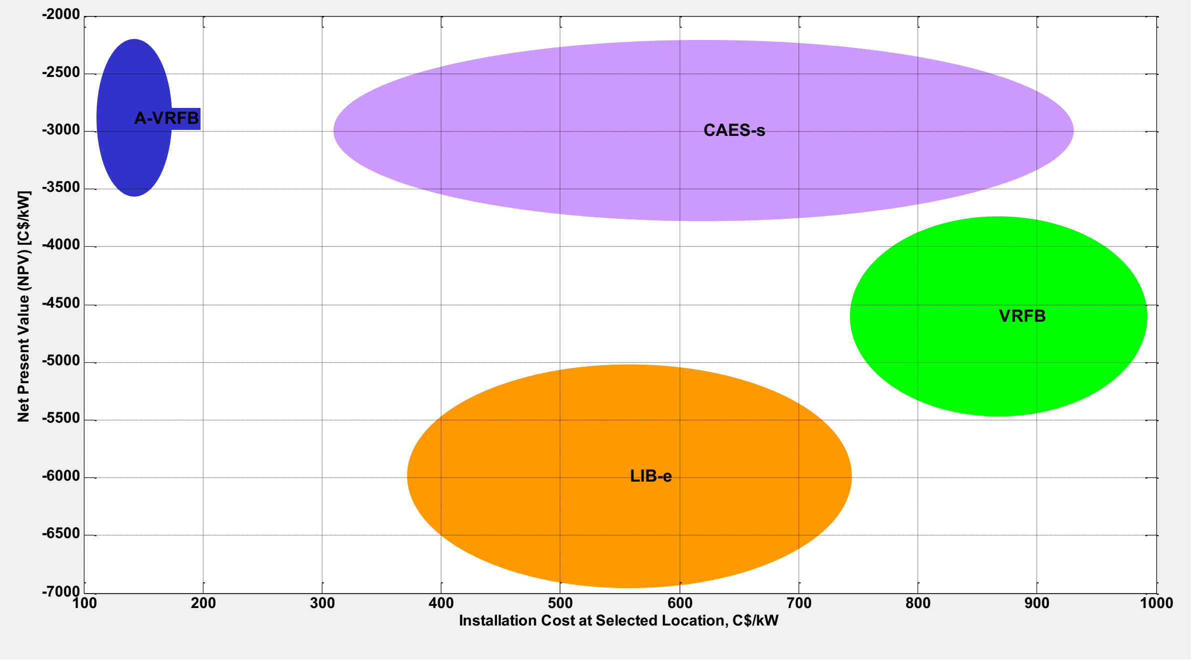


Figure 8-5 NPV vs Installation cost of all ES technologies for IPP business model at 4 Hr duration.

In terms of total cost of ownership per lifetime throughput energy under the IPP business model, CAES technology is the clear choice among the competing technologies. Although Li ion is the better technology on a performance basis, high O&M and initial capital cost make it the least favorable on a total cost of ownership basis. Another advantage is that where VRFB showed similar NPV and lower costs compared to CAES, VRFB has a significant cost in year 10 where CAES does not show a significant cost up until at least year 16. The latter implies an equipment replacement / rebuild expenditure for CAES. In fact, up to the first 10 years, VRFB shows the highest probability of payback. CAES system shows a repair and or maintenance cost at year 16, whereas Li ion and VRFB show none over the 20-year time period.

Finally, under a utility-side business model, cumulative net cash flows, given in a yearly range, are lower than that for IPP or service contracted models. The ranges show an increased risk, that there may never be a payback. Overall for CAES, cumulative net cash flows under a utility business model are lower than they are under other business models and show a slightly higher risk that there may never be a payback. Of the three business models, the service-contracted model shows the best NPV and highest total feasibility score, overall. The results also show Li ion as having the highest total cost of ownership, while CAES has the lowest. CAES can out compete Li ion in terms of NPV and total cost of ownership. Also, in terms of NPV and installation cost, VRFB is comparable with CAES but less favorable compared to Li ion, despite the fact that VRFB is more commercially mature.

8.6.3 De-regulated Market

A valuation analysis for selected ES technologies under a de-regulated market structure was performed using ESVT to compare their performance and economic values. The NPV cost benefits were modelled and discussed based on the LCOE and IRR. The first analysis compared CAES and other technologies under IPP and service-contracted business models. Grid service applications are the same as those studied in the previous section for a regulated market, i.e. backup power (reliability) and renewables arbitrage (retail TOU energy time shift). Table 8-6 show financial and economic inputs for a service contracted model. **Figure 8-6** provides cost-benefit summary based on NPVs, levelized cost, or levelized benefit for the baseline CAES system with 48% round trip efficiency. The results are obtained under a service-contracted business model. The total NPV cost is calculated at ~$2M (levelized at 450$/kW-yr), whereas total aggregated benefit from all of grid service sources indicates a benefit of ~0.77M only (levelized at 170$/kW-yr), thus, overall project is not profitable.

Table 8-6 ESVT financial and economic inputs, adopted to a service-contracted business model [161].

Financing Inputs	% Debt (40%)
	Tax Rate (40%)
	Income Tax (8%)
	Amortization (5 years)
	Tax Credit (0%)
	Inflation Rate (2%/Year)
	Fuel Escalation Rate (1 %/Year)

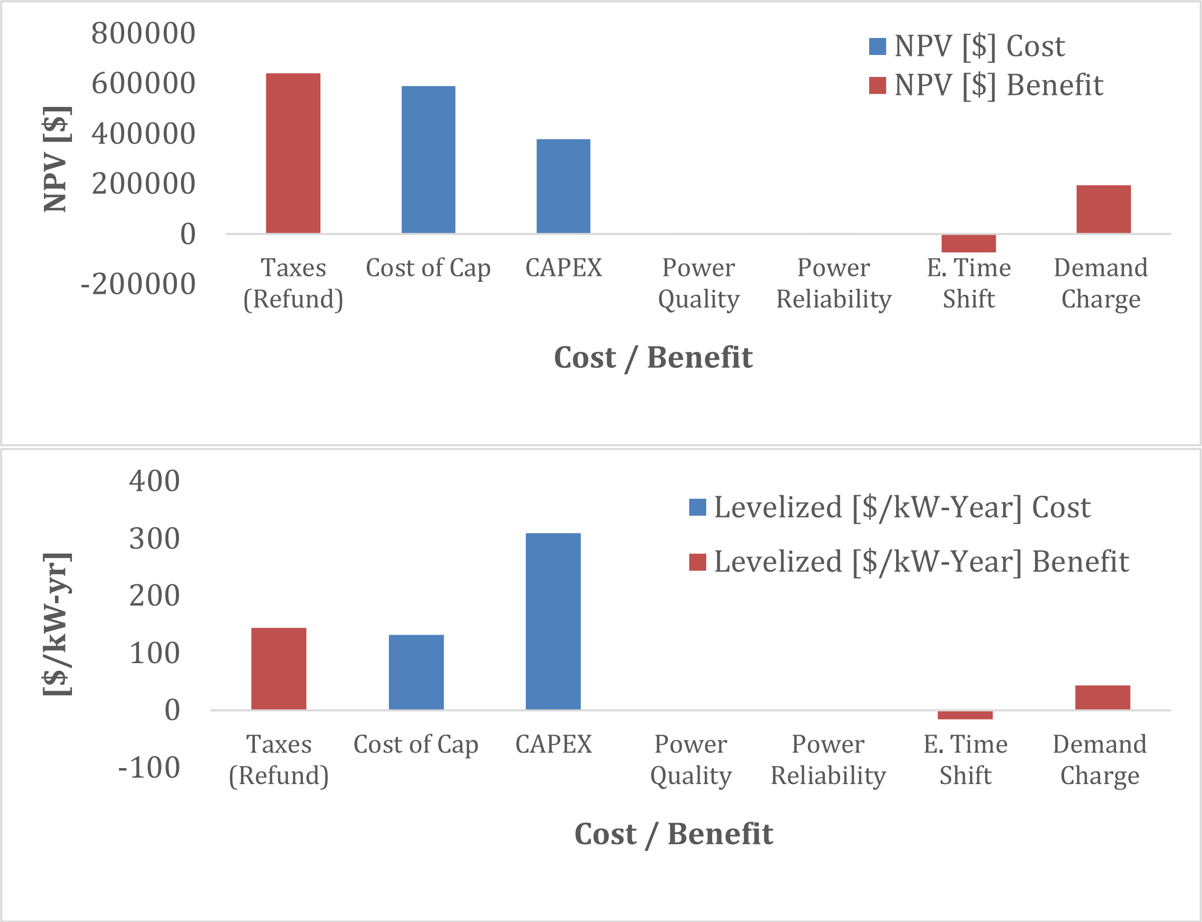


Figure 8-6 Key cost-benefit outputs for CAES with 48% round trip efficiency under a service-contracted business model.

CAES systems turn a profit in NPV terms. The NPV more than doubles when the roundtrip efficiency increases from 48% to 80%. However, the same trend occurs where a 32% increase in round trip efficiency translates into a 4% increase in ROI (from 4% to 8%). Levelized electricity also shows a net profit, paying $45 per kW year for CAES with a breakeven point at $85 and an IRR of 22%, Table 8-7.

Table 8-7 Summary of high value service selection outputs including ROI for CAES

Round Trip Efficiency	ROI [%]	NPV [$]	Levelized [$/kW-Year]	Breakeven [$/kWh]	IRR [%]
48%	4%	$98,744	$22	$42	18%
80%	8%	$198,961	$45	$85	22%

8.7 Summary

The business model and ES valuation analysis performed in this chapter provide systematic analysis of several case studies for individual ES technologies. Although at the system level, both regulated and de-regulated market structures can optimally adopt ES systems for certain services along the electricity supply chain, certain business models can offer higher profit depending upon technology attributes, asset ownership and costs. A choice of appropriate business model combined with thorough valuation analysis can guarantee that deployments of individual storage technologies are economically and technically optimized.

Here, three ES technologies were evaluated: Li-ion, CAES, and VRFB. Simulations are performed under regulated and de-regulated market structures. Moreover, utility-side, service contracted, and IPP business models were used to examine various case studies under single or bundle service scenarios. Results are based on given technology lifetimes normalized to the 20-year technology lifetime. Evaluation results were categorized into profitability in terms of NPV, IRR and breakeven point.

In a regulated market structure, CAES showed low cumulative net cash flows under a utility business model compared to that under other business models. CAES, however showed a higher risk of never achieving a payback. Of the three business models, the service-contracted model showed the best NPV and highest total feasibility score, overall. A de-regulated market, however, is more favorable for CAES under the same service-contracted business model, as it can turn a profit in NPV terms and for high value services selected.

9 Conclusions

The main goals of this research work are to develop, validate, and analyze new business models to ensure near-term market success of the grid-scale ES technologies. The ultimate success with national energy policies for implementation of renewable sources is reliant on practical and reliable business-operation models. Grid-scale storage technologies can enhance utilization rates of renewable assets and improve the reliability of the entire power system. The latter is particularly critical in reducing overall costs of the electricity grids that are integrating greater amounts of renewable generation. To these ends, a user-friendly tool has been customized and utilized to evaluate the feasibility of certain business models for maximizing the benefit of grid-scale ES technologies.

9.1 Research Contributions

The main contributions of the proposed research are the following:

- A typology of business models was developed for grid-scale storage technologies that can be used as a practical framework to support management in decision-making for investment and operational requirements. The framework tackles some of the difficult issues related to accurate screening of storage technologies to capture the value and unique benefits of ES technologies (discussed in Sections 1.2-1.4). For industrial stakeholders looking to adapt new ES technologies, an analysis framework for various business models can inform critical technical and financial decisions.
- A review of current technical and business-management literature was performed that emphasized the urgent need for practical and innovative business models for commercialization of grid-scale ES technologies. The characterization of various existing business models can address temporal (size and maturity of the storage technology) and spatial factors (type of service, location, application and market or electricity pricing structure). The current business models are not robust enough for delivering an accurate assessment of profitability and value created by adoption of ES technologies in the electricity power grid. This thesis addresses the shortcomings of the current business models by developing and analyzing new business models and assessing value propositions, risks, and opportunity profiles of storage technologies.
- A business model framework was validated, and a thorough and robust valuation analysis was performed to identify scenarios in which deployments of individual storage technologies are economically and technically optimized. The business model concept developed in the course of this research is not only an analytic tool but it is also a valuable research and practical management tool for analyses and management of storage technologies, in particular, and clean energy technologies, in general. Using the business model concept, the outcome is a classifying platform that can be utilized to build a generic blueprint of business models for understanding various business phenomena during the operation of a storage asset. The business model concept can

also help asset owners and operators fully design and optimize operational costs while optimizing their business processes.

- A bottom-up approach was demonstrated for identifying remaining R&D priorities necessary to ensure near-term market success of grid-scale ES technologies. The resulting framework and analysis platform therein employ a set of technology management frameworks in the context of storage technologies to support grid services and variable electricity generation. Among the technology management tools, several are employed from matrix management techniques such as a Technology Development Matrix, Technology Landscape Road Mapping, an innovation matrix, and a linkage grid. The objective of this effort was 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.
- Several case studies were performed to evaluate business models, ES technology, and financial performance. The case study analysis utilized a systematic framework for individual or multiple ES technologies under various market structures and service bundling criteria.
- A comprehensive study was performed to identify policy and regulatory priorities that drive the future storage market and analyze policies and regulations that may affect the competitive environment.

9.2 Future Research

9.2.1 Levelized Cost of Energy Storage

Levelized Cost of Storage (LCOS) is a key characteristic of storage technologies that quantifies their cost with respect to their actual grid services. In contrast to LCOE, LCOS is a cost-oriented parameter that is specific to use cases for ES technologies:

$$LCOS = \frac{Cost\ (initial) + \sum_{y=0}^{y} Cost\ (operating)}{\sum_{y=0}^{y} Capacity \times (discharge\ \ efficiency) \times \Delta t} \tag{1}$$

The initial inputs for LCOS were developed by Lazard [65,66] and later measured by NEC Energy Solutions [162] in consultation and partnership with leading storage technology vendors and consultants to the power and energy industry. Using LCOS, installation costs over the asset lifetime are primarily estimated based on anticipated returns for various technologies. They are designed for a series of identified use cases, thus providing an “apples-to-apples” basis for comparison of various technologies within the same or similar use cases [65,66]. Comparative LCOS is a useful addition to the storage valuation and analysis tools that were utilized in this thesis. Energy Storage Innovation Council’s Cost Tool [120], lists the full set of cost items, including LCOS, for a variety of distribution-connected ES technologies from initial project development through decommissioning. The cost template contains capital, recurring annual or periodic costs, repair and maintenance costs, and end-of-life costs. Such cost components and, in particular, TCOES (Total Cost of Energy Storage) in conjunction with LCOS and the business model framework developed in this research work are highly practical tools for screening the quality of regional and national Request for Proposal or Request for Quotation (RFP/RFQ) processes [163].

The majority of current valuation models, including those based on the production cost model or price-taker optimization model are based on levelized cost of energy that inherently ignores the impact of different grid services on levelized cost values. A validated list of quantifiers for levelized cost of ES results in improved storage cost-effectiveness and is also compatible with existing network models, thus maximizing the consistency between the simulated results of both the production cost and price-taker models. A validated levelized cost of storage also substantially improves the consistencies among results from different valuation and cost model analysis tools and provides a common view and consistent methodology for quantifying the value of ES within a use case and specific location or market structure.

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11 APPENDIX

The Storage Monetization Analysis and Reliability Tool (SMART) is intended to evaluate overall economic value and monetization strategies for adoption of energy storage systems, across distributed- and transmission- connected electricity networks. Currently a beta-version, the tool is built upon an existing screening tool, ES-select™, ensuring a consistent and recognized approach on the valuation methodology and user interface. It was essential, however, to include a new module based on scoring various business models to help resolve the challenge with valuation of the best monetization strategy. These new key features make this analysis tool complementary to, rather than competing or duplicating with, existing analysis tools. This appendix explains the workflow, the tool requirements, features and functions of the tool, and the source of databases therein.

11.1 Introduction

Several valuation tools for Energy Storage have been developed, tested, and widely used. Among the most common valuation approaches and tools that have been utilized by utilities and independent consultants are NREL valuation tools that enable users to evaluate the operational benefit of commercial storage, including load-leveling, spinning reserves, and regulation reserves [91]. Energy Storage Valuation Tool (ESVT) and its current version, StorageVET™, were developed by EPRI [92] and employ a methodology for separating and clarifying analytical stages for storage valuation. ESVT calculates the value of ES by considering the full scope of the electricity system, including system/market, transmission, distribution, and customer services. In ES-Select™, developed by DLV-KEMA. The user needs to choose where ES is connected to an electric grid [94]. Finally, the Energy Storage Computational Tool (ESCT) developed by Navigant Consulting is an Excel-based platform for analyzing the economic benefits of grid-connected ES technologies over the system lifetime. Similar to ES-select, ESCT defines a use-case by selecting the storage technologies and a suitable grid application. The tool then identifies the key economics identifiers and environmental benefits the storage system can offer. None of the existing tools provide an explicit distinction between revenue streams and benefits thereof and recommendation of a suitable business model. Primarily targeting the technology demonstration and investment communities, SMART was developed to address the latter need. In particular, it is designed to identify the risks associated with the uncertainties of suitable business models, while applications characteristics and cost-benefit considerations are calculated within a reasonable accuracy interval. SMART leverages the prior screening and valuation model developments of the ES-select and provides a range of new capabilities such as cloud-base access, expanded databases for various electricity market structures, and a comprehensive module for analyzing best-practice business model. It has, however, limitations that should be carefully noted. SMART does not currently provide a complete cost-benefit analysis using historical or real-time load or dispatch data. A number of other storage valuation technologies such as EPRI's ESVT are better suited for that purpose, as detailed in Chapter 8. Because the prices are provided on an annual average, the model also limits the flexibility of market selection to de-regulated or mixed-regulated.

11.2 Overview of ES-select ™

ES-select is a highly interactive decision-support and technology screening tool that suggests most feasible energy storage solutions for a specific location across value chain of electricity grid. The tool has been first developed and maintained by DNV GL [94]. has extensively been used and tested by various stakeholders, including consultants, technology vendors, policy makers, and investment community [36,94,164]. The tool ranks various storage technologies on two main criteria of total feasibility score and probability of achieving a payback over a fixed time period.

The total feasibility score is calculated by aggregating relative feasibility scores of certain sub-criteria, such as maturity or technology readiness level for commercial deployment, appropriateness of technology for the selected grid location, meeting application requirements, and meeting minimum cost of installation. Based on input financial data, it can also compute the probability of meeting a payback point and the statistical distribution of the payback over project life time. User is allowed to change default values for storage technologies and type of services and add new storage technologies to the model database. All input data carry certain uncertainties or ranges as determined by a statistical distribution. The techno-economic parameters are entered in range from low to high values, where the uncertainties are addressed through on-the-fly Monte Carlo simulations of cost, benefit, cycle life, efficiency, discharge duration, and other parameters according to their distribution on a given interval. The output feasibility rankings are determined based on the probability of reaching a payback point as a function of the storage costs and benefits using an embedded sensitivity analysis of the required cost to recover payback and other technical requirements. User is able to change energy storage and application databases. A Monte Carlo analysis allows user to handle uncertainties in cost, benefit, cycle life, efficiency, discharge duration, and other parameters.

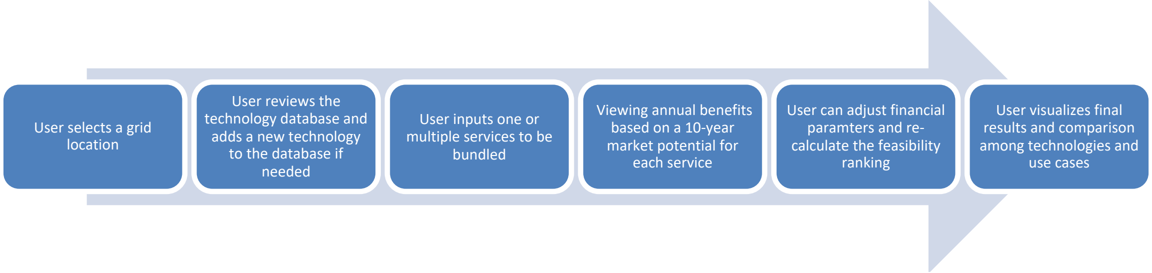

Figure 11-1 Overall process design of ES-Select ™

11.3 Feasibility Score Algorithm

In ES-Select, the decision for best-fit storage option is based on a total feasibility score, depending upon certain criteria: maturity or commercial readiness which is a relative feasibility score at the database; appropriateness of the selected grid location based on size, weight, and geographic requirements; application requirements in terms of discharge duration, cycle life, efficiency; and cost of installation as an input in the technology database. Figure 11-2 and

Figure 11-3 illustrate relative maturity scores of the technologies and grid location, respectively, included in the ES-Select database. Note that ES-Select allows a 5-level weighting scale for each of the relative feasibility scores for more balanced assessment of specific applications and cases.

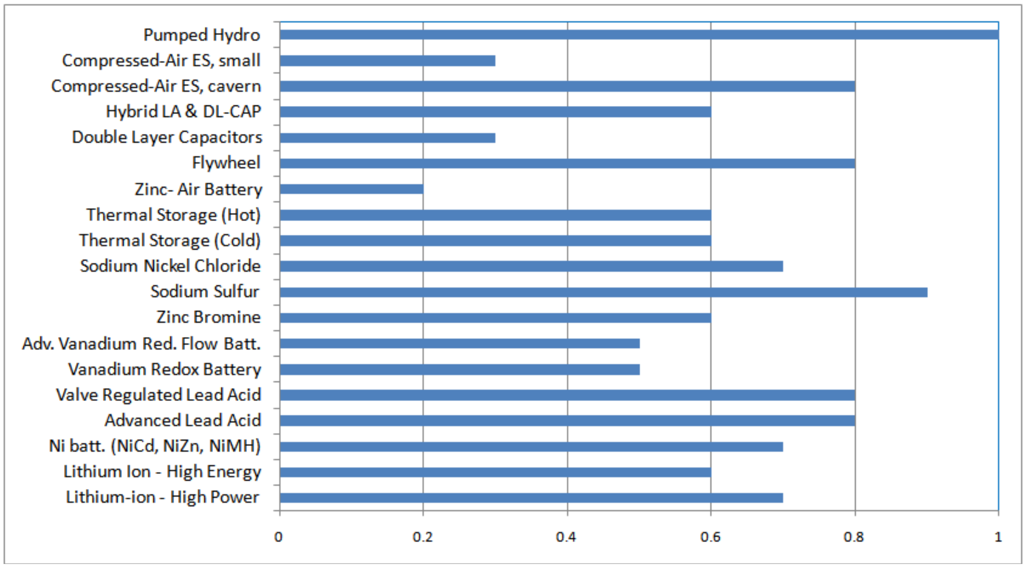

Figure 11-2 ES-select™ relative maturity scores for grid-scale storage technologies [94]

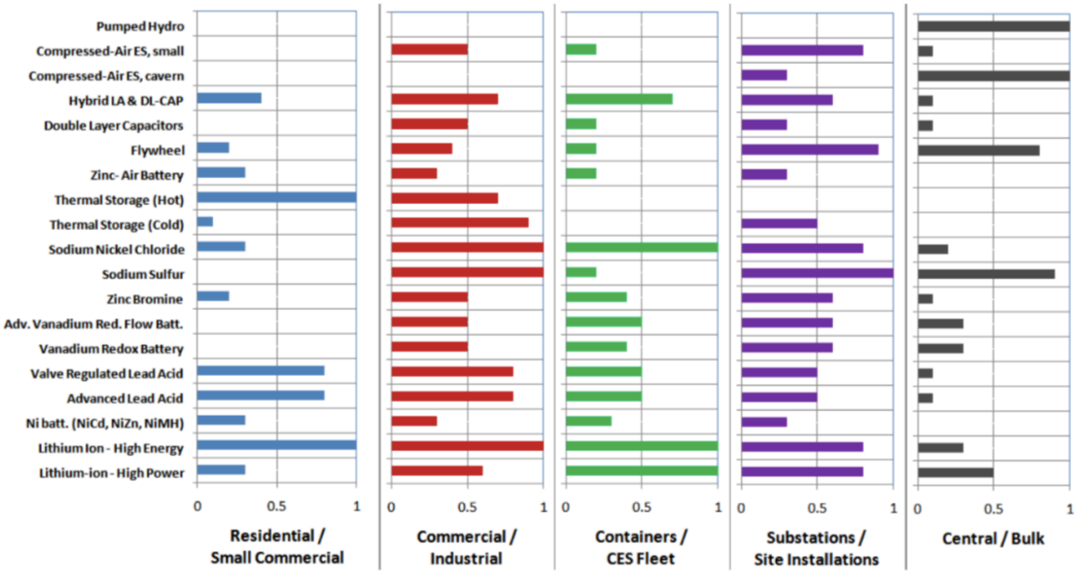

Figure 11-3 ES-select™ relative feasibility scores of grid-scale storage technologies for different grid locations [94].

11.4 SMART's Work Flow

The architecture of the SMART's user interface is identical to that for ES-select except that user is required to select a business model before calculating the overall feasibility score for service application and type of storage technology. User can initially enter only one business model and one or more grid applications. The output is then a priority list of feasible energy storage technologies to serve one or a bundled set of those applications (if more than one application is selected initially). Figure 11-4 shows the work flow of SMART and the direction of data between the different process steps.

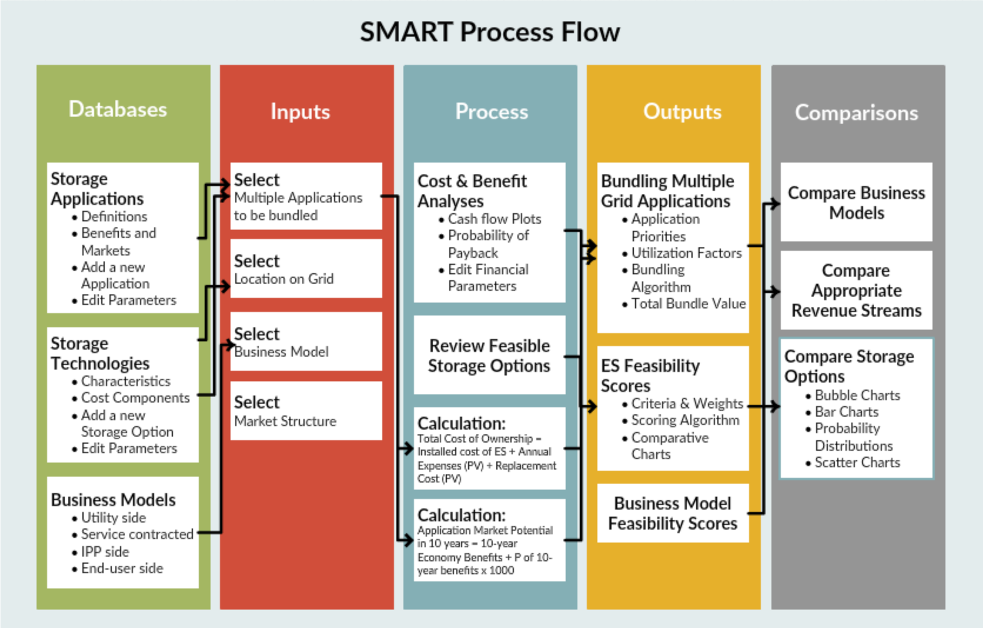

Figure 11-4 SMART work flow and data structure

11.5 Databases

The updated databases in ES-Select™ are mainly utilized for the majority of technical attributes needed for various storage technologies. Where possible, the cost data have been updated to with the most recent values available. ES-Select™ works with a range from Low (L) to High (H) values and a Monte Carlo process with a normal distribution randomly picks values and calculates the outputs within the provided L-H ranges of input parameters.

One of the key databases utilized in SMART is the service application database that includes 23 different services along any grid location. There is inconsistency in the business and academic literature on the terminology and definitions of grid services. An ongoing effort will ensure there is consistency among the definitions for each of the 23 grid services and comparisons to other tools such as ESVT. Each grid service is characterized by number of different attributes, in particular, the market size over a given project life time and annualized benefits.

Our approach to collecting data for the market size for each service application consists of several available forecasting data sets in various Canadian provinces, mainly ON and AB, in addition to data collected from two workshops and surveys [165]. The surveys included key service application inputs and the factors users and other key storage stakeholders, and investors use for making decisions including selecting a suitable service application for a given storage technology. In view of storage cost, the key questions related to the overall technology cost number and the parameters used to characterize all technologies and the performance for a specific service application. The results of these surveys were then compared to the key market size data and performance characteristics in literature and provided in L-H format.

11.5.1 Baseline Application Databases

Baseline assumptions were used in this thesis to evaluate the market size for ES in various market structures. A detailed grid-level production cost model, together with historical pricing and network data, is generally required for an accurate estimation of overall available capacity for ES.

Table 11-1 to Table 11-4 illustrate the key storage market size databases used in this thesis. The methodology is designed to allow an ES technology-agnostic approach for estimating total market size and storage capacity in each market.

For a mixed regulated market structure, the following parameters were used to eliminate least viable grid services before estimating the overall market size and storage capacity, based on an energy time shift (arbitrage) service assuming off-peak pricing at 0.077 $/kWh, mid-peak pricing at 0.114 $/kWh, and on-peak pricing at 0.14 $/kWh [166].

Table 11-1 Initial input parameters for estimating storage application size for a mixed regulated market [165,167].

	MW (L)	**MW (H)**	**$/kW (L)**	**$/kW (H)**	**CAD ($B) (L)**	**CAD ($B) (H)**	**(GW) (L)**	**(GW) (H)**
	Annual Capacity	Annual Capacity	Benefit	Benefit	10-yr Potential	10-yr Potential	10-yr Potential	10-yr Potential
Energy Time Shift (Arbitrage)	50	250	15.4	28	0.0385	0.35	0.5	2.5
Supply Capacity	50	250	15.4	28	0.0385	0.35	0.5	2.5

Table 11-2 and Table 11-3 provide the values used for estimating the overall market size and capacity attributed to each service. Services such as area regulation, fast regulation, capacity firming, wind, and solar energy smoothing are shown among the viable grid services. The total service opportunity in this market is therefore evaluated at 213-396 GW equivalent to $1.7 to $3.25B. All cost values are in USD.

Table 11-2 Example of annualized service benefits for estimating market size in a mixed regulated market [165,167].

Off peak	**mid peak**	**on peak**									IESO	
0.077	0.114	0.14	$/kWh									
			MW (L)	MW(H)	$/kW(L)	$/kW(H)	CAD ($B) L	CAD ($B) H	L (GW)	H (GW)		
			Annual Capacity	Annual Capacity	Benefit	Benefit	10 yr potential	10 yr potential	10 yrs Pot.	10 yrs Pot	5 times max capacity	ISEO/RFQ plan
Energy Time Shift (Arbitrage)			50	250	15.4	28	0.0385	0.35	0.5	2.5	used average 5 hrs time of use	
Supply Capacity			50	250	15.4	28	0.0385	0.35	0.5	2.5	used average 5 hrs time of use	

Table 11-3 Values used for estimating the overall market size and capacity attributed to each service in a mixed-regulated market [165,166,167].

Applications Name	**Min. Required Discharge Duration @ rated power (Low|High)**		**Annual Benefit (Low/High)**		**Total 10-Year Market Potential (Low/High)**		**Market Potential 10 years (Low|High)**	
	Hours		$/kW		Billion USD		GW	
Energy Time Shift (Arbitrage)	3	7	15.4	28	0.0385	0.35	0.5	2.5
Supply Capacity	4	6	15.4	28	0.0385	0.35	0.5	2.5
Load Following	2	4	**450**	**850**	**0.28**	**0.35**	25.99	36.86
Area Regulation	0.3	0.5	**0**	**0**	**0**	**0**	1.68	3.31
Fast Regulation	0.3	0.5	**0**	**0**	**0**	**0**	1.68	3.31
Supply Spinning Reserve	0.3	1	12	61	**0.01**	**0.03**	3.28	7.72
Voltage Support	0.3	1	**0**	**0**	**0**	**0**	0	0
Transmission Support	0.0006	0.0014	**0**	**0**	**0**	**0**	0	0
Transmission Congestion Relief	3	5	**0**	**0**	**0**	**0**	22.31	57.04
Dist. Upgrade Deferral (top 10%)	3	6	108	320	**0.08**	**0.12**	3.49	7.85
Trans. Upgrade Deferral (top 10%)	3	6	153	540	**0.19**	**0.25**	4.54	12.36
Retail TOU Energy Charges	4	6	166	184	**0.48**	**0.68**	32.36	41.65
Retail Demand Charges	5	8	79	87	**0.13**	**0.36**	19.37	45.54
Service Reliability (Utility Backup)	0.5	2	80	330	**0.09**	**0.11**	3.24	9.53
Service Reliability (Customer Backup)	0.5	2	100	380	**0.09**	**0.10**	2.53	7.59
Power Quality (Utility)	0.003	0.02	50	150	**0.05**	**0.10**	5.86	11.95
Power Quality (Customer)	0.003	0.02	63	170	**0.08**	**0.11**	6.42	13.23
Wind Energy Time Shift (Arbitrage)	3	6	14	80	**0.10**	**0.17**	19.33	54.49
Solar Energy Time Shift (Arbitrage)	3	5	33	56	**0.11**	**0.16**	29.79	40.94
Renewable Capacity Firming	2	3	**0**	**0**	**0**	**0**	28.62	34.72
Wind Energy Smoothing	0.3	0.5	**0**	**0**	**0**	**0**	1.81	2.74
Solar Energy Smoothing	0.3	0.5	**0**	**0**	**0**	**0**	0.16	0.24
Black Start	1.5	2	4.6	8.9	**0.00**	**0.00**	0.17	0.3

Similarly, for a regulated market structure, Table 11-3 provides the default market sizes for each viable service. The assumption for a deregulated market is that all services have the opportunity to support the grid.

Table 11-4 The database used for estimating the overall market size and capacity attributed to each service in a regulated market [166,167].

Applications Name	Min. Required Discharge Duration @ rated power (Low|High)		Annual Benefit (Low|High)		Total 10-Year Market Potential (Low|High)		Market Potential 10 years (Low|High)	
	Hours		$/kW		Billion USD		GW	
Energy Time Shift (Arbitrage)	3	7	57	100	8.5	11	14.37	21.34
Supply Capacity	4	6	51	101	7.61	12.1	14.61	22.85
Load Following	2	4	86	143	22	28.2	25.99	36.86
Area Regulation	0.3	0.5	112	287	2.7	3.92	1.68	3.31
Fast Regulation	0.3	0.5	168	560	0.68	1.96	1.68	3.31
Supply Spinning Reserve	0.3	1	12	61	0.52	2.1	3.28	7.72
Voltage Support	0.3	1	55	60	3	4.68	7.75	10.97
Transmission Support	0.0006	0.0014	26	29	2.4	2.5	12.22	13.16
Transmission Congestion Relief	3	5	5	20	2.14	4.19	22.31	57.04
Dist. Upgrade Deferral (top 10%)	3	6	108	320	6.18	9.43	3.49	7.85
Trans. Upgrade Deferral (top 10%)	3	6	153	540	15.5	20.3	4.54	12.36
Retail TOU Energy Charges	4	6	166	184	38	54	32.36	41.65
Retail Demand Charges	5	8	79	87	10.6	29	19.37	45.54
Service Reliability (Utility Backup)	0.5	2	80	330	7.31	9.01	3.24	9.53
Service Reliability (Customer Backup)	0.5	2	100	380	7	8.2	2.53	7.59
Power Quality (Utility)	0.003	0.02	50	150	4	8.3	5.86	11.95
Power Quality (Customer)	0.003	0.02	63	170	6	9	6.42	13.23
Wind Energy Time Shift (Arbitrage)	3	6	14	80	7.8	13.4	19.33	54.49
Solar Energy Time Shift (Arbitrage)	3	5	33	56	8.9	13.1	29.79	40.94
Renewable Capacity Firming	2	3	101	131	24.8	26.8	28.62	34.72
Wind Energy Smoothing	0.3	0.5	71	143	1.15	2.3	1.81	2.74
Solar Energy Smoothing	0.3	0.5	71	143	0.1	0.2	0.16	0.24
Black Start	1.5	2	4.6	8.9	0.01	0.012	0.17	0.3

For a de-regulated market structure, the market potential is estimated based on a sample annual price depicted in Table 11-4 extracted from available historical data for AB. Here, we evaluate the effect of the addition of ES to the electrical grid on electricity prices.

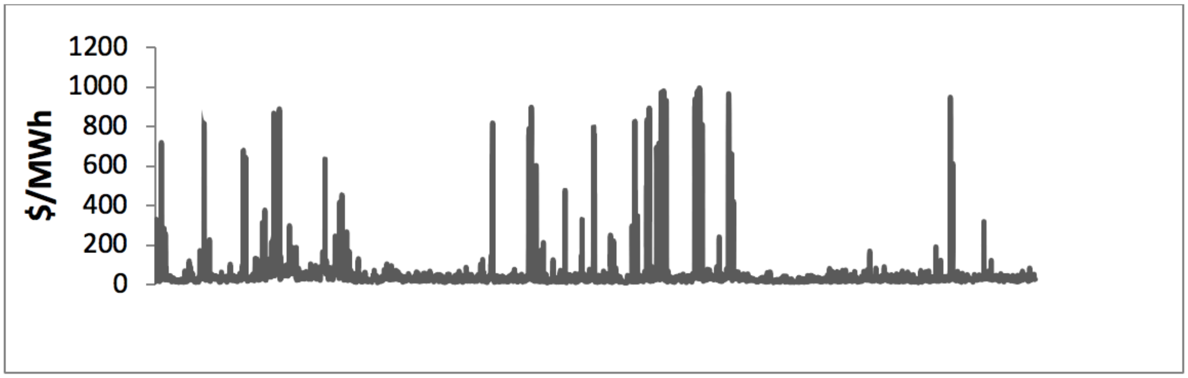

Figure 11-5 Annual hourly electricity prices for a deregulated market structure. Data is extracted from Alberta hourly price in 2014 [168].

As a result, the total service opportunity in a de-regulated market is calculated to be $1.7 - $2.7B. In a deregulated market structure, similar services are shown from the possible grid services similar to those in the mix-regulated market, Table 11-5.

Table 11-5 Values used for estimating the overall market size and capacity attributed to each service in a mixed-regulated market.

Application Name	**Min. Required Discharge Duration @ rated power (Low/High)**		**Annual Benefit (Low/High)**		**Total 10-Year Market Potential (Low/High)**		**Market Potential 10 years (Low/High)**	
	Hours		$/kW		Billion USD		GW	
Energy Time Shift (Arbitrage)	3	7	**400**	**900**	**0.11**	**0.14**	14.37	21.34
Supply Capacity	4	6	**0**	**0**	**0**	**0**	0	0
Load Following	2	4	**450**	**850**	**0.28**	**0.35**	25.99	36.86
Area Regulation	0.3	0.5	**0**	**0**	**0**	**0**	1.68	3.31
Fast Regulation	0.3	0.5	**0**	**0**	**0**	**0**	1.68	3.31
Supply Spinning Reserve	0.3	1	12	61	**0.01**	**0.03**	3.28	7.72
Voltage Support	0.3	1	**0**	**0**	**0**	**0**	0	0
Transmission Support	0.0006	0.0014	**0**	**0**	**0**	**0**	0	0
Transmission Congestion Relief	3	5	**0**	**0**	**0**	**0**	22.31	57.04
Dist. Upgrade Deferral (top 10%)	3	6	108	320	**0.08**	**0.12**	3.49	7.85
Trans. Upgrade Deferral (top 10%)	3	6	153	540	**0.19**	**0.25**	4.54	12.36
Retail TOU Energy Charges	4	6	166	184	**0.48**	**0.68**	32.36	41.65
Retail Demand Charges	5	8	79	87	**0.13**	**0.36**	19.37	45.54
Service Reliability (Utility Backup)	0.5	2	80	330	**0.09**	**0.11**	3.24	9.53
Service Reliability (Customer Backup)	0.5	2	100	380	**0.09**	**0.10**	2.53	7.59
Power Quality (Utility)	0.003	0.02	50	150	**0.05**	**0.10**	5.86	11.95
Power Quality (Customer)	0.003	0.02	63	170	**0.08**	**0.11**	6.42	13.23
Wind Energy Time Shift (Arbitrage)	3	6	14	80	**0.10**	**0.17**	19.33	54.49
Solar Energy Time Shift (Arbitrage)	3	5	33	56	**0.11**	**0.16**	29.79	40.94
Renewable Capacity Firming	2	3	**0**	**0**	**0**	**0**	28.62	34.72
Wind Energy Smoothing	0.3	0.5	**0**	**0**	**0**	**0**	1.81	2.74
Solar Energy Smoothing	0.3	0.5	**0**	**0**	**0**	**0**	0.16	0.24
Black Start	1.5	2	4.6	8.9	**0.00**	**0.00**	0.17	0.3

11.6 Treatment of Business Models

Storage services for the grid can be utilized through several business models. A phenomenological approach was taken to define and select various business models based on the industry best-practice business model [92]. These business models are mainly characterized based on contracting grid services with or without owning the storage system. EPRI's handbook has provided various guidelines, indicating processes for ownership of energy storage, as the required elements to be determined during procurement. Based on EPRI's definition of ownership of storage, four groups were defined that have distinct characteristics to be met by ownership, commercial operation, application, revenue value stream, market structure, and asset technology maturity (TRL) level. Score mapping between feasibility of grid services and typology of business models for different market structures are provided in Table 11-6. The scoring criteria in our valuation methodology follow the same logic as that in ES-Select™ methodology, whereas a new scoring scheme is introduced for business models. An example is provided in Table 11-7, based on feasibility scoring explained in Chapter 3.

Table 11-6 Example of score mapping between feasibility of grid services and typology of business models for different market structures [92]. (A B C): A=Regulated, B= Mixed Regulated, C=de-regulated

Grid services/business model	**Utility-side**	**Service-contracted**	**IPP**	**End-user**
Entergy time shift	(1,1,1)	(1, 1,0)	(1,1,1)	(0,0,0)
Frequency regulation	(1,1,0)	(1,0.5,0)	(1,1,1)	(1,1,0)
Power Quality	(0,0,0)	(0,1,1)	(0,1,1)	(1,1,1)
Backup Power	(1,1,0)	(0.5,0.5,1)	(0,1,1)	(1,1,1)
Demand responses	(1,1,0)	(0.1,1)	(0,1,1)	(1,1,1)
Resource Capacity	(1,1,0)	(1,0.5,1)	(1,1,1)	(0,1,1)

Table 11-7 Example for calculation of a total feasibility factor.

		1	2	3	4	5	6	Average	Weight
Feasibility Criteria	App Requirement	0.60	0.60	0.60	0.60	0.70	0.70	0.632	1
	Location requirement	1.00	1.00	1.00	1.00	1.00	1.00	1.000	1
	Cost	0.33	0.33	0.33	0.33	0.33	0.33	0.326	1
	Maturity	0.67	0.67	0.67	0.67	0.67	0.67	0.667	1
	Business model	0.5	0.5	0.25	0.75	0.25	1	0.541	1
								Combined Feasibility Score	**63.33%**

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[164] Georgiev, I. G. Techno-Economic Energy Storage Assessment in Denmark 2030-A case of selecting best-fit storage technologies with ES-Select decision-support tool, MSC Dissertation, University of Copenhagen. Copenhagen, Denmark. 2015.

[165] http://www.ieso.ca/en/Power-Data/Data-Directory
http://www.ieso.ca/-/media/Files/IESO/Power-Data/data-directory/Average-Weighted-Hourly-Price-kWh.xlsx?la=en
http://www.ieso.ca/sector-participants/settlements/global-adjustment-components-and-costs
http://www.ieso.ca/en/Corporate-IESO/Media/News-Releases/2017/12/IESO-Announces-Results-of-Demand-Response-Auction
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http://www.ieso.ca/Power-Data/Market-Summaries-Archive

[166] Alberta Electric System Operator, 2017, www.aeso.ca

[167] **Notes:**
[1] Based on Sandia report, section 5.2.3.2
[2] http://www.aeso.ca/downloads/Ancillary_Services_Participant_Manual_0714.pdf page 11
"Regulating reserves fall under the Operating Reserved market. If asset meets the minimum requirement, they are considered in calculations."
"We do not have a market for voltage support or reactive power (transmission support). We expect all generators to contribute but they do not get compensated for it."
"Transmission relief and smoothing renewables is very complicated in Alberta with current framework because markets and transmission are decoupled."
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[168] Alberta hourly price rate, 2014 http://www.aeso.ca/market/153.html