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A Review on Techno-Economics and Financing for Grid Energy Storage Systems

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***Abstract*—Several renewable energies such as wind and solar are intermittent. To increase renewable energy penetration, Electrical Energy Storage (EES) systems are becoming increasingly important. There is an increasing need for wide deployment of EES from generation to distribution systems. This requires relevant financial resources, and economics and finance are the important factors to determine if installing EES is profitable. Hence, this paper reviews the recent economics and financial analyses performed for EES in the energy system context. The paper begins with examining the EES technologies. Then, the difference between energy economics and finance are explained. The recent EES techno-economic studies and financial studies are reviewed. Under the uncertain economic, financing, and technical environment, it is important to examine EES projects with real options analysis. Finally, the paper concludes with future research directions for EES finance and economics.**

Keywords— Energy storage, financing, real options, techno-economics

I. INTRODUCTION

To battle climate change, several countries are aiming to increase the use of renewables in the coming decades, with the ambitious goal to be 100% renewable by 2050 [1-3]. Several renewable energy generators such as solar and wind are intermittent and non-dispatchable (except curtailment). These issues pose challenges to the grid and jeopardize the secure grid operations, including operating within voltage and power limits. Technologies and methodologies were developed to achieve generation-demand power balance, under uncertain power generation and consumption. With incentives, demand-side management can motivate consumers to change energy consumption behaviour [4]. The other technology that can improve the generation-demand power balance is Electrical Energy Storage (EES).

Grid EES systems involve converting energy from forms that are difficult and dangerous to store (e.g., electricity) to more conveniently or economically storable forms (e.g., heat). EES systems can absorb (by charging) or release (by discharging) electricity in a power system. EES can participate in a range of grid services such as energy arbitrage. There is a growing number of EES technologies in the past decade and energy producers are interested in the EES economic and financial assessments. Due to the technical differences between EES systems (e.g., round-trip efficiency, energy and power density), the economic and financial appraisal proves to be difficult.

Since EES is the unit of analysis, Section II gives a short overview of the EES technologies. Section III examines the definitions of economics and financial studies for energy systems. Section IV presents and discusses the recent techno-economics studies for EES. Due to limited financial studies for EES, Section V examines the financial studies for EES and renewable energy systems. Financial models and an overview of Real Options Analysis (ROA) for EES is given in Section VI. Section V concludes the paper.

II. GRID EES TECHNOLOGIES

There are many types of grid EES. Luo et al. [5] gave a review of the technical and economic properties of EES technologies. Amirante et al. [6] provided a review on hydrogen, electrical (superconducting magnetic energy storage (SMES) and supercapacitors); mechanical (Flywheel Energy Storage (FES), Compressed Air Energy Storage (CAES), and Pumped Storage Hydropower (PSH)); and electrochemical (lithium-ion batteries, lead-acid batteries, and flow batteries) energy storages. CAES and PSH provide minimal costs of energy storage capacity when they are built on large scales, and capable of long discharge times and high-power ratings. FES systems give very high power but have small storage capacity. Hydrogen energy storage with carbon nanotubes and clathrate hydrates is in development. Fig. 1 presents the dominant EES technologies for energy systems. The choice of EES (e.g., Sodium-Sulfur (NaS), Nickel-Cadmium (NiCd), and Nickel Metal Hydride (NiMH)) depends on the grid application, such as Uninterruptable Power Supply (UPS), Transmission and Distribution (T&D) support, and is related to the discharge time at rated power and system power ratings.

III. Economics and Finance

Much work on the economic appraisal of EES has had a focus on the Levelized Cost of Electricity (LCOE) and Levelized Cost of Storage (LCOS), with the literature found in Section IV. Nevertheless, these works have focused on the economic and costs aspects. Similar to other energy projects such as nuclear, coal, and gas power plants [9], one of the critical factors for an EES project to be successful is to study the financial aspects, i.e., the investment and allocation of liabilities and assets across the project lifetime. To achieve this, it is crucial to account for equity and debt investments. Since economics and finance are related disciplines, the distinction between the two is provided as follows:

Economics is a social science concerned with the study of management of goods and services, comprising production, consumption, and the elements affecting them [10-12]. Macro and micro economics are the two main disciplines. Macroeconomics consider the wider aspects of economy. Factors considered include national income, inflation rate, and unemployment rate. Macroeconomics is used to examine the effects of fiscal and monetary policy. Microeconomics is the study of supply and demand for goods. This includes market studies, to survey the quantity of supplied goods in demand and to achieve equilibrium at a price point under government regulations. LCOE is a common metric used in economic studies of electrical generators. Usually, economic models do not consider elements such as the payment of taxes, remuneration of debt or equity, or amortization. Simplistic economic models even if useful at a very preliminary stage (e.g. during a feasibility study), are unrealistic for representing the "real appraisal" of an infrastructure.

Finance is concerned with managing funds by taking account of time, money and the risk involved [12-15]. The aim is to address the trade-off between risk and profitability. In the energy sector, a financial model is concerned, for example, with the analysis of cash flows for both debt and equity holder, establishing a remuneration of the capital according to different risk attitudes [16]. Financial models consider additional stakeholders, since financial models deal with the payment of taxes and/or subsidies (relevant to a government), raising debt (relevant to debt providers such as banks and export credit agencies), and equity (relevant to project developers). Payback Period (PP), Net Present Value (NPV), and internal rate of return (IRR), Debt Service Coverage Ratio (DSCR) are metrics commonly used in finance studies.

The financing cost is an important input since it affects the rate by which both costs and electricity output are discounted [17]. The Weighted Average Cost of Capital (WACC) is a holistic (considering more stakeholders) discount rate for financial project appraisal. The WACC can be calculated by Equation (1) as follows [17, 18]:

$$\mathrm{WACC} = D.K_{\mathrm{d}}.(1-t) + E.K_{\mathrm{e}} \quad (1)$$

E and D are percentage of equity (%) and percentage of debt (%) respectively. This is summed to 100%. t denotes the corporate tax rate (%). K_{d} and K_{e} are cost of equity (%) and cost of debt (%) respectively.

IV. EES Techno-Economics Analysis

The techno-economic study examines the development, research, and deployment areas with a focus on costs, benefits, timeframes, risks, and uncertainties [19]. LCOE is commonly used to compare generation cost for an energy system or asset [20, 21]. An energy system normally operates over a predetermined lifetime; a photovoltaic plant, for example, may operate for 25 years [22]. Therefore, LCOE includes a discount rate that transforms future cash flows into their present value. A classical formulation of LCOE is provided in Equation (2) below [23]:

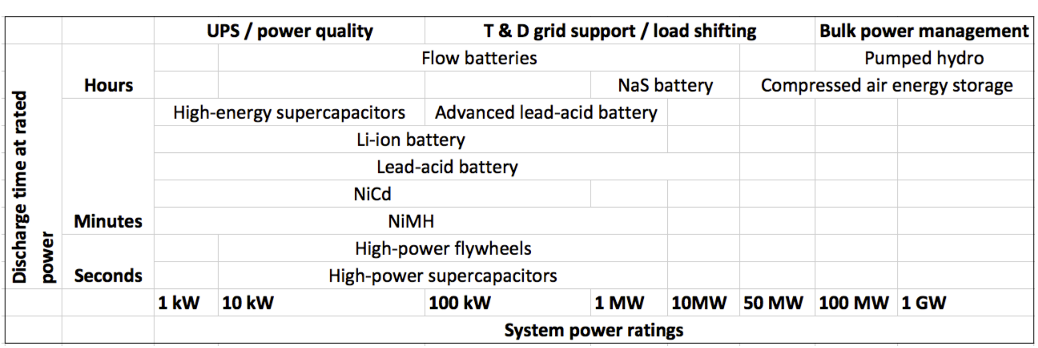

Fig. 1. Rated capacity and discharge time for various EES technologies [7,8].

$$\mathrm{LCOE} = \frac{\sum_{n=0}^{N} C_{\mathrm{cap}_n} + \frac{C_{\mathrm{O\&M}_n}}{(1+\mathrm{WACC})^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+\mathrm{WACC})^n}} \tag{2}$$

Where $C_{\mathrm{O\&M}}$ is the operation and maintenance cost ($), C_{cap} is the capital cost ($), N is the system lifetime in years, E is the energy output (kWh), and WACC is the discount rate. The cost of an asset usually consists of fixed and variable O&M costs, and a fixed capital cost. The energy output of an asset is calculated with an annual average value (kWh) considering the plant capacity factor (%). One of the key challenges in calculating LCOE is to identify the energy produced (including round-trip efficiency) and costs (fixed, variable, direct, and indirect).

The following section provides a review on recent works in techno-economic studies for EES.

Shaw-Williams et al. [24] presented a techno-economic analysis to study the economic impacts on distribution networks with EES and photovoltaic investments. Photovoltaic-only installations give the largest return. The economics of a combined photovoltaic and EES system is little according to the current EES capital cost.

Kaldellis et al. [25] derived a mathematical model to minimize the life-cycle electricity generation cost of remote island networks and to maximize the contribution of the photovoltaic generator and. The system consists of an EES system and one or more photovoltaic generators, in remote islands. It is learned that for islands with plentiful solar resources, it is cost effective to use a photovoltaic-EES system than thermal power stations. Xia et al. [26] presented a stochastic cost-benefit analysis model. The energy system consists of conventional generators and wind generation. The model accounts both the EES's amortized daily capital cost and the generation fuel cost expectation. According to the cost-benefit analyses, it is shown that the capital cost, EES charging/discharging efficiency, and lifetime are affecting factors for optimizing the EES size, while it is not economically feasible to use EES in power systems at all times. Bordin et al. [27] proposed linear programming models for the off-grid systems optimal management. Battery degradation is included in the optimization model and the terms "cost per kWh" and "cost per cycle" for batteries were discussed. Obi et al. [28] examined a method to calculate the LCOE for utility-scale EES. The goal is to give financiers, policy makers, and engineers a method by which to examine various EES systems with a common economic metric.

Zakeri and Syri [29] studied the life-cycle costs and LCOS with Monte Carlo method to consider uncertainties. The LCOS metric is derived from LCOE. The LCOS is given in Equation (3) as follows [23, 30]:

$$\mathrm{LCOS} = \frac{\sum_{n=0}^{N} C_{\mathrm{capEES}_n} + \frac{C_{\mathrm{O\&MEES}_n}}{(1+d)^n}}{\sum_{n=0}^{N} \frac{E_{\mathrm{out}}}{(1+d)^n}} \tag{3}$$

$C_{\mathrm{O\&MEES}}$ and C_{capEES} are the O&M costs and capital cost of EES respectively. E_{out} is the EES energy output.

Jülch [30] studied the LCOS for PSH, electrochemical EES, and CAES. The LCOS depends on the plant design, cost data, and annual operation hours. Belderbos et al. [31] presented three different LCOS metrics and their use for electricity arbitrage. These metrics are known as "required average discharge price", "required average price spread", and "required average operational profit". Lai and McCulloch [23] examined the LCOS for Li-ion battery and vanadium redox flow battery for a photovoltaic system.

In summary, there is an increasing significance and interest in examining the EES economics. Therefore, LCOS is a commonly adopted metric due to the computation simplicity and the capability to compare different EES costs "at a glance". Having reviewed EES techno-economics studies, the next section presents the financial studies for EES and energy systems.

V. EES Techno-Economics Analysis

Due to technical uncertainties and high capital cost, financing is potentially more important for renewables than for fossil fuel-based power plants [32, 33]. In contrast to dispatchable plants, blackouts and brownouts easily occur in renewable energy systems due to intermittent generation. A short-time period (e.g., several hours) of blackout can cost millions of dollars to the economy and the grid operators [23, 34].

Financing decentralized renewable energy infrastructures is a challenging task. Private investors are reluctant to invest due to high costs and risk-return-concerns [35-37]. Financing concepts need to be introduced to promote economically viable energy transitions. For several renewable energy projects, start-ups depend on their capital, government support (seed funds and grants) or private funding sources (venture capital and angel investor) [38, 39].

Projects can be financed through equity and debt [33]. The sponsor determines whether a project is feasible according to a cash flow analysis, and increases the value of a firm with tax shields. The merit of a particular investment in renewable energy technology can be determined by calculating the NPV, IRR, and PP [40]. The selection of financing structures, e.g., sales before construction, corporate financing, and leveraged lease for renewable energy projects; depends on technical maturity, financial viability, and the availability of natural resources, in addition to the supported and regulatory environment government policies [39].

There are many categories of technology-related risk which need to be inspected for an investment decision. This can be divided into six categories as follows [18, 32]:

- Market risk: Future market uncertainties in terms of both price and volume;
- Technological risk: Demonstration stage technology may not function as expected;
- Operations and Maintenance (O&M) risk: Cost uncertainties with technology operations and maintenance;
- Political risk: Future policy mechanisms and regulation uncertainties change the expected return;

- Construction risk: Problems related to subcontractors and supply chain constraints; and
- Supply risk: Uncertainties with availability and cost of resources.

The above risks are often judged to be high for new technologies, and this is reflected in an escalated cost of financing (i.e., K_e and K_d increase with the perceived investment risk). For instance, loans can be obtained from banks and generally guarantees are needed, the cost of the loan increase with the risk of the project [39].

Having summarized the EES financing issues, the following section provides a review on the recent works in EES and energy system financing.

Miller and Carriveau [41] reviewed the factors and mechanisms of renewable energy financing that could be adapted for the EES industry. Innovative financing schemes applied to renewable energy systems is also applicable to energy storage systems. As the need for EES is largely due to address renewable intermittency, partnering with renewable energy projects is a feasible attempt to EES financing. Cucchiella et al. [42] used a Discounted Cash Flow (DCF) model to study the NPV and financial feasibility of photovoltaic integrated lead acid EES systems. Subsidies are required for the energy system to be profitable. Avendano-Mora and Camm [43] used the DCF to examine the benefit-cost ratio, IRR, PP, and NPV of battery EES, for market-based frequency regulation service in a regional transmission organization. Systems larger than 5 MW with little battery replacements are expected to have the best financial performance. Jones et al. [44] combined life-cycle assessment and DCF analysis to find the financial and carbon dioxide impact by adding battery EES to a photovoltaic system. Battery costs need to be lowered rapidly, or extra revenue from delivering electricity system services is needed to make batteries financially attractive in areas with less insolation.

Krupa and Harvey [18] studied the current and future financing of renewable electricity options. Over the past ten years, private equity has contributed to the growth of the U.S. renewable electricity industry. A portion of the capital came from large investment banks and commercial banks [45], which exercised private equity funds to develop public companies. Private equity funds and venture capital are pooled investment vehicles that raise money from large investors and wealthy individuals, e.g., pension funds for targeted investments.

As described by Yildiz [35], financial citizen participation is a financing approach that is getting popular in Germany, where private individuals can invest in renewable energy projects. The two main equity-based financial citizen participation business models are "Closed-end funds" and "The energy cooperative". Karltorp [32] examined the difficulties of financing the development of biomass gasification and offshore wind power in Europe. Renewable energy tends to have low return and high risks. Therefore, it needs support from private to public finance. Energy bonds can promote energy system investment.

Another financing method with growing popular for renewable projects is crowdfunding [39, 46-49]. It is the practice by obtaining small amounts of cash from many people, normally via the internet. Compared with traditional financing, crowdfunding has the benefit of low search and transaction costs, and savings can be passed on to investors [48]. It is feasible to get project feedback via comment features on the crowdfunding page. Nevertheless, due to the viral nature of this financing method, the project is prone to public failure if the funding campaign's goals are not achieved. Cybersecurity is also a problem as the funding is conducted via the internet.

Lam and Law [46] examined multiple crowdfunding models with different returns and reward for biogas energy, energy efficient cookstoves, solar home systems, solar-powered lights, photovoltaic systems, wind turbines, and solar panels projects. Reward-based and donation-based crowdfunding are effective for small-scale sustainable and renewable energy projects during early prototype stages.

Chen et al. [47] aimed to determine the critical success factors of sustainable entrepreneurship projects with crowdfunding, based on 63 cases from U.S. and China. A system dynamic model was built to simulate the influence of government policies and the development of sustainable crowdfunding. The results show that policy combinations can promote crowdfunding, which attracts additional sustainable entrepreneurs to provide sustainable products/services.

Zhu et al. [49] analyzed the crowdfunding financing advantages for promoting electric vehicle charging piles constructions. A three-level Stackelberg game is proposed to model the interactions between the crowdfunders, charging infrastructure operator, and electricity supplier. The crowdfunding's performance is influenced by crowdfunders' risk attitude. High risk-taking crowdfunders have stronger incentives for charging piles investment.

The deployment of EES to renewable energy systems is limited by economics and project financing more than the technology itself [41]. These include high capital costs and a lack of financing incentives and options. Similar for renewable energy, regulations and market rules can impact strongly on whether EES is economically viable. Miller and Carriveau [41] evaluated the factors and mechanisms of renewable energy financing that can be adapted for the EES industry. Compared to renewable energy, EES financing is more difficult to comprehend due to multifunctional capabilities and services.

In summary, EES projects are limited more by economics and financing than by the technology itself [41]. It is possible to finance a project if it is economical. These include high capital costs and a lack of financing incentives and options. Similar for renewable energy, regulations and market rules can greatly impact on whether EES is economically viable. Compared to renewable energy, EES financing is more difficult to comprehend due to multifunctional capabilities and services.

VI. Financial Models

DCF method is a traditional and effective technique for project appraisals. However, DCF has drawbacks and is not effective in real-life situations, especially in high uncertainty business environments. The critical limitations include [50]:

- It is a deterministic model or stochastic model (e.g. Monte Carlo simulation) with a single set of input values;
- No flexibility in management (e.g., the choice to make alternative decisions in managing the project) as the project changes its course, with a fixed path project outcome; and
- Risk premium is added to the risk-free rate for projects with high uncertainty. The project will be seen as unfavourable as the high risk will likely to outweigh the expected payoff.

A. Options

In options theory, options can be classified as real options and financial options [50-52]. Different to financial options, real options do not refer to a derivative financial instrument. Real options are decisions a company's management makes. A real option itself is the right, but not the obligation to undertake certain business opportunities (or options) based on changing economic, technological or market conditions. This paper focuses on real options due to the scope of work, and will commonly be referred to as options.

Uncertainty is a key factor that drives the option's value. The value of an option increases as the project uncertainty increases [50], since options provide management flexibility to alter the course of the project in a more profitable direction. The aim is to maximize the expanded NPV (i.e. the static NPV plus the option premium) [53, 54]. For projects with very high or very low NPV, the option does not provide much value as the valuation is very clear (e.g., invest when NPV >> 0).

To account for uncertainty (similar to DCF), probability distributions and Monte Carlo analysis are used for the investigations. Some common uncertainties for EES projects are [54]:

- Lifetime: Mainly depends on EES degradation;
- Capital cost: This is affected by technological breakthrough and EES material cost, e.g., cost for cobalt [55];
- Energy input/output: Due to intermittent generation and uncertain electricity consumption; and
- Revenues from price arbitrage: The uncertainty in purchasing and selling market prices.

B. Real Options Analysis for EES

Common types of options (e.g. option to expand, option to contract, and option to abandon) can be applied to EES projects to provide project management flexibility [50]. At present, there are seldom works conducted on EES investments with ROA.

Muche [56] built a valuation model to evaluate the investments in PSH, by considering power price volatility and optimization of unit commitment. Without ROA, the NPV will have a lower contributions margin that may mislead investment decisions. Reuter et al. [57] examined the investment for PSH with a wind farm in Norway and Germany. It considered the electricity price variability, incentives benefits, and wind intermittency. The electricity price needs to be high for PSH investments. Kroniger and Madlener [58] used the Black and Scholes real options model to examine the uncertain revenue streams and investment timing for the wind power and hydrogen storage project. With ROA, it is possible for the project value to be twice the investment cost. Locatelli et al. [54] used the DCF and ROA to examine the NPV for PHS and CAES. The optimal EES capacity and incentives that guarantees zero NPV were determined.

For batteries, Bakke et al. [59] examined the lithium-ion EES profitability with ROA, based on optimal investment timing, uncertain future revenues and investment cost. The NPV is higher when ROA is used. The discount rate is assumed to be 4% in the study, and in reality, this can be affected by the corporate tax, cost of equity, and cost of debt. Also, the EES model is simplified such that degradation is not considered. The EES lifetime is assumed to be 15 years and this can be different with degradation. Xiu and Li [60] studied the lithium-ion, redox flow, and sodium sulfur batteries investment decision with binary tree option pricing model. The cost of EES is too high for the project to be profitable. Similar to the work above, the study employs simplified storage assumptions.

In summary, many of the reviewed works on ROA for EES focus on the project uncertainty (e.g. [56] and [57]) but not the flexibility (e.g., option to expand or contract). Current works on financial analysis focused on few EES types, such as PSH, CAES, Li-ion [61], and hydrogen storage. Real options techniques can be applied for different EES technologies, such as flywheel, thermal EES, and electro-chemical EES. EES models need to be more complicated to make effective EES comparisons. Machine learning has been applied to evaluate financial options in electricity markets [62], the future direction can examine machine learning in real options for EES.

VII. Conclusion

Finance and economics are important disciplines for the successful entrepreneurship and management of technologies. This paper provides a critical review on the recent techno-economics and financing studies for electrical energy storage (EES). Economics and finance are closely related disciplines, and hence, this paper begins with defining the terms: economics and finance for energy projects. As EES is the unit of analysis, several EES technologies were reviewed. The levelized cost of storage is a popular metric to compare EES economics. Financial studies present the investment feasibility for EES projects. The financing studies for EES are reviewed. Due to technical, financing, and economic uncertainties, real option analysis is a powerful financial tool for EES projects financial appraisal, and future works in this direction were highlighted.

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