Economic Analysis of Chemical Energy Storage Technologies

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Abstract. Smart Grid Technologies are set to transform electric power systems and energy storage is a key tools that will enable this transformation. Energy storage provides innumerable services such as energy arbitrage, frequency regulation, transmission and distribution system deferral, etc. In electric power systems, asset procurement is based upon investment models that ultimately minimize net amortized annual asset costs to supply a unit of electric energy. Accordingly, energy storage procurement is also scrutinized for cost-effectiveness. This paper provides cost effectiveness of different electrical energy storage technologies when used for single and multiple energy storage services. Different popular economic parameters like Net Present Value, Internal Rate of Return, Cost-Benefit Ratio, etc. are estimated to find out cost effectiveness of the technologies.

Keywords: Evaluation · Time value · Discounting · Pay-back period · Debt-service coverage · Net present value · Internal rate of return · Weighted average cost of capital · Benefit-cost ratio · Viable

1 Introduction

Energy exists in different forms in the universe and among those, some can be consumed directly and some by transforming into another useable form. Some of the transformation process could be controlled depending on demand or loads and others could not be controlled, that is, once the process is started, it goes continuously till the input(s) are available and don't depend on demand or loads. Without storage, energy generation must equal energy consumption. Energy storage transfers a part of the generated energy (excess of loads) at one time so that excess energy can be used at another time [1].

Due to different environmental factors and scarcity of non-renewable energy sources, increase in energy generation from renewable sources becomes obvious. But these types of energy generation are by nature intermittent and unpredictable, and the supply of renewable energy resources fluctuate independently from demand. This creates imbalances within the system and develops risk of not meeting the demand by supply. Energy storage is being considered as a solution to maintain the energy balance within the renewable energy system with consistency [2]. Thus, significant contribution of renewable energy to sustainable energy use will require considerable further development of cost-effective energy storage technologies [3].

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1.1 Energy Storage Services and Benefits

Up to mid-1980s, energy storage was used only to time-shift from coal off-peak to replace natural gas on-peak so that the coal units remained at their optimal output as system load varied. But till now about 17 services under 5 categories have been identified which these emerging energy storage technologies could provide [1].

Among these 5 categories, bulk-energy services are the most important. Bulk-energy services include electric energy time-shift (arbitrage) which involves charging of the storage system during off-peak periods or by storing excess energy produced by renewable sources during their pick production hours and utilizing the stored energy as and when needed [1]. Such service of energy storage also helps deferral and/or reduction of developing new generation capacity.

Ancillary services are the second most important services that energy storage can provide which include maintaining grid frequency known as regulation service; maintaining smooth operation of an electric grid through spinning, non-spinning, and supplemental reserves; voltage support to manage reactance at the grid level; black start service to provide an active reserve of power and energy within the grid which can be used to energize transmission and distribution lines and provide start-up power to bring power plants on line after a catastrophic failure of the grid; and other uses like load following/ramping support for renewables and frequency response [1]. Spinning, non-spinning, or supplemental reserve is the reserve capacity required for smooth operation of electric grid during unexpected failure of some portion of the normal electric generation resources and hence being considered the most important among ancillary services of energy storage [1]. This type of service requires larger size of energy storage like bulk-energy services and hence can be integrated in the same storage system.

Other categories of energy storage services are transmission infrastructure services (transmission upgrade deferral, transmission congestion relief, etc.); distribution upgrade deferral and voltage support; and customer energy management services (maintain power quality, reliability, retail energy time-shift and demand charge management) [1]. These types of transmission and distribution services can be performed by adding a relatively small size of energy storage within the grid system.

1.2 Electrical Energy Storage Technologies

Several electricity storage technologies are currently under commercial operation and a considerable number of emerging technologies are anticipated to be available within the next two to three years. One of the most popular storage technologies is Pumped Hydroelectric energy storage. This is a large, mature, and commercial utility-scale technology currently being used at many locations around the world. Compressed Air energy storage is also commercially available technology being used for large scale applications.

Besides, the above technologies' chemical storage or battery is the most popular and frequently used method of energy storage. Most of the batteries fall into the two main types; flow batteries and normal cell batteries.

Flow batteries are generally used for large scale applications. In these types of batteries, the electrolytes are kept separately in reservoir tanks and moved into the electrochemical cell using pumps. These batteries are deemed 75–85 % efficient and have a long life span [1]. Due to the fact that the electrolytes are stored separately, very little self-discharge occurs. But these batteries are quite costly as they require other components, such as pumps to move the electrolytes between the reservoirs and the electrochemical cell [1]. Vanadium Redox batteries (VRB), Iron-chromium batteries (Fe-Cr) and Zinc-bromine batteries (Zn-Br) are among the emerging technologies in this field [1].

Cell batteries are another type of chemical storage in which storage is achieved through electrochemical accumulators. There are a wide range of technologies used in the fabrication of accumulators (lead–acid, nickel–cadmium, nickel–metal hydride, nickel–iron, zinc–air, iron–air, sodium–sulphur, lithium–ion, lithium–polymer, etc.). The main assets of this storage are their energy densities (up to 150 and 2000 Wh/kg for lithium) and maturity of the technologies [1]. Their main inconvenience, however, is their relatively low durability for large-amplitude cycling (a few 100 to a few1000 cycles) [3]. Sodium-sulphur batteries (NaS), Sodium-nickel-chloride batteries ($NaNiCl_2$), Zinc-air batteries (Zn-Air) and Lead-acid family of batteries are among

Table 1. Maturity level of different chemical storage technologies

	NaS	$NaNiCl_2$	VRB	Fe-Cr	Zn-Br	Zn-Air	Lead-Acid
Maturity Level	A	C	B	E	D	E	C

A: Significant recent commercial experience; B: Pre-commercial; C: Demonstration; D: Demonstration trial; E: Laboratory

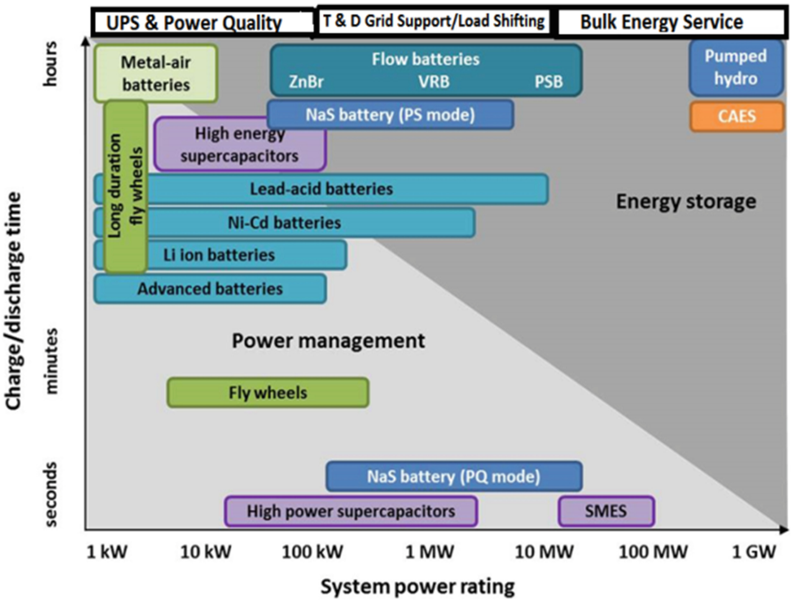

Fig. 1. Position of different energy storage technologies [14]

popular choices for energy storage [1]. Table 1 below shows the maturity level of different chemical storage technologies mentioned above.

Among others, hydrogen fuel-cells, super-capacitor and fly-wheel energy storage technologies are also commercially available but till now these are being used as small range energy storage.

1.3 Suitability of Different Energy Storage Technologies

Not all the technologies are suitable for all type of energy storage services due to their different energy density, power and discharge time. Figure 1 shows the power-energy relationship of different energy storage technologies and their suitability in different categories of storage services. From Fig. 1, it is obvious that CAES and Pumped Hydro are capable of discharge times in several hours with correspondingly large sizes ($\pm$1000 MW). In comparison of these technologies, flywheels and various chemical storages (batteries) are positioned around lower power and shorter discharge times [1].

2 Literature Review

To analyze the cost effectiveness, different economic & financial analyses are being done. In some cases, time value of money is taken into consideration but in some cases it is ignored to simplify the calculation depending on the context.

2.1 Economic Evaluation without Considering the Time Value of Money

Time value of money is an important element on financial and economic analysis, even though in some situation it is reasonable to deal with the face value of monetary amounts and ignore time value i.e. discounting of the face value. The most popular economic tool in this category is Simple Pay-back Period [4]. Beside this, the financers are also interested in another yearly indicator called Debt-service Coverage Ratio. These indicators are discussed briefly below:

Simple Payback (SP). Simple payback in economic analysis refers to the period of time required for the return on an investment to repay the original investment. Shorter payback periods are preferable than longer payback periods [4]. The following Eq. (1) is used to calculate the payback period [5]:

$$Payback\,Period = n_y + \frac{\left(CFn_{y+1} - CFn_y\right)}{CFn_{y+1}} \tag{1}$$

Where, n_y = The number of years after the initial investment at which the last negative value of cumulative cash flow occurs, CFn_y = The value of cumulative cash flow at which the last negative value of cumulative cash flow occurs, and CFn_{y+1} = The value of cash flow at which the first positive value of cumulative cash flow occurs.

Debt-Service Coverage Ratio (DSCR). The Debt-service Coverage Ratio (DSCR) is the ratio of cash available to meet the obligations of debt and repayment amount of debt which includes interest, principal and lease payments. It is a popular benchmark used to measure the ability of a creditor to produce enough cash to cover its all types of debt payments. The higher this ratio is, the easier it is to find out and convince a financer. It is generally calculated by using the following equation [6]:

$$DSCR = \frac{Cash\,available\,to\,meet\,debt\,of\,obligations}{Total\,of\,debt\,of\,obligations} \tag{2}$$

If the debt coverage ratio is less than one, it means that the income that the business/entity property generates or supposed to generate is or will not be enough to cover the debt obligations after meeting its operating expenses.

2.2 Economic Evaluation Taking Time Value of Money into Consideration

This type of evaluation starts with the premise that the value of money is declining over time and therefore, the values in the future should be discounted relative to the present. The most popular economic tools in this group are Present Net Value (NPV), Internal Rate of Return (IRR) and Benefit Cost Ratio (BCR) [4, 5].

Net Present Value (NPV). To find out NPV total of discounted present value of cash inflows is subtracted from the total of discounted present value of the cash outflows. If the NPV of a prospective project is found positive, then it is considered to be economically viable. However, if it is negative, then the project should probably be rejected, as the project will not be able to return the minimum attractive rate of return (MARR) [5]. The following equation is being used to estimate NPV of a project [5].

$$NPV = \sum\nolimits_{n=0}^{m} \frac{CFn}{(1+i)^n} \tag{3}$$

Where, ‘n’ is the number of year from 0 to life of the project (m), ‘CF_n’ is cash flow for the year ‘n’ and ‘i’ is the weighted average cost of capital (WACC) also known as discount rate.

WACC of a project can be calculated by using the following equation [4]:

$$WACC = \sum\nolimits_{n=0}^{m} \left[\left\{ (1 - Taxrate) \times I_d \times \frac{D_n}{D_n + E_n} \right\} + \left(I_e + \frac{E_n}{D_n + E_n} \right) \right] \tag{4}$$

Where, I_d is cost of debt or external capital, I_e is cost of equity or internal capital, D_n is amount of external capital at year n and E_n is amount of internal capital at year n.

Internal Rate of Return (IRR). The internal rate of return on an investment or project is the annualized effective compounded return rate or the rate of return that makes the

Net Present Value (NPV) of all cash flows (both positive and negative) from a particular investment equals to zero. Internal rates of return are commonly used to evaluate the desirability of investments or projects. The higher a project's internal rate of return, the more desirable it is to undertake the project. The project with the highest IRR would be considered the best and undertaken first [5].

If 'n' is the period (n = 0 to N where N is equal to the economic life of the project), CF_n is the net cash flow from the project at any period of 'n' and NPV is the net present value of the project and 'r' is th internal rate of return (IRR), then the value of 'r' i.e. the IRR can be found by solving the following equation [5]:

$$NPV = \sum\nolimits_{n=0}^{m} \frac{CF_n}{(1+r)^n} = 0 \tag{5}$$

Benefit-Cost Ratio (BCR). Benefit-cost ratio (BCR) is the ratio of monetary value of the benefits of a project to its costs [4, 6]. All benefits and costs are expressed in discounted present value at WACC. If BCR of a project stands > 1 then project is considered as economically viable since this indicates that the present value (PV) of all benefit will be more than the costs [4, 6].

$$BCR = \frac{\sum PV\ of\ benefits}{\sum PV\ of\ costs}. \tag{6}$$

3 Results and Discussions

Economic viability of any project depends on the location where it is going to be set-up. If the main input of the project is coming from that location and the output is also consumed to the same or adjacent location like an energy storage project, then the location becomes a major driver of economic viability of such project. This report analyzed the economic viability of chemical energy storage technologies considering Ontario, Canada as the location of projects.

Cost of a project has also an important role on overall project viability. The following figures (Figs. 2 and 3) are showing the present value installed cost in $/kw of chemical storage technologies for spinning and bulk energy services (units of 50 MW) and utility transmission and distribution services (units of 1 MW) as estimated by Sandia National Laboratories, USA (SAND2013-5131) [7].

The popular economic tools as mentioned above are calculated for different types of chemical storage of energy for a combination of bulk storage and an ancillary service (Spinning service), and transmission and distribution (T&D) services. Economic evaluation for a mix of services (bulk, T&D and frequency services) are also done by preparing an MS excel spread sheet. The basic information regarding cost of system, system's performance like depth of discharge and average O&M costs are taken from the SANDIA Report (SAND2013-5131) [7]. Rests of the required information are taken from the web site of IESO and other related web sites.

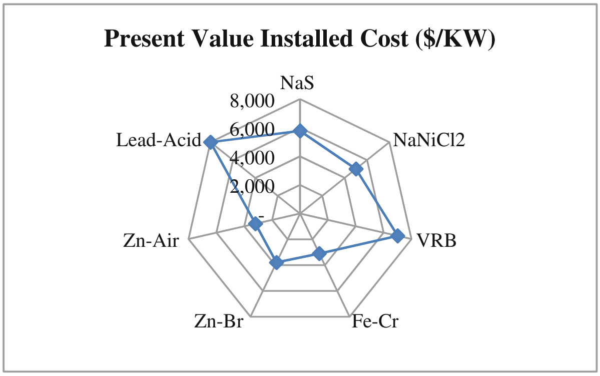

Fig. 2. Present value installed cost for bulk energy services [7]

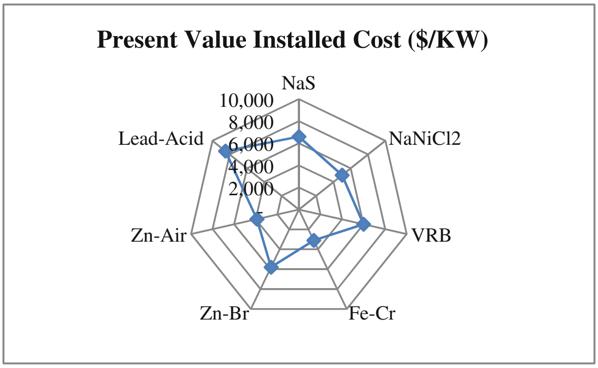

Fig. 3. Present value installed cost for T&D services [7]

Assumptions:

a. Average market rates (last 4-months) of different energy storage services are being taken as sale price of the services [9]
b. Energy Price will be at $ 135.00 per MWh which is little less than present threshold price for demand response [9]
c. System Capacity will be 50 MW for bulk services, 1 MW for T&D services and 3 MW for frequency regulation
d. Discharge duration will be within 5 and 6 h per cycle and total 365 cycles per year for bulk and T&D services and 1 h per cycle with 3650 cycles per year in case of frequency regulation [7]
e. Round trip AC/AC efficiency for Bulk, T&D and Frequency regulation services will be 75 %, 80 % and 90 % respectively with 100 % depth of discharge in each case
f. The Energy Storage System will be charged during the off-peak hours when the electricity is the cheapest and here it is considered at $ 0.03/kWh (weighted average in 2013 was $ 0.026) [10]

g. No repair & maintenance will be required in first 5-years and after that, it will cost about 0.1 % of total cost of system every year
h. Useful life of the systems will be 15-years and the project will flow straight line method for calculation of depreciation
i. The projects will be financed by at 50: 50, Debt – Equity ratio
j. Cost of debt will be 5 % per annum (Average yield in Govt. bonds over 10 years– 2.85 %, Prime Rate in Banks–3 %) [8]
k. Debt repayment will be made by 10 equal yearly instalments
l. Cost of equity is considered at 7 % per annum [11, 12]
m. Corporate Tax Rate 27.5 % [13]
n. Operating costs, battery replacement costs and time are considered as it shown in SANIDA report [7].

3.1 Spinning and Bulk Energy Services

Based on the above mentioned cost structure and other assumptions, economic analysis of the technologies for spinning and bulk energy services has been done, results of which are shown and discussed below.

Figure 4 below shows the profitability (net profit after tax) of the technologies after meeting all expenses including tax. From Fig. 4, it is clearly found that only Iron-Chromium (Fe-Cr) battery, Zinc-Air (Zn-Air) battery, and Zinc-Bromine (Zn-Br) battery systems will be economically profitable i.e. will be able to make some profit after meeting all obligations including tax. But, as the amount of profit of Zinc-Bromine battery is minimal and hence it might fail to generate profit if small increase in expenses or small decrease in income generation occurs. From the fore-casted results, it is also found that Sodium-sulphur (NaS) and Vanadium Redox (VRB) batteries will even not be able to meet the cost of services to be provided from its generated revenue (Gross Profit of these two systems are negative).

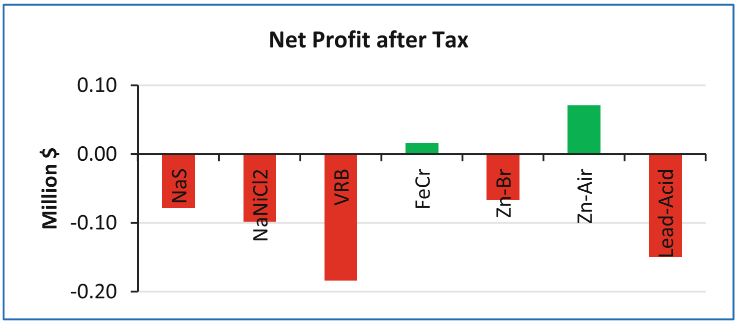

Fig. 4. Net Profit after Tax of different chemical storages for spinning reserve and bulk energy services

If we look at the Debt-service Coverage Ratio (DSCR) of the technologies as shown in Fig. 5, it is found that only Iron-Chromium battery and Zinc-Air battery have DCSR greater than one which means that only these systems will be able to meet the

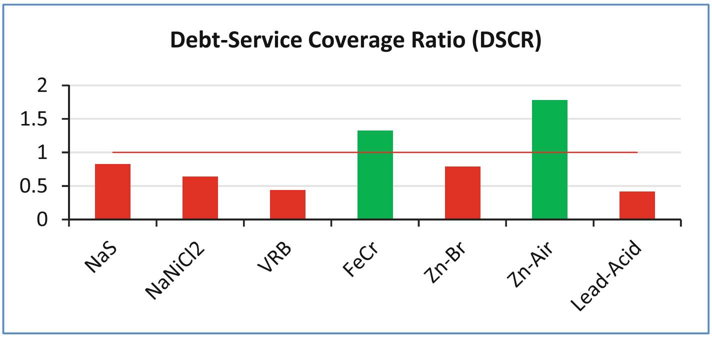

Fig. 5. Debt-service coverage ratio (DSCR) of different chemical storages for spinning reserve and bulk energy services

financial liabilities against the debt though it is considered that debt will only be 50 % of total cost. Though Net Profit after Tax of Zinc-Bromine battery is found positive but the DCSR is below one which indicates that this technology might earn some profit but will not be able to repay the debt (including principal repayment).

From the rest of figures (Figs. 6, 7, 8 and 9) shown below, it is found that in overall consideration only Iron-Chromium (Fe-Cr) battery and Zinc-Air (Zn-Air) battery systems will be economically feasible at present conditions (the IRR of these systems are higher than WACC, their NPVs' are positive, Payback Period are less than 15 years and the BC Ratios are greater than one). Though Zinc-Bromine (Zn-Br) battery system has positive retained earnings, DSCR greater than one and payback period is less than 15 years, but still it is not economically feasible as the IRR is less than WACC, NPV is negative and BC ratio is less than one. Hence, we can say that at the set assumptions only Iron-Chromium Battery and Zinc-Air Battery systems are economically feasible. All other technologies are not found economically feasible in overall consideration as due to higher capital cost of the systems (due to higher capital cost depreciation expenses of these technologies are more than 70 % of revenue generation).

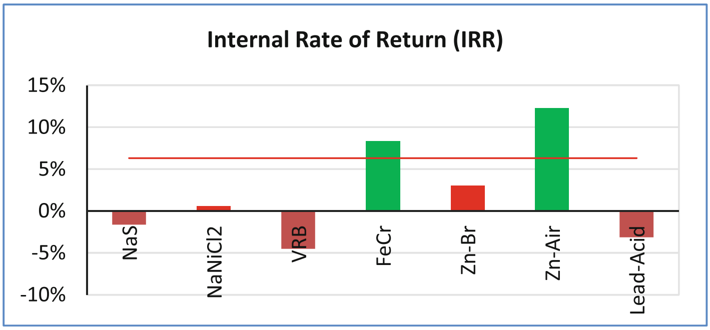

Fig. 6. Internal rate of return (IRR) of different chemical storages for spinning reserve and bulk energy services

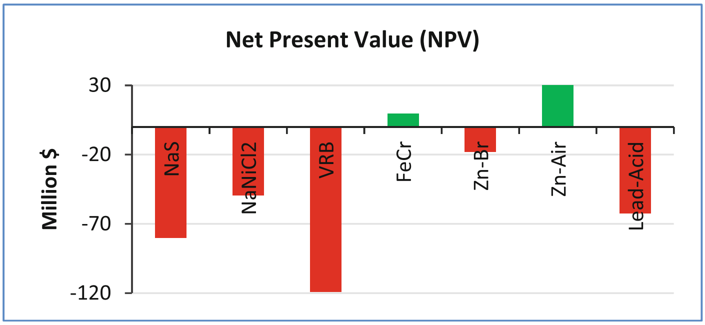

Fig. 7. Net present value (NPV) of different chemical storages for spinning reserve and bulk energy services

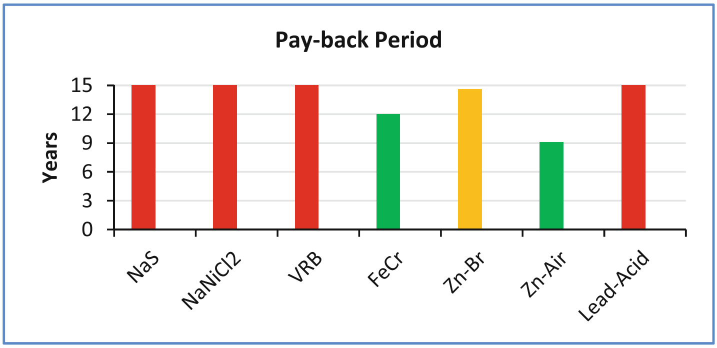

Fig. 8. Pay-back period of different chemical storages for spinning reserve and bulk energy services

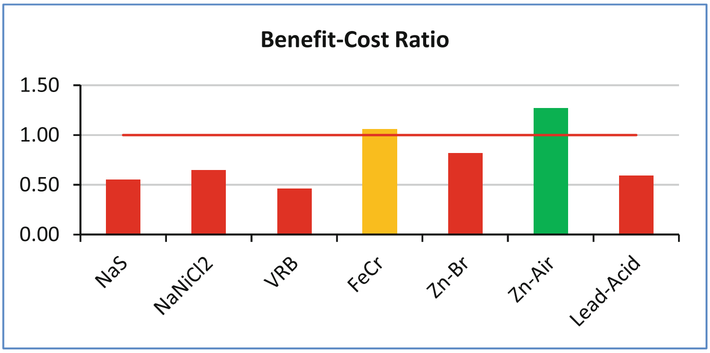

Fig. 9. Benefit-cost ratio of different chemical storages for spinning reserve and bulk energy services

3.2 Utility Transmission and Distribution Services

Based on the above mentioned cost structure and other assumptions, economic analysis of the technologies for utility transmission and distribution services have been done, results of which are shown and discussed below.

Figure 10 below is showing the profitability (net profit after tax) of the technologies after meeting all expenses including tax. From Fig. 10 it is clearly found that only Iron-Chromium (Fe-Cr) battery and Zinc-Air (Zn-Air) battery systems will be economically profitable in case of utility transmission and distribution (T&D) services (Net Profit after Tax of these technologies are positive). But, as the amount of profit of Iron-Chromium (Fe-Cr) battery will be very low and hence it might fail to generate profit if small increase in expenses or small decrease in income generation occurs.

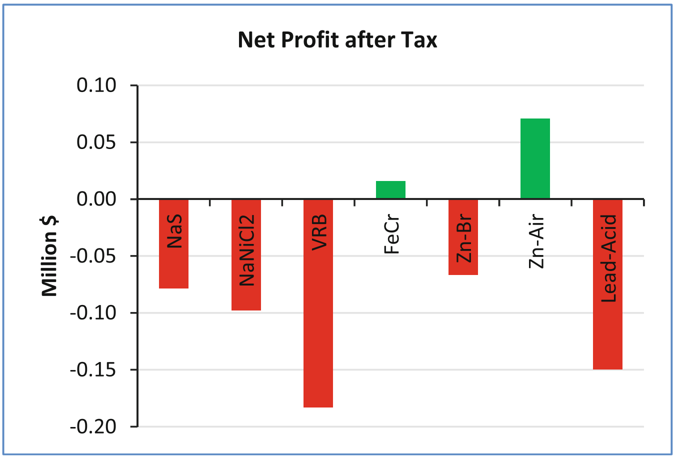

Fig. 10. Net profit after tax of different chemical storages for utility transmission and distribution services

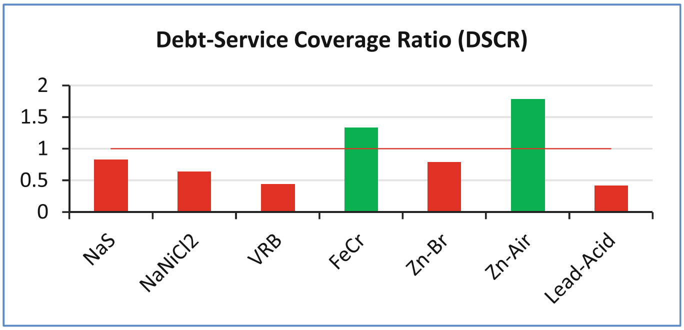

Fig. 11. Debt-service coverage ratio (DSCR) of different chemical storages for utility transmission and distribution services

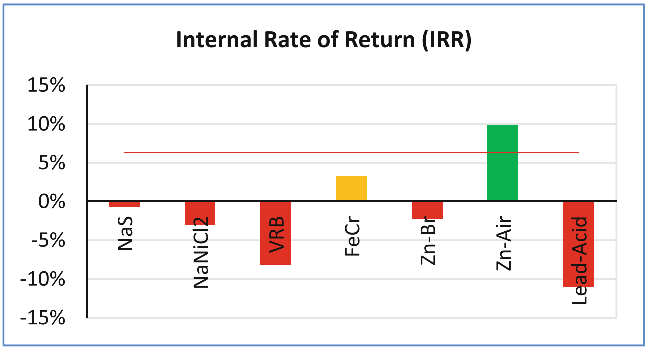

Fig. 12. Internal rate of return (IRR) of different chemical storages for utility transmission and distribution services

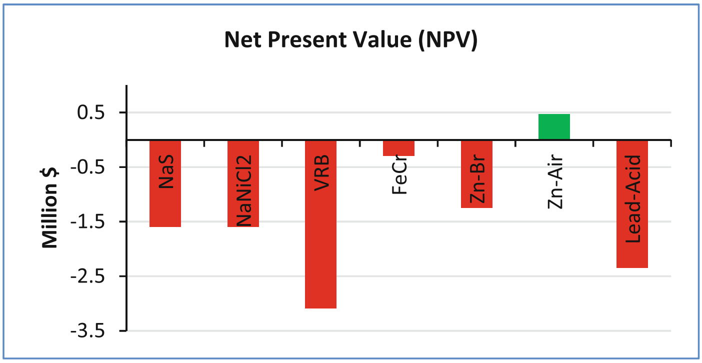

Fig. 13. Net present value (NPV) of different chemical storages for utility transmission and distribution services

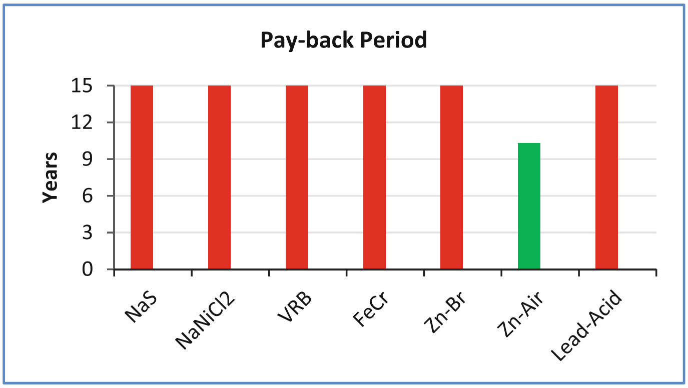

Fig. 14. Pay-back period of different chemical storages for utility transmission and distribution services

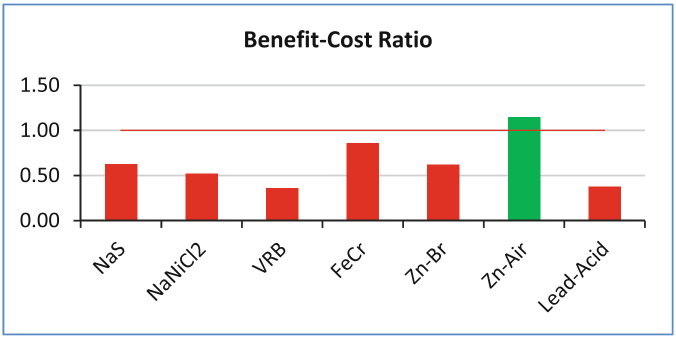

Fig. 15. Benefit-cost ratio of different chemical storages for utility transmission and distribution services

From Fig. 11 below it is found that debt-service coverage ratio (DSCR) of only Zinc-Air battery id greater that one i.e. only this technology will be able to meet the financial liabilities against its debt. Though Net Profit after Tax of Iron-Chromium (Fe-Cr) battery is found positive but its DCSR is below one which indicates that this technology might earn some profit but will not be able to repay the debt.

From the rest of figures (Figs. 12, 13, 14 and 15) shown below, it is found that in overall consideration only Zinc-Air (Zn-Air) battery technology will be economically feasible at present conditions (the IRR of these systems are higher than WACC, their NPVs' are positive, Payback Period are less than 15 years and the BC Ratios are greater than one). Though Iron-Chromium (Fe-Cr) battery system has positive net profit after tax but still it is not economically feasible as its DSCR is less than one, IRR is less than WACC, NPV is negative, pay-back period is more than 15-years and BC ratio is less than one. Hence, we can say that at present condition only Zinc-Air battery technology is economically feasible.

3.3 Combination of Multiple Services

To see the economic aspects of the technologies when some of those will be combined to provide more than one energy storage services, we forecasted the results considering

Table 2. Economic indicatore of combination of multiple energy storage services

Indicators	Results
Net Profit after Tax ($ /Yr)	5,338,268
Debt-Service Coverage Ratio (Times)	2.05
Weighted Average Cost of Capital (WACC)	6.27 %
Internal Rate of Return (IRR)	13.55 %
Net Present Value (NPV)($)	54,093,970
Modified Internal Rate of Return (MIRR)	9.36 %
Pay-Back Period (Years)	8.31
Benefit-Cost Ratio	1.28

a combined system of 3–technologies (Iron-Chromium for mainly for bulk services, Zinc-Air for T&D services and Li-ion for frequency regulation). Summary of results are shown in the following table (Table 2).

From all the above, it is revealed that if a combined system is made for multiple energy storage services the system becomes more feasible economically (DSCR, IRR, NPV, MIRR, Payback period and BC ratio all are better in case of combined system then the other two cases) than the individual systems.

4 Conclusion

From all the above shown economic analysis, it is revealed that only two chemical storage technologies (Iron-Chromium (Fe-Cr) battery and Zinc-Air (Zn-Air) battery) will be economically feasible at present condition. Some of the technologies like Lead-Acid batteries and Vanadium Redox Batteries are very far from economic feasibility (even gross profit of these technologies is found negative). It is also found that a combined system for multiple energy storage services will be more feasible than a system designed for single service. The technologies which are found more economically attractive are still at laboratory or early stage of demonstration trials. So, it is expected that with further research and development of these technologies and commercialization, their reliability and the overall cost of the technologies will decrease further and these energy storage technologies will become more economically attractive.

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