Techno-economic analysis of energy storage systems using reversible fuel cells and rechargeable batteries in green buildings

Assia Chadly, Elie Azar, Maher Maalouf, Ahmad Mayyas

Department of Industrial and Systems Engineering, Khalifa University, Abu Dhabi, United Arab Emirates

A R T I C L E   I N F O

Article history:
Received 19 November 2021
Received in revised form 20 January 2022
Accepted 10 February 2022
Available online 14 February 2022

Keywords:
Buildings
Levelized cost of energy storage (LCOS)
Lithium-ion battery
Energy storage systems
Reversible fuel cells
Solar energy

A B S T R A C T

Green and energy-efficient buildings have gained wider acceptance in the last few years due to their ability to save energy and, in certain cases, the ability to generate electricity using rooftop photovoltaic solar cells or other renewable energy sources. One of the major challenges for these buildings is having economic energy storage systems (ESS) that can reduce the effect of electricity curtailment. This paper proposes a techno-economic model that evaluates and compares three ESS technologies linked to a stand-alone photovoltaic system, namely lithium-ion (Li-ion) batteries (LIB), proton-exchange membranes reversible fuel cells (PEM RFC), and reversible solid oxide cells (RSOC). The model accounts for the degradation of the considered systems while evaluating their economics using the Levelized Cost of Energy Storage (LCOS) metric. The capabilities of the model are illustrated using a case study of a typical commercial building located in Los Angeles, California. The resulting LCOS levels without considering degradation are 41.73¢/kWh for PEM RFC, 28.18¢/kWh for RSOC, and 25.85¢/kWh for LIB. On the other hand, while considering the degradation the resulting LCOS at the end of the first year are 41.79¢/kWh for PEM RFC, 28.29¢/kWh for RSOC, and 27.35¢/kWh for LIB. Sensitivity analyses show that the LCOS of three considered ESS is sensitive to changes in capital costs, lifetime, discount rate, and round-trip efficiency. Moreover, the changes along the polarization curve show the most efficient configuration (highest efficiency and lowest LCOS) for PEM RFC. The study shows how Li-ion batteries and fuel cells are economically attractive and help improve the reliability and resiliency of power grids in the long term although they are prone to degradation.

© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Green building design and retrofits have gained significant interest in building science research over the last decade, contributing towards the sustainability goals of many organizations [1]. They have consistently contributed to higher energy efficiency and helped achieve green development goals [2]. Low-energy buildings can be designed to be self-sufficient if connected to a suitable size renewable energy system, supported by energy efficiency measures that minimize their energy demand. Since a energy generation is often intermittent (i.e., weather-dependent), it is necessary to consider and plan for situations where energy is not available, potentially resulting in load curtailment. In addition to disrupting building operations, curtailing energy can adversely affect the financial performance of renewable energy systems. Curtailment of energy can be avoided by several approaches, such as limiting energy generation, proportional energy generation or reduction for a certain period [3]. Similar to energy curtailment, an excessive production of energy that is unconsumed also results in financial losses.

To better match and balance energy supply and demand, energy storage systems (ESS) are often employed as viable techno-economic solutions that can reduce energy costs and carbon emissions while improving the resiliency of the building. The main role of ESS is to store energy in the when the supply exceeds the demand and use it when the situation is reversed (i.e., demand exceeding the supply). They have also been extensively used to reduce greenhouse gas emission [4]. ESS have a wide range of specifications and classifications, depending on their storage mechanism and potential applications. There are five major classes of ESS: electrical, chemical, electrochemical, mechanical, and thermal [5]. The key differences between these ESS lie in their structure and mode of operation. Supercapacitors, lithium-ion
batteries, fuel cells, and flywheels are distinguishable models of different mechanisms. These ESS differ at some important levels, such as the round-trip efficiency and the lifetime or the expected life measured in the total number of cycles [6]. Table 1 summarizes some technical and lifetime aspects of different ESS. The advantages of the batteries and the hydrogen-based ESS are higher power rating, energy density, and storage duration that make them suitable for medium and long-term storage needs. System round-trip efficiency is another crucial factor in choosing ESS technology and is usually considered among the most important factors in selecting ESS technology for any given application.

One of the major challenges that still face ESS is system ageing which lowers their performance and usually increases the energy storage cost. ESS generally undergo two types of degradation: calendar aging and cyclic aging, and both vary depending on the ESS parameters as lifetime and life cycles are not necessarily standard [12]. Calendar aging is the loss in storage capacity that the ESS encounters naturally. In other words, calendar aging is a natural process that ESS's undergo, whether they were utilized or not. On the other hand, cyclic aging is a result of usage and is dependent on the duty cycles and other operating conditions (temperature, pressure, humidity, etc.). Self-discharge or the loss of charge with time due to natural effects is one of the most parameters that play a key role in favoring certain ESS technology over others. This is considered a determinant factor when choosing some ESS for short-term and others for long-term energy storage applications. Besides costs and lower efficiency of the hydrogen storage systems, this ESS is attributed to the higher levels of degradation at the cell and stack levels which lower the system efficiency with time [5].

The goal of this paper is to develop a techno-economic model

| Technology | Power Rating | Storage Duration | Cycling or lifetime | Efficiency | Response Time | Self-Discharge | Cyclic Degradation |
|------------|--------------|------------------|--------------------|------------|---------------|---------------|-------------------|
| Li-ion battery | 0.1–100 | 1 min – 8 hr | 1000–10,000 cycles | 85–98% | 10–20 ms | 1–3% | Due to the duty cycles and continuous charging/discharging cycles, and the corrosion at the anode levels. Is usually between 10% and 15% |
| NaS battery | 10–100 | 1 min – 8 hr | 2500–4400 cycles | 70–90% | 10–20 ms | 0.05–20% |
| Hydrogen (fuel cells) | 0.01–1000 | Min – weeks | 5–30 years | 25–45% | Sec – min | 0–4% | Accelerated due to the reversible nature of the hydrogen generation and consumption process, especially for reversible solid oxide cells (RSOC) which operates at elevated temperatures that exceed 600 °C. Is usually at 10% for PEM RFC, and at less than 20% for RSOC. Negligible degradation because flywheels are designed for short-term use only |
| Flywheels | 0.001–1 | Sec – hours | 20,000–100,000 cycles | 70–95% | 10–20 ms | 1.3–100% |
| Supercapacitors | 0.01–1 | Ms – min | 10,000–100,000 cycles | 80–98% | 10–20 ms | 20–40% | Accelerated with decreased capacitor area, lower conductivity, and variable electric field. Varies between 6% and 30% |
| Pumped Hydrogen Storage | 100–1000 | 4–12 h | 30–60 days | 70–85% | Sec – min | 0 | Almost 0, any aging is due to low-quality maintenance of the system |
| Compressed Air Energy Storage | 10–1000 | 2–30 h | 20–40 years | 40–75% | Sec – min | 0 |  |
that evaluates and compares three ESS technologies connected to a stand-alone photovoltaic (PV) system. The technologies are lithium-ion (Li-ion) batteries (LIB), proton-exchange membranes reversible fuel cells (PEM RFC), and reversible solid oxide cells (RSOC). Previous studies on ESS for buildings often overlooked the degradation of the systems under study. Accounting for degradation is important as it could have significant effects on the technical performance of the systems, and consequently, their economic viability. Another part of the literature uses degradation to optimize the lifetime and other specifications of the ESS. The main contribution of this research is quantifying the effect of the cell and system degradation of the considered ESS, capturing the resulting impacts on their technical and economic performances. The model is demonstrated through its application in a typical commercial building (office building) located in Los Angeles, California. The rest of the paper is organized as follows: Section 2 presents a short literature review about the ESS and their degradation. The methodology followed to model the building, the solar PV systems, and the three ESS technologies are presented in section 3. Section 4 presents and discusses the results, and finally, section 5 concludes the work with a summary of the findings and main contributions.

2. Literature review

In this section, we will summarize the recent literature and highlight the research gaps in the literature that encouraged us to conduct this work. The first section highlights the differences between the selected ESS and serves as an extension to the table presented in the introduction. The second part discusses the degradation and self-discharge of LIB and fuel cells, and how they impact the lifetime of these ESS.

2.1. Differences between ESS

One of the main differences between hydrogen energy storage systems and rechargeable batteries is the operating schemes. Fuel cells are designed to operate continuously, mainly reversible solid oxide cells and, to a lesser extent, the PEM fuel cells in the load following mode (i.e., the storage duration is in the range of minutes-months), while batteries are expected to be idle for longer periods (storage duration in the range of minute to several hours). This implies that fuel cells can have zero depth of discharge as long as the feedstock is needed to complete the reactions in both modes are available to complete the electrochemical reactions (hydrogen and oxygen in the fuel cell mode, and power and water in the electrolysis mode).

While the operating profile could favor the use of the reversible fuel cells, this technology suffers from several issues that could limit its use in some ESS applications. For example, reversible fuel cells are associated with lower round-trip efficiency if compared to the efficiency we can get from the Li-ion batteries (in LIB, round-trip efficiency can easily reach 80% or more) [13]. Capital cost in $/kW is another limitation of the reversible fuel cell technology, which can be partially offset by using a single stack that operates in both modes (also called a unitized stack). That is, combining the electrolyzer and the fuel cell functions in a unitized stack can help reduce the initial system cost, but the expected low round-trip efficiency usually outweighs this advantage, thus lowering the levelized cost of energy storage may not be easily achieved [14]. The schematics of the fuel cell show that the stack is the most important component of the system where the electrochemical reactions take place. Stack is the core of the system which is surrounded by the balance of plant (BOP) that consists of several subsystems to maintain the operations of the fuel cell and electrolysis modes. The major functions of the BOP are the transport of the required gases and power to the stack (air and liquid loops, and power system), regulating temperature and humidity inside the stack (cooling and water management systems), and regulating the humidity and pressure of the hydrogen in the hydrogen dryer and compressor, respectively [1]. Parasitic losses in the BOP are part of the main drivers that cause a drop in the overall system efficiency [18–20]. BOP is composed of pumps, blowers, AC/DC rectifiers, DC/AC inverters, transducers, accumulation tanks, humidifiers, heat exchangers, compressors, pipelines, and many other parts [17,21].

2.2. Cell degradation and the effect on the lifetime of LIB and fuel cells

The complex electrochemical reaction system takes place inside the stack resulting in several sources for cell degradation and migration across the membrane. Li et al. [19] predicted the performance and degradation of the proton-exchange membrane (PEM) fuel cells by experimenting changes in operational and structural parameters; their results show that increasing gas pressure, low carbon loading, and high platinum loading in the catalyst coated membrane increase the initial performance of the fuel cells and decrease voltage degradation rates. Also, mechanical stress and strain, and improper humidity have been reported in the literature as the primary sources of membrane degradation and loss of durability [11]. Catalyst layers are also subject to an acidic chemical medium inside the stack, which could lessen platinum group metals (PGM) particles in the electrode layers. Carbon corrosion is another important source of degradation in the PEM fuel cells. The carbon structure breaks into particles that migrate into the membrane and gas diffusion layer (GDL). The migration of platinum and carbon particles weakens the membrane structure, causing irreversible structural damages that eventually results in tears and pinholes in the membrane and catalyst layers [11,20]. The gas diffusion layer (GDL) is also subjected to several modes of degradation, such as those associated with the effect of the mechanical stresses and temperature variations. Both composite and metallic plates suffer from a corrosive environment inside the stack which can lower their expected life. Metallic plates also suffer from the differences in the polarization, which could result in the formation and change in the thickness of the oxide films, which may induce some significant change in the cell resistance in the PEM stack [20].

Reversible solid oxide cells on the other hand undergo four different degradation mechanisms at different levels: in the interconnections, in the cathode, in the electrolyte, and in the anode [18]. These come in the form of oxide layer formation, structural changes with changes in operating temperature, reactions with the anode or cathode materials, crack formation, and others [18]. As the electrode structure coarsens during operation, the stack durability is impacted and the system performance is deteriorated [19,20]. Further, several optimization models were developed to understand the intensity of the impact of those mechanisms, as which one impacts the RSOC’s lifetime more. It was concluded that the electrolyte degradation mechanism is the main one impacting the solid oxide fuel cell, and its deterioration is marked by a reduction in the cell voltage [18].

Similarly, cells in LIB packs are subject to degradation over time as a direct result of operating conditions. The LIB’s useful lifetime depends on several factors such as operating temperature, charging and discharging rates, lowest depth of discharge, and cathode chemistry. The estimated lifetime for nickel-manganese-cobalt LIB is 5000 cycles assuming the lowest depth of discharge is 20% [14], with a remaining storage capacity of 80% of the original rated storage capacity in kWh. Round-trip efficiency (RTE), another
important metric for techno-economic evaluation of LIB is also known to change with time. A constant RTE is often assumed in the economic models; however, it is essential to highlight that RTE is dynamic in nature and depends on the operating conditions, including the charge/discharge rate, temperature, pressure, state of charge, and rest time [23].

Among other operating and design factors, cathode chemistry is also known to play a key role in the cell degradation. In their experimental study on commercial LIB cells, Preger et al. [24] found that lithium-iron-phosphate (LFP) cells experience lower degradation in the round-trip efficiency (RTE) than nickel-cobalt-aluminum (NCA) and nickel-manganese-cobalt (NMC) cells at all experimental conditions, though the differences are minimized at lower discharge rates. They also found that NCA cells exhibit particular sensitivity to higher discharge rates (C-rate), with RTE dropping 5%–10% for an increase in discharge rate from 1C to 2C at all operating temperatures (15–35 °C). The reason behind this degradation in the cell performance is attributed to the increase in cell resistance as the solid-electrolyte interphase layer grows during charging/discharging cycles. The three major degradation mechanisms in the LIB cells are loss of active materials, loss of lithium inventory, and loss of conductivity [25]. It is noteworthy to mention that some aging mechanisms are driven by the presence of two or more extrinsic factors making the control of these factors so much challenging. For instance, lithium plating is strongly associated with a state where the battery is cycled with high C-rates at low temperatures [26]. Li plating can occur only during charging; thus, solid-electrolyte interface growth is the dominant degradation mechanism during calendar aging and is accelerated more with higher temperatures which promote the reaction of electrolyte solvent and Li salts [25].

3. Methodology

Fig. 1 presents a flowchart of the different steps and analyses developed in this study, which are detailed in the following subsections.

3.1. Building description

The commercial building considered in this research is a medium office building. The U.S. Department of Energy identifies a medium office building as a 3-floor office building with a floor area of 53,628 ft². This building is labeled under the 3B-Coast climate zone for our case since we are considering a building in Los Angeles, California [27]. Just like residential buildings, commercial buildings play significant roles in modeling the energy demand patterns on different levels, accounting for about 13% of the world energy demand [28]. Energy end uses in commercial buildings vary across different business activities and by building systems. According to Pérez-Lombard et al. [29], the main end use of the energy in office buildings is heating, ventilation, and air-conditioning (HVAC), and that takes up about half of the energy consumed. Another 15% is consumed in lighting, followed by appliances which consume nearly 10% of the energy, whereas activities such as water or food heating, and refrigeration take up to 25% of the cumulative demanded energy.

Energy demand patterns vary depending on several factors such as the climate zone, or location, elevation and the season of the year, and energy expenditures inside the building. Fig. 2 shows the yearly electricity demand for a medium office building in Los Angeles, California, based on the load profile pulled from EnergyPlus [30]. This figure shows an almost uniform distribution of the load during the year with slight variation between hot summer and cold winter months. The minimum value of electricity demand is 18.79 kW during the night and a maximum demand of 178.30 kW in August.

3.2. PV system modeling

The photovoltaic (PV) generation profile was pulled for an average year using System Advisor Model, SAM from the Department of Energy’s National Renewable Energy Laboratory (NREL). SAM is a functional software that helps designers extract the information about renewable energy systems, and estimate for multiple economic performance measures such as the system generated power, expected capacity factor (%), net present value (NPV), simple and discounted payback periods, and the LCOE (Levelized Cost Of Electricity). The program comes with a built-in weather library, where the location can be selected from the list, or the user can import his own weather files in case if he is interested in analyzing a new location that is not included in the library. After uploading the right weather file, the user can adjust the PV specifications, in our case, the PV size was adjusted to 400 kW.
module selected in the present study is “SunPower SPR-E19-310-COM” with a maximum power of 310.15 Wdc and a nominal efficiency of 19% [31].

3.3. Overview of ESS

For this study, we consider three types of energy storage systems: Li-ion battery (LIB) as an example of mature ESS technologies, and proton-exchange membrane regenerative fuel cells (PEM RFC) and reversible solid oxide cells (RSOC) as emerging hydrogen-based ESS. System schematics are presented in Fig. 3 below. Reversible fuel cell ESS, PEM, and RSOC, have a similar balance of plant; yet they differ in the operating temperature, as RSOC operate at temperatures between 600 °C and 800 °C; whereas PEM RFC operate at temperatures between 50 °C and 80 °C. For simplicity, only the PEM schematic is presented, keeping in mind that an air preheater, water boiler, and high-performance heat exchangers are needed for the RSOC.

Overall, the equations of the electrochemical reactions taking place in the three selected ESS are shown in Table 2.

3.3.1. Hydrogen production for fuel cells

To ensure higher resiliency and non-stop operation of the reversible fuel cell, the hydrogen storage system should always start with a strategic storage position that ensures the cumulative hydrogen is always greater than zero, that is the hydrogen storage size as a function of time can be expressed as [1]:

\[ S_t + S_0 = S_{t-1} + H_{RFC,t} + S_0 \]  

where:

- \( S_0 \) is the strategic hydrogen storage position that RFC must maintain at any time (kg)
- \( S_t \) is the amount of stored hydrogen at time \( t \) (kg)
- \( S_{t-1} \) is the amount of stored hydrogen at time \( t-1 \) (kg)
- \( H_{RFC,t} \) is the amount of hydrogen produced or consumed by the RFC system (kg) at time \( t \) (for one year, \( t \) is given \( 0 \leq t \leq 8760 \))

3.4. ESS technical modeling

The previous section emphasized the importance of the stack in the system. It is where all the chemical reactions take place; therefore, any change in the cell performance will directly affect the stack and system efficiencies. Cell degradation is one of the major contributors to the loss in cell and stack performance [1]. As mentioned earlier, there are two types of degradation in the Li-ion batteries: calendar aging and cyclic aging. Calendar aging happens while the battery is at rest, and cyclic aging is a function of the number of charging/discharging cycles [32]. The calendar aging is due to the reactions taking place between the electrolyte and the lithium compounds. Some of those reactions are: 1) phase change that results in releasing oxygen, 2) oxidation of the lattice oxygen, which results in dissolving TM or forming rock salts, 3) electrolyte decomposition and loss [32]. In addition, the operating temperature is another factor impacting the self-discharge of the battery. In Ref. [6], authors found that higher temperatures accelerate the battery aging and therefore reduce its lifetime.

On the other hand, self-discharge for fuel cells is usually low [33]. Also, the degradation rate of fuel cells tends to be higher than that of batteries due to continuous electrochemical reactions inside the stack. Similar to batteries, cyclic degradation is also present and has a great impact on the fuel cell’s performance over time. That is usually due to the cycling between electrolysis and fuel cell modes which induce changes in the current density [34]. The high operating temperatures in the RSOC stack are also a main factor causing its cell degradation.

Tables 3–5 below summarize the functional specifications of the ESS considered in this study. Most of the data presented in the tables were retrieved from literature; references are cited accordingly.
Tables 3 and 4 above highlight the low efficiency of the hydrogen-based ESS. The efficiencies of the fuel cells stem from a series of equations. The stack round-trip efficiency is a product of the net efficiencies in the fuel cell and electrolysis modes. That is [14]:

\[
\eta_{\text{Stack}} = \eta_{\text{FC, net}} \times \eta_{\text{EC, net}}
\]  

(2)

Taking into consideration the parasitic losses due to the balance of plant energy consumptions, then net system efficiency can be expressed as:

Fig. 3. System Schematic of (a) reversible fuel cell (PEM RFC and RSOC), and (b) Li-ion battery.
\[ \eta_{\text{net}} = \left( 1 - \frac{\text{Total Parasitics Power}}{\text{Stack Power}} \right) \eta_{\text{stack}} \]  

(3)

where \( \eta_{\text{stack}} \) is the voltage efficiency.

Practically, the electrical efficiency is the ratio of the electricity produced over the higher heating value (HHV) for hydrogen [36]:

\[ \eta_{\text{electrical, FC}} = \frac{\text{Electricity produced}}{\text{HHV of Hydrogen}} \]  

(4)

To assess the stack efficiency separately from the system efficiency, researchers developed the voltage efficiency formula in the form of a ratio of the operating voltage to the thermodynamic voltage [33,34].

\[ \eta_{\text{voltage, FC}} = \frac{\text{Operating Voltage}}{\text{Thermodynamic Voltage}} \]  

(5)

The thermodynamic cell voltage takes into consideration prevailing conditions, including temperature, the gas constant R, the number of electrons transferred, and the Faraday constant. The thermodynamic voltage under certain conditions can be calculated using the following equation [37]:

Table 2
Electrochemical reactions in the selected ESS.

| ESS       | In fuel cell mode: \( 4H^+ + O_2 + 4e^- \rightarrow 2H_2O \)  | In electrolysis mode: \( 2H_2O \rightarrow 4H^+ + O_2 + 4e^- \)  |
|-----------|-------------------------------------------------|-------------------------------------------------|
| PEM RFC   | In fuel cell mode: \( 2H_2 + O_2 + 2e^- \rightarrow 2H_2O + 2e^- \) | Reduction at the cathode: \( \text{Co}_3O_2 + \text{Li}^+ + e^- \rightarrow \text{LiCo}_2O_2 \)  | Oxidation at the anode: \( \text{LiC}_6 \rightarrow \text{C}_6 + \text{Li}^+ + e^- \) |

The functional specifications for each ESS are detailed in Tables 3 to 5.

Table 3
Functional specifications of the PEM RFC.

| Parameter                  | Fuel Cell | Electrolyzer | Note/Reference |
|----------------------------|-----------|--------------|----------------|
| Stack Power                | 251.4 kW  | 591 kW       | [35]           |
| Current Density            | 0.4 A/cm² | 1.0 A/cm²    | [35]           |
| Reference Voltage          | 0.71 V     | 1.73 V    | [35]           |
| Power Density              | 0.284 W    | 1.730 W     | [35]           |
| Cells per Stack            | 124        | 124         | [35]           |
| Cells per System           | 25         | 25          | [35]           |
| Cells per System           | 3106       | 3106        | [35]           |
| Stack Voltage Efficiency   | 57.77%     | 85.61%      | [36]           |
| Total Parasitic power consumption | 35 kW    | 61 kW        | [35]           |
| Net Efficiency             | 49.73%     | 76.77%      | [35]           |
| Total System Efficiency    | 38.18%     | 10%         | [29], over the PEM's lifetime |
| Degradation                | 10%        | [35], Cost based on modeled 250 kW PEM stack cost at 10,000 units per year |
| ESS Cost                   | 667 $/kW  | [35]         |
| O&M                       | 3.5% of TIC | [35]        |
| System Life Expectation    | 11 years   | [35]         |

Table 4
Functional specifications of the RSOC.

| Parameter                  | Fuel Cell | Electrolyzer | Note/Reference |
|----------------------------|-----------|--------------|----------------|
| Stack Power                | 250 kW    | 454 kW       | [35]           |
| Current Density            | 0.44 A/cm² | 0.44 A/cm²  | [35]           |
| Reference Voltage          | 0.71 V    | 1.29 V        | [35]           |
| Power Density              | 0.312 W    | 0.568 W      | [35]           |
| Cells per Stack            | 21        | 21           | [35]           |
| Cells per System           | 2676       | 2676         | [35]           |
| Stack Voltage Efficiency   | 58%       | 95%          | [35]           |
| Net Electrical Efficiency  | 53%       | 83%          | [35]           |
| Total System Efficiency    | 43.99%    | 17.6%        | [32], over the RSOC's lifetime |
| Degradation                | 10%        | [35], Cost based on modeled 250 kW RSOC stack cost at 10,000 units per year |
| ESS Cost                   | 500 $/kW  | [35]         |
| O&M                       | 3.5% of TIC | [35]        |
| System Life Expectation    | 11 years   | [35]         |

Table 5
Functional specifications of the LIB.

| Parameter                  | Nominal/Median Value | Note/Reference |
|----------------------------|----------------------|----------------|
| Battery Size               | 400 kWh              | Nominal storage size of the battery |
| Battery chemistry          | NMC                  | Nickel–Manganese–Cobalt cathode, and graphite in the anode |
| Charging Rate              | 0.5C (200 kWh)       | Variable |
| Lowest Depth of Discharge  | 0.25C (100 kWh)      | Minimum discharge level |
| Round-trip Efficiency      | 92.5%                | [32]           |
| Degradation %              | 10%                  | [33], over battery's lifetime (5000 cycles) |
| ESS Cost                   | 339 $/kW             | [32]           |
| O & M                      | 1% of TIC            | [33]           |
| System Life Expectation    | 14 years             | [32]           |
\[ E = E^0 - \frac{RT}{N_F} \ln \left( \frac{[H_2]O}{[H_2][O_2]^\frac{1}{2}} \right) \]  
\[ E^0 = \frac{\Delta_f H^0}{zF} = 1.229 \text{ V} \]  

For PEM fuel cells operating at standard conditions, the thermodynamic voltage is 1.229 V \([33, 34]\). The thermoneutral voltage, or electrochemical potential, or Nerst Potential, is the voltage required to split water molecules. For the fuel cells, it is expressed in the following equation \([37]\):

\[ E = E^0 - \frac{RT}{N_F} \ln \left( \frac{[H_2]O}{[H_2][O_2]^\frac{1}{2}} \right) \]

where \( \Delta_f H^0 \) is the energy required, and \( z \) is the number of electrons needed to create a molecule of hydrogen \( (z = 2) \) \([36]\). At standard temperature and pressure, the thermoneutral voltage for the electrolyzer is 1.481 using HHV for hydrogen \([36]\). The thermoneutral voltage at standard conditions using LVH of hydrogen is 1.253 V. For the sake of consistency, the HHV was considered in this study rather than the LHV.

The electrical efficiency in electrolysis mode is different from that in the fuel cell mode since it operates at different voltage levels. The electrical efficiency is the ratio of the HHV of the hydrogen produced to the electricity input \([37]\):

\[ \eta_{\text{electrical,elec}} = \frac{\text{HHV of Hydrogen}}{\text{Electricity used}} \]  

For the electrolyzer, the voltage efficiency is \([37]\):

\[ \eta_{\text{voltage,elec}} = \frac{\text{Thermoneutral Voltage}}{\text{Cell Operating Voltage}} \]

In addition to that, it is crucial to mention that the operating voltages for both the fuel cell and the electrolyzer are not random. In general, the reference voltage for the electrolyzer should be greater to about double that of the fuel cell in the RSOC, as recommended by many researchers \([35]\). And to those reference voltages, specific current densities should be applied. That curve relating the values of those important variables is called the polarization Curve. Generally, a polarization curve for reversible fuel cells is composed of 3 regions: the activation region where the electrolysis takes place, the Ohmic region, which is the transition between the electrolyzer and the fuel code modes, then the diffusion region in the fuel cell mode. Unlike the first and last regions, the Ohmic region is a straight line, as it is the product of the current density and the resistance. Fig. 4 presents the polarization curves at standard operation temperatures for PEM FC. PEM RFC are generally more sensitive to changes in the current density when compared to the RSOC making it favorable for load-following applications such as when it’s connected to intermittent renewable energy sources \([40]\) (see Fig. 5).

The starting voltage for PEM RFC is generally higher than that of the RSOC, typically 1.2 V for PEM RFC and 1.0 V for RSOC. That potential is called the “no loss voltage”, and is marked in the figure as Nerst potential, or equilibrium potential. Thanks to their high operating temperature, RSOC do not undergo a sudden voltage drop at the beginning of the reaction, unlike PEM RFC. That voltage drop is so-called “activation losses”. On the other hand, the “Ohmic losses” are a direct result of the resistances (electrolyte material, membrane, and interconnections) of the different components of the fuel cell. It is the major loss in fuel cells. Finally, the “concentration losses” are a result of the quick and extensive use of the fuel resulting in a low concentration of that latter \([41]\).

The parameters impacting the polarization curve are not limited to temperature only; pressure and material can influence the behavior of the i-V curve as well.

3.5. ESS economic modeling

The economic analysis parameters of the designated ESS are summarized in Table 5 below. The ESS’ size was determined based on the expected discharged kWh from the system and the ability of the system to meet the building demand (even at peak times).
System cost and other financial parameters were pulled from similar techno-economic studies and represent the average values for these ESS.

Regarding the degradation of the ESS, that was tackled using two methods. The first method consists of including the degradation in the hydrogen production formula for fuel cells. As per the batteries, the degradation percentage was considered in the kWh charged and discharged, thus the degradation can be expressed in the following equations:

For fuel cells:

\[
H_2 \text{Production}_{\text{degradation}, t} = H_2 \text{Production} \times \left(1 - \frac{t}{t=0} \int HDR_t \right)
\]  

(10)

And for the battery:

\[
kWh \text{ Charge}_{\text{degradation}, t} = kWh \text{ Charge} \times \left(1 - \frac{t}{t=0} \int HDR_t \right)
\]  

(11)

\[
kWh \text{ Discharge}_{\text{degradation}, t} = kWh \text{ Discharge} \times \left(1 - \frac{t}{t=0} \int HDR_t \right)
\]  

(12)

where \(HDR_t\) is the hourly degradation rate at any given time (when the battery is in charge or discharge state), and \(0 \leq t \leq 8760\) h per year.

The second method consists of calculating a yearly efficiency for the three ESS. This calls for a second method even while considering the degradation in the fuel cells. The degradation here is an hourly degradation with an average value of \(10\) \(\mu\)V/h [31,32]. Regarding the indirect relationship between the voltage and the efficiency, that hourly change in the voltage will change the efficiency as well. Therefore, the new yearly efficiencies can be calculated as follows:

For the battery:

\[
\eta_{\text{LIB}, t} = \eta_{\text{LIB}, t-1} \left(1 - \frac{t}{t=0} \int HDR_t \right)
\]  

(13)

Since the data was retrieved for one year, then \(0 \leq t \leq 8760\) h.

As per the fuel cells, the same efficiency formula was used; however, this time new voltages were considered. The hourly voltages were found using the following equation:

\[
V_t = V_{t-1} \left(1 - \frac{t}{t=0} \int HDV_t \right)
\]  

(14)

where \(HDV_t\) is the hourly voltage degradation \(= 10\) \(\mu\)V/h.

3.5.1. Levelized cost of storage

The Levelized cost of storage (LCOS), as the name indicates, is the levelized cost using amortized capital cost in addition to the electricity cost and O&M cost. Capital and O&M costs are normalized over the expected kWh discharged, while the cost of electricity is adjusted for the system’s round-trip efficiency. The LCOS can be calculated using the following equation [13]:

\[
\text{LCOS} = \frac{\text{TIC}}{kWh_{\text{dis}} \eta_{\text{RTE}}} \left(\frac{r}{1-(1+r)^{-n}}\right) + \frac{Pt}{\eta_{\text{RTE}}} + \frac{C_{\text{O&M}}}{kWh_{\text{dis}}}
\]  

(15)

where:

- TIC is the total installed cost,
- \(r\) is the discount rate,
- \(n\) is the system lifetime,
- \(kWh_{\text{dis}}\) is the total discharged kWh from the ESS,
- \(\eta_{\text{RTE}}\) is the round-trip efficiency, and
- \(C_{\text{O&M}}\) is the O&M cost.

The numerical values of the above parameters are listed in Table 5.
3.6. Sensitivity analysis

Finally, sensitivity analysis was run to understand and better predict the behavior of the LCOS as a function of changing the input variables. All the variables in Table 5, except for the installation factor, were changed one at a time using \( \pm 50\% \) of the base value. Further, for LIB we studied the effect of changing the battery size on the charging and discharging rates and their expected effects on the economics of the energy storage. On the other hand, the impact of the changes in load factors (turndown ratio) was done using the polarization curve for both PEM-RFC and RSOC. For RSOC, the recommended operating windows to ensure higher system performance suggest using current density in the electrolysis mode that is in the range of \( 2 \)–\( 4 \) times the current density in the fuel cell mode \([45,48]\). In this study, we set this value to 2. Thanks to the equations discussed earlier, the voltage efficiency can help us find the efficiency of the system, and therefore the LCOS at each change in the current density.

### Table 6
Economic analysis parameters.

| Parameter                  | PEM RFC | RSOC  | LIB   | Note/Reference |
|----------------------------|---------|-------|-------|----------------|
| System Size                | 591 kW  | 454 kW| 400 kWh|                |
| System Cost                | $667/kW | $500/kW| $339/kWh| [32,33]        |
| Installation Factor        | $1.33/kW| $1.33/kW| $1.25/kW| [35,36]        |
| Total Installation Cost (TIC) | $524,282| $301,910| $169,500| Product of System size, System cost, and Installation Factor |
| O&M                        | $18,350 | $10,567| $1695 | Product of TIC and corresponding O&M percentage |
| Electricity Price          | $0.0237/kWh| $0.0237/kWh| $0.0237/kWh| LCOE \( a \) for PV system modeled in SAM \([31]\). |

\( a \) LCOE: Levelized cost of electricity.

### Table 7
Breakdown of LCOS for PEM RFC, RSOC, and the LIB.

| ESS     | PEM RFC | RSOC  | LIB   |
|---------|---------|-------|-------|
| Capital Cost | $0.284/kWh | $0.187/kWh | $0.215/kWh |
| Electricity Cost | $0.062/kWh | $0.054/kWh | $0.026/kWh |
| O&M Cost | $0.071/kWh | $0.041/kWh | $0.018/kWh |
| LCOS    | 0.4173  | 0.2818 | 0.2585 |

\( * \) Percentage of the total LCOS.

4. Results and discussion

This section is organized in three different subsections which discuss the results of the PV solar system from SAM model in section 3.1, followed by the calculations of the LCOS and parameters that play a key role in shaping it, with more discussion of the flexibility of the ESS and the expected resiliency it can provide in section 3.2. In section 3.3, we discuss the effect of cell degradation on the system performance (charging/discharging capacity) and the impact on the LCOS.
4.1. PV system performance and economics

According to the results from SAM model for a PV solar panel installed in Los Angeles, California in Fig. 4, the LCOE is around 2.37 ¢/kWh. For a PV system with $0 equity and $857,424 in debt, SAM model returned a positive net present value (NPV) of $210,690 over the system lifetime of 25 years. The expected discounted payback period for this PV system is 12.6 years.

This figure shows that the annual energy generation of this PV system is 961,708 kWh, with a maximum daily generation of 178.30 kWh. Also, the chart on the right shows that the peak performance is during the summer months (May, June, and July), while the winter months (November and December) witness the lowest monthly generations. That performs in line with the size of the PV calculated to supply enough power to the medium office building.

4.2. Levelized cost of storage

Calculations of the LCOS in Table 6 showed that the value can reach $0.417/kWh using PEM RFC, $0.282/kWh for RSOC, and $0.259/kWh for LIB. The breakdown of the LCOS is shown in the same table.

As can be seen, the highest portion of the LCOS for the three ESS comes from their capital costs, as they require complex installations and high capital investments, making their capital cost about 66–68% for the fuel cells, and 83% for LIB. Although the LIB system has a lower capital cost, the share of the capital cost component in the LCOS is higher than the reversible fuel cells due to the lower utilization and higher idle times. Noteworthy to highlight the lower discharged kWh from LIB compared to the reversible fuel cells, which also contributes to the higher value of the capital cost component. For both PEM RFC and RSOC, the capacity factor for the electrolysis mode is at 38.24% versus 61.76% at fuel cell mode; with a kWh discharge of 258,410 kWh. For the LIB, the kWh discharged is 95,575 kWh.

Increasing the size of the LIB can increase the discharged kWh per year, but unfortunately, this increase in kWh discharged will be outweighed by the increase in the system capital cost. Overall, this tradeoff will result in an increasing cost pattern in the LCOS. The LCOS, annual discharged kWh, and percentage of time in charge/discharge/idle states as a function of the battery size are shown in Fig. 6. The slopes of the straight-line segments for LIB>1200 kWh indicate a sort of nominal effect of the battery size in the expected system utilization factor (%charge, %discharge, and %idle). These charts in Fig. 6a and b indicate that with the current load profile, a smaller battery size would be more economical than the larger LIB but may not be able to cover all of the building needs. Fig. 6a shows that using a LIB of a size of 2000 kW would result in an LCOS of about $0.475/kWh, which would be linked to a total discharge of
approximately 250,000 kWh. Considering that battery size would make the LIB the most expensive ESS amongst the three ESS technologies. Increasing LIB size will improve the building resiliency but it might not be the most economical solution. This implies that hydrogen-based ESS may work better in standalone building settings. In addition, Fig. 6b shows that for a larger battery size, the idle time percentage is decreased while encountered by an increase in the charging time.

**Fig. 10.** Tornado Charts for the change in LCOS of: (a) PEM RFC, (b) RSOC, (c) LIB.
According to Beuse et al. [46], a benchmark for the values should be done with reference to the base case values of the selected ESS as projected in the coming 10 years. Having said so, and according to the same study, the benchmark value of the LCOS for li-ion batteries is around $0.055/kWh. Also, and according to Wei et al. [35], the 2030 target LCOS for RFC is $0.20/kWh, and the ultimate target is $0.10/kWh. In a more recent report, Papageorgoulos [47] estimated a $0.20/kWh target LCOS for fuel cells in general. The same sources stated that the reference LCOS are $1.60/kWh for PEM RFC, $1.11/kWh for RSO in 2020, and about $19/kWh for LIB in 2017 [35,46,47]. With regards to the actual statuses and the benchmarks, we can say that the values stated above in Table 7 are within those ranges and ensure the fact the LCOS are decreasing with time.

Since fuel cells operate on hydrogen as a feedstock in the fuel cell mode and as a product in the electrolysis mode, the cumulative hydrogen level generated/consumed is another important performance measure that needs further discussion. If the system can produce enough hydrogen to cover building needs, then any extra generated hydrogen can be used or sold to other end uses (e.g., as a fuel for fuel cell electric vehicles). If we start with a strategic level of 2500 kg, the level is in continuous decrease in the first 3 months as the fuel cell fluctuates between electrolysis and fuel cell modes. Fig. 7 below shows how the levels of hydrogen for both PEM RFC and RSO change throughout the study period. During summer, the period in which the generation of energy is peaked, the fuel cells generate hydrogen, and even larger hydrogen quantities in the case of RSO, before it start to decline again and mark a hydrogen consumption that continues until the end of the year (see Fig. 8).

The maximum storage capacity for PEM RFC is 2656.1 kg, and 3959.9 kg for RSO, whereas the level of hydrogen at the end of the year is at 154.6 kg for PEM RFC, and 2193.9 kg for RSO.

4.3. Effect of cell degradation on the system performance and LCOS

The first degradation model results show how the LCOS for PEM RFC, RSO, and LIB increases throughout each ESS’s lifetime. On the other hand, the kWh discharge decreases drastically which also implies the need to change the stacks in the reversible fuel cells (PEM and RSO), and the functional cells in the LIB. The charts in Fig. 7 show how both the LCOS and the kWh discharge change throughout the lifetimes for the PEM-RFC, RSO, and LIB, respectively.

The decreasing discharge and the increasing LCOS are partly among the reasons why the cells and stacks are refurbished or replaced every 2–3 years depending on the allowable loss in the system storage efficiency, usually these ESS are replaced when the ESS loses 20–30% of its storage capacity, and when the battery’s efficiency reaches 80% in the primary end use, excluding the applications with a second life use such as when LIB are used in the stationary storage in the power plants that reuse end-of-life automotive batteries to store electricity [29]. The change in the LCOS for the three ESS from year 1 to the end of their corresponding lifetimes is not large. That is, the LCOS for PEM-RFC increases by 9.5% in 11 years, that of RSO increases by 17.11% in 9 years, and that of LIB increases by 9.7% in 14 years. The expected LCOS at the end of lifetime of the selected ESS are: $0.4578/kWh for PEM RFC, $0.3313/kWh for RSO, and $0.2839/kWh for LIB.

The efficiency degradation model’s results support the first one, but at a faster LCOS pace for hydrogen storage systems. Differently expressed, the percentage changes in the LCOS in this model were greater than in the first model. Fig. 9 below presents the changes in the LCOS for selected ESS throughout their lifetimes. The LCOS for the PEM-RFC after 11 years is almost 3 times its LCOS at year 1.

Similarly, the LCOS for the RSO is about 3.6 times more at the end of its lifetime. The figure shows this noticeable increase of the LCOS of the fuel cells. In contrast, the change in the LCOS of LIB is surprisingly not large, and it appears from the figure that the LCOS level is approximately steady throughout its lifetime. Accordingly, the LCOS of PEM RFC after 11 years would be $0.6098/kWh compared to $0.4173 in year-1, and that of RSO after 9 years would be $0.4860/kWh compared to $0.2818 in year-1, and finally that of LIB after 14 years would be $0.2618/kWh compared to $0.2585 in year-1.

The before mentioned degradation models illustrate how the LCOS changes if the ESS are exposed to cyclic aging alone. Self-discharge was not considered for fuel cells initially due to lack of data, and for LIB because that requires applying it during idle hours only, otherwise the LCOS values would be inflated.

4.4. Sensitivity analysis results

The sensitivity analysis run by changing variables values by −/+ 50% results in the following tornado charts (Figs. 10–12).

These charts show how sensitive the LCOS is to capital cost, lifetime, discount rate, system round-trip efficiency, O&M, and electricity prices. Of the three storage systems, the LIB is most sensitive, unlike the RSO, which experiences moderate impacts that are small-scaled. The efficiency highlighted the most changes in the variables as the difference between the last and first values is large. Regarding the batteries, the value of the LCOS stagnates after the 110% increase in the efficiency, since after that a stable value of 100% efficiency is set, as the efficiency cannot go beyond 100%.

The polarization model demonstrates how the efficiency changes with changes in initial basic parameters such as the reference voltage and the current density. As indicated before, those values shall not be selected randomly, rather they change simultaneously. That translates into different pairs of increasing current density and reference voltage that will result in increasing round-trip efficiency and decreasing LCOS for PEM RFC until reaching a breaking point. The 3D plot below shows pictorially the impact of those changes on the pair of voltage and current density vs. round-trip efficiency and LCOS.

Logically, the higher the efficiency, the lower the LCOS, and in our case, that is linked to a higher current density. The results show that the current density and its corresponding reference voltage
positively impact the round-trip efficiency. Yet, as can be seen through the plot, the efficiency starts decreasing after a peak of 40.15% corresponding to an LCOS of $0.4142/kWh. This implies that the optimal current density to be applied to the electrolyzer is 400 mA/cm² with a reference voltage of 1.65 V. Considering the 2:1 current density ratio between fuel cell and electrolysis modes that...
was suggested by many researchers (e.g. Refs. [45,48]), the current density of the fuel cell would be around 400 mA with a voltage of 1.65 V, equivalent to a power of 0.66 W/cm².

The battery's charging rate is, as mentioned earlier, an important parameter in the operating regime of lithium-ion batteries. In our case, the discharge rate and depth of discharge are directly and linearly linked to the considered charging rate (C-rate). Moreover, the charge rate majorly depends on the applied current; therefore, it is controllable. Plots a and b illustrate the kWh discharge, LCOS, and percentage of time at increasing charge rates (from 0.1 to 1) for a battery of size 400 kW; Plots c and d present similar charts for a battery of size 1000 kW, and finally, the results for battery size 2000 kW are presented in plots e and f.

The figures clearly show that as the C-rate increases, the kWh discharge decreases; and the LCOS increases. Also, an increase in the charging rate induces an increase in the charging time and a decrease in the discharging time. In addition, the higher the charge rate, the more idle time the battery would experience, making it less efficient for long-term energy storage needs. The higher the battery size, the lower the idle time to start with. On the other hand, the discharging time begins higher and starts decreasing as the charging rate increases. Similarly, as the battery size increases, the same variables behave as before. This encourages considering a smaller battery size with a smaller charging rate (C-rate). Possibly, the results are related to the nature of the load data input where the need for power is lower. Regarding the LCOS and the kWh discharge, it can be seen that the higher the battery size, the steeper the descent, as the discharge decreases at a faster rate than the LCOS increases.

5. Conclusions

The adoption of batteries and fuel cells as energy storage systems is growing substantially in the commercial and power generation sectors, helping increase the resiliency and reliability of smart grids and decrease energy losses. This paper showcased a techno-economic model for storing energy using lithium-ion batteries and fuel cells (PEM RFC and RSOC). The results show how economically appealing the three systems are. The resulting LCOS were 41.73 €/kWh, 28.18¢/kWh, and 25.85¢/kWh for proton-exchange membrane fuel cells, reversible solid oxide cells, and Li-ion batteries, respectively. The breakdown of the LCOS shows that with the considered pairs of current density and reference voltage, the maximum efficiencies that could influence the work reported in this paper.

References

[1] Mayyas A, Chadly AA, Khaledi I, Maalouf M. Techno-economic analysis of the Li-ion batteries and reversible fuel cells as energy-storage systems used in green and energy-efficient buildings. Clean Energy Jun. 2021;5(2):273–87. https://doi.org/10.1093/cem/ckab009.
[2] Li Q, Zhang L, Zhang L, Wu X. Optimizing energy efficiency and thermal comfort in building green retrofit. Energy Dec. 2021;237:121509. https://doi.org/10.1016/j.ijhydene.2021.121509.
[3] Andrzychowicz M. Comparison of the use of energy storages and energy curtailment as an addition to the allocation of renewable energy in the distribution system in order to minimize development costs. Energies Jul. 2021;14(13):3746. https://doi.org/10.3390/en14133746.
[4] Hajiahiass S, Salemmia A, Hamzeh M. Hybrid energy storage system for microgrids applications: a review. J Energy Storage Feb. 2019;21:543–70. https://doi.org/10.1016/j.est.2018.12.017.
[5] Guney MS, Tepe Y. Classification and assessment of energy storage systems. Renew Sustain Energy Rev 2017;75:1187–97. https://doi.org/10.1016/j.rser.2016.11.102. Elsevier Ltd.
[6] Renewable Energy Agency: Energy storage and renewables: costs and markets to 2030. 2017 [Online]. Available: www.iresa.org.
[7] Deloute. Energy storage: tracking the technologies that will transform the power sector. 2015.
[8] M. Kamibayashi and K. Furuta, “High charge and discharge cycle durability of the sodium Sulfur (NAS) Battery.”
[9] Tamyurek B, Nicholas DK. Performance analysis of sodium sulfur (NAS) Battery.
[10] Active Power. “Why Flywheel Energy Storage?” https://www.activepow- er.com/en-GB/2814/why-flywheel.
[11] Sedlakova V, et al. Supercapacitor degradation assessment by power cycling and calendar life tests. Metrol Meas Syst. Sep. 2016;23(3):345–58. https://doi.org/10.1515/mms-2016-0038.
[12] Mostafa MHI, Abdel Aleem SHE, Ali SG, Ali ZM, Abdelaziz AY. Techno-economic assessment of energy storage systems used among annualized life cycle cost of storage. Energies Jun. 2020;29. https://doi.org/10.3390/en13145870.
[13] Mayyas A, Chadly A, Amer ST, Azar E. Economics of the Li-ion batteries and reversible fuel cells as energy storage systems when coupled with dynamic electricity pricing schemes. Energy Jan. 2022;239:121941. https://doi.org/10.1016/j.energy.2021.121941.
[14] Mayyas A, Wei M, Levis G. Hydrogen as a long-term, large-scale energy storage solution when coupled with renewable energy sources or grids with dynamic electricity pricing schemes. Int J Hydrogen Energy Jun. 2020;45(33):16311–25. https://doi.org/10.1016/j.ijhydene.2020.04.163.
