IJHSR
ijhighschoolresearch.org
REVIEW ARTICLE

Hydrogen Fuel Cells and Lithium-Ion Batteries for Solar Energy Balancing at Varying Climates: A Review

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ABSTRACT: The use of renewable energy has shown a drastic increase over recent years as an effort to minimize greenhouse gas emissions from fossil fuels. Among renewable energy sources, solar energy has experienced the largest growth due to improvements in efficiency, longevity, and reliability. However, due to the inconsistent fluctuations in solar radiation, domestic photovoltaic (PV) cells require energy balancing for the distribution of energy during periods of inadequate solar irradiation for self-sufficient use. This paper reviews the technical feasibility of integrating hydrogen systems, PV cells, and lithium-ion batteries (LIB) in various climates. It also discusses the costs, efficiencies, and usage of a hybrid energy storage system. This paper compares the performance of PV cells powering electrolyzers, batteries, and fuel cells. It evaluates the combination of H2 storage and LIB systems for year-round energy storage solutions in different climates. Ultimately, the findings suggest that a hybrid energy storage system combining LIBs and hydrogen systems provides an effective solution for balancing solar energy across varying climates.

KEYWORDS: Hydrogen storage system, Energy balancing, Electrolyzer, Regenerative Fuel cell, Lithium-ion battery.

Introduction

A main contributor to achieving global decarbonization is renewable energy sources, which have shown significant growth in the last several years. Solar energy has witnessed one of the largest investments and growth worldwide, with a major increase of installments by 87% in 2023, followed by an additional 29% increase in 2024.[1-3] However, this increase may present challenges due to inadequate consistency of the fluctuations in solar irradiation, which can be categorized into three types:[2,4,5]

(a) hourly fluctuations

(b) daily fluctuations (e.g. clouding)

(c) seasonal fluctuations (irradiation change dependent on seasons)

It is essential to consider that the fluctuations are heavily dependent on the geographical location of the photovoltaic (PV) system. This challenge highlights the need for a sustainable and reliable solution to balance solar energy and ensure a continuous electrical supply.[6]

Hydrogen systems are a good candidate for energy balancing, as the chemical storage of hydrogen can store large amounts of energy for a longer duration of time.[5,7] Electricity is converted to green hydrogen through an electrolyzer powered by photovoltaic (PV) cells and stored for later use. During energy shortage periods, the hydrogen is fed to a fuel cell for the reproduction of electricity, producing water and energy as their sole products. The general hydrogen system comprises three main components: an electrolyzer for generating hydrogen, a hydrogen tank for storing hydrogen, and a fuel cell for generating electricity from the stored hydrogen.[7] The efficiency of hydrogen systems is not heavily affected by time, as hydrogen can be stored for extended durations without deteriorating.[8] However, hydrogen systems are not ideal for short storage cycles due to the low chemical conversion efficiency in comparison

Another method for energy balancing is batteries. Out of the many battery types, lead-acid and lithium-ion batteries (LIB) have been identified as practical methods to store electrical energy, and they are highly suitable for integration with PV-based systems.[2,9] For this paper, we will be focusing on LIBs as they show better performance in terms of efficiency, life cycles, and power density compared to other batteries.[2] LIB have a much higher rate of efficiency and response time compared to hydrogen systems. However, the electrochemical properties of LIB are temperature sensitive,[10] experiencing degradation at temperatures exceeding 45 °C and typically face daily self-discharge issues that are unsuitable for long-term storage; hence they are more favorable when hourly balancing is needed.[2,7]

A key factor to understanding what method energy storage systems should use is based on the energy production and demands of each household. While countries with abundant solar radiation may only require storage capacity on an hourly or daily basis for sufficient operations, northern climates with drastic seasonal changes require a capacity increase to several weeks or months to achieve self-sufficiency.[7,9] In such a case, secondary batteries would be too bulky and too costly to serve the purpose.

This paper reviews the integration of LIB and hydrogen systems as a strategy for solar energy balancing. It also discusses the method of utilizing a hybrid system for optimal energy balancing throughout the year and evaluates the impacts of geographical location and climate on performance and feasibility.

DOI: 10.36838/v7i3.16

Overview of LIB and RHFC:

This section provides an overview and analytical comparison between the characteristics of LIB and RHFC systems.

Hydrogen system:

Hydrogen energy is increasingly valued, as it does not produce any emissions as a result of combustion reactions.[11] Hydrogen systems often rely on a fuel cell, electrolyzer, and hydrogen tank. When PVs generate excess energy, the surplus amount runs through an electrolyzer, producing hydrogen gas, which can be stored for later use for the reproduction of electricity in a fuel cell providing consistent and reliable power, especially during low-generation periods.[2,4,6] This process ensures reliable baseload power, which is the minimum level of electricity generation required to meet continuous demand on the power grid. Since the efficiency of these systems remains high over long periods, incorporating them in energy balancing for renewable energy (RE) gives flexibility with adjustable storage capacities for longer periods.[5,7]

RHFC:

Regenerative hydrogen fuel cells (RHFC) offer a clean and efficient alternative to on-grid electricity sources by generating power through an electrochemical reaction (a reaction that occurs due to a passage or absorption of electric current)[12] between hydrogen and oxygen through a proton exchange membrane (PEM).[13] The RHFC performs the functions of an electrolyzer and a fuel cell but does not typically include built-in hydrogen storage, so a separate component for storing hydrogen is needed. However, considerable losses have to be taken into account due to the kinetics of the evolution of oxygen (energy lost during water electrolysis and the reduction of oxygen in a fuel cell).[9] The integration of PEM electrolyzers in green energy production is ideal as they can sustain high current densities, providing a certain 'overdrive capability' and therefore, can be easily integrated with RE systems.[9,14] RHFC also has a relatively quick start-up time (compared to other fuel cells), high lifespans, and low maintenance costs.[2,13]

Equation 1: Reaction in electrolyzer

$$2H2O \rightarrow 2H2 + O2$$

Equation 2: Reaction in fuel cell

$$2H2 + O2 \rightarrow 2H2O$$

Hydrogen storage:

RHFC requires a separate component to store the hydrogen gas produced. There are many methods proposed for the storage of hydrogen, such as cryogenic liquefaction, solid storage, the binding of hydrogen to a storage material, or through underground salt caverns.[7,8] The preferred approach in the literature is pressurized gas for domestic use due to its low self-discharge rate and scalable storage capacity, making it a fitting candidate for seasonal storage.[7] Hydrogen presents a strong potential as a storage medium due to its highest gravimetric energy density of all fuels, (higher heating value (HHV) of hydrogen= 39.4 kWh/kg, compared to HHV of gasoline =12.9kWh/kg) meaning it stores the highest energy per unit mass.[5,7,11,15] However, due to their extremely low density, it has a low volumetric energy density (5.6 MJ/L when compressed to 691 atm, compared to 32 MJ/L for gasoline at ambient conditions),[16] high diffusion rate, and destructive capability such as hydrogen embrittlement, giving hydrogen the ability to escape through material, which proposes some safety concerns due to their high flammability.[2,17] Therefore, additional engineering measures are required to ensure safe utilization.[5,15] These safety measures also result in a very low self-discharge rate in undamaged pressurized hydrogen storage. One of the major highlights of "hydrogen energy storage systems is their long life span, low maintenance cost",[11] and long-term energy storage, making them an ideal candidate for seasonal balancing.

Li-ion Battery:

Another method for solar energy balancing is LIBs. These continuously-improving secondary electrochemical batteries can be reused by discharging and recharging,[5,15] and much like RHFC convert between electrical and chemical energy.[9] Compared to other available batteries, LIBs have a high energy density, "low self-discharge, high roundtrip efficiency, and short reaction time", making them well-suited for short-term storage.[2,18] However, they are highly sensitive to temperature. Temperatures above 45°C can rapidly deteriorate its battery lifetime,[2,17] as well as the risk of facing safety problems that include fire and explosion, 10 making it inherently difficult to implement this system in hot summer regions. Batteries are well established for equalizing electricity supply and demand in the seconds to hours timescale, however, they are less ideally suited on a day to months timescale due to the high self-discharge rate of 0.1-0.3%, making them far more suitable for short-term balancing.[2,9,17,19] LIB can contribute to baseload power, especially covering for high peaks when coupled with a separate system that releases energy steadily over longer periods.

Comparison of systems with PV applications:

Characteristics:

Table 1: shows the general comparison of LIB and RHFC:

	RHFC	LIB	Ref.
Efficiency	Average (30 - 70%)	High (75 - 97%)	2,13
Power density (W/kg)	Average (5 - 500)	High (100 - 5000)	2
Energy density (Wh/kg)	High (600 - 1200)	Average (75 - 250)	2
Operating temperature	60 - 80 °C	15 - 35 °C	10,13
State of charge (SOC) of 0% effect on lifetime	0%	-53%	18
Nominal voltage	0.2 - 1.1	3.6 - 4.2	17
Daily self-discharge rate	0%	0.1 - 0.3%	2,17,19
Recharging time	Fast (3min - 4min)	Very slow (30min - 720min)	2
Safety concerns	Hydrogen is a very flammable gas and can cause fires and explosions if not handled properly.	Lithium is flammable if exposed to air; electrolyte is flammable if pressurized, and requires overcharge protection and temperature control.	2,17

Seasonal storage requires high energy density and low discharge rate, hence RHFC and hydrogen tanks are more suitable than LIB storage, as hydrogen can be stored for long-term use.[2] However, the total round-trip efficiency of hydrogen systems is only 30-70%, which is less suitable for short-term energy balancing compared to the higher efficiency of LIBs

DOI: 10.36838/v7i3.16

(75-97%). This is due to the series of energy conversion processes (electricity to hydrogen and vice-versa as seen in Figure 1).[2,20] Additionally, significant energy is required to compress or liquefy hydrogen for storage, which leads to further efficiency losses. The main disadvantage for LIBs is the daily self-discharge issues that make them unfit for seasonal storage, while RHFC subsystems have negligible energy losses.[2,9] Hence, LIB storage is better suited for "short-term storage" (lasting seconds to hours), whereas RHFC is applicable to "medium and long-term storage", spanning hours to months.[2]

A common control parameter for LIBs is the state of charge (SOC), which measures the ongoing charge level in the battery relative to its total capacity. The SOC greatly affects its lifetime as LIBs degrade faster (leading to a swift decline in capacity) when operated at unrestricted SOC ranges.[2] Hence, battery management systems must be incorporated into the PV-LIB system to monitor the operation of the battery to keep SOC within a strict operational window. If the SOC of a LIB drops to 0%, the lifetime reduces to 47% of its original lifetime,[2,18] whereas the percentage of capacity used in an RHFC does not show any effects on its lifetime. Therefore, PV LIB systems have very limited design flexibility and must be paired with large PV and LIB capaciti es to maintain a reasonably high battery lifetime. On the other hand, PV RHFC systems have no such limitations.[2,9]

Another drawback for LIBs in extreme climates is their temperature sensitivity. While the acceptable temperature region is generally -10°C – 45°C,[2,20] its optimal temperature range is 15 °C–35 °C.[2,10,20] It is also necessary to monitor the cell operating temperature to avoid the operation of the battery outside its limits, which would result in reduced efficiency.[2,19] Temperatures out of this range may alter the performance and cause irreversible changes to the LIBs.[10] In contrast, RHFCs are typically more temperature-tolerant, withstanding temperatures up to 80°C. However, for optimal conductivity in PEM fuel cells, there must be a sufficient amount of water in the electrolyte membrane, imposing limitations on the operating temperature.[2,9]

The sizing of each system is heavily dependent on its demand and environment. For example, a household in a northern climate might require a larger electrolyzer and hydrogen storage units as the seasonal fluctuations may be more drastic than a household at equatorial latitudes. While sizing LIB systems may be easier due to their simple configuration, they require more complicated management and operating schemes to maintain operation within strict SOC ranges and avoid premature battery aging.[2,9] Sizing a hydrogen system is more challenging as it requires more integrated and calibrated components that must be properly coupled to achieve the desired energy capacity. This process varies case by case and can be complicated. Hydrogen systems are generally resistant to corrosion which reduces maintenance needs.[2,9,22] However, they require more space due to hydrogen's low volumetric density, whereas LIBs are compact and easily scalable. Due to the significant influence of temperature and solar irradiation fluctuations on each technology's performance, tailoring the energy-balancing approach to local climate conditions may lead to both cost savings and efficiency gains.

A hybrid system combining LIB energy storage with a hydrogen system would be optimal because it mitigates the drawbacks of both LIB and RHFC technologies, LIB's limited long-term storage capacity, and hydrogen's lower efficiency for short-term needs.[2,21] The utilization of different storage methods is determined by the desired behavior of the system. A simulation run in Finland concluded that standalone battery or hydrogen systems are insufficient for annual off-grid operations in "northern climate with typical isolation conditions". However, combining these energy storage systems together enables an off-grid PV-based energy system. In Australia, a simulation of different scenarios of energy balancing systems was analyzed. Results show that the PV hybrid LIB-Hydrogen system diminished "only 33% of RE generated", in contrast to the 74.9% diminished energy in the PV-LIB system, which requires a continuous input or external energy source to achieve a constant energy flow. The study concluded that the hybrid system is a "promising innovative approach for 100% renewable energy-based stand-alone microgrid systems" as the combined output of these components consistently meets the peak load with a reliability of over 99.9%.[5]

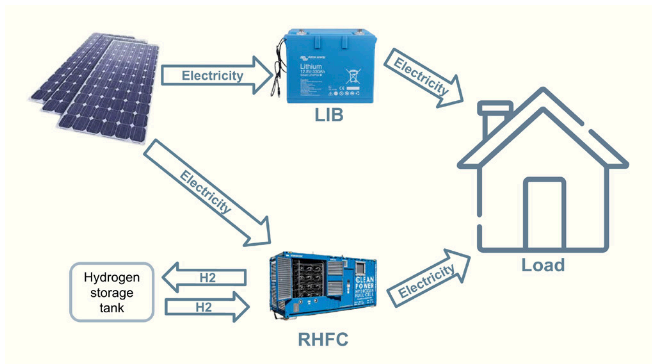

Figure 1: Energy pathways of LIB and RHFC systems

Sustainability:

Previous methods for PV energy balancing, such as conventional diesel generators, are unsustainable because they rely on fossil fuels and produce greenhouse gas emissions.[5] Furthermore, diesel fuel for energy balancing is expensive and continues to rise due to transportation and storage fees. Hence, decarbonizing energy supplies through locally produced RE is vital for future energy sustainability and further economic growth.[4,5] The clean energy conversion of RHFC and LIB makes them essential in decarbonizing RE storage systems. However, sustainability concerns may arise, such as recyclability or material availability.[2,9] For RHFC subsystems, the disposal of fuel cell and electrolyzer stacks must be carefully managed, as toxic materials are used as electrodes or catalysts.[10] A large number of LIBs will need to be recycled after reaching the end of their lifetime; as improper disposal poses a significant environmental threat due to toxicity, which is expected to become a very challenging task. For LIBs, raw materials like lithium and graphite are currently abundant (common materials for anode and cathode are platinum, iridium, ruthenium,

DOI: 10.36838/v7i3.16

and platinum on carbon).[22] However, these materials could be depleted soon if demand continues to grow rapidly, which would also drive up costs.[2] For RHFC components, materials are currently available, although their availability cannot be safely predicted, especially if future demand increases.[2,17] For the widespread and long-term deployment of these technologies, we must address the environmental impacts of improving the recyclability of the material used or replacing the materials with a sustainable alternative, as well as improving current recycling methods.

Costs:

Currently, PV systems are the most cost-effective option for distributed electricity generation. Prices for solar panels have decreased by 90% over the past decade, and further declines are expected, supporting future growth.[4,7,23] In RHFC technology, both lifetime and cost are more difficult to estimate, because an RHFC subsystem consists of three main components (in comparison to just a single main component in the case of LIB storage). This is because these three main components do not necessarily have the same lifetime, so the exact value can only be determined for a specific application. Additionally, the total cost is the sum of these components, which may vary significantly in terms of a specific application. For example, Hydrogen storage units, which are typically simple devices, have a much lower initial cost and much higher lifetime (~15 years) than LIBs.[2] Similarly, degradation rates may be affected, where for example the fuel cell may degrade faster than the Hydrogen storage units and electrolyzer.[2] Efficiencies also play a major role in the overall costs of the system. A case scenario in Australia 5 concluded the hydrogen-PV system is less cost-effective than the PV-LIB system, however, it significantly reduces wasted RE production by 56% more than the battery system (due to the advantage of seasonal cycling), enabled by its electrolyzer capacity. This efficiency allows for fewer solar panels to be used while maintaining the same energy balance. However, a proposed system of both hydrogen and LIB is deemed the most cost-effective system for a 100% RE-based stand-alone microgrid, breaking even at 6.01 years (compared to 7.91 years for LIB alone).[5] A recent analysis revealed a significant drop in LIB pack prices in the last decade, from $1400/kWh in 2010 to $151-126/kWh in 2023,[24] representing one of the "fastest cost declines of any energy storage technology".[25] Whereas the estimated cost of RHFC is harder to decipher as each RHFC system is specific to its location, demand, and individual components.

Effects of climate/ latitude on solar balancing:

The abundance and consistency of solar irradiation and temperature variation play a crucial role in the method of energy balancing needed. A city in western Turkey,[11] located at 37.76 ° N with a hot-summer Mediterranean climate, experiences varying hydrogen production rates throughout the year, with the highest rates recorded during the summer months when solar radiation levels peak. As solar flux increases, higher production of useful energy occurs, however, the efficiency of the system decreases as there is an increase in losses.[11] Cold climates may also cause a loss of efficiencies in the balancing system due to loss of efficiencies at cold starts, as it requires more electrical input energy to produce hydrogen and to warm the system to its optimal temperatures.[13]

How temperature affects the efficiencies of the systems LIB/RHFC in cold climate:

Around and over 60° of latitude North or South, the climate can generally be considered cold, with temperatures reaching below 0°C.[26] During winter, the available electrical energy that needs to be stored is low because PV-generated electricity is low. If LIB storage is used, some battery units would have to remain inactive during this season. Inactive storage of LIBs may lead to capacity reduction.[2] While LIBs are ideally operated in lower temperature ranges, they are less suited for regions with prolonged summer-like conditions.[2] However, at temperatures below 0°C, the performance of LIBs will degrade. A case study showed that an operating temperature drop from 25 °C to −15 °C gives a ~23% decrease in the maximum battery capacity due to an increase in internal resistance.[10,27] This challenge can be countered by proper management of the operating temperature of LIBs. Accurate temperature monitoring of LIBs is one of the important processes in proper temperature management. It is, however, difficult to monitor the temperature distribution inside the tightly sealed batteries.[10]

A case study in Finland, where temperature can reach -20 C, repurposed the waste heat generated in the PEMFC (as 80 ∘C waste heat would be well-fitting for domestic hot water heating),[2,7,9] effectively improving the overall energy efficiency of the hydrogen system.[13] On the other hand, Operating at lower temperatures can pose challenges in starting PEMFCs, as water freezing can lead to ice blockage.[13] Proper water management systems in the fuel cells may minimize the effect of icing and successfully start in temperatures below 0 C.

Integrating waste heat recovery technology promises substantial improvements in energy utilization efficiency, yet cost constraints and potential utilization inefficiencies present setbacks to commercialization and widespread adoption. Developing an optimized waste heat recovery framework emerges as a crucial facet in propelling PEMFC technology and enhancing overall energy conversion efficiency.[13]

LIB/RHFC in hot climate:

Climates with summers commonly reaching over 45 ºC may pose a threat to LIBs capacity and lifespans, risking future safety problems that include fire and explosion.[2,10,17] Increasing the operating temperature above the optimal scope will accelerate the aging process and lead to the degradation of LIBs.[2] Therefore, the operating temperature outside their typical acceptable range (-10 – 45 ºC) significantly affects the lifetime of LIB storage units.[20]

RHFC systems are designed to operate at higher temperatures without a significant impact on their lifetime (70 ºC or higher).[2] However, the PEM and catalyst layer degrades faster if temperatures exceed the optimal range, reducing efficiency and lifespan.[13] Additionally, a specific amount of water retention is required in the electrolyte membrane to provide peak conductivity as low water content diminishes the conductivity of the PEM, excessively high temperature can lead to water loss from the electrolyte membrane.[9,13] So implemented water

DOI: 10.36838/v7i3.16

management systems are required to keep water content consistent in the RHFC at all times.

PV efficiency by climate:

PV panels are sensitive to heat, so the efficiency decreases linearly with increasing temperature; this property can be exploited in cold climates.[11,26] Despite a reduction in solar irradiation, it is worth implementing PV systems for certain uses. It is reasonable that PV systems advanced under hot and sunny climates.[26] However, in hotter climates like Iraq, where temperatures in June and July can exceed 45 C, PV cells experience a reduced efficiency in energy production by 7.0% leading to a yearly energy degradation of approximately 96.6 kWh.[1] Nevertheless, the total production of energy through PV cells in hot climates far surpasses the production in colder climates despite the decrease in efficiencies.

Solar irradiation abundance effects on the viability of energy balancing systems:

Countries located near the equator often have hot Mediterranean climates coupled with high yearly solar radiation, experiencing a milder change in day lengths regardless of the season, hence they may be less reliant on seasonal energy balancing systems. In arctic and antarctic latitudes, solar irradiation is abundant in the summer months yet insufficient during winter, requiring an energy storage capacity of a few months. Consequently, energy consumption surges during the "dark, cold winter months due to increased heating demand".[7] Such locations are heavily dependent on seasonal energy balancing for sufficient yearly use of PV energy. In equilateral countries, a storage capacity of a few days will be sufficient for the autonomous operation of the electricity supply. In regions such as Central Europe, the capacity must be increased to several weeks.[9] Based on the average electrical energy consumption per day in Europe (16.2 kWh), a LIB being able to store 15 days equivalent would weigh approximately 974kg and cost in the range of 27.8k € - 33.4k € per person, which is impractically large and costly for an energy storing unit.

A case study done in Finland (61.5° N)[7] found that PV electricity generation drops to almost zero during the winter months (November to February). To maintain energy balance, the system relies heavily on a fuel cell that runs almost continuously to keep the battery charged. This approach significantly reduces the surplus energy produced by the PV system during the summer. In contrast, during the summer months, the energy systems mainly relied on the LIBs. Algeria has good solar potential that can generate electricity.[14] A simulation concluded that the estimated amount of hydrogen produced was more favorable in southern cities, with a higher yearly abundance of solar irradiation as the hourly hydrogen production depends on the available solar radiation.[14] Algiers (36.5° N) had more drastic seasonal changes and produced less hydrogen than Tamanrasset (22.5° N), with a more constant solar irradiation throughout the year. However, in these conditions, LIBs may be more suitable for providing a constant energy supply, as seasonal balancing is less of a concern in Mediterranean climates with fewer fluctuations in solar irradiation.

A case study in Italy (41.2° N), using PV and wind turbine technology, showed that high PV energy production generates a surplus of electricity during central hours in the summer.[6] The energy deficit at night is supplied by the batteries while the fuel cell is not required. The hydrogen storage system is used less frequently during autumn and spring.[6] In contrast, during winter, fuel cells are preferred over batteries to meet the significant energy deficit in the middle of the day. Fuel cells are heavily relied upon inwinter, as PV and wind generation only partially meet energy demands.[6]

Conclusions

Immediate action must be taken to accelerate the growth of renewable energy (RE) for global decarbonization. Lithium-ion batteries (LIB) and regenerative hydrogen fuel cells (RHFC) have been identified to be promising methods of implementing sustainable solar energy balancing techniques. In this Review, we go over and compare RHFC, LIB systems, and the effects of climate and solar irradiation abundance. Implementing adaptive control systems that switch between LIB and RHFC usage based on real-time and seasonal conditions could optimize energy balance while extending component lifetimes and lowering overall system maintenance requirements.[2,9]

There are 2 main factors regarding the effect of climate on these systems which are solar irradiation abundance, and temperature. As temperature increases from a certain point, the efficiencies of the PV energy generation decrease.[1] Temperatures exceeding 45 °C may raise concerns for LIB as the degradation of their lifespan and capacity takes place and increases the risk of facing safety problems that include fire and explosion.[2,9,10,20] Monitoring the cell operating temperature to avoid the operation of the battery outside its limits may be necessary.[2,19] RHFC are typically temperature tolerant, however, PEM and catalyst layer degrade faster if temperatures exceed the optimal range (exceeding 80 °C), reducing efficiency and lifespan.[13] The main concern for RHFC is their water content as higher temperatures may lead to water loss, reducing the efficiency. This issue can be resolved by implementing a water management system.[13]

In northern climates, where solar irradiation fluctuations are "drastic and highly abundant during the summer months, yet mostly non-existent during winter",[7] long-term energy balancing of a hydrogen system may be prioritized over short-term balancing. In solar-abundant climates such as Mediterranean climates, a storage capacity of a few days will be sufficient for the autonomous operation of the electricity supply,[9] so dependency on RHFC for seasonal balancing will be minimal.

Although RHFC and LIB systems are promising green energy balancing methods, the system's performance depends on multiple aspects, such as climate conditions and monitoring and control systems.[21] The utilization of these energy-balancing techniques is unique to every application and is climate-dependant. Future research must focus on enhancing LIBs temperature tolerance so that it may be more applicable in arid conditions, where the dependence of LIBs is typically greater. Additionally, research must be done for applications on hybrid RHFC and LIB for energy balancing in diverse climates.

Acknowledgments

I would like to express my special thanks of gratitude to my mentor Dr. Steve Bullock who guided me through writing this paper, as well as the faculty of Indigo research for allowing me to make this project possible.

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DOI: 10.36838/v7i3.16