Proceedings of the 10th International Conference on Economic Management and Green Development
DOI: 10.54254/2754-1169/2026.36795

Simulation-Based Design of a Solar–Hydrogen Hybrid Energy System for a Los Angeles High School with Reduced Battery Use

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Abstract. Green hydrogen has become an increasingly relevant topic in the clean energy transition. Its energy-dense properties, as well as its minimal carbon footprint, make it a desirable energy storage system. To remain carbon neutral, many projects paired hydrogen storage with solar power and a lithium battery system for a clean hydrogen-powered microgrid. This study investigates whether battery capacity can be reduced while maintaining grid-independent operation for a representative 2,000-student high school in Los Angeles. A simple Excel model consisting of solar panels and those energy storage systems is used to simulate energy flow with 24-hour and 7-day periods. Excel Solver identified a feasible configuration consisting of 4,536 m² of solar panels, 48.21 kg of hydrogen storage, a 75 kW fuel cell, and 683.2 kWh of battery capacity. The Excel Solver did not identify a solution in which a zero-battery system is feasible. However, these results demonstrate the potential for hydrogen storage to reduce battery dependence in school-scale renewable microgrids while highlighting tradeoffs among battery capacity, hydrogen storage, fuel-cell capacity, and excess solar energy.

Keywords: Green Hydrogen, Microgrid, Systems Simulation, Optimization, Renewable Energy

1. Introduction

Hydrogen is the most abundant element in the universe. In its gaseous form, hydrogen can act as fuel, combining with oxygen in a fuel cell to produce electrical current [1]. Unlike other combustion reactions that emit greenhouse gases, a hydrogen fuel cell produces electricity, water, and heat. Hydrogen can be produced through several pathways, but green hydrogen is generally understood as the cleanest, as it is produced by water electrolysis using renewable electricity. Electrolysis separates water into hydrogen and oxygen; a fuel cell reverses the

overall reaction to recover electricity from hydrogen and oxygen. With rising energy demands and concerns over greenhouse gas emissions, green hydrogen can provide long-duration storage for renewable electricity in low-carbon energy systems.

Hydrogen is more accurately characterized as an energy carrier than as a primary energy source [2, 3]. Hydrogen does not commonly occur in its gaseous diatomic form. Therefore, its production

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DOI: 10.54254/2754-1169/2026.36795

requires an upstream energy input, and its life-cycle greenhouse-gas emissions depend on the production pathway. A hydrogen-based electricity system that uses

water electrolysis therefore requires an external supply of electricity. When reducing operational greenhouse-gas emissions is the design objective, coupling electrolysis to renewable electricity is a deliberate system choice rather than an inherent property of hydrogen The ideal renewable energy source differs according to each area's geographical features. Given its comparatively high solar resource, Los Angeles provides an appropriate case study for a grid-independent solar hydrogen system [4].

Solar photovoltaic systems are often paired with lithium-ion batteries, but batteries and hydrogen be treated as direct substitutes. Hydrogen fuel is a separate entity from the fuel cell, the generator. The mechanisms of batteries differ in that they store the chemical energy inside themselves [5]. Hydrogen storage and lithium-ion batteries have different roles in a hybrid energy system. While the battery can respond quickly to changes in solar output and demand, hydrogen can hold energy for much longer periods despite the losses associated with electrolysis and fuel cell conversion [6, 7]. The case for reducing battery capacity is based on the multitude of environmental challenges that lithium extraction poses. Expansion of battery-material supply chains accelerate land degradation and strain water resources [8, 9]. This does not mean that hydrogen can simply replace batteries. Demonstration projects such as SoCal Gas's H2 Innovation Experience combine solar, hydrogen, and batteries [10]. However, fewer studies have focused specifically on minimizing battery capacity in school-scale solar-hydrogen microgrids. As such, this study investigates the extent to which hydrogen storage reduces the battery capacity requirement of the solar-hydrogen energy system. The question examined here is therefore narrower: can hydrogen take on part of the energy-storage role in a school microgrid so that the battery can be smaller without leaving electrical demand unmet? The model tests this question by varying solar panel area, hydrogen-storage, fuel-cell capacity, and battery storage.

2. Methodology

A simple diagram illustrates the energy flow directions, sourced from the sun.

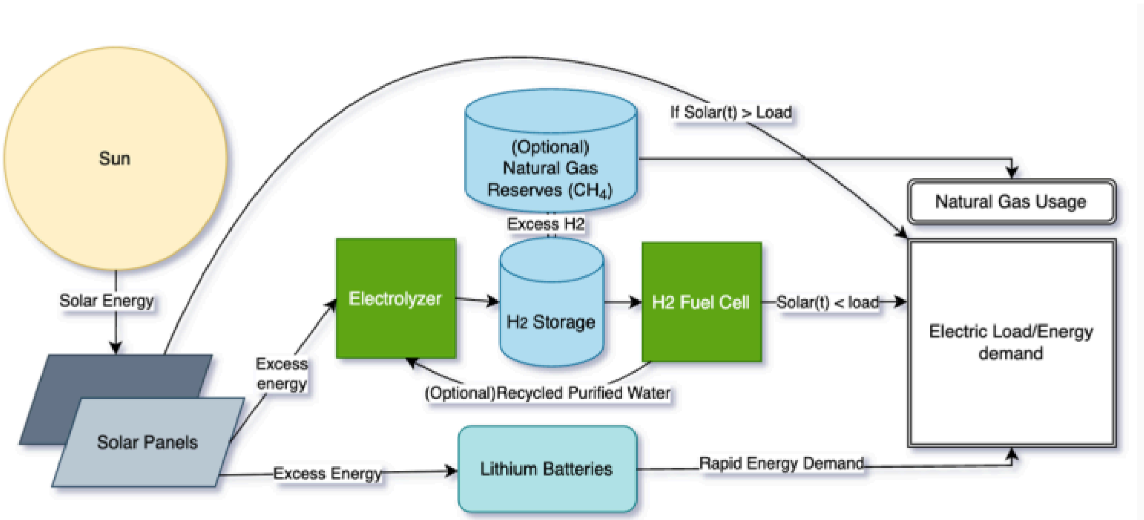

Figure 1. Energy system diagram

DOI: 10.54254/2754-1169/2026.36795

A spreadsheet with modifiable design parameters quantitatively describes the energy flow in the solar-hydrogen-lithium battery system in an LA high school with 2,000 students. Furthermore, the spreadsheet evaluates four scenarios: a 24-hour summer case, a 24-hour winter case, a seven-day summer case, and a seven-day winter case. The variables tracked in each tab are identical.

2.1. Variables

Time (hour): used to track fluctuations over time. In this simulation, a Δt of 1 hour is used to facilitate the conversion from kilowatts to kilowatt-hours. Power and energy are not interchangeable. Energy during each time step is calculated by multiplying power by the one-hour time interval. Because $\Delta t = 1$ hour, the numerical values in kW and kWh are equal for each hourly interval, even as their units and physical meanings are different. Two weather conditions, summer and winter, are tested in this project. A 24-hour period is modeled to visualize the solar and load graphs, while the other spans a week to monitor trends over 168 hours. Midnight is designated as hour zero in this simulation.

Solar (kW): The power generated by the solar panels is estimated from the average daily solar irradiance (kWh/m^2/day). In Los Angeles, this value historically peaks at 7.14 and dips at 5.26 during the winter [11]. Through this, one can calculate the peak solar irradiance through the formula:

$$I_{peak} = \frac{\pi I_{avg}}{2\mathrm{d}} \tag{1}$$

Where I_{peak} is the peak solar irradiance (kW/m^2), I_{avg} is the average daily solar irradiance, and d represents the daylight length.

Daylight length is longer above the equator during the summer, averaging 14.4 hours from hour 5.6 at sunrise to hour 20 at sunset [11]. With this information, the peak solar irradiance comes out to 0.78 kW/m2 of installed solar panels during the summer. A similar process can be employed to calculate corresponding values during the winter. The function to calculate the converted solar power:

$$S(t) = \begin{cases} E_s m I_{peak} \sin \frac{\pi(t - t_{sunrise})}{d} & if\ t_{sunrise} \leq t \leq t_{sunset} \\ 0 & otherwise \end{cases} \tag{2}$$

Where S(t) is the solar power over time, E_s is the solar panel efficiency, m is its surface area, t is the time in hours from midnight, $t_{sunrise}$ is the hour at which the sun rises, and t_{sunset} is the hour at which the sun sets.

Solar panel efficiency, solar panel size, and peak solar irradiance control the amplitude of the sine wave used to model instantaneous power available at each hourly interval. The sunrise hour shifts the sine wave so that it starts at sunrise, while *d* adjusts the width of the wave so that it corresponds with the daylight length. It is assumed that the amount of sunlight before sunrise and after sunset is negligible; thus, solar power is equivalent to zero at night. Note that the solar energy is distributed across a simple sine curve over daylight hours, which does not account for seasonal changes in solar elevation [12]. Therefore, the peak solar irradiance in winter may be overestimated.

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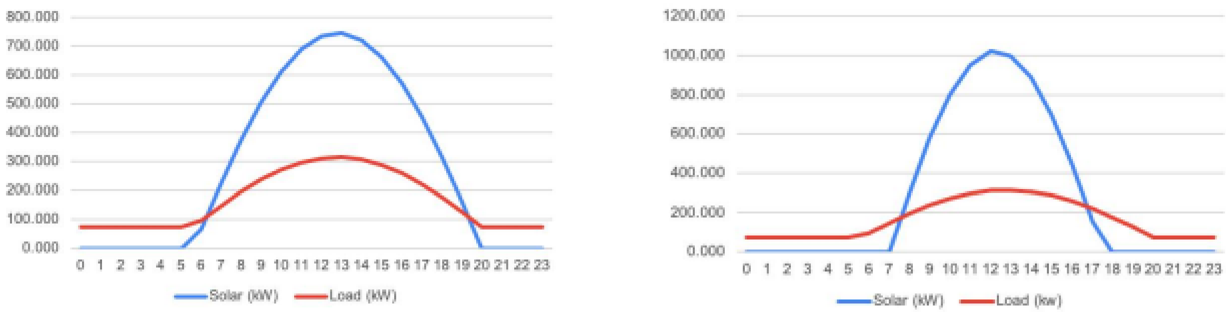
Load (kW): The load, or the electrical demand of the school, is modeled after a large high school with 2000 students. Since the average daily electricity consumption is assumed to be approximately 2.0 kWh, the model assumes a daily energy demand of approximately 4,000 kWh [13]. A school with 2,000 students is a large public institution, and similar simulations can be run on different numbers. For instance, while the monthly electricity consumption for the school in the described simulation is approximately 120,000 kWh, the mean monthly load for a small school is little over a sixth of that figure at 24,170 kWh [14]. Like the solar power function, a sine wave provides a close estimate of a hypothetical load over 24 hours:

$$L\left(t\right)=\begin{cases} 75+204\ \sin\frac{\pi(t-t_{sunrise})}{d} & if\ t_{sunrise}\le t\le t_{sunset} \\ 75 & otherwise \end{cases} \tag{3}$$

Where L(t) is the electrical load at hour t in kilowatts.

Background electrical appliances such as refrigeration or minimal lighting remain in operation even at night. Therefore, there is a baseline for the school's electrical load of 75 kilowatts [15]. Outside of those hours, the school's electrical load follows the shape of a sinusoidal wave. Unlike the electricity consumption of a standard residential unit that has a morning and evening peak due to the usage of kitchen appliances, the school electrical load peaks during midday [16]. The amplitude of the sine wave is the nearest whole number to which the daily energy consumption approximates 4,000 kWh.



(a) Day (Summer) (b) Day (Winter)

Figure 2. Solar power and electric load in the summer and winter

Net Power (kW) / Net Energy (kWh): The net power is the difference between solar power and electrical load, while the net energy is power converted to energy through integration. Since the time difference is one hour, those two values are equal. A positive net energy means that excess energy from the solar panels is going into the energy storage systems, while the opposite signifies a deficit that must be met either through the battery or the fuel cell.

$$N(t)=[S(t)-\ L(t)]\,\Delta\,t \tag{4}$$

where $N(t)$ represents the net energy during the one-hour interval, in kWh.

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Hydrogen Stored (kWh): As the input and output of hydrogen fuel are both energies, it is more convenient to create a separate column where hydrogen is measured in the kilowatt-hour unit as well. Conversion between the two units is simple, as one kilogram of hydrogen translates to 33.33kWh of usable energy [17]. The first value at hour 0 is equal to the amount of energy in the hydrogen storage unit at maximum capacity. Of course, this value can be modified as well to simulate different scenarios. The hydrogen stored is impacted by the electrolyzer efficiency, which has a wide range and may be adjusted.

$$H_e\left(t\right) = \begin{cases} H_e\left(t-1\right) + \ e_{ele}K_{ele}\left(t-1\right) \ - \ \frac{O_{fc}(t-1)}{e_{fc}} & if\, t \neq 0 \\ 33.33H_{Max} & if\, t = 0 \end{cases} \quad (5)$$

Where $H_e(t)$ is the energy stored in the form of hydrogen at hour t, e_{ele} is the electrolyzer efficiency, $K_{ele}(t)$ is the amount of energy transferred to the electrolyzer at hour t, $O_{fc}(t)$ is the amount of energy outputted by the hydrogen fuel cell at hour t, e_{fc} is the fuel cell efficiency, and H_{Max} is the hydrogen storage capacity in kilograms.

Energy to Electrolyzer (kWh): Since the system design prioritizes minimizing the battery usage, excess energy is first transferred to the electrolyzer to produce hydrogen.

$$K_{ele}\left(t\right) = \begin{cases} \min\left(N\left(t\right), 33.33(H_{Max} - H\left(t\right))\right) & if\, N\left(t\right) > 0,\ H < H_{Max} \\ 0 & otherwise \end{cases} \quad (6)$$

Where N(t) is the net energy at hour t and H(t) measures kg of hydrogen in storage at hour t.

Hydrogen Fuel Cell Energy Output (kWh): One of the main reasons hydrogen systems are often paired with battery ones is their fuel cell operating capacity, which maxes out at levels below the maximum electrical demand. Similarly, the hydrogen fuel cell energy output is dependent on the fuel cell efficiency, which is also a part of the design parameters.

$$O_{fc}\left(t\right) = \begin{cases} \min\left(-N\left(t\right), 33.33e_{fc}H\left(t\right),\ P_{fc}\right) & if\, N\left(t\right) < 0 \\ 0 & otherwise \end{cases} \quad (7)$$

Where $O_{fc}(t)$ is the energy outputted by the fuel cell at hour t, P_{fc} is the max power output of the fuel cell, and e_{fc} is the hydrogen fuel cell output efficiency.

Battery Charge/Discharge (kWh): As the secondary energy source, the battery discharge is equivalent to the energy deficit whenever the electric load is greater than the fuel cell capacity. In similar fashion, the battery charges when not all the excess energy is stored in the form of hydrogen fuel. The model imposes a maximum battery state of charge of 80%, leaving additional storage capacity available for short-term fluctuations in renewable generation and electrical demand. Energy that cannot be accommodated by either hydrogen or battery storage is treated as curtailed energy [6].

DOI: 10.54254/2754-1169/2026.36795

$$K_B(t) = \begin{cases} \min\left(N\left(t\right) - K_{ele}(t),\ 0.8C - B_e\left(t\right)\right) & if\ N\left(t\right) - K_{ele}(t) > 0,\quad v\left(t\right) < 0.8 \\ 0 & otherwise \end{cases} \tag{8}$$

Equation (8) describes the battery charging patterns, where $K_B(t)$ is the amount of energy transferred into the battery at time t, C is the battery energy capacity in kilowatt-hours (kWh), v(t) is the battery percentage, and $B_e(t)$ is the kilowatt-hours of energy stored in the lithium batteries at hour t.

$$O_B(t) = \begin{cases} \min\left(-\left(N\left(t\right) + O_{fc}(t)\right),\ B_e\left(t\right)\right) & if\ N\left(t\right) + O_{fc}(t) < 0 \\ 0 & otherwise \end{cases} \tag{9}$$

Equation (9) describes the battery discharging patterns, where $O_B(t)$ is the battery output in kilowatt-hours at time t.

Battery Energy (kWh) and Battery State: The former is dependent on the battery charge and discharge and keeps track of the amount of energy stored in the lithium battery system. The latter expresses this value in its percentage form.

Final Energy: (kWh): This category, not to be confused with net energy, is the difference between the initial solar energy and the energy stored in the electric-hydrogen system. In other words, this describes the excess energy that was dispersed instead of stored. To stay true to the objective of off-grid functionality, this value must always remain nonnegative. With those objectives and constraints in place, one can optimize for minimal battery use in a grid-independent system.

3. Results

Table 1. Design parameter constants

Symbol	Description	Value
E_s	Solar Panel Efficiency	0.22 [18]
Δt	Time Step (Hour)	1
E_{lee}	Electrolyzer Efficiency	0.65 [19]
E_{fc}	Fuel Cell Efficiency	0.66 [20]
v	Max. Battery State	0.80

Besides the variables across the four scenarios, another tab houses design parameters that are independent of climate and modeling duration. It includes constants such as solar panel efficiency, time step, electrolyzer efficiency, hydrogen fuel cell efficiency, and maximum battery state. Other variables are also considered and are restricted within a certain range determined based on data applicable to an average 2000-student high school in Los Angeles.

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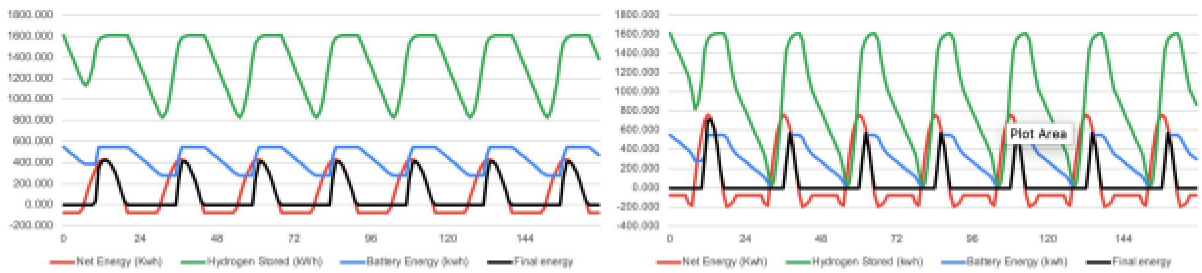
Table 2. Design parameter variable range

Symbol	Description	Units	Range	Used Value
H_{max}	H2 Storage	kg	1-50 [21]	48.21
m	Solar Panel Size	m^2	1-17000 [22]	4536
P_{fc}	Fuel Cell Output	kW	1-250 [23]	75.00
C	Battery Capacity	kWh	1-800 [24]	683.2
P_b	Battery Power	kW	1-200 [24]	101.4

Excel Solver identified the parameter values shown in Table 2. Under the selected component-capacity bounds, Excel Solver did not identify a feasible zero-battery configuration. Therefore, the optimization was performed using a combined hydrogen-battery storage system. The solver minimized a weighted objective combining curtailed energy and battery capacity, with a weighting factor of 10 applied to battery capacity to emphasize battery reduction. The GRG Nonlinear method was used subject to the parameter bounds listed in Table 2 and the requirement that unmet electrical demand remain zero throughout the simulated periods. Because the solution depends on the selected weighting factor, parameter ranges, and Solver method, the resulting configuration is interpreted as a feasible low-battery design rather than a proven global optimum. For instance, the solved variables must fall within the designated range, and unmet load was constrained to zero. In other words, there are no negative values in the final energy column, meaning the energy system is entirely independent. Figure 3 shows the temporal patterns of net energy, hydrogen storage, battery energy, and remaining energy during the seven-day summer and winter simulations.



(a) Week (Summer) (b) Week (Winter)

Figure 3. Net energy, hydrogen stored, battery energy, and final energy patterns

4. Discussion

Under the selected component-capacity bounds, some solar energy could not be absorbed by the electrolyzer, hydrogen storage, or battery and was therefore curtailed. This indicates a tradeoff between ensuring grid independence and efficiently utilizing the generated solar energy. However, there exists a solution within the selected constraints. The Solver result should consequently be read as one feasible balance between curtailment and battery size, not as a unique design. For instance, higher solar panel area or hydrogen tank storage capacity may compensate for less battery usage. This allows further reductions in battery capacity. Different Solver settings and parameter combinations may yield slightly different solutions as well. For instance, when excess energy is available, a higher-powered battery may compensate for a lower energy capacity by charging and discharging more rapidly. However, it is worth taking note that more charge and discharge cycles may affect battery life. Finally, increasing the solar panel area can only reduce energy deficits up to a certain threshold, since solar generation remains zero outside daylight hours.

Excel Solver was sufficient for this initial sizing exercise, but it provides limited information about how sensitive the result is to the chosen bounds and weighting factor. A code-based model could test a wider range of component sizes, different operating objectives, and more

weather and load scenarios. Going above this theoretical threshold yields limited additional benefits relative to changes in hydrogen storage or solar capacity. There are several reasons why no zero-battery configuration was found: in the winter scenarios, shorter daylight hours produced longer periods of energy deficits. The fuel-cell output limit restricted the rate at which stored hydrogen could supply electricity. Therefore, a relatively small battery remains useful for meeting short-duration power deficits, while hydrogen provides longer-duration energy storage.

5. Conclusion

This study simulates a simplified solar-hydrogen-battery model for the average 2,000-student high school in Los Angeles. Under the design parameters and weather conditions, Excel Solver identified a grid-independent solution using 4,536 m² of solar panels, 48.21 kg of hydrogen storage, a 75 kW fuel cell, 101.4 kW of battery power, and 683.2 kWh of battery capacity. A feasible zero-battery configuration was not identified within the tested design bounds. Therefore, a relatively small battery remains valuable for managing short-duration power deficits while hydrogen provides longer-duration storage. The current analysis does not establish an overall minimum battery capacity, but it demonstrates that battery dependence may be drastically reduced in a hydrogen-integrated school microgrid.

The model has several limitations. Solar generation and electrical demand were represented using simplified repeated daily profiles, and simulations only lasted up to seven days. Equipment degradation, variable weather, hydrogen leakage, water requirements, economic costs, and long-term operational changes were also excluded. A next step would be to use measured hourly weather and school load data over at least one full year and to include component costs, degradation, and broader component-capacity ranges. That analysis would provide a more credible estimate of the minimum practical battery capacity and the conditions under which hydrogen storage is most useful.

Acknowledgement

The author gratefully acknowledges Li Zhu for mentorship and guidance throughout this research project.

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DOI: 10.54254/2754-1169/2026.36795

Appendix

The complete simulation and optimization model is further explained as follows. The simulation considers four scenarios with different durations and weather conditions: summer day, summer week, winter day, and winter week. The summer and winter days were juxtaposed to contrast the effects of high and low solar energy generation, respectively. On the other hand, week-long simulations track energy fluctuations over 168 hours under summer and winter conditions.

Each scenario considers thirteen variables to visualize the energy flow. The methodology section details how each variable is used in the equations. Design parameters, listed in Table 1 and Table 2, remain constant throughout the simulation.

The optimization was carried out using the GRG Nonlinear Excel solver. The objective function is defined as the sum of the positive final energies across all four scenarios and ten times the battery capacity. The weight factor of ten is placed to emphasize battery reduction while minimizing excess energy. For constraints, all variables must remain in the specified range, and the sum of the negative final energies must be zero. This ensures that the model finds a configuration such that the hydrogen-battery hybrid energy system is grid-independent.