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Microgrids for Green Hydrogen Production for Fuel Cell Buses – A Techno-Economic Analysis for Fiji

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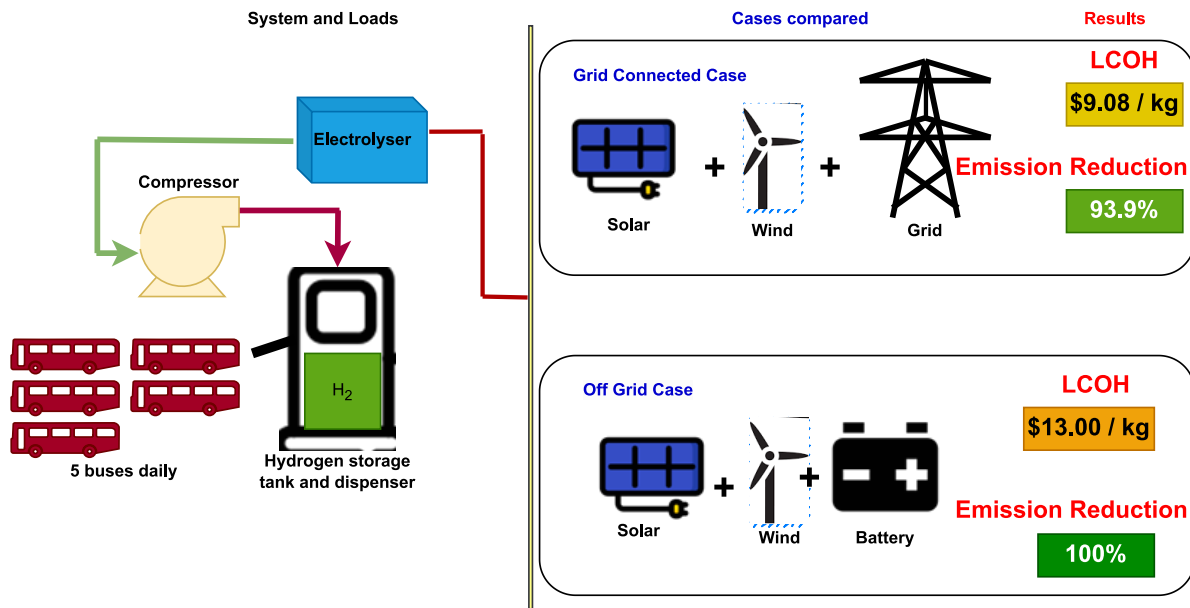
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Abstract - The study examines the feasibility of producing hydrogen for fuel cell buses in Fiji. The paper focuses on sizing hybrid microgrids comprising solar panels and wind turbines as the primary power source for hydrogen production while considering both off-grid and grid-connected cases. As no fuel cell vehicles exist in Fiji at present, five long-distance buses with daily travel of 380 km are proposed as a pilot scale baseline system, which would operate in the daytime only. Detailed technical and economic modelling was done using the HOMER Pro software with cost inputs derived from literature. A total of 3 cases for the on-grid and 4 cases for the off-grid systems are analyzed based on the various combinations of components. HOMER Pro optimized the grid configurations to minimize the Net Present Cost (NPC) values. All 7 cases were also modelled with and without the effects of hydrogen gas compressors to emulate the production of low-pressure gas without compression and compressed high-pressure hydrogen required for fuel cell buses. It was found that a grid-connected system with solar and wind hybrid was the most feasible configuration and yielded the lowest NPC of \$6 million. The grid-connected case also yielded a Levelized Cost of Electricity (LCOE) of \$0.10/kWh and a Levelized Cost of Hydrogen (LCOH) of \$9.08/kg with compression to 400 bars. The LCOH stood at \$8.73/kg for hydrogen generation without compression. The most feasible off-grid configuration using solar and wind power attained an LCOE of \$1.15/kWh while giving a LCOH of \$13.00/kg for compressed hydrogen. It was also found that neglecting hydrogen compression load and costs can underestimate the LCOH by as much as 6.92%. The off-grid best case had no CO₂ produced during its operation, leading to a net zero process that offsets 929.9 tons of CO₂ compared to the baseline. The grid-connected system does have some emissions but leads to a 93.9 % reduction in CO₂ emissions, offsetting 873.3 tons of CO₂ compared to the baseline. The study updated the cost inputs to account for inflation, logistics, and hydrogen gas compression, which are not available directly in HOMER Pro software. At the time of writing this paper, no feasibility study existed for hydrogen production in Fiji using renewable energy.

Graphical Abstract



Keywords: Hydrogen; Techno-Economic; Fuel Cell; Wind; Solar; Sustainable Transport.

Abbreviations

GHI	Global Horizontal Irradiation
CAPEX	Capital Expenditure
REPEX	Replacement Expenses
OPEX	Operational Expenses
O&M	Operation and maintenance
LCOE	Levelized Costs of Electricity
LCOH	Levelized Costs of Hydrogen
NPC	Net Present Cost
EFL	Energy Fiji Limited
RAB	Regulated Asset Base Model
FCCC	Fiji Competition and Consumer Council
POWER	Prediction of Worldwide Energy Resource

Nomenclature

$C_{ann,tot}$	Total annualised cost of the system (\$/yr)
C_{boiler}	Boiler marginal cost (\$/kWh)
H_{served}	Total thermal load served (kWh/yr)
E_{served}	Total electrical load served (kWh/yr)
V_{ele}	Value of electricity (\$/kWh)
E_{prim}	Primary electrical load (kW)
E_{def}	Deferrable load (kW)

$E_{grid,sales}$	Total energy sold to the grid (\$/kWh)
$M_{hydrogen}$	Total hydrogen production (kg)
$C_{i,ref}$	Nominal annual cash flow for base/reference system
C_i	Nominal annual cash flow for the current system
R_{proj}	Project lifetime in years
C_{cap}	Capital cost of the current system
$C_{cap,ref}$	Capital cost of base/reference system
P_{comp}	Compressor Power required
Q	Flow rate in kg/day
Z	Hydrogen compressibility factor
T	Compressor inlet temperature
R	Universal gas constant
N	Number of compressor stages
γ	Specific heat ratio
P_{out}	Outlet pressure of the compressor
P_{in}	Inlet pressure of the compressor
M_{H_2}	Molar mass of Hydrogen
η	Compressor efficiency

1.0 Introduction

Fiji Islands is situated in the South Pacific Ocean, with Australia and New Zealand as neighboring countries. With almost 300 islands scattered across an Exclusive Economic Zone (EEZ) of 1,290,000 km² [1], the island nation has a population of around 900,000 [2]. The main island of Viti Levu has an area of 10,429 km², hosting around 81% of the country's population [3] [4]. The country had a GDP of around \$5.58 billion in 2018, dropping by around 19% to 4.53 billion in 2020, mainly due to COVID-19. Fiji imports all its fuel from overseas countries as it has no reserves. In addition to environmental impacts, the importation of fossil fuels also leaves the Fijian economy vulnerable to the effects of global price fluctuations. Fiji's fuel imports ratio to merchandise imports was close to 30% between 2004 -2012 [5]. Around 60% of this fuel is used in the transport sector [6]. The global increase in oil prices will put added pressure on the Fijian economy, which has been severely affected by post-pandemic and governmental instabilities. In July 2022, the price of motor spirit (gasoline) reached FJ\$3.67 per litre, while Diesel was priced at FJ\$ 3.61 per litre [7]. In comparison, the price of motor spirit and diesel in December of 2021 were FJ\$2.75 and FJ\$2.31 per litre, respectively [8]. There was a 34% rise in motor spirit prices, while diesel prices increased by 56%. A major factor in this was the Russian invasion of Ukraine, which affected the entire world adversely.

This is another painful example of how vulnerable Fiji and other island nations are to global fuel supply disruptions. Given that almost 100% of Fiji's energy is imported and international geopolitical rivalry will likely intensify in future, it is imperative to seek more sustainable solutions for Fiji's transport sector. Regarding emissions, Fiji ranks far behind larger countries and emits around 0.006% of global emissions [9]. Despite this, Fiji has ratified the Paris Agreement and set ambitious Nationally Determined Contributions (NDCs). In its updated NDC plan, Fiji has targeted a 30% absolute reduction in carbon dioxide equivalent emissions and near 100% renewable-based energy generation by 2030 [10]. Several developed countries have adopted Electric Vehicle (EV) technology and introduced charging infrastructure to reduce emissions. Fiji has also leaned towards this trend, starting with increasing its imports of electric – Internal Combustion (IC) engine hybrid vehicles in 2013 [11]. In 2022, the country saw the launch of fully electric vehicles, which take around 7 hours to charge for a range of 200 km [12]. Several other EVs' have been launched in the country since then, and in 2023, the first electric vehicle charging stations were set up and opened to the public [13]. Along with EVs, Hydrogen Fuel Vehicles or Fuel Cell Vehicles (FCV's) have also gained commercial popularity globally [14]. FVC's operate in some developed countries [15], and neighbors Australia have recently introduced hydrogen-powered buses into their transport mix [16]. Hydrogen utilization through Fuel Cells (FC) produces zero emissions, and thus, it fits in well with the sustainable development goals of most countries [17]. The production of hydrogen is, however, a different venture. The emissions and costs caused during hydrogen production depend on the process used to produce hydrogen. The color of hydrogen gas is named after the process used to produce it. Green hydrogen is the term for hydrogen produced using renewable energy and has almost no emissions [18]. This is the most environmentally friendly process of hydrogen generation. While several different methods can be used to produce hydrogen, green hydrogen is mostly produced through the electrolysis of water [19]. This involves splitting water using electricity to form hydrogen and oxygen gas. An electrolyser performs this function. Specifically, Alkaline Water Electrolysis (AWE) is a cheap and common method for producing hydrogen [20]. For this study, AWE is the preferred type of electrolyser. Hydrogen generated in an electrolyser is normally compressed, stored, or dispensed directly to a vehicle or stationary fuel cell. A Fuel Cell performs the opposite function of an electrolyser – it generates electrical energy from hydrogen and oxygen gases [21]. Hydrogen production is needed via electrolysis, storage, and electricity generation via fuel cells using hydrogen and oxygen gases for a sustainable hydrogen economy. The transition from introducing hybrid electric vehicles to adding EVs to the transport mix took around a decade in Fiji (2013 to 2023).

The introduction of Fuel Cell Vehicles (FCVs) may occur in a shorter period, given the rapid growth in global FCVs. But before this feat is achieved, feasibility studies must be carried out to optimize investments in future. Several stakeholders have already expressed interest in setting up hydrogen generation facilities in Fiji [22]. The only literature available for hydrogen production comes from Kodicherla et al. [23], presenting potential annual hydrogen production capabilities at 3 locations in Fiji using wind energy only. From the literature review, no such feasibility studies currently exist relating to hydrogen generation in Fiji for use on FCVs. This is the information gap that the authors wish to address using this study.

In this paper, the authors have attempted to conduct a feasibility study of hydrogen production in Fiji using different grid configurations. The constraints, inputs, and outcomes are the key results of this study. To achieve sustainable development goals amid rapidly deteriorating climate conditions – zero emission measures need to be put in place urgently. Larger developed countries have already developed strategies to produce large-scale hydrogen to meet their emission targets and gain economic value by generating this fuel. Future fuel shortages during geopolitical conflicts will cause price increases, as experienced in the Russia – Ukraine (2022) conflict and the Israel – Hamas war in 2023. For developing countries like Fiji, the fluctuations in fuel prices, directly and indirectly, impact almost all facets of the economy. Dependence on fossil fuels forces more emissions and makes the nation vulnerable to economic crises caused by changes in global fuel supply lines. Fiji must consider alternative forms of fueling its energy needs. Australia has ambitious hydrogen generation targets for the long run [24]. Given Fiji's location – hydrogen imports from Australia may also be an option in the near future. Fiji also has considerable renewable energy potential to generate hydrogen for its needs.

This paper will investigate hydrogen-powered buses for transport between its major cities as a pilot case to determine the techno-economic parameters of hydrogen production in Fiji along with emission reductions. The aim is to determine the levelized cost of hydrogen production for different grid-connected and off-grid configurations and determine the best grid configurations for emission and cost reduction. All calculations and results are shown in US dollars for easy comparison with other studies. The study also proposes innovative ways to adjust the cost inputs available in literature to ensure the inputs are more realistic for the location of study and the end use of hydrogen. Additionally, this study also shows how much of a difference can be caused by neglecting hydrogen gas compression in green hydrogen production systems. Section 2 provides more detail on Fiji's energy mix and the current scenario in its transport sector. Section 3 provides a detailed methodology and covers all

definitions, components and equations used in modelling the cases followed by a results section. Each section is divided into small concise subsections to keep the information more comprehensive.

2.0 Fiji's Energy and Transport Sector

A. Generation Mix

Fiji's grid is critical to the country's energy infrastructure, providing its consumers with a reliable and consistent electricity supply. The Fiji grid has a peak demand of 204 MW, with a total installed capacity of 252 MW. Currently, 60% of Fiji's energy demands are being met by numerous hydropower plants ranging in size from 1MW to 72MW, 7% from Independent Power Producers (IPPs), less than 1% from wind, and the rest is catered via diesel or thermal power plants. Evidently, solar and wind resources are still under-utilized in Fiji; however, there are projects to develop a 5MW solar farm in Qeleloa, a 1MW PV system on the island of Taveuni, and a grid-interfaced solar power plant on Viti Levu [25]. The grid frequency is 50 Hz, and the nominal voltage is 240V. The grid operates according to the IEEE 1547-2018 grid code, which sets the technical requirements for interconnecting distributed energy resources to the grid. Energy Fiji Limited (EFL) operates the grid and ensures consumers' reliable and consistent electricity supply. The nominal characteristic of the grid is presented in Table I.

Table I. Operating Network Parameters

Characteristic	Description
Frequency	50 Hz
Nominal Voltage	240V
Peak Demand	204 MW
Total Installed Capacity	252 MW
Grid Code	IEEE 1547:2018
Grid Operator	Energy Fiji Limited (EFL)

B. Transportation

Figure 1 shows the increase in vehicle registration in Fiji from 2014 to 2021 [26]. Besides the slowdown in 2020 and 2021 due to COVID-19, vehicle imports have gradually increased in the country since 2014. Consequently, Fiji's annual CO₂ equivalent emission [27] also increased over the same period. With this trend, Fiji's goal of 30% emission reduction by 2030 will be challenging unless drastic changes are made. As urban centers grow, the need for

mobility between towns and cities will continue to rise. This will raise fuel importation, leading to a burden on the economy and environment.

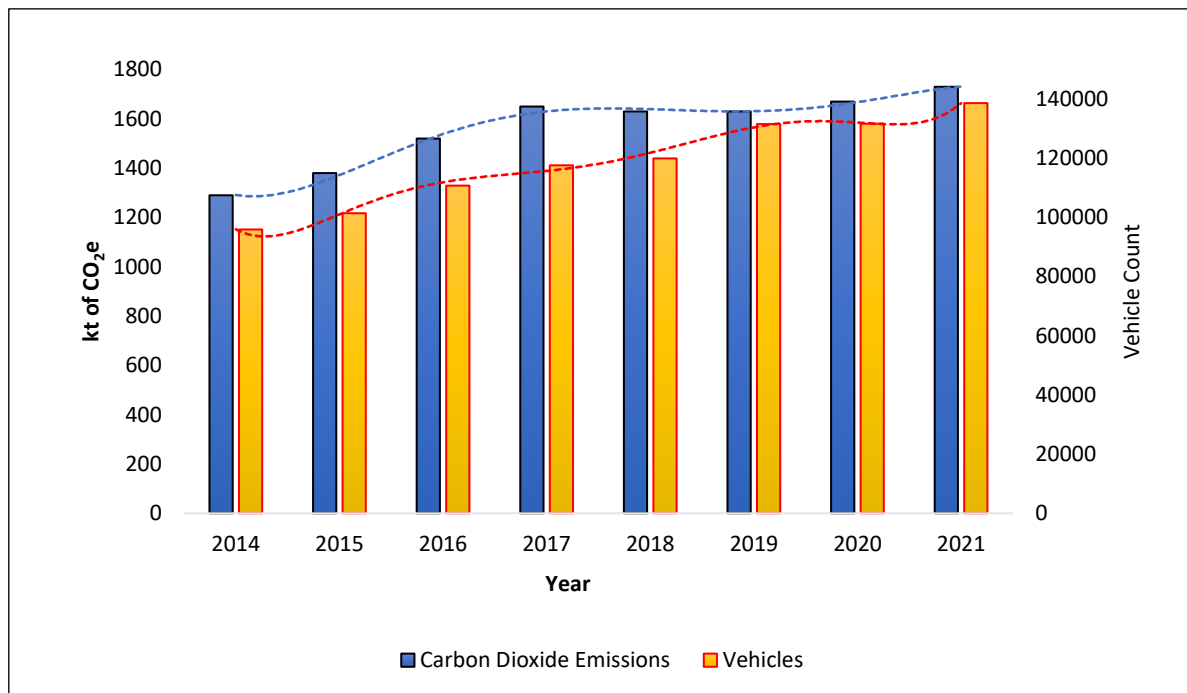


Figure 1. Fijis' emissions, along with the change in total vehicle numbers

C. Comparison of Electric and Hydrogen Vehicles

Both FCVs and EVs are viable options for emission-free transportation in Fiji. As highlighted earlier, hydrogen powered FCVs convert hydrogen gas into electrical energy for the vehicle's functionality. The only by-product in this process is water vapor emission, making FCVs environmentally clean. Sustainably produced green hydrogen negates emissions at the fuel generation stage and leads to a zero-emission scenario. EVs rely on energy stored in batteries, while FCVs rely on energy stored in compressed hydrogen. In both cases, an electric motor replaces the IC engine to power the wheels. Batteries are known to have higher power densities than hydrogen energy systems, but hydrogen systems have higher energy densities [28]. Energy density is the energy stored per unit mass, while power density is the power dissipated per unit mass. Hence, hydrogen systems can store much more energy per unit mass than batteries. Buses require much more energy; therefore, the battery volume and mass are significantly higher than those used in cars. This makes hydrogen fuel cells more appropriate for use in buses and trucks. Large FCVs have more range than conventional battery electric vehicles [29]. The extended range reduces the frequency of vehicle re-fueling, especially for long-haul routes. Charging time in most EVs is slow, with around 6-8 hours required for full recharge [30]. Comparatively,

fuel cell buses have been found to have an average hydrogen refill time of about 10.28 minutes [15]. Most buses in Fiji and the region run on diesel and are poorly maintained. Emissions from these buses form a large share of the emissions from the transport sector. Hence, the zero-emission reforms must start with the heaviest emitters, such as buses and trucks. Another issue EVs would face is their inability to use imported energy. The Fijian power grid reliability depends on various factors, such as weather, ageing infrastructure, and the daily electricity demand. Recently, many upgrades have been seen in the local grid; however, despite these efforts, power outages can still occur in Fiji, particularly during severe weather events such as tropical cyclones or heavy rain. A report [31] from Fiji Meteorological Services states that the number of cyclones in Fiji has increased in frequency and intensity. More cyclones would lead to more power outages and grid blackout periods become longer with higher-intensity cyclones. These situations would turn off grid-tied charging stations. In addition, some remote areas of Fiji may experience more frequent power outages or voltage fluctuations due to the challenges of maintaining and upgrading infrastructure in these areas. While both FCVs and EVs rely on the grid, FCVs are more robust during natural disasters, given that imported energy can be used to maintain their operation during prolonged periods of grid downtime. Hydrogen can be compressed and transported easily from one location to another. In case of nationwide power outage for long periods – hydrogen can also be imported from other countries in future. Australia has already begun a shift towards hydrogen production [32] and may be an alternate source of hydrogen gas for these vehicles during natural disasters. For EVs in the long term, power outages will force all the loads onto standby diesel generators, increasing GHG emissions. This would also require large amounts of diesel fuel to be held in storage or imported and the generators to be regularly maintained. For FCV's, there is always an option to import green hydrogen and not cause elevated emissions during production downtimes locally. Like fossil fuel tanks, hydrogen tanks are structurally designed to withstand storm conditions. Any hydrogen leakage from the tank will quickly be diluted in open spaces, and since the content is not toxic, it would pose no significant environmental risks unlike stored fossil fuels. During global conflicts, fossil fuel supply chains would face considerable impacts, but green hydrogen produced locally or by nearby countries would have the least impact. The idea should be to not rely on diesel in long term downtime scenarios.

3.0 Methodology

The main objective of the present study was to determine the most feasible microgrid for green hydrogen production in Fiji for powering fuel cell buses. An additional comparison was also

made to the possible offset in carbon emissions from the baseline scenario where diesel buses are currently in use. HOMER software was used to carry out the analysis. HOMER has been used in similar analyses by several studies [33], [34], [35], [36]. The following sections discuss in detail the methodology applied to this techno-economic analysis including the baseline cases, resources, choice of components, economic parameters, cost inputs and other details that were essential to model the different cases in HOMER.

A. Baseline Scenario

The baseline scenario for this study is to consider five diesel buses operating between Suva city and Nadi town. The route of current diesel IC engine buses is shown in Figure 2. Each bus covers 190 km each way daily, amounting to 380 km of daily commute per bus. One liter of diesel fuel combustion releases around 2.7 kg of CO₂ [37]. The average fuel economy of buses in Fiji was reported as 2.52 km/L [6]. Another study examined diesel buses in Mexico City and found the fuel economy to be 1.8 km/L [38]. This study takes an average fuel consumption value of 2.16 km/L for diesel buses.

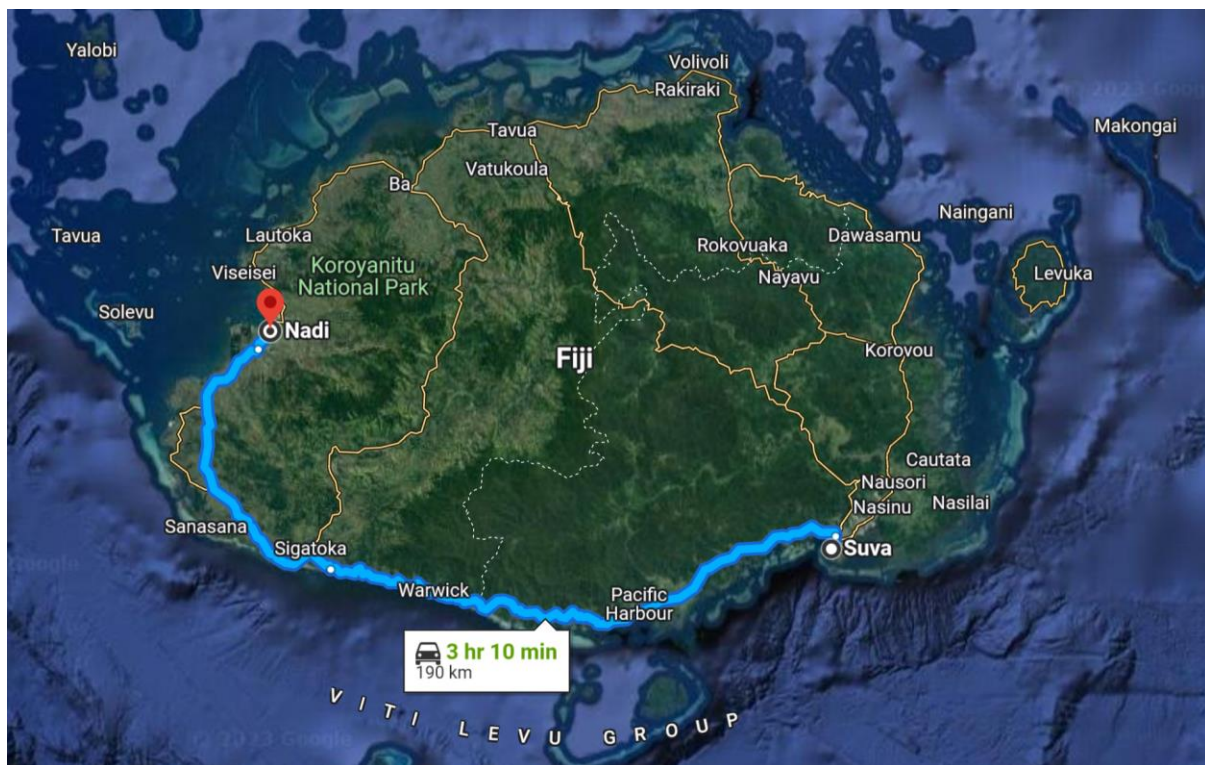


Figure 2. Commute route between Suva and Nadi (Source: Google Maps)

In a recent study in China, conventional diesel buses have been reported to have emissions of around 1.009 – 1.341 kg/ km [37]. For Fiji, the higher value can be used, given the age of buses. Diesel costs of around FJ \$3.00/liter (US \$1.31) can be used as an average, given that costs had

even reached FJ \$3.61/liter in July 2022. The baseline parameters of fuel economy, emissions and costs for the current diesel buses servicing the route are provided in Table II.

Table II Baseline Parameters of Diesel Bus Commute

Parameters	1 Bus		5 Bus	
	Per day	Per annum	Per day	Per annum
Travel distance (km)	380	138,700	1900	693,500
Fuel Usage (L)	175.92	64,210.80	897.60	321,054
Emission (CO₂) (kg)	509.58	185,996.70	2547.90	929,983.50
Fuel Cost – (\$US)	232.21	84758.25	1161.07	423791.28

B. Solar and Wind Resource Inputs

The proposed site's wind and solar PV data were extracted directly from HOMER software. A comparison of the wind data was made with other studies [38], [39], which have recently measured wind speeds in Fiji. The average monthly global horizontal irradiation and wind speed variation used per month is shown in Figure 3. Nadi's Global Horizontal Irradiation (GHI) levels were obtained from the NASA Prediction of Worldwide Energy Resource (POWER) database at a Latitude = -171.75 and Longitude = 177.25. The annual average Global Horizontal Irradiation (GHI) is approximately 5.64 kWh/m²/day, and the average wind speed is 6.04 m/s at 10 m height for the site. The monthly average wind speeds and solar irradiation data are shown in Figure 3. In the months of March to July as solar irradiation reduces, the average wind speeds increase and thus a hybrid renewable energy system is ideal for the site.

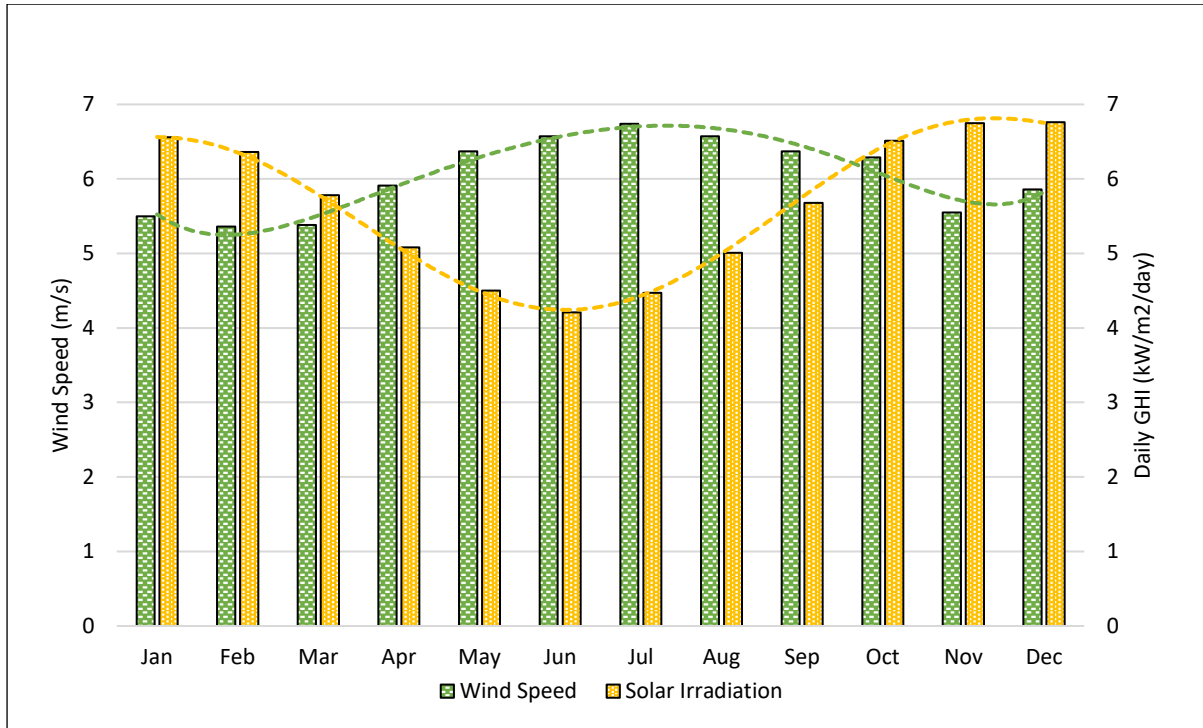


Figure 3. Annual average wind speed and solar irradiation in Nadi

3.1 Economic Parameters

A. Capital Expenditure (CAPEX)

Capital Expenditure (CAPEX) refers to the initial capital incurred in setting up the project's components, including the power sources, electrolyser, storage tanks, and all other equipment required for hydrogen production and storage. The CAPEX includes the total installed cost of these components, mainly purchasing and installing the equipment. It also consists of the costs associated with designing and engineering the system. The CAPEX for all components used in the design has been selected using manufacturers' and suppliers' prices [40]. The actual cost inputs are presented later.

B. Replacement Expenses (REPEX)

The replacement expense is the cost of replacing a component at the end of its lifetime. The replacement cost may differ from the initial capital cost due to various factors [40] [41]. For instance, not all components may require replacement at the end of their lifetimes, and the initial capital cost may have been reduced or subsidized by an external organization. Additionally, fixed costs, such as travel expenses for site visits shared during the initial construction phase, may no longer be shared during replacement. It is also essential to consider the potential reduction in the purchase cost of technology over time when calculating

replacement costs. These factors have been considered to estimate the REPEX input cost for each component accurately.

C. Operational Expenses (O&M)

The Operation and Maintenance (O&M) cost is another input parameter and refers to the expenses associated with the operation and maintenance of the project's various components. These costs include routine maintenance, repair, and replacement of faulty equipment, labor costs, and any necessary spare parts. The total O&M cost of the project is the sum of the O&M costs of each component. These expenses are usually entered as an annual amount, except for specific details such as the PV and the Wind turbine, where the cost is entered as an hourly value (kWh), which is then multiplied by the operating hours per year to calculate the annual O&M cost. In addition to these costs, HOMER also considers other charges, including system-fixed O&M costs, emissions penalties, and capacity shortage penalties. The grid cost is also factored in the annual cost of buying power from the grid minus any revenue earned from selling power to the grid.

D. Levelized Costs of Electricity (LCOE)

The LCOE is an output parameter used to calculate the average cost of producing electricity from a power generation system over its lifetime. In HOMER, the LCOE is calculated by dividing the total annualized cost of the plan (which includes both the initial capital cost and ongoing O&M costs) by the total electric load served minus the fee of serving the thermal load. The LCOE equation also considers the boiler marginal cost and the total thermal and electrical loads served [33].

$$LCOE = \frac{C_{ann,tot} - C_{boiler}H_{served}}{E_{served}} \quad (1)$$

The second term in the numerator (C_{boiler}) accounts for the cost of serving the thermal load, which is zero in systems like wind or PV that do not have a thermal load.

E. Levelized Costs of Hydrogen (LCOH)

The LCOH is an output parameter which gives the cost of producing a kg of hydrogen using the modelled system. It is useful in comparing the cost of hydrogen production from different energy sources, considering various factors such as the total cost of the system's lifetime [40]-

[41]. For the optimization purpose in HOMER, the following equation is used to determine this parameter.

$$LCOH = \frac{C_{ann,tot} - V_{ele}(E_{prim,AC} + E_{prim,DC} + E_{def} + E_{grid,sales})}{M_{hydrogen}} \quad (2)$$

Nasser et al. [42] used MATLAB and Simulink simulations to estimate Egypt's minimum and maximum LCOH values using wind turbines and solar PV. The LCOH were between \$3.73/kg – \$4.65/kg for that study. Rezai et al. [43] found a LCOH between \$2.118/kg and \$2.261/kg in a survey focused on Afghanistan for hydrogen generation using wind energy. Another study [44] reported costs of \$3.49/kg – \$5.96/kg, while a separate study [45] found a LCOH of \$17.2/kg - \$33.8/kg for off-grid systems. Grid-connected and standalone systems will yield different LCOH values depending on the grid tariffs and energy mix of the grid. The LCOH values will also be affected by the grid configuration, choice of hydrogen generation method and compression costs. The LCOH is one of the key output parameters of this study.

F. Net Present Cost (NPC)

The NPC of a system is calculated as the present value of all costs, and this includes capital costs, replacement costs, operation and maintenance costs, fuel costs, emission penalties, and the cost of buying power from the grid, minus the present value of all revenues, including salvage value and grid sales revenue earned over the lifetime of the system [40]. HOMER determines the total NPC by summing each year's discounted cash flows for the project lifeline. The total NPC is the primary economic output of HOMER, used to rank all system configurations in optimization results, and the basis for calculating the total annualized cost and the levelized cost of electricity. A lower NPC is desirable for any hydrogen production case.

3.2 HOMER Pro Software Details

The primary instrument used for this study is the HOMER Pro software, a computer-aided design tool developed by the US National Renewable Energy Laboratory (NREL). It performs three major tasks: simulation, optimization, and sensitivity analysis. The simulation process determines the feasibility of a designed power system. This study depends on the system's ability to adequately supply the primary electrical and hydrogen loads while incurring minimum NPC, LCOH, and LCOE. In addition, it computes the total life cycle cost or NPC of the designed system, including the installation, operation, and maintenance cost minus the revenues earned over the project lifetime. During the optimization process, HOMER iteratively

determines the best possible system configuration. Usually, the design which yields the lowest NPC and satisfies all user-defined model constraints is the prime choice for implementation. During this process, the size of the PV array, number of wind turbines, battery bank capacity, converter size, electrolyser size, and storage volume are also optimized based on the input assumptions. Sensitivity analysis involves performing multiple optimizations using all possible combinations of the input arguments. It reveals how the outputs may change for variations in the input data. A variable with multiple values over a period can be considered a sensitivity variable. Some of these are fuel price, grid power purchase or sell-back price, interest rates, and project lifetime [46]. However, for this study, all the key variables are kept constant, and both the grid-connected and standalone models are simulated for 25 years to maintain comparability with a nominal discount rate of 8% and an expected inflation rate of 2% over the projects life. The overall optimization algorithm is shown in the flowchart in Figure 4.

3.3 Model Component Description

This section provides the details of the different components used to model the grid connected and off – grid cases for hydrogen production.

A. Solar PV Module

Solar energy is a vital energy component for the design and optimization of this project. With abundant sunshine throughout the year, Fiji has excellent potential to harness power directly through solar energy as a clean and sustainable alternative. The SunPower SPR-X21-335-BLK model of the PV array was selected for this project from the database in HOMER software. The board has a rated power output of 345 W with an efficiency of 21.5 %. The panel has 96 monocrystalline cells and a recorded lifetime of 25 years. The derating factor in this study is set as 88% with a maximum operating temperature of 43°C.

B. Wind Turbine

Harnessing wind energy represents a promising opportunity to establish a sustainable, clean energy source. The WES30 wind turbine model, a high-performance turbine manufactured by Wind Energy Solutions, was selected for this project. The WES30 turbine delivers a rated power output of 250 kW, with an efficiency of 32%. The turbine is a two bladed type with a rotor diameter of 30 m and a hub height of 48 m. The relationship between the wind turbine's power output and the available wind speed is shown in Figure 5.

C. Grid

Fiji's only electricity distribution provider is Energy Fiji Limited (EFL), a public enterprise. The tariffs EFL charges for energy usage are based on the approved regulatory framework proposed by Fiji Competition and Consumer Commission (FCCC) in 2019, built on the Regulated Asset Base Model (RAB) to allow a fair return on investment in the power sector. An increase in the reactive power usage in the country by 46% in 2021 compared to the previous year has also prompted EFL to implement a reactive energy usage tariff to maintain compliance with the power factor requirement specified under the 2021 Electricity Act [25]. In HOMER, a grid power price of \$0.19/kWh and a sell-back price of \$0.12/kWh was used for the grid with monthly net purchases calculation. The grid sellback is applied when the excess energy is sold to the grid.

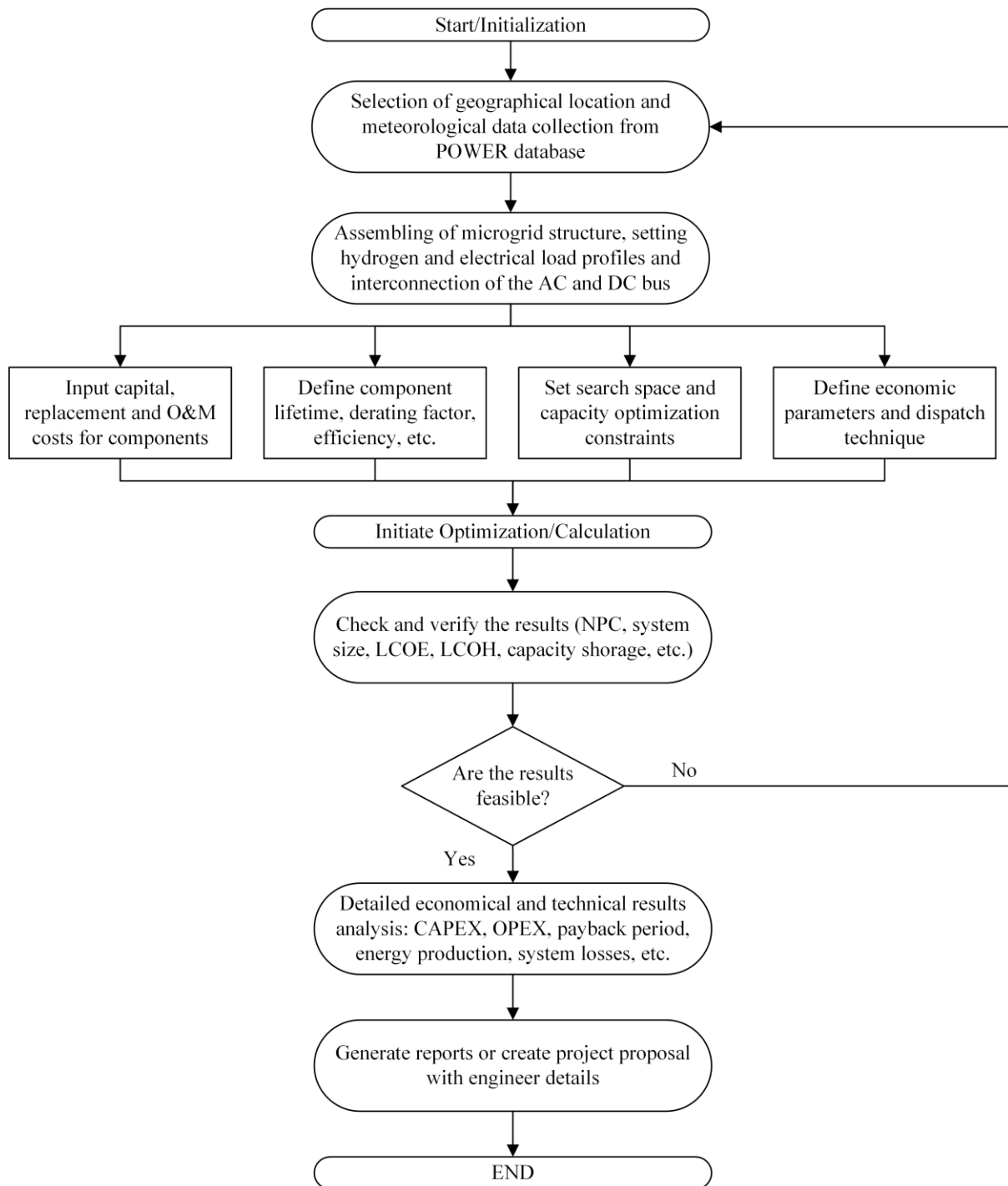


Figure 4. HOMER optimization algorithm

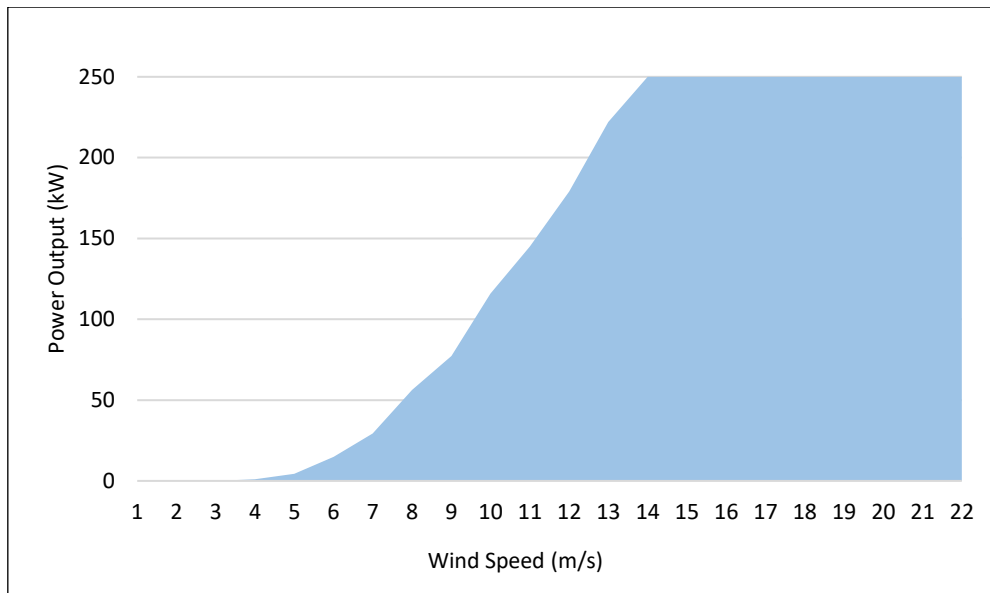


Figure 5. WES30 Wind turbines' power output curve

D. Converter

The use of a converter in this study is to connect the DC side with the AC side efficiently. It plays a crucial role in efficiently transforming the generated energy from renewable energy systems into usable electricity for AC loads. In a standalone system, the converter is also responsible for maintaining power quality standards by regulating the specified operating voltage levels and frequency setpoints and reducing current harmonics [47], [48]. A bidirectional DC/AC/DC converter is desirable in most microgrid applications. The HOMER generic converter has been used for this case study, accounting for any power conversion losses.

E. Battery

Batteries are essential in the standalone scenario, where power generation and consumption are isolated. The selected battery model for this project is the 1kWh Lead Acid [ASM] battery, providing a reliable energy storage solution. The battery system's critical specifications include a nominal voltage of 2V and a capacity of 1.03 kWh, or 513Ah. This battery's minimum allowed state of charge is 30%. A string size of 375 connected batteries, would result in 750V at the DC bus.

F. Electrolyser

The most common form of hydrogen production is Steam Methane Reforming (SMR) [16]. However, this method produces carbon dioxide as a by-product, so the process of electrolysis is fast becoming an alternative to produce cleaner hydrogen. Electrolysis is an electrochemical reaction in an electrolyser where water molecules break into hydrogen and oxygen gas in the

presence of electricity and a catalyst. Alkaline electrolysis is a standard method where an alkaline solution of sodium hydroxide or potassium hydroxide is used as the electrolyte [49]. Current passing through the electrodes generates hydrogen at the cathode and oxygen gas at the anode. Another type of electrolyser is the Polymer Electrolyte Membrane (PEM) electrolyser which uses a solid polymer membrane as an electrolyte [50]. While they can produce high-purity hydrogen, PEM electrolysers are more expensive than alkaline electrolysers [51]. This study assumes the use of alkaline electrolysers for hydrogen generation with 85% efficiency. Most alkaline electrolysers operate at a pressure of around 25 – 30 bars [52], while hydrogen buses typically require hydrogen at 350 bars. Hydrogen compression is needed before it can be dispensed to the buses. It is worth mentioning that research is also accelerating in the area of seawater electrolysis [53], which can have enormous potential for Fiji and other maritime nations.

G. Hydrogen Tank and Compressor

An electrolyser can generate hydrogen at low pressure. It must then be compressed to a higher pressure to make hydrogen more viable and compactly stored [54]. While a hydrogen compression module is unavailable in HOMER, a simple equation was used to determine the compression power. The calculated load was then added to HOMER as an electrical load profile to simulate the compressor load. The following equation [55] was used to estimate the power required for hydrogen compression from 30 bars to 400 bars.

$$P_{comp} = Q \left(\frac{1}{(24)(3600)} \right) \frac{Z.T.R}{M_{H_2} \cdot \eta} \frac{N \cdot \gamma}{\gamma - 1} \left(\left(\frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{N\gamma}} - 1 \right) \quad (3)$$

The compressor power was added as an electrical load in the system along with the stations auxiliary load. Hydrogen compression contributes to around 17.4 % [56] of the total costs of a hydrogen production setup. Using this value as an estimate, the electrolyser capital cost per kW was increased by 17.4 % to account for the compressor capital costs. An additional 8% [57] increase was applied to the electrolyser O&M to account for the operational expenses of hydrogen compression. While most buses require hydrogen storage at 350 bars [15], using the higher value of 400 bars in calculations accounts for pressure losses during the storage and transfer of hydrogen. The hydrogen tank component ensures that hydrogen storage is initiated, and a suitable size is estimated based on the capacity. Assuming two days of autonomy, the hydrogen tank capacity is kept at 280 kg while the daily demand is 140 kg for the five buses. If the compression-related costs are not accounted for in the analysis, an unrealistic low cost of

hydrogen may result. In systems where hydrogen needs to be stored at high pressure to be dispensed to vehicles, hydrogen compression cost cannot be neglected. Compression costs may not be as significant when stored hydrogen is fed directly into fuel cells to generate electricity. This study also compares the LCOH values resulting from analysis with and without the compressor costs to determine the differences on costs by neglecting hydrogen compression.

H. System Load Profiles: Hydrogen Dispensing and Electrical loads

The proposed microgrids have two types of loads: hydrogen and electrical. The primary hydrogen load is the fuel demand of five buses between 6:00 a.m. and 3:00 p.m. daily at the hydrogen dispensing station. While the actual travel distance is 380 km, an additional 20 km range is added for safety and off-route flexibility. The hydrogen consumption for fuel cell buses was taken as 7 kg/hour [15], and with the daily distance the hydrogen load per bus was found to be 28 kg per round trip.

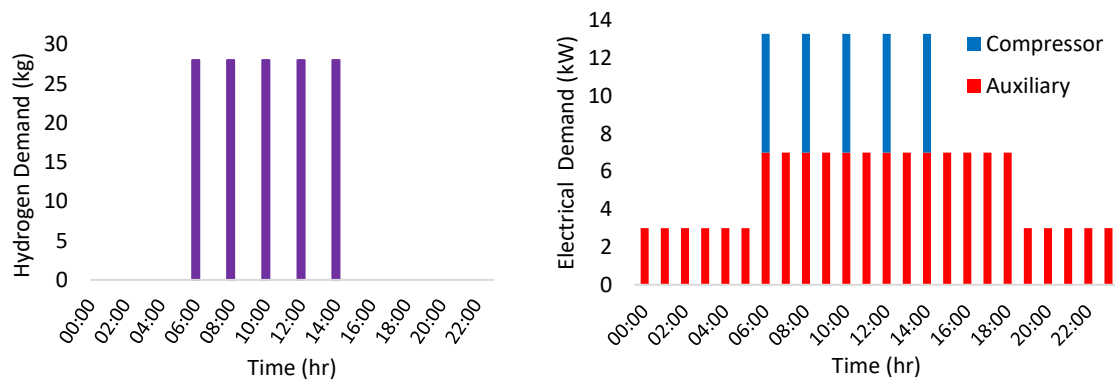


Figure 6. Daily hydrogen and electrical load demand

The compressor was assumed to be activated simultaneously with the electrolyser to maintain the optimum storage pressures. Using equation 3, the compressor power was estimated to be around 6.3 kW as seen in Figure 6. A varying auxiliary load was also assigned to the refueling station which would cater for lighting, communications, and other minor operational equipment. This load (Figure 6) was estimated to be 7 kW during the station’s operational hours in the daytime and 3kW otherwise. Both the electrical loads are connected to the AC bus. The electrolyser is also an electrical load; however, the exact capacity is unknown until the optimization process is completed and HOMER then uses this value directly.

3.4 Component Cost Inputs

The cost of each component used in the power conversion topology is the critical aspect of the HOMER optimization algorithm. Table III shows the original per unit costs of the components derived from literature. These values were not used directly and adjustment factors were

multiplied to these costs. Initial capital, replacement costs, and operation and maintenance costs are key factors that determine the NPC of the proposed system in various possible configurations over the 25-year project lifetime. Since the capital cost data in some cases were more than three years old, they needed to be adjusted for historical inflation and escalation factors. It was expected that the price of goods would have increased since these values were published, so the inflation rates of the past years till the current year were used to approximate the new inflation-adjusted capital costs. For ease, it was assumed that all components would originate from the United States of America, and its inflation rates were used. In actual projects multiple quotations from several equipment manufacturers would be more realistic but it would also be very complex and time consuming.

Table III. Cost data for different components derived from literature

Components	Type/Model	Unit Capacity	Capital Cost	Replacement Cost	O&M Cost	Ref
Solar Panels	SPR-X21-BLK	0.335kW	\$1192.81/kW	\$1192.81/kW	\$16/kW	[58]
Wind Turbine	WES250	250kW	\$800,000	\$800,000	\$9,600	[59]
Battery	1kW Lead Acid	1.03kWh @ 513 Ah	\$300/unit	\$300/unit	\$10/unit	[60]
Electrolyser	Generic	0-1500kW (optimization allowed)	\$1500/kW	\$1200/kW	\$30/kW	[61]
Converter	Generic	800kW	\$500/kW	\$500/kW	\$0/kW	[62]
Hydrogen Tank	Generic	220 kg	\$383/kg	\$383/kg	\$3.83/kg	[63]

Additionally, Fiji is located relatively far from the major equipment suppliers, and costs such as freight and handling would play a more pronounced role in the hydrogen production system in this study. To approximate these costs, a logistics cost factor (L) of 4 % [64] for solar PV panels was used and assumed to be the same for all other components, given that the panels form the bulk of the capital costs. Using the inflation rates (I_n) over the last n number of years and the logistics cost as a percentage of the capital cost, a new capital cost value was approximated, which was given as:

$$\text{Adjustment Factor} = (1 + I_1)(1 + I_2) \dots (1 + I_n)(1 + L) \quad (4)$$

$$\text{Adjusted Capital Cost} = \text{Literature Capital Cost} \times \text{Adjustment Factor} \quad (5)$$

Using the inflation rate and logistics costs, an adjustment factor of 1.2 was found. This value was multiplied by the capital costs in Table III to determine the adjusted capital costs suitable for this study in Fiji which was then fed into HOMER. The changed or increased capital costs

accounted for the effect of historical inflation until this study, and HOMER further applies inflation rates to the analysis over the project's lifetime at 2 % per year.

3.5 Case Configurations Compared

A. Grid Configurations

Two primary system configurations are considered: the grid-connected or on-grid and the standalone or off-grid scheme, as portrayed in Figure 7. In both scenarios, primary power production sources are solar panels and wind turbine generators connected to a common DC bus. The electrical loads (electrolyser, compressor, auxiliary, and community) are placed on the AC bus with a bidirectional converter for power transfer between the DC and AC bus. The hydrogen load is coupled in parallel with the hydrogen storage tank for an autonomous mode of operation during low hydrogen production from the electrolyser. This study has considered seven different system configurations (Table IV). Cases G1-G3 are on-grid systems where the grid supplies the electrolyser and auxiliary loads when the wind turbines and solar panels cannot satisfy load demands. Cases S1-S4 represent off-grid systems where a battery bank is used for power storage and autonomous mode of operation during low power production from renewable sources. The combination of different components for the 7 different cases is summarized in Table IV.

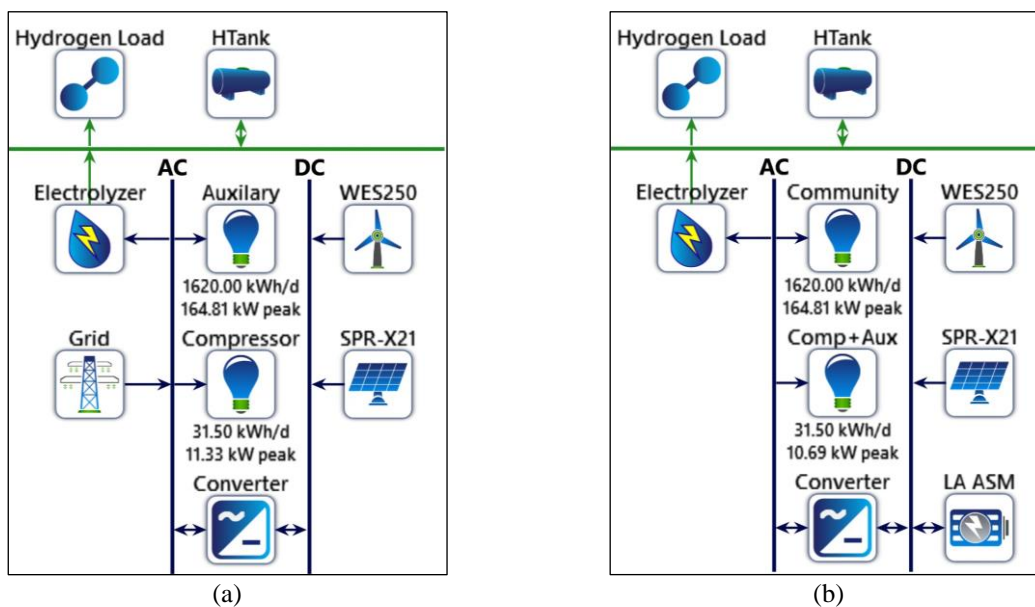


Figure 7. Proposed (a) on-grid and (b) standalone hydrogen production system.

Table IV. Microgrid Configurations Tested

Case #	Grid	Battery	Solar PV	Wind Turbine	Electrolyser	Hydrogen Tank	Electrical Loads
G1	•		•	•	•	•	•
G2	•		•		•	•	•
G3	•			•	•	•	•
S1		•	•	•	•	•	•
S2		•	•		•	•	•
S3		•		•	•	•	•
S4			•	•	•	•	•

4.0 Results and Analysis

A. Optimized System Sizes

The optimized sizes for the grid connected cases G1-G3 are presented in Table V. The columns show the optimized sizes of the components for the load cases as determined by HOMER. The load profiles remained the same for all cases, so the hydrogen tank size was 280 kg for all cases.

Table VI summarizes the optimized system sizes for off-grid hydrogen production using the Load Following (LF) algorithm. The solar panel, wind turbine, converter, and battery sizes are optimized according to the algorithm. The optimization was based on minimizing the NPC and as such some components such as the electrolyser was sized differently for different cases depending on the variability of the renewable energy sources.

Table V. On-grid Optimized System Size

Case #	Solar Panels (SPR-X21)	Wind Turbines (WES250)	Converter (kW)	Electrolyser (kW)	Hydrogen Tank (kg)
G1	3180	3	2232	500	280
G2	3464	-	2232	750	280
G3	-	20	2232	1000	280

Table VI. Off-grid Optimized System Size

Case #	Solar Panels (SPR-X21)	Wind Turbines (WES250)	Battery (LA ASM)	Converter (kW)	Electrolyser (kW)	Hydrogen Tank (kg)
S1	1659	2	375	8660	750	280
S2	3028	-	2625	1212	1000	280
S3	-	23	375	857	1000	280
S4	1933	10	-	670	500	280

B. Economic Analysis of Cases

A key aspect of selecting the best system for implementation is the NPC. This has typically been optimized to a minimum value for maximum long-term profit or the lowest losses. Figure

8 shows the contribution of the different cost components to the project over its lifetime. As seen in Figure 8, cases G1 and G2 have the lowest NPC (\$6.00 million) and consequently are the most cost-effective options in the grid-connected cases. Case G3 requires the highest capital expenditure for grid cases at \$ 22.28 million, whereas cases G1 and G2 have a capital expense of \$9.96 million and \$8.01 million, respectively. The high CAPEX requirement for G3 is due to the elevated costs of wind turbines. A related pattern is noted in the prices of replacing the components at the end of their lifetime, in which G3 expects a replacement cost of \$6.17 million. As for the O&M cost, the system tends to supply excess power to the grid to recover some operating expenses. Therefore, the O&M cost shown in Figure 8 is the plant maintenance expense minus revenue generated via grid sales. For all cases due to high revenue generation from the sale of excess electricity, the O&M values are negative.

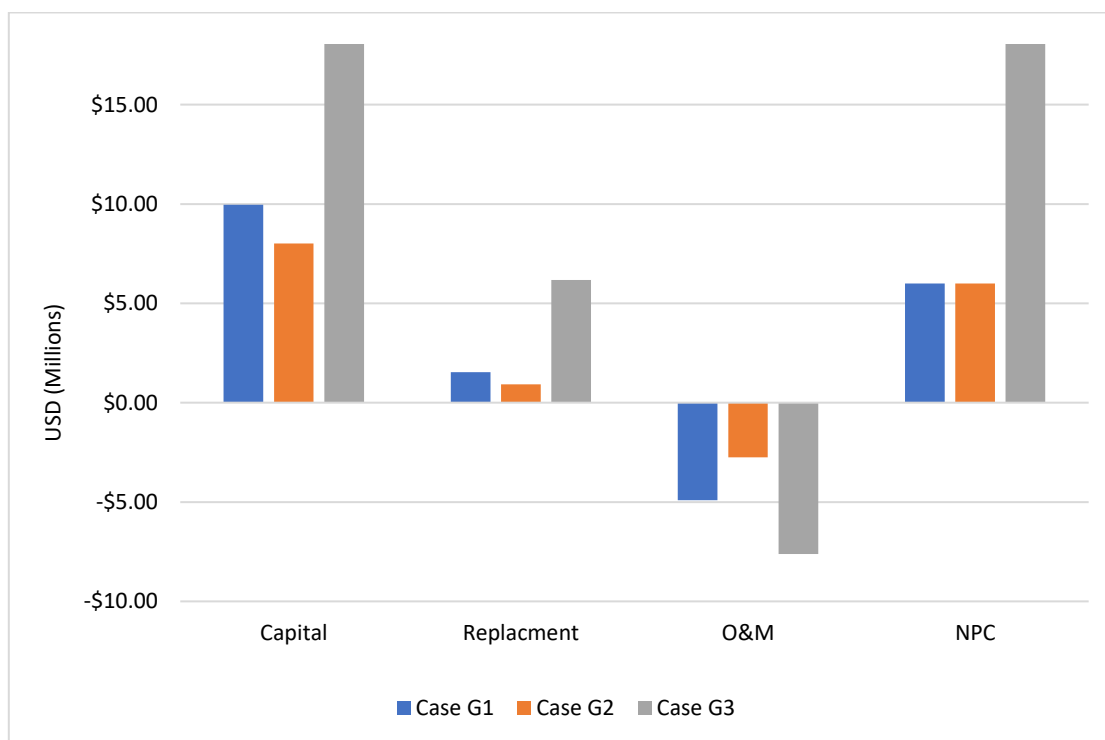


Figure 8. NPC comparison for grid-connected configurations

Evaluating the cost for the off-grid cases (Figure 9), Case S1 has the lowest NPC of \$8.60 million. Case S2 is close in terms of NPC with \$10.99 million given that it uses a mix of solar PV panels and wind turbines for energy generation. Case S3 has a much higher NPC of \$31.75 million, mainly due to the high costs of wind turbines like case G3. There is an absence of an energy storage component in case S4, causing the algorithm to oversize the solar panels and wind turbines to meet the electrolyser and other load demands, eventually resulting in high capital expenditure. As for the replacement and O&M cost, case S1 has a significantly lower price (\$1.31 million) than cases S3 and S4, which cost \$6.81 and \$2.99 million. On the other

hand, case S2 has a reasonable replacement cost of \$1.52 million due to the lower costs of solar PV systems compared to wind turbines. It should be noted that the revenue generated via sales of hydrogen fuel is not accounted for in the modelling due to constraints in the HOMER software. The net NPC for all the cases will be much lower when accounting for the sale of hydrogen to bus companies.

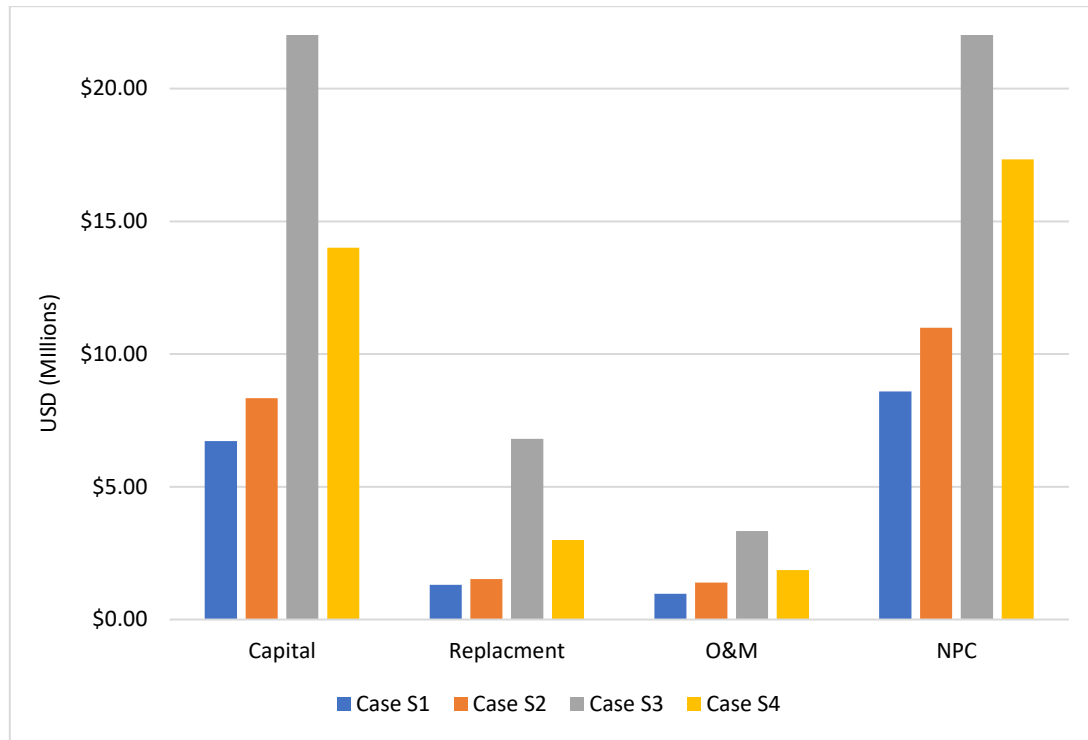


Figure 9. NPC comparison for off-grid configurations

C. Annualized Energy Production for Best Case Scenarios

Case G1, being the optimum grid case has an average of 98.8 % renewable energy penetration of which 71.5% is generated via solar panels and 27.7% via wind turbines. Approximately 57.8 % or 4068 MWhr/yr of the energy is sold back to the grid as excess electricity, generating a net revenue of \$6.17 million annually. The solar panel are expected to produce 5633 MWhr/yr of electricity at a Capacity Factor (CF) of 20.2%. The wind energy production is around 2184 MWhr/yr, with a CF of 33.3%. In the power conversion between the DC-AC bus, the total losses are 367 MWhr/yr after 7,991 hours of operation. The converter has a CF of 35.7 % and can output 2232 kW at its peak. The average hydrogen production rate of the electrolyser in case G1 is 5.83 kg/hr with a peak production capability of 10.8kg/hr, leading to a total production of 51.11 tons of hydrogen annually. For the G1 case, the electrolyser consumes 46.4 kWh to produce 1 kg of hydrogen at a CF of 54.1%.

Table VII also shows the LCOE and LCOH for the grid connected cases. The lowest LCOE is recorded for case G1 at \$0.10/kWh with an LCOH of \$9.08/kg. Case G2 yielded a similar LCOH of \$9.06/kg but has a higher LCOE of \$0.14/kWh owing to a larger sized electrolyser. It should be noted that the addition of hydrogen compression costs and adjustment of capital cost values increased the LCOH values for this study compared to similar studies for other countries. The effect of adding hydrogen compression factors is discussed in detail in later sections.

Table VII. Average Annual Energy Production for Cases G1-G3

Case #	Ren Fraction (%)	Solar Panels (kWh/yr)	Wind Turbines (kWh/yr)	Converter Mean Output (kW)	Grid Energy (kWh)		LCOE (\$/kWh)	LCOH (\$/kg)
					Purchased	Sold		
G1	98.8	5,633,829	2,184,960	797	57,820	4,068,430	0.10	9.08
G2	94.1	6,137,621	-	633	197,649	2,764,196	0.14	9.06
G3	99.0	-	14,566,398	1120	74,941	6,908,300	0.19	27.60

Table VIII gives the same energy production parameters for off-grid cases S1 to S4. In case S1, 66.90% of electricity is produced by solar panels and 33.10% by wind turbines. Excess electricity accumulating to 1276 MWh/yr charges the battery bank, which outputs 49.36 MWh/yr. However, there is a 5.09% capacity shortage where the production from the microgrid is unable to meet the electrical load demand. This issue can be rectified by using a larger battery bank for storage, although it will incur a higher cost. The electrolyser operates for 4901 hours annually and consumes 46.40 kWh/kg, eventually producing 51.15 tons of hydrogen in the standalone configuration. For case S1, the lowest LCOE and LCOH are obtained at \$1.15/kWh and \$13.00/kg, respectively, denoting it as the best standalone configuration for hydrogen production. The higher cost is due to the addition of the battery storage system to account for periods of autonomy. The wind power system is much more prominent in the standalone cases allowing enough capacity to supply and charge the batteries for night loads.

Table VIII. Average Annual Energy Production for Cases S1-S4

Case #	Ren Fraction (%)	Solar Panels (kWh/yr)	Wind Turbines (kWh/yr)	Converter Mean Output (kW)	Battery (LA ASM)		LCOE (\$/kWh)	LCOH (\$/kg)
					Nominal Capacity (kWh)	Usable Capacity (kWh)		
S1	100	2,939,273	1,456,640	337	385	231	1.15	13.00
S2	100	5,365,027	-	340	2,693	1,616	1.41	16.60
S3	100	-	16,751,358	337	385	231	4.28	47.90
S4	100	3,425,584	7,283,199	335	-	-	2.39	26.20

D. Expected Daily Microgrid Operation

The daily operation results were exported from HOMER Pro into MS Excel for further analysis. The daily power production and consumption pattern for case G1 for an arbitrary day is shown in Figure 10. This would be the anticipated behavior of the system daily throughout the year with some minor changes due to resource availability. Solar power generation starts at 5.30 am and ceases at 6.00 pm for that day. The main AC loads of the system are supplied during the day while excess electricity is fed to the grid. Solar power production averages around 663kW, while the average wind power output is around 83.1kW. Approximately 1.6 % of the total annual energy is purchased from the grid to cater to the load demand during off-peak production. Just before 6:00 a.m., solar power production begins to increase and reaches a peak of 2910kW at around 1:00 p.m. The first bus needs to be refueled with hydrogen at 6:00 a.m. when the electrolyser is seen to increase power consumption to reach its peak production gradually. At its peak, the electrolyser uses 500kW power, while the renewable energy produced is much greater than this load. The electrolyser operates at 500 kW until 3:00 p.m. and gradually slows to a stop. The last bus is refueled at 2:00 p.m., and the remaining hydrogen produced after this time is fed into the 280 kg storage tank to maintain the tank's autonomy for two days.

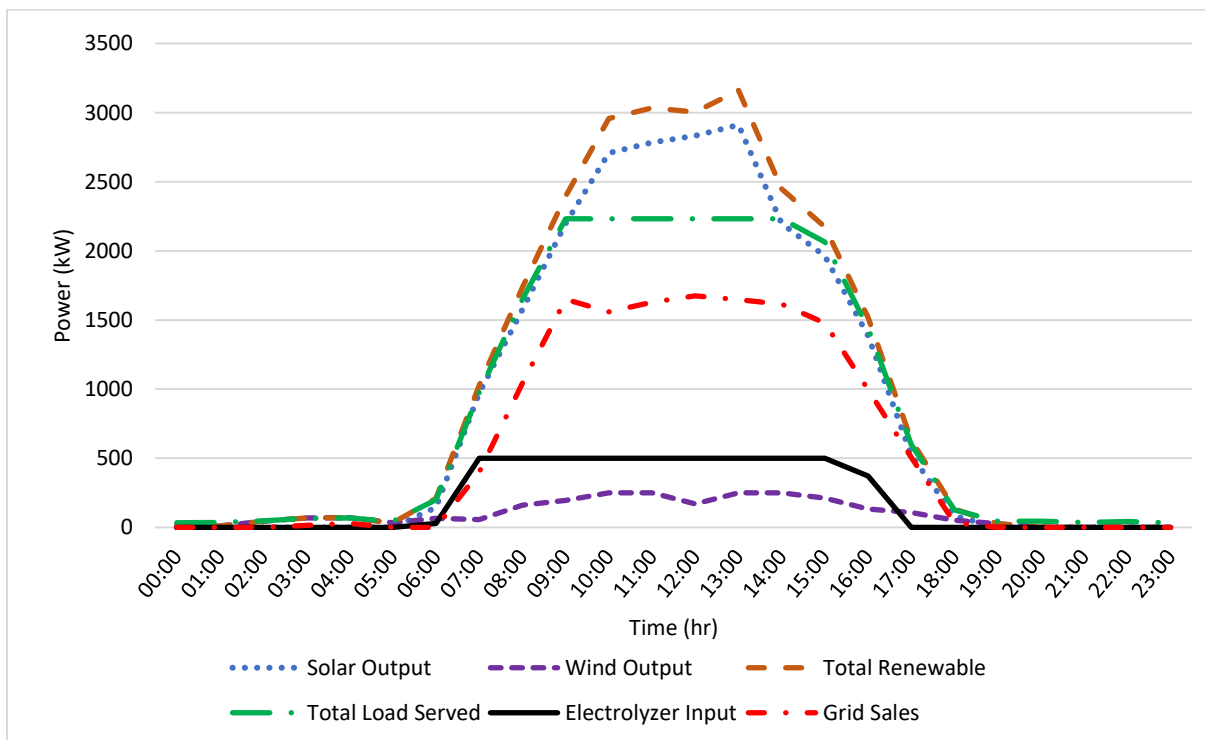


Figure 10. Power generation and utilization for the grid-connected system (Case G1)

At 1:00 p.m., renewable power production is at its peak of 3160kW and declines afterwards. Wind power peaks at 250kW and is highly variable compared to solar. Since most loads occur during the daytime and the renewable energy system is large compared to the loads, excess electricity is sold into the grid to improve the LCOE and LCOH. The grid connection also allows the loads to be supported by grid power in and when the renewable power production drops or shuts down for maintenance. More than half the power produced in case G1 is sold to the grid. The system is large enough to expand electrical load demand in future, but this would reduce the sale of electricity back into the grid.

The production, use and storage of hydrogen is shown in Figure 11 for a typical day. The hydrogen tank is seen to be less than 100 kg at midnight and uses the grid to run in a low production mode to raise the hydrogen tank level to 103 kg just before the first bus is refueled. The hydrogen tank dispenses 28kg of hydrogen to the first bus at 6:00 a.m. and causes the stored hydrogen tank level to dip. While hydrogen was previously produced at low flow rates, the electrolyser ramps up production to 10.77 kg/hr from 7:00 a.m. till 3:00 p.m. This allows efficient refueling of the remaining four buses while increasing the stored hydrogen levels.

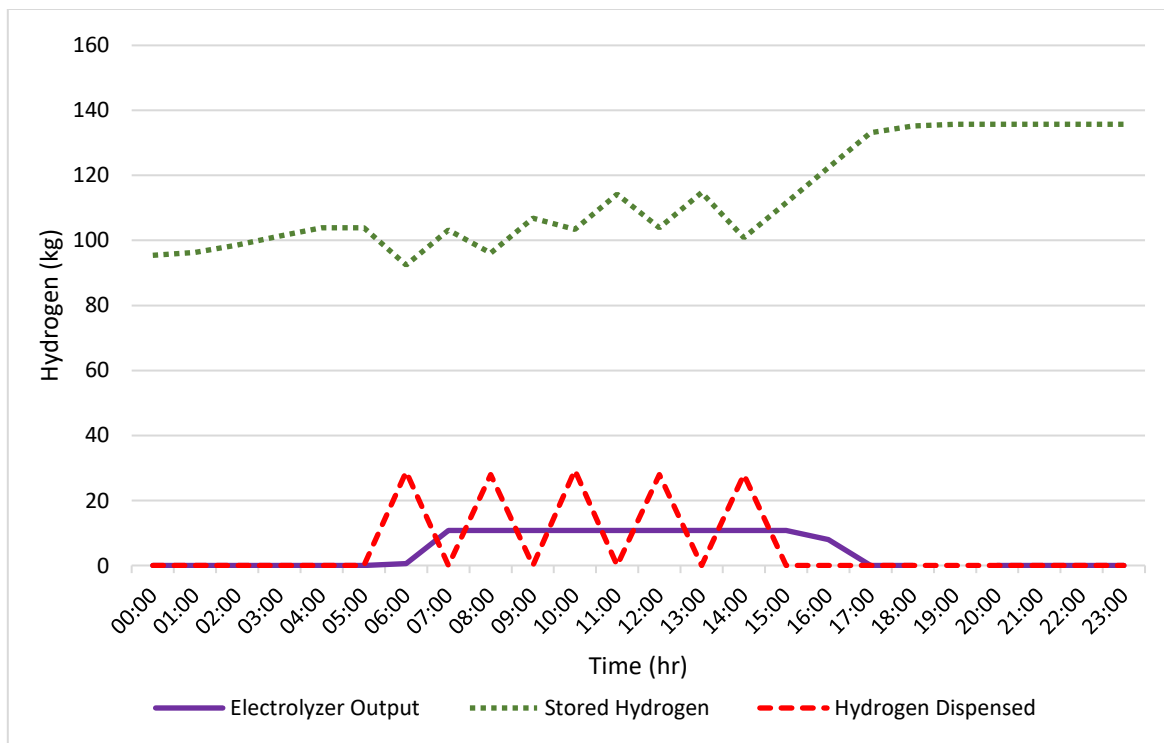


Figure 11. Regular hydrogen production, storage, and usage

The electrolyser does not shut down immediately after refueling the last bus. Instead, it continues production and gradually slows down after 4 pm allowing a peak value of 135kg stored hydrogen at 6:00 p.m. The stored hydrogen will be used the next day, and the cycle

continues. The hydrogen tank has autonomy for 48 hours by design, forcing the tank to maintain a high level of stored hydrogen. This would allow maintenance operations and even cater for zero or low solar power output days. The power production and usage for Case S1 is shown in Figure 12. The hydrogen for the first bus is supplied by the hydrogen tank, which gets replenished by the electrolyser operation in the daytime. The electrolyser only starts hydrogen production at around 6:00 a.m. when the solar power output increases. Wind energy also has greater output during the daytime, peaking at 392 kW that day. After 8 a.m., the electrolyser operates at its peak and consumes around 500 kW until 4:00 p.m. when hydrogen output slows. Like the grid-connected case, the electrolyser does not shut down immediately after meeting the daily load. It gradually slows down production to keep filling the hydrogen storage tank. When solar power output reduces after 6:00 p.m., power from the wind and battery is used to run the electrolyser.

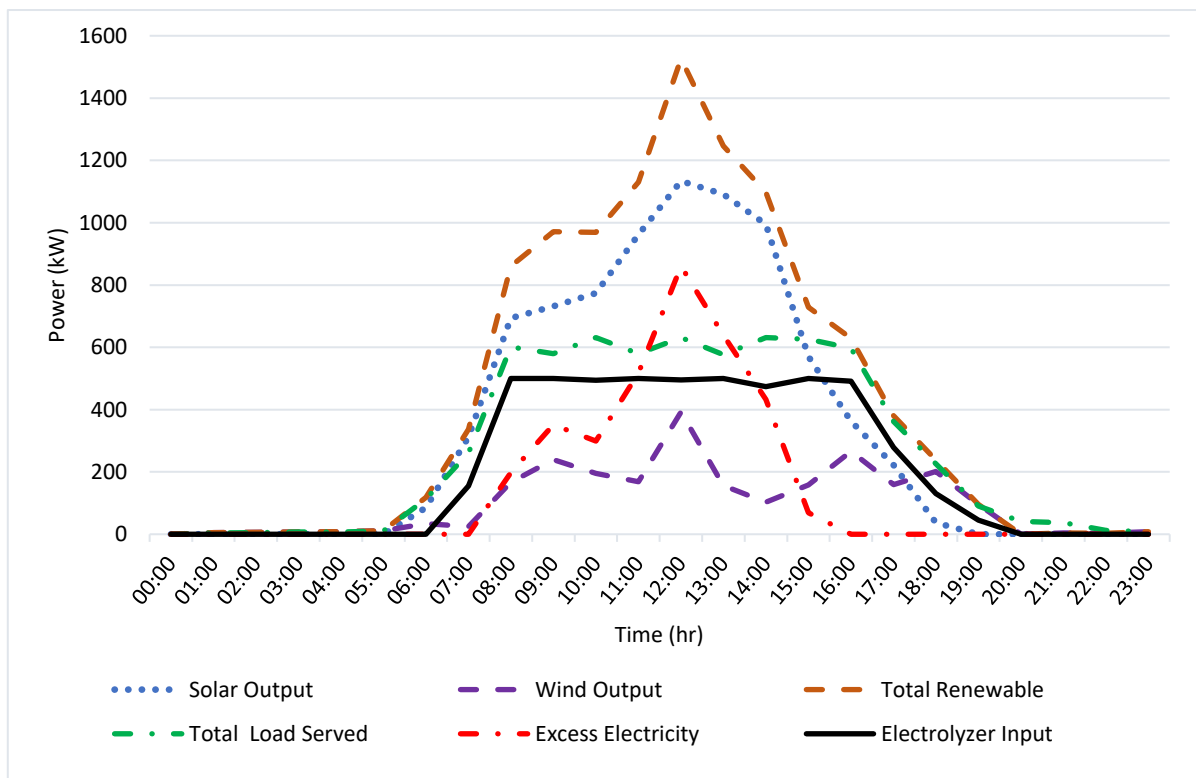


Figure 12. Power generation and utilization for the off-grid system (Case S1)

Hydrogen is produced until enough is stored for around 48 hours of autonomy. The total load served is uniformly higher than the electrolyser load as it includes the compressor, the facility auxiliary loads on top of electrolyser load. While excess electricity is sold to the grid in case G1, the same option is not available in case S1, and hence, it has lower returns, leading to higher LCOE and LCOH values. Approximately 29% of excess electricity is produced and directed toward charging battery storage units under optimum conditions. It should be

mentioned that energy produced by the wind turbine during nighttime is also diverted to setting the battery storage system due to the low energy demands of the primary loads at night. The capital cost of batteries, the replacement cost, and unused excess renewable power add to the expenses in case S1 compared to case G1. However, once the sources are in full operation, enough power is generated to supply the loads and fully charge the battery units simultaneously, as shown in Figure 13. At 100% charge, a maximum of 385 kWh of energy can be stored with an expected battery lifetime of 6.31 years. In energy conversion, around 11.57 MWh of energy loss is expected annually. The battery bank operates at a maximum of 750V with a probable 4.47 hours of autonomy.

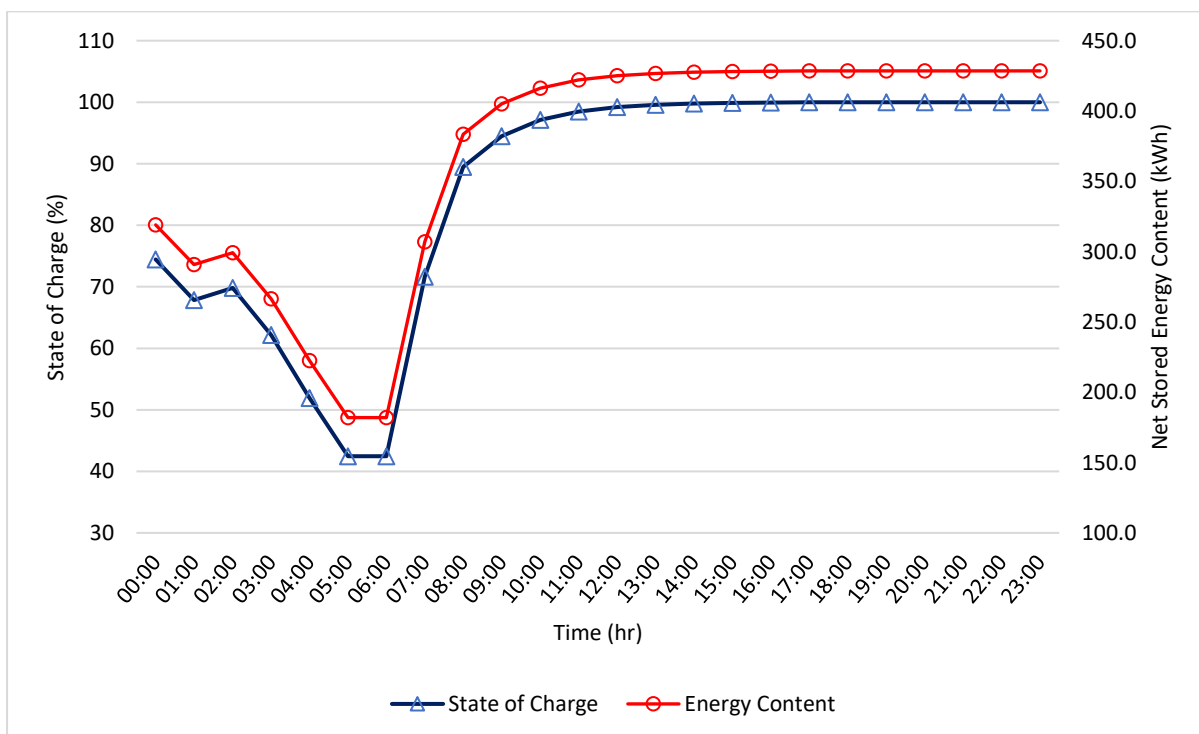


Figure 13. Battery state of charge and corresponding energy content

A separate analysis was carried out for cases G1 and S1 with 100 buses instead of 5 buses to see how the system could scale up from this pilot study. For the 100-bus scenario, the LCOH was \$11.20/kg for case G1 and \$14.67/kg for S1. The increased costs come from the fact that as the system scales up, more power must be generated from wind turbines, as solar PV systems require much larger land space. Given the scarcity of land, the use of large land areas for solar farms may not be feasible in small island nations. The choice of 5 buses is suited to a pilot scheme that will allow the country to gather data on the actual costs of hydrogen production, which would help upgrade models for sizing much larger systems in future. Large-scale

hydrogen production can be proposed as the cost of hydrogen generation components reduces, and the pilot schemes build more public confidence in hydrogen-powered vehicles.

E. Effect of Modelling Compressor Load and Costs

For all cases, the compression costs and the electrical load for the compressor were added to the analysis as described earlier. For the best cases of the grid-connected and off-grid systems (cases G1 and S1), an analysis was done where the compressor costs and compressor electrical loads were removed. For case G1, while the actual LCOH for hydrogen production is \$9.08/kg, it drops to \$8.73/kg when hydrogen compression effects are removed. The results show that the LCOH is underestimated by 3.85% in this case by neglecting hydrogen compression costs. Similarly, for case S1, the LCOH is \$13.00/kg when compressor costs and load are considered and decreases to \$12.10/kg when the compressor effects are not considered. For the off-grid case this means that the LCOH would have been underestimated by 6.92% if compression parameters were neglected. The LCOH is affected by each component cost and load in the system. Since most mobility applications require hydrogen at higher pressures than stationary applications, the LCOH values will differ. The LCOH for stationary power applications may not require high-pressure compression and thus would be lower. The results show that LCOH values for stationary power applications cannot be equated to mobility applications as it severely underestimates the project costs. For this reason, the LCOH values with and without high-pressure compression are shown in this study so that the appropriate value can be used to estimate projects' costs depending on the end application.

F. Projected Emission Reduction for Best Cases

The initial reason for proposing hydrogen buses in Fiji was to reduce GHG emissions, reduce fuel purchases and foster greater energy independence. Table 9 shows the projected annual summary for fuel consumption and carbon dioxide emissions for the two best case scenarios. The baseline case is explained in detail in Table II earlier. Hydrogen, when used in FCVs, does not emit any CO₂, but its production may cause the emission of some CO₂ and other gases. Case G1, which is connected to the grid and has the lowest cost of hydrogen production, also emits around 56,730 kg of CO₂ per year. This is because the grid is not based on 100% renewable energy sources but uses fossil fuels depending on energy demand. Despite this, the emissions using case G1 are very low and, if implemented, would lead to a 93.90% decrease in CO₂ emissions from the baseline case of 5 diesel buses.

Table 9 Annual fuel consumption and emissions for baseline and proposed cases.

Case	Fuel Used	CO ₂ Emission (kg)	Emission Reduction (%)	Fuel Cost (US\$)	Fuel Cost Increase (%)
Baseline	321,054 L Diesel	929,983	0	423,791	0
G1	48545 kg H ₂	56,730	93.90	440,789	4.01
S1	48545 kg H ₂	0	100	631,085	48.91

Case S1 is not connected to the grid and relies only on wind and solar power to generate the hydrogen. Hence, if case S1 is implemented, all CO₂ emissions will be eliminated during hydrogen production. To estimate bus refueling cost using hydrogen, the LCOH of hydrogen production for each case was assumed to be the selling price of hydrogen fuel. Since the load remained the same in all cases, the 5 five buses would need a cumulative 48.545 tons of hydrogen annually to complete the same operations as the baseline case. For case G1, this would result in a 4.01% increase in purchased fuel costs per year compared to the baseline scenario where diesel was purchased as fuel. The fuel in case G1 and S1 would be hydrogen and not diesel. It must be noted that the capital cost of new fuel cell bus purchases is not factored in these calculations as it is assumed that the buses would have the same cost as IC engine buses. For case S1 a 48.91 % rise in refueling costs would result due to its higher LCOH value. Given its low LCOH of \$9.08/kg, massive reduction in CO₂ emissions (93.9%) and a minor fuel cost increase of 4.01 %, case G1 looks to be the better grid configuration option when introducing hydrogen-fueled buses into the country. While the cases do look promising for offsetting emissions, several detailed studies on hydrogen infrastructure safety requirements may also be needed and could affect these economic parameters. However, as cost of equipment reduces for green hydrogen production systems, reductions in LCOH can be expected in future.

5.0 Conclusion

This study used a pilot project of replacing five diesel buses with fuel cell buses to investigate Fiji's hydrogen generation feasibility. A baseline scenario of the diesel buses in daily operation, travelling 380km, was considered and used in developing the daily load profiles. The load profiles were replicated in HOMER as inputs to seven different grid configuration cases to generate around 280 kg of hydrogen daily, allowing at least 48 hours of autonomy. Cost inputs found in the literature were adjusted using historical inflation and logistics costs to obtain more realistic inputs suited to Fiji. The study also considered hydrogen production for high and low pressure storage by modelling the cases with and without a hydrogen gas compressor. Case

G1, or the grid-connected setup with both solar and wind power ranked as the most suitable configuration due to its NPC of \$6 million and its ability to offset 93.6% of CO₂ emissions from the baseline case. While generating around 51.11 tons of hydrogen, case G1 can offset 873.3 tons of CO₂ annually. The grid-connected configuration yielded a LCOH of \$9.08/kg for compressed high-pressure hydrogen (400 bars) suitable for fuel cell buses. In contrast, low-pressure hydrogen without a compressor yielded a LCOH of \$8.73/kg, ideal for stationary power applications. A solar–wind–battery hybrid system (case S1) provided the best off-grid configuration, resulting in net zero CO₂ emissions. However, for this case, the LCOH for compressed high-pressure hydrogen was \$13.00/kg while for hydrogen production without compression, the LCOH stood at \$12.10/kg. The study also shows that the LCOH value for fuel cell buses or trucks can be underestimated by as much as 6.92% if the compression effects are not factored into the system's electrical load, capital costs and operating expenses. The HOMER software also optimized capital investment and LCOE values for all seven grid scenarios. The grid-connected case G1 can be implemented with a capital investment of around \$9.96 million for this pilot system. It can produce electricity at a LCOE of \$0.10/kWh, which could be sold back to the grid to generate income. For case S1, the capital cost of \$6.72 million gives an elevated LCOE of \$1.15/kWh, primarily due to the increased battery storage and wind power capacity required for this off-grid system. The study estimates the LCOH values for use in Fiji to approximate the costs of future hydrogen-related projects while carefully adjusting all inputs to suit Fiji's scenario. It must be noted that the LCOH values will change with time as component production costs reduce and inflation rates change along with other cost factors. Each project for hydrogen production will, therefore, require its assessment of the cost of hydrogen production. The values presented here can be used to approximate project costs in Fiji and the South Pacific region and start the investigations on introducing hydrogen into the region.

6.0 References

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