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OPTIMAL DESIGN OF AN OFF-GRID SOLAR AND WIND POWERED HYBRID EV-HFCV CHARGING STATION

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In this paper, a hybrid charging/refueling station for electric vehicles (EVs) and hydrogen fuel-cell vehicles (HFCVs) is proposed. The proposed station is fully electrified by a renewable energy system comprised of wind turbines and a photovoltaic (PV) battery system. Daily charging patterns for both EVs and HFCVs are used to investigate the performance of the station. The model of the proposed charging system was developed in the HOMER Pro software program to investigate the technical and economical viability of the system. Based on the charging pattern of the energy required by the system, it was observed that wind turbines produce more electrical energy compare to the PV system: over 89% of the electrical energy demand was generated by wind turbines followed by 10.1% generated by the PV system. Furthermore, it was observed that some hydrogen surplus was available since the fuel cell contributed 0.412% of the power required. The station produced 9680 kg of hydrogen yearly, with 76% servicing the hydrogen load of 14 HFCVs at a levelized cost of hydrogen production of US$3.20/kg. Economically, it was observed that the capital investment and the total costs associated with the PV system were higher than those of the wind turbines. The levelized cost of energy was found to be US$0.369/kW·h, while the city charges US$0.33/k·Wh. However, additional costs payable to the city make the off-grid system more favorable.

KEY WORDS: *off-grid, electric vehicles (EVs), hydrogen fuel-cell vehicles (HFCVs), HOMER Pro*

1. INTRODUCTION

Efforts toward the decarbonization of the electricity sector are well underway. The utilization of renewable energy sources (RESs) has gained irreversible momentum in developing countries. To meet local loads, several micro-grid configurations have been put forward. Quansah et al. (2017) achieved 48% cost of energy (COE) reduction by introducing a photovoltaic (PV) system to a standalone diesel generator supply for a base transmitter station in Ghana. Nedaei et al. (2020) carried out a study on the optimal planning of a wind energy power plant. For a selected site, the payback period

NOMENCLATURE

C_{OL}	cost incurred over the lifetime of the system
COE	cost of energy
DC	direct current
EV	electric vehicle
F	Faraday constant
f_{PV}	derating factor
FC	fuel cell
G_i	current irradiation
G_r	reference irradiation
HFCV	hydrogen fuel-cell vehicle
HT	hydrogen tank
I_{el}	electrolyzer current
k	shape parameter
LHV_{H_2}	lower heating value of hydrogen gas
N_s	number of cells in a series
n_{bat}	number of batteries
n_F	Faraday efficiency
n_{HT}	number of moles in a hydrogen tank
n_{PV}	number of photovoltaic panels
n_{WT}	number of wind turbines
NOTC	nominal operating temperature of the cell
NPC	net present cost
P_p	peak photovoltaic power
P_r	rated power
P_1	inlet pressure
P_2	outlet pressure
PV	photovoltaic
R	gas constant
R_{H_2}	rate of hydrogen production
R_{OL}	revenue generated over the lifetime of the system
RES	renewable energy source
T	compressor inlet temperature
T_a	ambient temperature
T_C	temperature of the cell
T_r	reference temperature
US$	United States dollars
V_{HT}	volume of the hydrogen tank
v_{ci}	cut-in wind speed
v_{co}	cut-out wind speed
v_r	rated wind speed
V2G	vehicle to grid
WT	wind turbine

Greek Symbols

α_T	temperature efficiency
η_c	compressor efficiency
η_{FC}	fuel-cell efficiency
η_{gb}	gearbox efficiency
η_{mt}	mechanical transmission efficiency
ρ_{H_2}	density of the compressed hydrogen
ψ	polytrophic coefficient

was estimated to be 2.7 years with the COE at US$0.234/kW·h. In addition, it has been shown that modeling of the available resources could be the basis for the development of micro-grids (Moorthy and Deshmukh, 2014).

To contribute to the decarbonization project, the transportation sector has made some serious gains in the development of carbon-free vehicles. These are electric vehicles (EVs) and hydrogen fuel-cell vehicles (HFCVs). These developments have called for the construction of unconventional refueling stations. Expectedly, these refueling stations would need an electric power supply, and should a conventional grid be used the decarbonization project could be further delayed. The batteries in EVs need to be regularly charged, while the hydrogen tanks (HTs) in HFCVs need to be refilled for smooth operation of the vehicles. A technological review of the fast charging of EVs was presented in Tu et al. (2019). The benefits of using solid-state transformers in these charging stations to replace line-frequency transformers were presented.

The planning for the deployment of the charging station is imperative to ensure that the refueling demand is always met. One such method was presented in Bryden et al. (2018). The typical gasoline vehicle demand was used to predict the future need for EVs to recharge. It was concluded that 45% of the fast charge requirement would be required between 3 and 7 PM. The data collected by the University of Western Australia from 23 charging stations showed that 55% of the EV charging activities occurred at home and business locations (Speidel and Bräunl, 2014). It was further observed that 33% of the charging events occurred at the charging stations. Of particular interest, the fact noted in Speidel and Bräunl (2014) was that the charging patterns resembled the solar patterns in Perth. Similar observations were made in Netherlands (Mouli et al., 2016) when the potential of 10 kW solar-powered vehicle-to-grid (V2G) EV charging stations was investigated. A solar-powered EV charging model was presented in Ye et al. (2015).

The economic feasibility of this model was investigated for Shenzhen City, China. The cost of the energy system was found to be US$0.098/kW·h, while it was observed that there was at least 99.8% reduction in pollution. Elgammal and Sharaf (2012) investigated the utilization of a hybrid PV fuel-cell (FC) renewable energy-based scheme for V2G battery-charging stations. Simulation and laboratory tests showed that the proposed scheme reduced the direct current (DC) inrush, thereby stabilizing the DC bus voltage. The work presented by Forrest et al. (2016) asserted that V2G technologies could eliminate the need for stationary energy storage. The potential to use RESs for EVs was further investigated by Schuller et al. (2015). From the empirical models, it was concluded that optimized charging could lead to increased utilization of RESs by a factor of 2. Some of the optimized charging include the heuristic method presented in Chen et al. (2014) to maximize the utilization of solar power in charging stations.

Nonetheless, the utilization of hydrogen-fueled vehicles is still at the infant stage; however, the preparation for what would be their influx into the market is imperative. Two types of hydrogen-powered vehicles were comparatively assessed in terms of their emissions in Ugurlu (2020), in which FC vehicles using gaseous hydrogen and internal combustion engine vehicles using liquid hydrogen were used for comparison. Evidently, hydrogen-powered vehicles may contribute to the decarbonization of the environment. Several advantages and disadvantages of using hydrogen-powered vehicles were presented in Turoń (2020). One of the advantages put forward is the reduction of greenhouse gasses and a major drawback is an appropriate infrastructure for the hydrogen supply. Fikri et al. (2020) estimated the possible waiting period for hydrogen-fueled vehicles. This is as a result of the lack of a charging infrastructure; therefore, making the estimation of waiting a critical task. It was argued in Li et al. (2020) that the refueling time also contributes to the willingness to opt for hydrogen-powered vehicles.

It is apparent that EVs and hydrogen-powered vehicles will be the means of mobility in the future since they may contribute to tdecarbonizing the environment. However, the charging station still needs electricity and conventional generation still contributes to carbonizing the environment. In this paper, we present the feasibility of installing an off-grid charging station for hybrid EVs and HFCVs in Cape Town, South Africa. The simulation of the model was done using the HOMER Pro software program. The station was designed to charge 14 EV Smart Fortwo ED and five HFCV 2021 Toyota Mirai.

The remainder of the paper is organized as follows. Section 2 presents a description of the site selected for the installation of the station. The potential and availability of renewable energy resources at the selected site are also presented with the configuration of the system. The mathematical modeling of the system is presented in Section 3. A discuusion of the results is presented in Section 4, and the conclusions drawn from results are given in Section 5.

2. SYSTEM AND SITE DESCRIPTION

The city of Cape Town (33.9249°S; 18.4241°E) in South Africa is one of the most developed cities in the African continent. Therefore, it can be expected that these EVs and HFCVs would dominate this particular city before other areas in the continent, thus making the charging infrastructure a necessity. Cape Town is located in the coastal region of South Africa. Therefore, it is expected that wind energy as a resource would be significantly higher than solar energy. The city has a high potential for using wind energy as a resource compared to solar energy based on the data collected from the National Aeronautics and Space Administration surface meteorology and solar energy database. Figure 1 shows the monthly wind speed and temperature characteristics of the site. It can be seen that the lowest temperature is in the month of July, which coincides with the highest wind speed. Notably, the period with the highest wind speed coincides

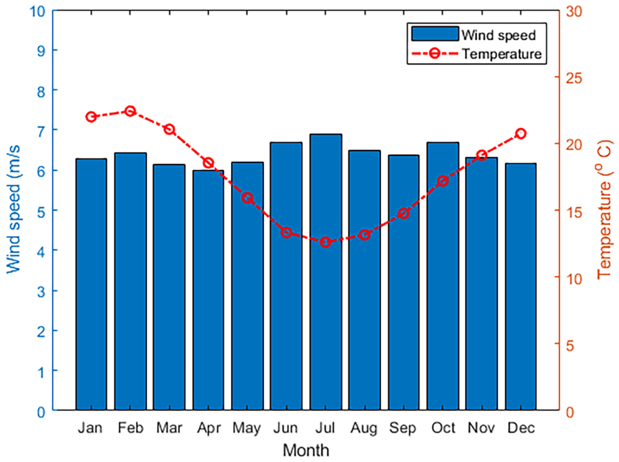

FIG. 1: Monthly average wind speeds and temperatures

with the lowest solar irradiation and the clearness index, as shown in Fig. 2. This period falls within the winter season in South Africa (Mosetlhe et al., 2018). Solar energy resources are at their peak during the summer months (i.e., January, November, and December) when the clearness index is also at its highest.

The proposed system in Fig. 3 is comprised of PV panels, a battery bank, wind turbines (WTs), an electrolyzer, and FCs. The electrical energy generated from the WTs is used to charge the EVs directly and to supply the electrolyzer to activate the chemical reaction. The electrolyzer is also fed by the PV-battery system. The hydrogen produced by the electrolyzer is stored in a compressed HT. The HT is used to refuel the hydrogen vehicles. The surplus hydrogen is fed to the FC to augment the electrical supply to the EV. The system was simulated in the HOMER Pro software program with the technical parameters as the input to the simulation. The cost of each component was also input into the simulation in order to investigate the economics of the model.

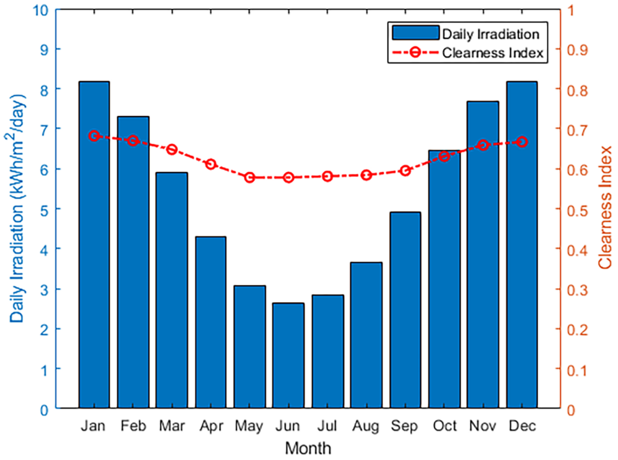

FIG. 2: Monthly average solar irradiation and clearness index

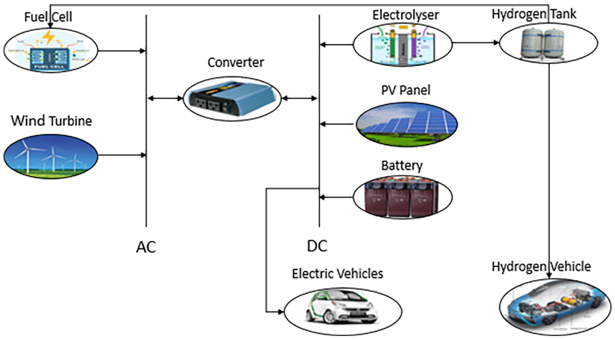

FIG. 3: Proposed system

The station was designed to initially charge 14 EV Smart Fortwo ED and five HFCV 2021 Toyota Mirai vehicles per day. The Smart Fortwo ED vehicle has a battery usable capacity rated at 16.7 kW·h. Therefore, to charge about 14 cars, the station must produce around 233.8 kW·h/day. The 2021 Toyota Mirai vehicle has a hydrogen storage capacity of 5 kg. Therefore, the hydrogen produced by the station should not be less than 20 kg. Generally, due to the amount of time needed to charge the vehicles, most drivers would ordinarily visit the station to fill up instead of refueling an empty tank. The 24-hour charging pattern for the station is shown in Fig. 4.

3. MODELING

3.1 Optimal Configuration of the Proposed Charging Station

The configuration and sizing of the capacity of a hybrid station for EVs and HFCVs can be modeled as an optimization problem. Generally, the HOMER Pro software program can be used to optimize the net present cost (NPC) of the system; however, some parameters, such as the land space and cost requirement, cannot be incorporated into HOMER. They require adequate consideration. The mathematical formulations for the optimization problem are given in Eqs. (1) and (2)

$$\min f\left(x\right)=\sum \mathrm{NPC} \tag{1}$$

and

$$\mathrm{NPC}=C_{\mathrm{OL}}-R_{\mathrm{OL}} \tag{2}$$

where C_{OL} and R_{OL} denote the cost incurred and the revenue generated over the lifetime of the system, respectively. Due to the inherent constraints that the site could have, es-

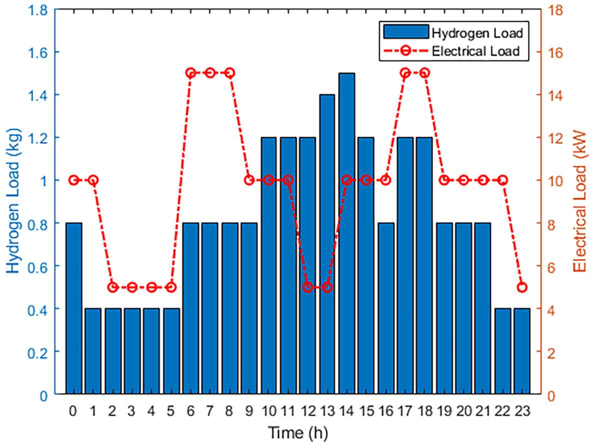

FIG. 4: Charging patterns of hydrogen and electric vehicles, based on Mehrjerdi (2019)

pecially in urban areas, the components should be limited. The number of components can be a constraint, as shown by the following equations:

$$\begin{aligned} n_{\mathrm{PV}} &\le n_{\mathrm{PV}}^{\max} \\ n_{\mathrm{WT}} &\le n_{\mathrm{WT}}^{\max} \\ n_{\mathrm{bat}} &\le n_{\mathrm{bat}}^{\max} \end{aligned} \tag{3}$$

where n is the number of components used in the system. In the HOMER Pro software program, this is achieved by limiting the search space for the optimization solution.

3.2 Wind Turbine Power Output

The power generated by a wind turbine (Ayodele et al., 2012) can be expressed as follows:

$$P_{\mathrm{turbine}} = \eta_{\mathrm{mt}} \times \eta_{\mathrm{gb}} \left\{ \begin{array}{cc} P_r \left(\dfrac{v^k - v_{\mathrm{ci}}^k}{v_r^k - v_{\mathrm{ci}}^k} \right), & v_{\mathrm{ci}} \le v \le v_r \\ P_r, & v_r \le v \le v_{\mathrm{co}} \\ 0, & v_r \le v_{\mathrm{ci}} \quad \text{and} \quad v \ge v_{\mathrm{co}} \end{array} \right\} \tag{4}$$

where P_r is the rated power of the WT; v_{co}, v_{ci}, and v_r are the cut-out wind speed, cut-in wind speed, and rated wind speed, respectively; k is the shape parameter of the site; and η_{mt} and η_{gb} denote the mechanical transmission efficiency and gearbox efficiency, respectively.

3.3 PV Power Output

The PV system consists of PV panels and an inverter. The PV panels are connected to the DC bus. An inverter is also connected to the DC bus and converts the power into alternating current. The output of the PV system can be mathematically expressed as follows (Raghuwanshi and Arya, 2020):

$$P_{\text{PV-out}} = P_p f_{\mathrm{PV}} \frac{G_i}{G_r} \times \left[1 + \alpha_T \left(T_C - T_r \right) \right] \tag{5}$$

where P_p and f_{PV} are the peak power of the PV module and the derating factor, respectively; G_i and G_r are the current and reference solar irradiations, respectively; and T_C,

α_T, and T_r represent the temperature of the cell, temperature coefficient, and reference temperature, respectively. The cell temperature can be obtained as follows (Mosetlhe et al., 2021):

$$T_\mathrm{C} = T_a + \left(\frac{\mathrm{NOTC} - 20}{0.8}\right) \times G_i \tag{6}$$

where T_a is the ambient temperature and NOTC is the nominal operating temperature of the cell.

3.4 Hydrogen Production

The production of hydrogen in the charging station is generated by an electrolyzer and then stored in a HT. The rate of hydrogen (R_{H_2}) produced by the electrolyzer from the RESs can be quantified as follows (Luta and Raji, 2019a):

$$R_{\mathrm{H}_2} = n_\mathrm{F}\left(\frac{N_s \times I_\mathrm{el}}{n \times \mathrm{F}}\right) \tag{7}$$

where n_F is the Faraday efficiency; N_s is the number of cells in a series; I_el is the electrolyzer current; n is the number of electrons per mole; and F is the Faraday's constant. The storage of hydrogen requires that it be compressed. The power required to compress hydrogen can be determined as follows (Luta and Raji, 2019b):

$$P_\mathrm{comp} = \left(\frac{\psi}{\psi - 1}\right) \times R \times \left(\frac{T}{\eta_\mathrm{c}}\right) \times \left[\left(\frac{P_2}{P_1}\right)^{\psi/(\psi-1)}\right] \times R_{\mathrm{H}_2} \tag{8}$$

The pressure of hydrogen in the HT can be expressed as follows:

$$Q_\mathrm{HT} = \left(\frac{R \times T}{V_\mathrm{HT}}\right) \times n_\mathrm{HT} \tag{9}$$

In Eqs. (8) and (9), ψ is the polytrophic coefficient; R is the gas constant; T is the compressor inlet temperature; η_c is the efficiency of the compressor; P_1 and P_2 are the inlet and outlet pressures, respectively; V_HT is the volume of the hydrogen tank; and n_HT is the number of moles in the hydrogen tank. The FC transforms the stored hydrogen into electrical energy. Mathematically, the electrical energy can be expressed as follows:

$$\mathrm{FC}_\mathrm{elect} = R_{\mathrm{H}_2} \times \mathrm{LHV}_{\mathrm{H}_2} \times \eta_\mathrm{FC} \times \rho_{\mathrm{H}_2}$$

where LHV_{H_2} is the lower heating value of hydrogen gas; η_{FC} is the efficiency of the fuel cell; and ρ_{H_2} is the density of the compressed hydrogen.

4. RESULTS AND DISCUSSION

The optimal values of the capacity of each component in the investigated system are given in Table 1. It was found that for optimal operation (in terms of cost), the PV modules must have at most a combined wattage rating of 100 W. About 50 lithium-ion 1 kW·h–rated batteries would be required to provide adequate storage for the system. Seemingly, the HT provides both the storage capacity for the hydrogen required to refuel the cars and for the hydrogen supplied to the FC during excess production of hydrogen. The required size of the hydrogen for this hybrid operation is 100 kg of compressed storage serviced by a 100 kW electrolyzer. It can be seen that in order to effectively harness the potential of wind resources, six XANT M-21 WTs rated at 100 kW each are required.

The system can serve 100% of the electrical load. The frequency of the energy withdrawals is shown in Fig. 5. The frequency distribution of the hydrogen refueling demand is depicted in Fig. 6. It can be seen that the highest demand for hydrogen amounts to 0.8 kg/h. Nonetheless, the performance of the system is satisfactory, where a deficit of 0.002 kg/h is observed. Further investigations revealed that the deficit occurs for 3 hours out of

TABLE 1: Optimal EV and HFCV charging station architecture

Number of wind turbines (100 kW)	PV (kW)	Number of batteries	Hydrogen tank (kg)	Electrolyzer (kW)	Converter (kW)
6	100	50	100	100	69

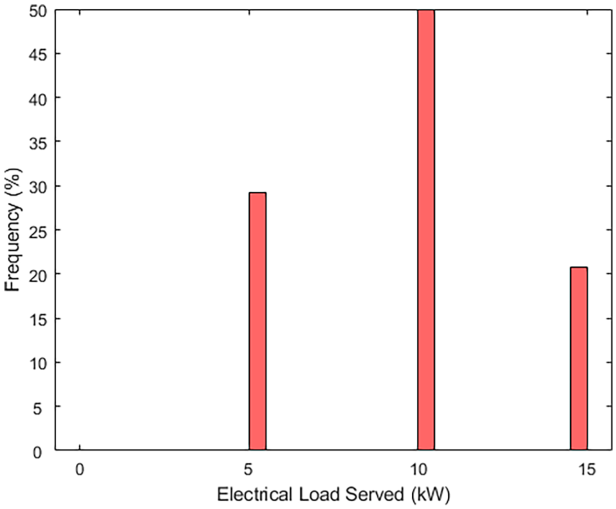

FIG. 5: Electrical load serviced by the charging station (EVs)

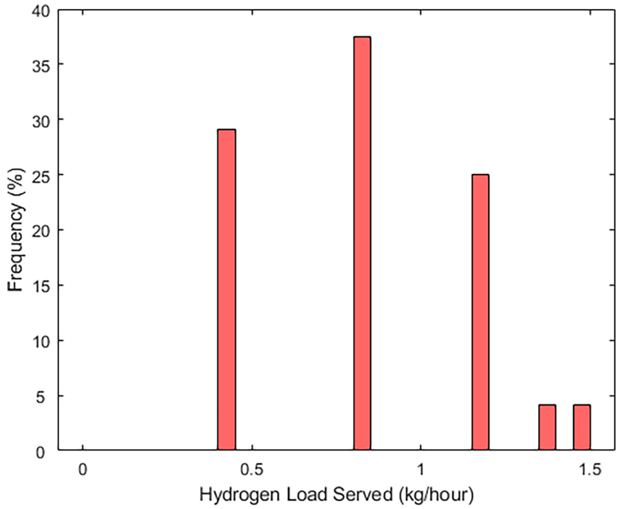

FIG. 6: Hydrogen load serviced by the charging station (HFCVs)

the 8760 yearly hours. Furthermore, it was found that it occurs between 11:00 PM and 12:00 AM when solar energy is not supplying any power to the system.

The annual contribution of RESs is depicted in Fig. 7. Evidently, WTs produce more energy compared to other sources. This is due to the high wind profile of the coastal region in South Africa. This observation was also made by Ayodele et al. (2012) and Raghuwanshi and Arya (2020) following investigations carried out to assess the potential of wind resources in coastal areas of South Africa.

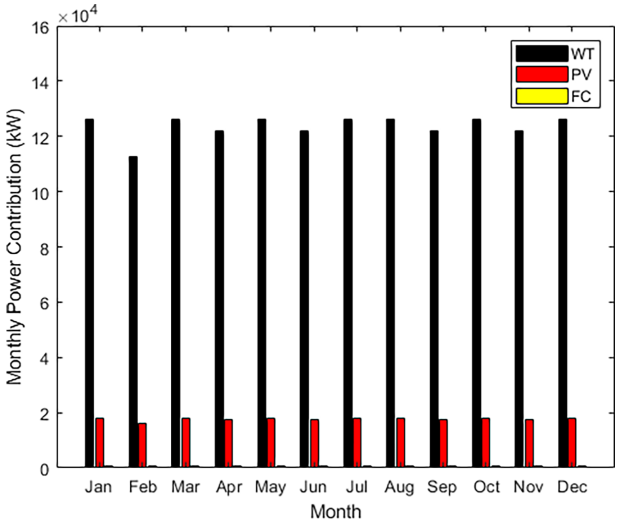

FIG. 7: Monthly contribution of renewable energy sources

Solar energy follows with a steady contribution during the year. This can be attributed to the low clearness index in the Cape Town region. However, although a deficit of hydrogen supply for certain periods of time during the year can be noted, it is evident from Fig. 7 that in some cases, excess hydrogen was produced. As a result, the FCs contributed to the total energy production over the year. Even though the contribution could be seen to be less, it nevertheless contributed to the energy mix. The FC used about 24% of the hydrogen produced by the electrolyzer and the rest of the hydrogen produced (i.e., 7 333 kg/year or 76%) was used to service the HFCV at the levelized cost of US$3.20. The summary of the contribution is presented in Table 2.

The total costs associated with the operation of the system are presented in Table 3. The highest capital cost was as a result of investments in a PV system and HT at US$100,000 followed by the WTs at US$90,000. This correlates to the highest contributors to the operation of the charging station. Nevertheless, an interesting observation was made. WTs contribute more than the PV system; however, the investment and total costs are lower than the PV system. This further suggests the fact that the combination of the chosen configuration and WT capacity is a good investment with regard to harnessing wind energy for the system under study. Furthermore, a HT costs around US$10,000 less than a WT; however, it must be installed due to the nature of the proposed system. A further investigation might need to be carried out to ascertain whether the station could be more cost effective without a PV system.

The levelized COE is US$0.369/kW·h. The COE for the 2020/2021 financial year in Cape Town peaks at US$0.33/kW·h (City of Cape Town, 2020). Although it may seem cheaper to buy energy from the city, several costs charged to these sorts of establishments may drastically increase the total cost. The city charges a service fee of US$8.50/

TABLE 2: Percentage of contribution from sources

Production	**k·Wh/year**	**Percentage (%)**
PV	174,789	10.1
FC	7103	0.412
WT	1,540,727	89.4

TABLE 3: Cost associated with each component

Component	**Capital (US$)**	**Replacement cost (US$)**	**Fuel (US$)**	**Total (US$)**
FC	8500	2377.63	0.00	10,877.63
BAT	27,500	11,667.53	0.00	39,167.53
PV	100,000	0.00	0.00	100,000
HT	100,000	0.00	0.00	100,000
WT	90,000	19,128.44	0.00	109,128.44
Total				**359,173.60**

day and a demand charge of US$14/kV·A. The cumulative costs payable to the city make the off-grid system a more favorable option. Moreover, the off-grid system contributes immensely toward decarbonization of the electricity supply.

5. CONCLUSIONS

In this work, an off-grid charging/refueling station system is put proposed as a viable option for charging EVs and refueling HFCVs. The system is comprised of WTs, PVs, a HT, a FC, batteries, and an electrolyzer. The sum total of the components contributes to stations fulfilling electrical energy demands and hydrogen production for HFCVs. A deficit for hydrogen of 0.002 kg/h was observed for 3 hours/year, while the electrical load was fully serviced. It was found that this site is more favorable to wind energy investment since WTs produce more energy at lower cost compared to PV systems.

The cost of electrical energy production by the system was found to be US$0.369/kW·h, which is relatively higher than what the city charged for the 2020/2021 financial year. However, service fees associated with this kind of establishment peaks at US$8.50/day for general services and US$14.00/kV·A. In order to service the hydrogen load, a cost of US$3.20/kg was incurred during the production of hydrogen.

Future studies could investigate the effects of a solar free station at this particular station to support the conclusions drawn in this work. Furthermore, a sensitivity analysis may be done to investigate the robustness of the proposed scheme.

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