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Cost, Footprint, and Reliability Implications of Deploying Hydrogen in Off-grid Electric Vehicle Charging Stations:

A GIS-assisted Study for Riyadh, Saudi Arabia

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Summary

We quantify the cost, footprint and reliability implications of using hydrogen in off-grid electric vehicle charging stations (CS) using an optimization model coupled with a geographical information system (GIS) analysis for the city of Riyadh, Saudi Arabia. We also account for the challenges associated with wind energy deployment as a generation technology for CS within city centers. The analysis is restricted to carbon-free technologies: photovoltaics (PV), wind, battery and hydrogen. We find that at current prevailing technology costs, hydrogen can reduce the required footprint of off-grid CS by 25% at a small incremental cost increase without impacting the charging reliability. By 2030, however, hydrogen will provide footprint and cost advantages simultaneously. If we allow as little as 5% of the annual load to be unmet, the required footprint for CS decreases by 60%. Levelized cost of energy values by 2030 could range between \$0.13-\$0.20/kWh depending on learning-curve assumptions. The footprints calculated are then mapped to five land-parcel categories in Riyadh: gas station, hospital, mall, school and university. Incorporating hydrogen CS increases the number of parcels that could accommodate CS by 15-45% by reducing the required PV array (i.e., footprint).

Key Points

- We assess the benefits that hydrogen fuel cells can bestow upon off-grid electric vehicle charging stations

- The analysis was conducted using a power optimization model and GIS analysis

- By 2030, hydrogen technologies can reduce the cost and required footprint of charging stations

- Hydrogen can reduce the footprint requirement of charging stations by 25%

- Hydrogen enables 15-45% more land parcels to host charging stations in Riyadh

Introduction

Except for a few years that witnessed economic recessions or pandemics, global anthropogenic carbon emissions have been increasing annually for decades. According to the International Energy Agency, CO_2 emissions increased from 20.5 billion tons in 1990 to 33 billion tons in 2021. A significant share of these emissions come from the power generation and transportation sectors. In the power sector, renewable energy can contribute to reducing emissions (Razmjoo et al. 2021). Electric vehicles (EV), in contrast, can reduce emissions in the transportation sector, provided they are charged from a low- or no-carbon technology (Elshurafa and Peerbocus 2020).

As far as EVs are concerned, it is necessary to assess the potential charging infrastructure options needed to support EV deployment. EV charging can occur either on-grid or off-grid. When the charging station (CS) is not connected to the grid (i.e., off-grid), the power must be generated on site. Both on-grid and off-grid CS have their pros and cons, as are detailed in the next section. In this study, we focus only on the technoeconomics of carbon-free off-grid CS. Off-grid CS have been a much researched topic in the context of various countries, including, for example, Bangladesh (Karmaker et al. 2018), the United Kingdom (Mohamed et al. 2020), Indonesia (Nizam and Wicaksono 2018), Canada (Hafez and Bhattacharya 2017), Qatar (Al Wahedi and Bicer 2020b), Turkey (Ekren, Canbaz, and Güvel 2021) and many others. However, Saudi-centric CS studies are lacking.

Off-grid CS that are carbon-free require a considerable (area) footprint. However, within city centers, land scarcity impedes deployment of photovoltaics (PV), and the presence of buildings impedes wind energy deployment. Most off-grid designs focus on meeting demand without fully considering the practicality of deploying PV and wind within city centers.

To overcome these land and urban constraints, we resort to hydrogen energy. Hydrogen technologies, including fuel cells and electrolyzers, have been used for over a century and are gaining increasing attention. While there is considerable room for improvement in regard to hydrogen technologies, they are considered mature and can be deployed safely and effectively in a variety of applications. As the efficiency of hydrogen technologies increase and their costs decrease (Brändle, Schönfisch, and Schulte 2021), the adoption of hydrogen will continue to grow. This is especially given that generating energy via hydrogen is carbon-free.

In this study, and for the first time, we assess the financial, footprint and reliability implications of deploying hydrogen-based generation technologies in off-grid CS in Riyadh, Saudi Arabia. One important aspect of this study is that it incorporates a detailed geographic information system (GIS) analysis. The GIS data are used to guide the subsequent assumptions used to design the CS microgrid by highlighting the areas available within land parcels. This is the first study that associates microgrid design and GIS analysis for the city of Riyadh. We also note that the analysis considered in this study fits well with recent announcements by Lucid Motors, an American electric vehicle company, to establish a manufacturing facility in Saudi Arabia in 2024. Further, the Saudi Standards, Metrology, and Quality Organization has granted permission to import EVs and their chargers (Saudi Gazzette, 2014).

In line with these announcements, the results of this study serve as one important piece in informing policymakers of the amount of investment required for EV CS. Of equal importance is arriving at a charging cost that would deem establishing off-grid charging financially viable. The Saudi government announced that investors will have the option to build their own CS and sell electricity at a price set by the investor (but with a ceiling price set by the regulator). Note that off-grid and on-grid charging are not mutually exclusive. Both solutions can be simultaneously adopted, with different shares, to support EV deployment. The candidate technologies considered for the off-grid CS design were solar PV, wind, battery storage and hydrogen (i.e., hydrogen fuel cells, onsite hydrogen production via an electrolyzer and hydrogen storage).

Compared with a CS without hydrogen, we find that hydrogen can decrease the footprint by 25% while maintaining the same level of charging reliability. This area reduction, however, is at the expense of a slight cost increase at current technology prices. By 2030, and given the cost declines that hydrogen technologies would likely achieve, hydrogen technologies will become economical in their own right. In other words, in addition to the reduction in footprint, deploying hydrogen becomes the economically preferred option at the same level of reliability.

From a land parcel perspective, we note that nearly 25%, 22% and 38% of hospital, mall and university land parcels, respectively, can host off-grid CS. These percentages assume that the EV charging demand is fully met. However, if we allow 5% of the demand to be unmet, the number of land parcels that can accommodate CS can double. For gas station land parcels, a maximum of 5% can accommodate CS, even if the CS with the smallest footprint is built.

The remainder of the paper is structured as follows. Section 2 provides a brief literature review and the scope of the study. Then, in section 3, we summarize the data and assumptions used. The results are presented and discussed in section 4 before finally concluding the paper in section 5.

Review and Motivation

Literature overview

For charging stations (CS) that are connected to the grid, we find that the literature justifiably focuses on the technical implications stemming from this connection. Within the distribution network, on-grid CS can have several negative impacts, including reducing the power quality, increasing losses or increasing voltage deviations (Mozafar, Moradi, and Amini 2017). Poor power quality in the distribution network results in overloading the distribution transformers and reducing their lifetimes (Khalid et al. 2019). Hence, algorithms are used to optimally place CS within distribution networks to minimize their impacts. Further, a distribution network will have a maximum capacity that it can host in terms of CS (Sugihara and Funaki 2020). Hence, off-grid CS can often present itself as the only other alternative available.

Off-grid CS, which are the focus of this study, offer some advantages over their on-grid counterparts. The advantages of deploying off-grid CS include: (1) avoiding the aforementioned power and voltage quality concerns regarding the distribution network, (2) deferring generation and/or network capacity investment, upgrade or reinforcement, (3) contributing to carbon emission reduction goals if the grid is (highly) polluting and the off-grid power supply is carbon-free, (4) serving various locations as they transition from petrol-based mobility to electricity-based mobile CS (Afshar et al. 2021, Răboacă et al. 2020). This enables off-grid CS to be a transitionary solution until the grid is enhanced or becomes less carbon-emitting. However, the cost of electricity for off-grid CS will generally be higher than for on-grid ones. Further, off-grid CS require a large amount of space to generate the necessary energy and, depending on the technologies used, may be noisy (Xu et al. 2021).

Al Wahedi and Bicer (2020a) designed a stand-alone CS for Qatar using several sources: photovoltaics (PV), wind, biodiesel, batteries and hydrogen. For charging 50 cars per day, their results show that a microgrid with the following capacities achieves the desired target: 468 kW of concentrated PV and 250 kW of wind, 10 kw of biodiesel, 595 kWh of storage and 200 kW of fuel cells. As expected, the cost of providing energy through this station was higher than the prevailing tariff in Qatar. Another variation of this study has been published by the same authors (Al Wahedi and Bicer 2020b), and it is worth noting that the wind turbines used in these studies possessed a rotor diameter of 54 m, which cannot be practically deployed within cities.

In the Spanish context, Grande, Yahyaoui, and Gómez (2018) assess the economic and environmental viability of an off-grid CS based on PV and batteries. For a single fast-charging load, the authors’ design requires nearly 280 kW of PV alongside a battery. To relax the design, an unmet load in the range of 5-15% was permitted. It was concluded that the system was both technically and economically viable. Note, however, that residential electricity prices in Spain exceed $0.22/kWh. Another off-grid CS was designed by Mehrjerdi (2019) to supply electric and hydrogen loads in a generic location. This design considered diesel, which resulted in a reduction in the cost of charging by around 15%.

A similar analysis was conducted for Denmark (Bansal et al. 2020). Wind energy was the technology of choice given the rich wind resources in Denmark. The capacity of the turbines ranged from 500 kW to 1,500 kW, corresponding to hub heights of 38 m to 100 m. A constant load profile of 25 kW was assumed for the 8 am to 7 pm time-period. A case study performed in Turkey (Ekren, Canbaz, and Güvel 2021) found that charging a maximum of five EVs per hour required 250 kW of PV and one wind turbine with a capacity of 200 kW, all for a cost of around $0.064 /kWh. Other papers have focused on designing off-grid CS that utilize PV only. The argument for this is based on the observation that a temporal overlap between solar availability and daytime charging exists (Ghotge, van Wijk, and Lukszo 2021). Here, it is also assumed that the EV owners would park their cars for extended periods of time (e.g., long-term parking lots in airports).

Based on the review above, several observations can be made. For the purposes of this study, we highlight two observations that are related to the inherent challenges associated with PV and wind deployment. After identifying these challenges, the role that hydrogen can play to address these challenges is articulated — all within the context of off-grid CS.

The first observation relates to the footprint of these off-grid CS. Generally, we note that the required PV capacity is at least 250 kW. Depending on the efficiency of the solar module, each one square meter area can host 0.1-0.15 kW (Elshurafa and Muhsen 2019). Hence, approximately 2,500 m^2 to 1,670 m^2 would be needed to deploy 250 kW. While a few papers did stipulate a maximum area of 1,500$m^{2,}$ no justification was provided to support this specific numerical choice. Further, even at an area of 1,500 m^2 (which equates roughly to the size of three basketball courts), and assuming the required area per vehicle to be 12.5 m^2 based on the Dutch regulations for covered parking spaces (Ghotge, van Wijk, and Lukszo 2021), the available space should be able to host 120 vehicles. Securing such a space may be prohibitive in many areas, especially in city centers.

Second, in all the papers referred to above, the practicality of installing wind turbines possessing a capacity of 250 kW and above was not considered. As mentioned, rotor diameters were larger than 50 m. The latter does not consider the hub height of the turbine. Such scales cannot be deployed within cities, especially keeping in mind that wind turbine suppliers recommend that turbines be double the height of surrounding obstructions and ideally as far away as possible from buildings and trees, which will block the wind and cause turbulence (Lubitz 2014). Increasing the hub height may address the latter problem. However, it is a costly solution. Further, beyond a certain threshold, permits from local authorities would be required if the wind turbine, or any other structure, exceeds a certain height. Other challenges that wind turbines pose within city centers are related to visual esthetics (Colafranceschi, Sala, and Manfredi 2021) and noise (Xu et al. 2021).

Motivation, scope and context

The optimal solutions that were sought in the above-mentioned papers were considered as such in terms of minimizing cost. However, the challenges associated with PV and wind deployment, as discussed, are not incorporated. Thus, in this study, we design off-grid CS while considering the limitations associated with PV and wind deployment. To keep the microgrid carbon-free, we exclude diesel generation. With that in mind, it is expected that hydrogen will play a bigger role in our design. Hydrogen fuel cells and electrolyzers are carbon-free and require a much lower footprint compared with PV and wind. However, this space saving may be achieved at the expense of higher energy delivery costs. As hydrogen technology matures further, off-grid CS utilizing high shares of hydrogen energy will become more cost-effective. The balance that needs to be struck between cost, footprint and other urban considerations is a primary motivation for initiating this study.

While off-grid CS have been designed for various cities around the world, no previous study has examined this in Riyadh. Solar resource in Riyadh, and in the Arabian Peninsula in general, is excellent. With a global horizontal irradiance (GHI) of more than 6 kWh/m^2/year (Zell et al. 2015), this solar resource can contribute to decreasing the PV area required for the CS. The lack of studies pertaining to Riyadh served as another motivating factor for this study.

To inform our modeling, our study utilizes GIS (Bian et al. 2019). Explicitly, our footprint considerations are guided by a detailed land parcel and land use analysis for the city of Riyadh. By capitalizing on these data, more realistic assumptions can be made with respect to the power capacities used in the CS. Further, we can quantify the share of these parcels that can accommodate the CS that we designed. To the best of our knowledge, no previous study has been conducted with the same scope.

As a final remark to this section, we note that the actual uptake of EVs within Riyadh, driving patterns of Riyadh residents, any associated incentives that the government may choose to implement, the cost evolution of EVs and consumer preferences/behavior toward EV ownership are beyond the scope of this study. All these aspects are important and will be ground for future studies. The study focuses, within the context of Riyadh, on what hydrogen can contribute to off-grid CS given the constraints that are inherent to PV and wind, as articulated above.

Data, Assumptions and Modeling

For the purposes of this study, a considerable amount of data are collected and numerous assumptions are made. We posit that the GIS data for the city of Riyadh and the load profile assumptions will serve as the foundation for subsequent analysis. Both the GIS data and load profile are the key factors impacting the success of the microgrid design in terms of its capacity, cost and footprint. Hence, we address these two factors first in this section. Following this, all data and assumptions related to the technologies are presented.

Riyadh GIS data and area constraints

Spatial land parcel data are obtained for the city of Riyadh from the Royal Commission for Riyadh City (www.rcrc.gov.sa). This dataset provides a detailed representation of all land parcels in Riyadh, including its designated use (i.e., residential, commercial, industrial, etc.) and area. The spatial analysis is conducted using the commercially available software ArcGIS Pro. Our focus is on the following five categories: hospitals, universities, schools, shopping malls and gas stations. Industrial facilities are excluded as they are mostly located in the outskirts of the city.

Although the area of each land parcel and its designated use are known, the share of each land parcel that can be utilized for deploying a CS is not. To arrive at the area that can be utilized to build a CS, we rely primarily on the maximum allowable area that can be built (MAAB) within a certain parcel. As the name suggests, the MAAB sets the upper limit for the share of the parcel area that can be built on and is expressed in percentage terms. For example, if a residential land parcel possesses an area of 1,000 m^2 in a certain city, and the regulations stipulate a MAAB of 60%, then only 600 m^2 could be utilized for building purposes. The remaining 400 m^2 could be used for parking, landscaping and/or other purposes. A detailed analysis of MAAB in Riyadh can be found in the literature (Elshurafa and Muhsen 2019).

With the land parcel area and associated MAAB value known, we can approximate the area that can be allocated to deploy CS. The area allocated for the CS will mainly be related to the parking area available. Note that for the categories we choose, and after applying the MAAB calculation, a considerable share of the remaining area would be dedicated for parking. Here, we assume that we can only utilize a quarter of the remaining area, after applying the MAAB, to deploy a CS. Equivalently, we assume that we can only utilize 10% of the total land parcel to deploy a CS if the MAAB is 60%, that is, 25% of (1 – 60%) = 10%.

After estimating the area that can be allocated to CS, we can then estimate the PV capacity that can be deployed. For every square meter, around 110 watts (0.11 kilowatts or kW) of solar PV capacity can be deployed (Elshurafa and Muhsen 2019). We restrict our discussion here to solar PV as it is the technology that is chiefly responsible for the total footprint of the CS. More details are provided in the following sections.

Table 1 summarizes the number of land parcels and subsequent mean areas for the five zoning categories selected. From the mean, we then calculate the area that can be allocated for CS. Finally, the PV capacity that can be deployed is derived.

Table 1. Categories, counts, mean areas and PV capacity that could be allocated for CS in Riyadh land parcels.

Land parcel category	Count	Mean area in m^2	Mean area available for charging station (i.e., PV) in m^2	Mean PV capacity that could be deployed in kW
Gas station	1,278	4,328	433	48
Hospital	114	38,802	3,880	427
Shopping mall	101	28,521	2,852	314
School	3,255	7,398	740	81
University	101	58,479	5,848	643

Source: Authors compilation based on data from the Riyadh Commission.

Table 1 provides at least three noteworthy observations. First, we note that the university, hospital and shopping mall land parcel categories can host the most PV capacity. Second, we conclude that there is little potential, on average, to deploy PV in the gas station and school categories. Third, the table provides actual numerical values for the PV capacities, which provides insight as to the average possible PV capacity that can be deployed. Qualitatively, these observations may have been expected. However, the actual numerical values are not immediately apparent.

It is important to reiterate that the values provided in Table 1 are mean values, and they serve as an initial guide to PV capacity (i.e., footprint needed) when designing the microgrid/CS. However, there will be land parcels in each category that are larger and can accommodate more PV capacity. The area variation in each category, along with their distribution, is considered further as we progress into the design and optimization phases. Nonetheless, these mean values set our expectations for the cost and footprint that will be needed. The latter is an important distinguishing aspect of this study compared with previous studies in the literature, where area constraints were chosen generically without relying on the specific prevailing area availability in the city of interest.

Charging profile

Synthesizing a charging load profile for a CS is a task that deserves an independent study. The profile depends on many factors, including, for example, the level of EV deployment within the jurisdiction (Hall and Lutsey 2017) and the location of the CS (Sun et al. 2020). Another important factor that impacts the load profile is the level of charging. Three levels of charging exist. These indicate the power rating: Level 1 rated at <2 kW, Level 2 rated at 2-20 kW and Level 3 rated at ~50 kW (Khalid et al. 2021). For the purposes of this study, we adopt previously developed profiles from the literature.

As highlighted in section 3.2, we focus on CS that serve parking lots for hospitals, shopping malls, schools, universities and gas stations in Riyadh. Three main parameters are to be identified: the time at which the EVs are to be charged, the number of EVs to be charged, and the charging level. We arrive at the previous parameters with the aid of Table 2, where a summary of previously published results is provided. Generally, it is expected that CS at these locations would be busiest between 9:00 am to 7:00 pm. Indeed, Table 2 affirms this expectation. The other two parameters (i.e., the number of EVs being charged and the level of charging) are heavily dependent on each other. For example, if five cars are being charged at Level 1, then the peak load would be 10 kW. However, if the same five cars are being charged at the upper limit of Level 2, then the peak load would be 100 kW. Hence, we find papers referring to the load either in the form of EV numbers or in terms of power (kW).

Based on Table 2, we posit the CS would serve six EVs. As far as the charging level is concerned, we opt to design the CS at the Level 2 rating as this is a the most common CS available in terms of infrastructure (Hall and Lutsey 2017). More specifically, within Level 2, we note that a rating of 11 kW is a common power rating for AC charging at public CS (Fachrizal et al. 2021).

Table 2. Review of load and time of charging for charging stations.

Reference	When bulk of EVs are being charged	Load: expressed either in number of EVs charged or in kW
Al Wahedi and Bicer 2020a	10am – 7pm	1 – 6 EVs
Al Wahedi and Bicer 2020b	8am – 7pm	1 – 9 EVs
Bayram et al. 2016	9am – 6pm	1 – 4 EVs
Grande, Yahyaoui, and Gómez 2018	8am – 7pm	50 kW
Mehrjerdi 2019	7am – 8pm	50 kW – 150 kW
Bansal et al. 2020	8am – 7pm	25 kW
Wang et al. 2020	7am – 11pm	50 kW – 150 kW
Fachrizal et al. 2021	8am – 6pm	40 kW

Source: Author compilation.

In our study, we seek to test the extreme case, whereby the CS is operating at its maximum capacity throughout the time of interest. The latter translates to charging six cars at 11 kW each, or 66 kW of continuous load, from 9 am till 6 pm. We reiterate that the number of cars that can be charged simultaneously at a certain station is a function of the charging level.

Solar PV

Once installed, solar PV is carbon-free, and is a technology that enjoys near-zero marginal cost of generation. However, solar PV modules occupy a considerable area, which may not be readily available, especially in city centers. One way to overcome this footprint limitation is to install PV modules on shades or canopies (Umer et al. 2019) at a higher capital (installation) cost. The assumptions used for PV are summarized in Table 3.

Table 3. Assumptions used for the PV panels.

Parameters	Value
Capital costs (including structural canopy)	$1,200/kW
Module efficiency at standard test conditions	17%
Temperature power loss coefficient	-0.4%/°C
Nominal operating cell temperature	47°C
Operation and Maintenance (O&M) costs	$5/kW/year
Total PV system losses	15%
Panel slope from horizontal	25°
Azimuth degree from north	180°
Solar resource	Irradiation data for the city of Riyadh

Source: (Elshurafa et al. 2019).

Wind

Wind turbines have advanced significantly over the past two decades. State-of-the-art wind turbines, with a capacity of 7 MW, can possess hub heights of 170 meters and rotor diameters of 160 meters. Evidently, these scales are only suitable for utility applications in specific geographic locations — not within a city setting. Ideally, wind turbines should be double the height of any nearby obstruction (e.g., buildings or trees). The latter may not be possible in a city setting, as permits from local authorities would be required if a wind turbine, or any other structure, exceeds a certain height. To overcome the height limitation, it is possible to resort to installing two smaller wind turbines. While this solution sounds reasonable in principle, wind turbines must be a certain distance away from each other so that the turbulence created from one turbine does not impact the other. We also reiterate that deploying wind turbines results in aesthetic and noise implications that are not welcome by the public.

Given the challenges associated with wind turbines, we limit the hub height here to 20 meters. This hub height translates to a turbine capacity of 25 kW. Further, we also restrict the possible number of turbines to be installed to one. Most wind turbines have a design life of 25 years. Table 4 below summarizes the assumptions for wind technology used in our modeling. Even at this conservative height, deploying wind turbines may still be problematic. As a result, our CS designs will consider options that exclude wind.

Table 4. Assumptions used for the wind turbines.

Parameters	Value
Capital cost	$1,000/kW
O&M costs	$20/kW/year
Lifetime	25 years
Maximum allowed hub height	20 m
Maximum capacity	50 kW
Maximum turbines allowed	1 turbine
Wind resources	Wind speed data for the city of Riyadh

Source: (Elshurafa et al. 2021).

Battery storage

For batteries, both power and energy ratings must be set. We choose the battery power rating based on our peak load: 66 kW. For the energy rating, the hours of autonomy (i.e., how long can the battery solely meet demand) must be set. For one full day of autonomy (nine hours) and for half a day of autonomy (around four hours), the energy capacities should be around 600 kWh and 300 kWh, respectively. For reliability purposes, we choose one full day of autonomy in our design. Clearly, this latter choice has cost implications as the size of the battery would be larger.

To ensure that batteries continue to perform reliably, the energy content must stay above a minimum level. This is known as the minimum allowable state of charge (MSOC). Typical values for MSOC range between 10-25% of the total energy content. Hence, the previous energy content of 600 kWh has to be adjusted to ~670 kWh assuming a 10% MSOC. From a practical viewpoint, finding a battery with the exact energy rating is not always possible. Hence, one must use capacities that are commercially available, which is 1 MWh in our case. As far as the area footprint is concerned, this battery capacity requires a modest footprint, certainly much less than PV. For context, commercial batteries with a capacity of 1 MWh are provided in 20-ft containers. Table 5 summarizes the assumptions used for the battery.

Table 5. Assumptions used for the battery.

Parameters	Value
Capital cost (1)	$700/kW
O&M costs	$1,200/year
Lifetime	10 years
Minimum allowable state of charge	10%
Roundtrip efficiency	90%

(1) This cost includes the balance-of-charging-station costs, including charging poles, cables, labor, permitting, site preparation, etc.

Source: (Frith 2021).

Hydrogen

In addition to the technologies discussed above, we also include hydrogen for electricity generation. The CS will require an electrolyzer to produce hydrogen on site, a hydrogen fuel cell to produce electricity and a hydrogen tank for storage. Given that our peak load is around 60 kW, we do not expect that the capacity of the fuel cell would be higher than that given the presence of other technologies. There are several fuel cell types to choose from. For the purposes of this study, we opt for a polymer electrolyte membrane (PEM) fuel cell. This type of fuel cell possesses typical capacities of less than 250 kW and efficiencies of 60%. It also enjoys quick start-up and load-following capabilities. Further, this type of cell is suitable for portable power and distributed generation applications (DOE 2015).

Ideally, 1 kg of hydrogen provides 33.6 kWh of electricity. However, at our chosen fuel cell efficiency and load, and assuming hydrogen is the only source of energy, we would require around 3 kg per hour for continuous operation. In other words, the storage tank should supply 30 kg of hydrogen per day assuming no other technologies contribute energy. The amount of hydrogen required determines the size of the electrolyzer needed. For this study, we assume a PEM electrolyzer efficiency of 60% (Buttler and Spliethoff 2018, Kumar and Himabindu 2019). To provide more context, if 48 kWh of electricity are required to produce 1 kg of hydrogen (Caumon et al. 2015), then the electrolyzer size (load) would be in the range of 150 kW.

While the optimization model arrives at exact capacities for the fuel cell, tank and electrolyzer, the calculations provided here shed light on the footprint required. Generally, and similar to the case with battery storage, the area requirements for all hydrogen-related components are reasonable. Commercial electrolyzers reaching several megawatts of capacity can be provided within 20-ft containers. Fuel cells in the range of 50 kW require around 10 m^2 to be installed. We observe the considerable difference between what is required for PV compared with either battery or hydrogen generation. The following table summarizes the assumptions for the hydrogen components.

Table 6. Assumptions used for hydrogen components.

Component	Parameter	Value
Hydrogen fuel cell	Capital cost	$1,500/kW
	Efficiency	60%
	Minimum load ratio	10%
	Lifetime	15 years
Hydrogen electrolyzer	Capital cost	$1,100/kW
	O&M costs (1)	$14/kW/year
	Efficiency	60%
	Minimum load ratio	10%
	Lifetime	15 years
Hydrogen tank	Capital cost	$800/kg/year
	O&M costs	$3/kg/year
	Initial tank level	Full
	Lifetime	25 years

[1] The O&M costs of the electrolyzer include the O&M costs for the fuel cell.

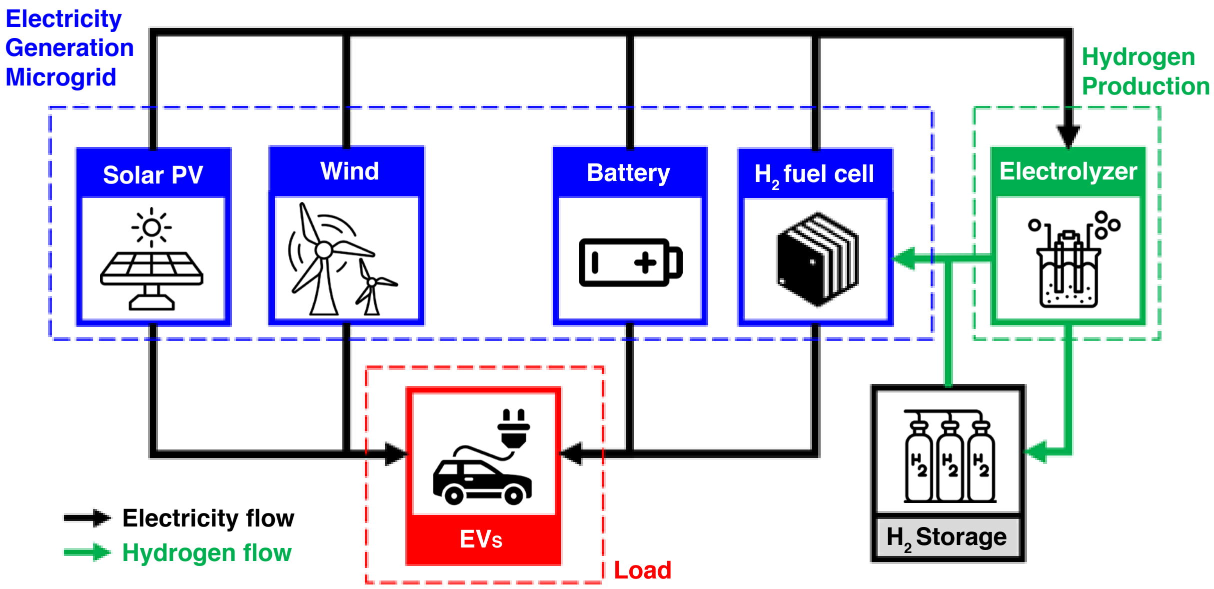
Sources: (Buttler and Spliethoff 2018, Caumon et al. 2015, Mongird et al. 2020, Nguyen et al. 2019, Zhang et al. 2020).

Microgrid configuration and model

With all assumptions related to the technologies presented, Figure 1 illustrates how these technologies interact to satisfy the load. The electricity generation technologies (i.e., solar PV, wind, battery storage and hydrogen fuel cell) are shown in blue. The electrolyzer, which produces hydrogen, is shown in green. In addition to the main load in this microgrid, which is the EVs (shown in red), there is the electrolyzer load, which is also satisfied by the electricity-generating technologies. Once the hydrogen is produced, it can be used directly by the fuel cell or stored in the hydrogen tank for later use.

Our modeling and optimization are performed using HOMER Pro, which is a commercially available software. In addition to finding the minimum cost solution from the technology suite, HOMER Pro also provides all other possible combinations (i.e., energy mix possibilities) that would satisfy demand. Once these solutions are obtained, they can be sorted by net present cost, capital cost, levelized cost of energy, emissions (if any) and area, among other parameters, to serve various purposes and priorities.

Figure 1. A conceptual schematic of the microgrid under consideration.



Source: Authors' illustration.

The electricity-generation technologies are depicted in blue. The electrolyzer, which produces hydrogen, is depicted in green. The EV load is depicted in red. Note the distinction between the electricity flow (black arrows) and hydrogen flow (green arrows) within the entire microgrid.

Results and Discussion

As mentioned, HOMER Pro is used to optimize our microgrid. For cost purposes, the optimal solution is the one that possesses the least net present value of cost (NPV). The discount rate applied for NPV calculations is 5%. Regarding the required footprint, we only consider the photovoltaic (PV) capacity size. Recall that the battery, electrolyzer, and fuel cell only occupy a small footprint share in the overall microgrid compared with the share for the PV array. Hence, it is safe to assume that the size of the PV array, or equivalently the PV power capacity, is the main factor that determines the footprint of the entire microgrid.

Optimal configurations: cost, area and supply shortage considerations

There are a total of four configurations that met demand. Combinatorically, and because we consider four generation technologies, we should theoretically have 24 = 16 possible configurations that meet demand. However, it is not possible to meet demand reliably without PV and battery. In other words, PV and battery are always part of the optimal solution within each microgrid configuration, which brings down the feasible configurations from 16 to four.

We consider three scenarios: (1) designing the charging station (CS) with 2022 prevailing technology costs, (2) designing the CS with the projected technology costs for 2030 and (3) designing the CS with 2030 projected technology costs and allowing a 5% capacity shortage. In the first two scenarios, all demand is fully met. However, in the third scenario, we allow 5% of the demand to be unmet. In other words, the reliability of the CS in the third scenario is compromised. Note that the reliability definition here is defined as unmet demand, and not the typical definition used in national power sector models (e.g., loss of load probability). As expected, this relaxes the design and may result in cost reductions.

Results for scenario 1: 2022 costs

The four configurations that satisfy our demand for each scenario are summarized in Table 7. We rank these configurations based on the NPV of the cost as well as other criteria. These criteria are summarized in dedicated rows. As can be seen, for scenario 1, the most economic configuration based on the NPV of cost is the one that includes a wind turbine, battery, and PV (i.e., configuration A). However, the costliest configuration based on the NPV includes hydrogen, battery and PV (configuration D).

Table 7. Summary of configurations: technologies, costs, capacity of technologies and ranking criteria based on prices in 2022, 2030, and 2030 with an allowed annual demand shortage of 5%.

		Scenarios											
		Scenario 1: 2022 costs				**Scenario 2: 2030 costs**				**Scenario 3: 2030 costs with 5% unmet load**			
Configuration		A	B	C	D	A	B	C	D	A	B	C	D
Technologies	Battery	√	√	√	√	√	√	√	√	√	√	√	√
	PV	√	√	√	√	√	√	√	√	√	√	√	√
	Wind	√	√			√	√			√	√		
	Hydrogen		√		√		√		√		√		√
Technology capacities (1)	PV Capacity (kW)	233	229, 207	456	348	233	212, 207	456	383, 348	121	121	179	177
	Tank Capacity (kg)	-	5, 20	-	20	-	5, 10	-	10, 5	-	5	-	5
	Electrolyzer (kW)	-	10, 30	-	30	-	10, 10	-	10, 10	-	10	-	10
	Fuel Cell (kW)	-	10, 10	-	10	-	20, 30	-	30, 10	-	10	-	10
Costs	NPV (M$)	1.74	1.80, 1.85	1.91	1.93	0.973	0.976, 0.979	1.10	1.07, 1.08	0.884	0.901	0.885	0.900
	LCOE ($/kWh)	0.349	0.360, 0.370	0.382	0.388	0.195	0.196, 0.196	0.221	0.215, 0.216	0.185	0.188	0.185	0.188
	Capital cost (M$)	0.930	0.956, 0.971	1.11	1.07	0.533	0.542, 0.548	0.669	0.651, 0.628	0.455	0.469	0.475	0.488
Ranking criterion	NPV	1	2	3	4	1	2	4	3	1	2	1	2
	PV Area/Capacity	2	1	4	3	2	1	4	3	1	1	2	2
	'Wind Limitation' and PV Area/Capacity	4	3	2	1	4	3	2	1	2	2	1	1

[1] The battery and wind capacities are not included because they are fixed.

Source: Authors' calculations.

However, if we assess the microgrid configurations based on the footprint, then the ranking changes to some extent. Referring to Table 7, we see that the configuration that requires the smallest footprint is configuration B, while configuration C requires the largest footprint. The area required for configuration C is almost double that required for configuration B. The reason for this large difference in required area is that the battery in configuration B has more opportunity to be charged throughout the day via the wind turbine. However, in configuration C, the battery can only be charged via PV. As a result, a larger PV array is required to simultaneously meet demand and charge the battery.

The final ranking criterion is based on the footprint required and the challenges associated with deploying a wind turbine within the city (this is referred to as "wind limitation" in the table). When considering this criterion, we find that the ranking changes entirely compared with that based on the NPV. As Table 7 shows, the most attractive solution based on the NPV criterion becomes the least attractive, and vice versa. In this last ranking criterion, both configurations A and B drop to the bottom of the list because they both require a wind turbine. Then, the required PV area is applied. In other words, the most attractive configuration would be the one that possesses the least PV capacity and no wind turbine. The least attractive configuration would then be the one that possesses the highest PV capacity with a wind turbine installed.

Qualitatively, we see that hydrogen provides the important benefit of reducing the required footprint for the microgrid. This reduction is especially significant between configurations C and D. As shown in Table 7, configuration C requires 456 kW of PV compared with 348 kW in configuration D. In other words, while incorporating hydrogen technologies into the microgrid design increases costs, these costs are counterbalanced by a considerable reduction in the overall footprint of the microgrid (around 25%). The area advantage, however, between configurations A and B is small due to the existence of the wind turbine.

As a final point to this subsection, we provide another example of the cost-area compromise by viewing configuration B, where two possible solutions are provided (separated by a comma). The first solution represents the lowest-cost solution, while the other solution represents the smallest-area option. Once again, note that the small footprint was attained at a slightly higher NPV of cost.

Results for scenario 2: 2030 prices

For this scenario, we redo the analysis with projected 2030 technology costs, summarized in Table 8. The results for this scenario are summarized in Table 7 in the corresponding column.

Table 8. Projected capital costs for technologies in 2030.

Technology	PV[1]	Wind	Battery[2]	Electrolyzer	Hydrogen Fuel Cell	Hydrogen Tank
Cost	\$700/kW	\$800/kW	\$350/kW	\$393/kW	\$854/kW	\$400/kg

1 Costs include canopies

2 Costs include inverter costs, balance-of-charging-station, charging poles, cables, permitting, site preparation, etc.

Source: Authors' assumptions.

Looking at the NPV rankings for this scenario, we notice that the ranking changes compared with scenario 1. An important observation in scenario 2 is that configuration C becomes more cost competitive than configuration D. In other words, in scenario 2, we benefit in three ways from deploying hydrogen: We reduce the required footprint for the CS, reduce the cost and maintain the same level of reliability (i.e., the demand is fully met). The reduction in area footprint between configurations C and D is lower in this scenario: 16%. Recall from the previous subsection (i.e., scenario 1) that the area reduction advantage is attained at the expense of higher cost. However, with the likely downward cost trajectory for hydrogen technologies, deploying hydrogen becomes the financially preferred option if wind turbine installations prove problematic. Compared with scenario 1, the fuel cell capacities chosen by the model are larger and the NPV is much lower in scenario 2. Explicitly, the NPV values in scenario 2 are nearly half of those in scenario 1.

Once again, we see in configurations B and D the cost-area compromise. In this scenario, the compromise in configuration D is larger than that of configuration B. This balance has implications on the sizes of the hydrogen technology devices as well. It should be noted that there were many sizing combinations for the hydrogen technologies that achieved a very close NPV cost. In Table 7, only one option is shown in the interest of brevity.

Results for scenario 3: 2030 prices with a maximum unmet demand of 5%

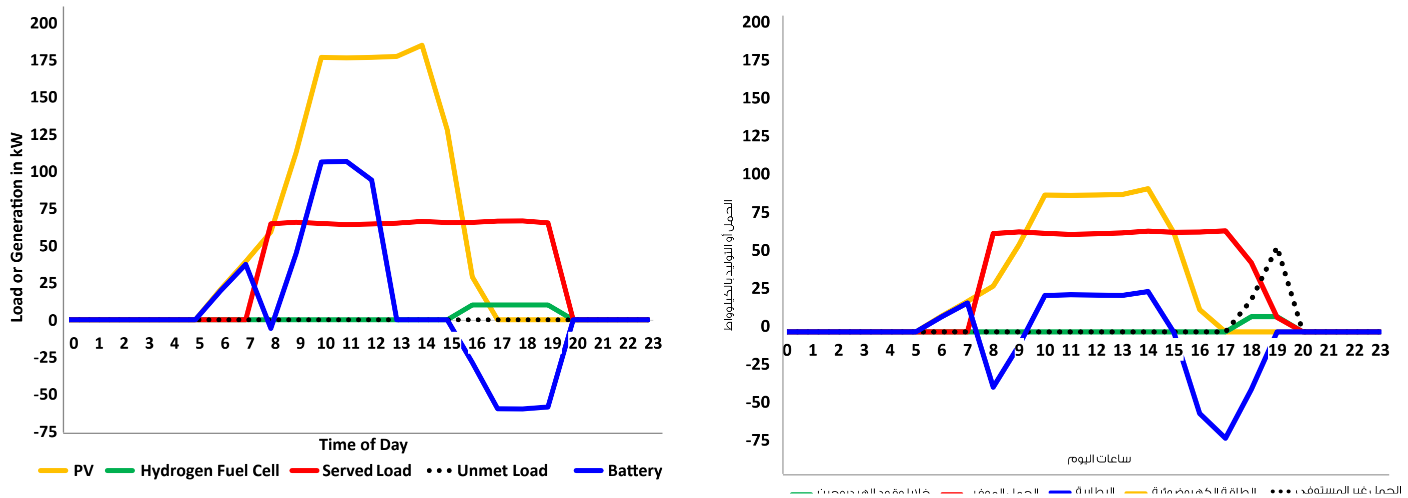
To fully understand how hydrogen contributes to the CS design, we run a simulation that is less constraining than the previous two: We allow a maximum of 5% of the demand to be unmet while keeping the demand constant at a 66 kW level. Hence, a 5% demand shortage is also equivalent to a 5% time shortage. The latter can also be viewed as 27 minutes of daily unmet load, on average, out of the nine continuous hours of daily load.

The result of this run is shown in Table 7 in the scenario 3 column. Given that meeting the load in this scenario is relaxed, we see that the PV capacity required is significantly lower compared with previous scenarios. In configurations B and D, where hydrogen is utilized, the size of the fuel cell is also smaller.

To better compare the impact that relaxing reliability has on the operation, Figure 2 provides a dispatch for a sample day. Figure 2a illustrates the dispatch for scenario 1 and Figure 2b illustrates this for scenario 3. Both figures are for configuration D. The results for configuration D in scenario 2 are not included as it is conceptually similar to scenario 1. In Figure 2a, the battery meets the demand in the early morning and early evening. PV, however, meets a significant share of the demand at midday. Further, any excess PV generation is used to charge the battery (hours 10-12). The PV surplus is high, to the extent that the battery is fully charged at hour 13, and the surplus is now diverted to the electrolyzer to produce hydrogen (not shown for simplicity). During the early evening hours, we see that hydrogen meets a few hours of the demand. The latter results in the battery not reaching its minimum allowed state of charge.

The role of PV in Figure 2b is also similar: It meets demand predominantly during midday, and the excess is used to charge the battery or produce hydrogen. However, because the PV array is much smaller, the battery does not fully charge. The hydrogen fuel cell meets part of the demand for shorter hours (note the difference in the hydrogen tank size between scenarios 1 and 3). At the end of the day, part of the demand is unmet.

Figure 2. The dispatch for a sample day in November to illustrate the difference between: (a) configuration D in scenario 1 and (b) configuration D in scenario 3.



Note the difference between the two scenarios in: PV generation (amber), battery charging and discharging (blue), fuel cell generation (green) and unmet load (black dotted line).
Source: Authors' calculations.

In scenario 3, we see that hydrogen contributes neither to reducing the CS footprint nor to reducing costs. Both configurations B and D (i.e., with hydrogen) are costlier than configurations A and C (i.e., without hydrogen). Moreover, the additional cost incurred does not provide further reliability, as all the configurations have the same capacity shortage value. Note that the rankings in this scenario are only restricted to "1" and "2" because the differences are very small. The results for this scenario, put into context with the previous scenarios, provide another important insight to the role of hydrogen in terms of reliability.

In scenario 2, where the load must be fully met, hydrogen provides three distinct advantages: reducing footprint, reducing cost and overcoming the limitation of deploying wind turbines. These three advantages are all attained at the same reliability level. However, scenario 3 shows that hydrogen provides no advantage if some unmet demand is to be allowed. The battery and PV are enough to provide the necessary energy. The reduction in NPV and capital costs between scenarios 2 and 3 are considerable, but the maximum benefit is seen in the PV array that is needed. Comparing configuration C in scenarios 2 and 3, we see that the PV array is reduced from 456 kW to 179 kW – a ~60% reduction. This balance between reliability, cost and footprint is one that a designer can strike depending on the situation.

Cost comparisons with grid electricity

Current retail electricity rates in Saudi Arabia for all sectors range between \$0.048 to \$0.085/kWh. As can be seen from Table 7, the levelized cost of energy (LCOE) value for scenarios 1 and 2 (approximately \$0.35 and \$0.20/kWh, respectively) are much higher than the prevailing rates in Saudi Arabia, even when considering the most expensive tier. There are two main reasons that contribute to this high cost. First, the high costs of the battery; the battery's share of the initial capital cost is nearly 75%. Second, the decision to maintain reliable charging throughout the year. We reiterate that the battery size is relatively large because we choose to have a single day of autonomy to ensure reliability. In parallel with the large battery, a relatively large PV array is needed.

Given that the battery is the main driver of the cost, we rerun our optimization assuming aggressive learning rates (Cole, Frazier, and Augustine 2021). Quantitatively, we assume that battery costs decrease to $200/kW. At these rates, the LCOE drops to $0.13-0.15/kWh depending on the configuration. These numbers are still higher than the current electricity rates.

Another simulation is run where the microgrid relied solely on hydrogen and PV. This configuration surmounts the cost challenge posed by including a battery in the design. Once again, the LCOE values were within the same range. However, as expected, a large PV array is required (>800 kW) because wind is not a candidate technology in this scenario.

Based on these numerical findings, and from a purely financial perspective, we conclude that it is not yet cost-competitive to charge EVs at off-grid CS. Unless electricity prices increase or the government chooses to incentivize the establishment of off-grid CS, charging EVs from the grid would be more economical for the consumer. Note, however, that when EVs are deployed, the distribution network operator may need to upgrade the distribution network. If the cost of the upgrade proves to be higher than the incentives associated with supporting an off-grid CS, then establishing a CS may be recommended over jeopardizing the voltage quality within the network. Note also that the distribution network would be governed by the EV hosting capacity. In other words, the cost of establishing an off-grid CS should be put in context with the required reinforcement and maximum charging capacities that could occur within a certain neighborhood.

Footprint and policy implications for Riyadh

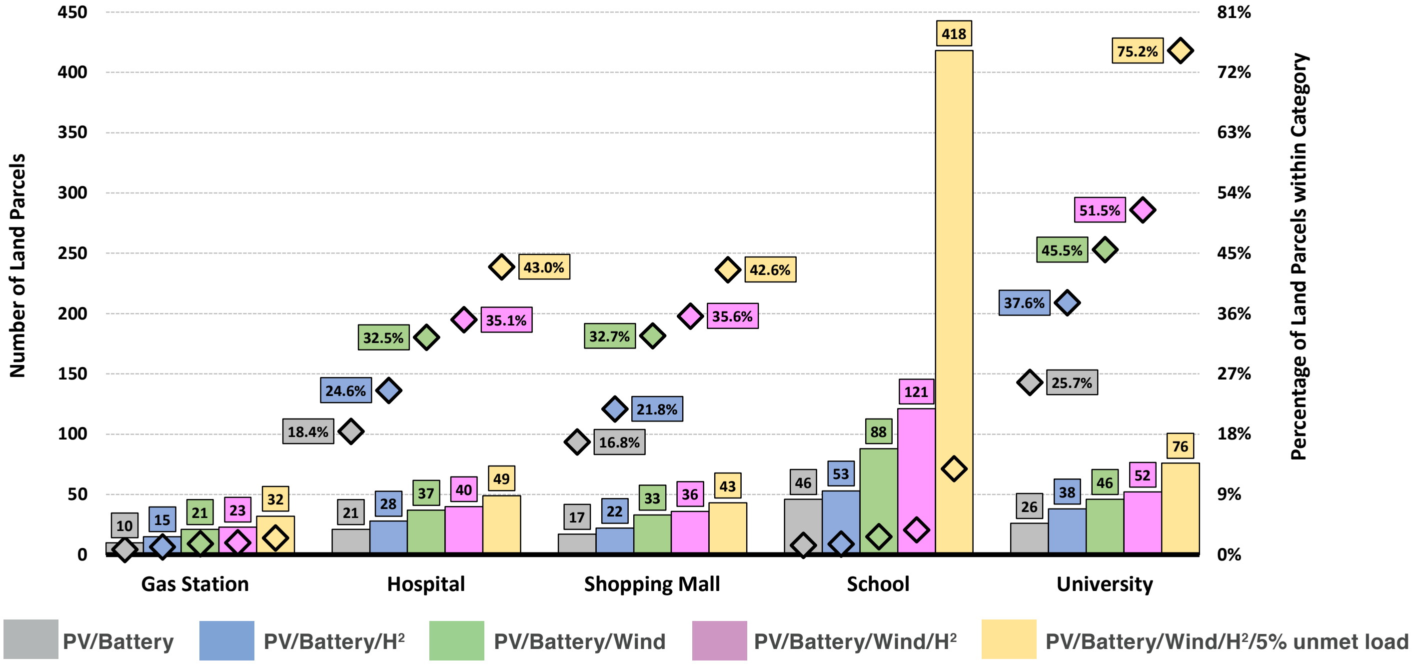
It has been demonstrated that hydrogen provides several advantages with respect to the deployment of CS, including reducing the footprint and overcoming the challenges associated with erecting wind turbines in city centers. Table 1 in section 2 provides a high-level summary of the land parcel areas in Riyadh and assisted us in setting realistic constraints. Now, further scrutiny with the aid of Table 7 provides additional insight regarding the number of parcels that can satisfy our needs. The latter is now possible because of the detailed simulations conducted above.

Figure 3 provides valuable insight as to how the number of suitable parcels (i.e., those that can accommodate a 66 kW CS) changes depending on the configuration. While the configurations that include wind are not in focus, we still include them for comprehensiveness. Recall from the previous modeling that hydrogen reduces the footprint required. In other words, the number of land parcels that can accommodate a CS increases when hydrogen is part of the energy generation mix. Additionally, if we relax the reliability, the footprint decreases even more, and once again, the number of parcels that can accommodate CS increases even further. These qualitative statements are translated to a quantitative description in Figure 3 below.

There are two values depicted in Figure 3. First, we plot the total number of land parcels that are suitable for CS deployment given a certain configuration (left-hand side axis) using a bar chart. Second, we plot the percentage of these land parcels with respect to the total number of land parcels in Riyadh (right-hand side axis) with a scatter plot using diamond-shaped points. The suitable number of land parcels are sorted from lowest to highest.

We explain how Figure 3 can be interpreted using an example for the hospital category. As noted, there are only 21 hospital land parcels that can accommodate a CS station with the PV/battery configuration (in grey). This is because the PV/battery configuration requires the largest footprint. The 21 parcels represent 18.4% of the total hospital land parcels. If hydrogen is added to the CS, the footprint decreases. Subsequently, there are seven more land parcels that can accommodate a CS, bringing the total number to 28 (in blue). Similarly, with a PV/Battery/Wind configuration, the footprint decreases even further compared with the previous configuration, which results in more land parcels being capable of accommodating a CS. The number of land parcels that can now house a CS grows to 37 (in green). Moving forward to the PV/Battery/Wind/H^2 configuration with a reliability compromise, we see that there are 49 land parcels that can house a CS (in yellow). These 49 land parcels represent 43% of the total land parcels with hospital zoning. This is the maximum possible number of land parcels that can accommodate a CS within the hospital category, given our design constraints. The rest of the figure can be read similarly.

Figure 2. The dispatch for a sample day in November to illustrate the difference between: (a) configuration D in scenario 1 and (b) configuration D in scenario 3.



The number of land parcels are shown as a bar chart and are related to the left-hand vertical axis. The ratio of these land parcels to the total number of land parcels available within the same category is plotted as a scatter plot and are related to the right-hand vertical axis. The percentages are not provided for the Gas Station and School categories because they are small. The colors depict the configuration of the charging station. See text for more details.

Source: Authors' calculations.

A number of observations can be made from Figure 3. Most notably, we observe that the number of gas stations that are suitable for hosting CS is small — both in absolute and percentage terms. We also note that even at the smallest footprint, only 32 land parcels are suitable for CS deployment. This number represents around 3% of the total gas station land parcels in the city of Riyadh. Moreover, we also note that within the school category, and even at the maximum case, only 15% of school land parcels are fit to have an off-grid CS on site.

Among all the cases shown in Figure 3, the PV/Battery/H^2 is the most suitable configuration. This configuration strikes a balance between cost, footprint, reliability and overcoming wind deployment challenges. With that in mind, we note that nearly 25%, 22% and 38% of hospital, mall and university land parcels, respectively, can host off-grid CS. These are significant shares. However, less than 5% of gas stations and schools can host these CS. One way to address this challenge is by reducing the charging level from Level 2 to Level 1, reducing the maximum number of vehicles that can be charged simultaneously or allowing for some demand to be unmet.

Conclusion

This study conducted a novel assessment of the cost requirements related to deploying off-grid charging stations (CS) in the city of Riyadh while simultaneously considering four important aspects in the design: (1) the footprint required, (2) the practicality of deploying a wind turbine within the city, (3) the reliability of the microgrid and (4) the actual land parcel areas and their associated zoning. A capacity of 11 kW (i.e., Level 2 charging) was chosen, and the microgrid was constrained to being carbon-free. At current prices, it was found that a microgrid consisting of PV/Battery/Wind would meet demand at the lowest cost. However, the microgrid with the PV/Battery/Wind/Hydrogen configuration requires the smallest footprint. Both these configurations assume that installing a wind turbine in the city center is possible.

From a practical viewpoint, however, erecting a wind turbine within a city may prove problematic for a variety of reasons, including adjacent buildings impeding wind flow, local regulations stipulating a maximum structure height, safety concerns, noise and esthetics. Incorporating this constraint in the optimization, and assuming current technology costs, we find that the PV/Battery configuration is the most cost-effective and that the PV/Battery/Hydrogen configuration requires the smallest footprint. In other words, hydrogen provides the advantage of decreasing the total required footprint to build the CS by about 25%, at a slightly higher cost (4% higher capital). Note that this reduction in footprint is achieved at the same level of reliability. By 2030, however, hydrogen will provide a smaller footprint at a lower cost while still maintaining the same level of reliability. This prediction assumes that hydrogen technologies follow their projected learning curves. Generally, we find that wind provides the benefits of minimizing cost and footprint. Nonetheless, it is not an ideal technology to deploy in a city center.

Relaxing the reliability requirement slightly, by allowing 5% of the demand to be unmet, reduces the footprint by a considerable 50%. If reliability is not to be compromised, then the load should be reduced. This could be achieved by either reducing the level of charging while keeping the same number of vehicles (i.e., increasing the charging duration) or reducing the number of vehicles but maintaining the charging power level. An online booking system (through a mobile application for example), could better manage car flow and charging patterns.

From a levelized cost perspective, off-grid CS were found to be much costlier than the current prevailing electricity tariffs in the Kingdom. This is an important finding for investors, the national utility and policymakers. Investors can further investigate purchasing electricity from the grid and installing the charging units only, rather than building an entire station with energy generation technologies. Similarly, the utility company, which is also in charge of distribution, may want to compare the costs required to build an off-grid station with the costs of upgrading the specific distribution network — keeping in mind the maximum EV hosting capacities that each network can accommodate. Note that off-grid and on-grid solutions are not mutually exclusive. Policymakers can also better assess the incentives needed to attract investors to build off-grid CS.

With respect to land parcel suitability, our analysis shows that a significant share of land parcels allocated for hospitals, malls, and universities can host off-grid CS. However, it was found that, within the category of gas stations and schools, less than 5% can accommodate off-grid CS. Incorporating hydrogen in the CS design increases the number of parcels that could accommodate CS by 15-45% by reducing the required PV array (i.e., footprint). If more CS are to be deployed, reductions in either the level of charging and/or maximum number of vehicles that can be simultaneously charged are recommended.

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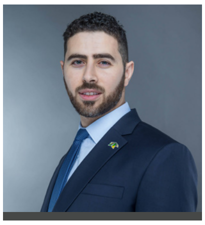

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About the Project

This project aims to quantify the cost, footprint and reliability implications of using hydrogen in off-grid electric vehicle charging stations (CS) using an optimization model coupled with a geographical information system (GIS) analysis for the city of Riyadh, Saudi Arabia.

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