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Role of Energy Efficiency in Designing Carbon-neutral Residential Communities: Case Study of Saudi Arabia

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Key Points

This study focuses on the impact of improving the energy efficiency of housing units on the design of carbon-neutral grid-connected residential communities in Saudi Arabia. Particularly, it examines the efficacy of both photovoltaic systems and wind turbines as on-site renewable power technologies in achieving carbon neutrality. Carbon-neutral communities are designed using a cost optimization approach to account for the cost of on-site power generation as well as grid electricity prices. The analysis indicates that, while carbon-neutral residential communities can be established in all Saudi regions, their cost effectiveness depends on the available solar and wind resources as well as on grid electricity prices and installation costs for solar arrays and wind turbines. The analysis also suggests that the cost effectiveness of carbon-neutral designs can be significantly improved, including more than a 50% reduction in capital cost, when electrical loads for communities are reduced through cost-effective energy-efficiency improvements to individual housing units.

Introduction

The concept of an energy community has become increasingly popular over the last decade in several countries, especially within Europe and North America (Dóci, Vasileiadou, and Petersen 2015; Walker et al. 2010; Rogers et al. 2008; Berry 2013; Viardot 2013). An energy community meets most, if not all, of its energy needs by generating electricity using renewable energy technologies (Dóci, Vasileiadou, and Petersen 2015). Since their main goal is to foster the generation and use of clean energy, energy communities are also referred to as sustainable energy communities, renewable energy communities (RECs), solar energy communities or shared energy communities (Walker et al. 2010). In addition to the planning and implementation of energy-related measures, energy communities often work to reduce and recycle resources, including waste and water (Romero-Rubio and Díaz 2015).

Several community models have been evaluated in terms of the ownership, planning and management of energy production assets (Walker et al. 2010; Rogers et al. 2008). Among these, solar and wind technologies are generally used to generate power. However, a wide range of planning and management models have been proposed, involving various regulated criteria, modeling approaches and multi-criteria decision-making tools (Trutnevyte, Stauffacher, and Scholz 2011; Hsueh and Yan 2011; Cai et al. 2009). In 2018, the European Union (EU) approved a legal framework for regulating the generation, storage and sale of energy within RECs, to be enforced by 2021 in all EU member states (European Parliament 2018, 2019a, 2019b; Lowitzsch, Hoick, and van Tuldera 2020).

A review of 67 energy community projects worldwide revealed that few meet the criteria set by the new EU legal framework (Lowitzsch, Hoick, and van Tuldera 2020). The reviewed communities are distributed across 18 countries and involve a wide range of energy technologies, including solar, wind, biomass, hydro power, storage, microgrids and combined heat and power systems. Several of the reviewed energy communities have diverse renewable energy resources but are owned/controlled by only one stakeholder or by members not located in the area. Specifically, projects serving urban centers are found to have difficulties meeting all the criteria because of their high energy demand and limited on-site generating capacities, particularly for renewable energy resources (Lowitzsch, Hoick, and van Tuldera 2020).

Moreover, a recent study compared the status of energy communities in Germany and Spain (Romero-Rubio and Díaz 2015). Both countries have benefited from successive EU regulations (European Parliament 2001, 2009, 2018, 2019a, 2019b) helping them to increase the share of renewable energy in their total electricity generation. In particular, the target of 12.5% renewable electricity consumption set by Germany was easily surpassed in 2010, and its 2020 goal of 35% is expected to be exceeded. In addition to EU regulations, the introduction of the feed-in tariff (FIT) and adoption of the Renewable Energy Act in the electricity sector have contributed significantly to the rapid growth of renewable electricity in Germany over the past two decades (Federal Ministry 2007). As a result, energy communities, including energy cooperatives, are common and well developed in Germany, helping to boost the share of renewable energy in total energy consumption (European Renewable 2020a). By contrast, there are very few energy communities in Spain, even though it has more favorable solar resources than Germany, is subject to the same regulations and directives and has access to the same financial support (Romero-Rubio and Díaz 2015). The comparative review presumes that the main barriers to the penetration of RECs in Spain include (i) higher financial risks in generating electricity due to a lack of incentive programs such as Germany's FIT, (ii) fewer financial resources, (iii) lower population density, and (iv) possibly less environmental sensitivity.

When successfully implemented, several benefits have been reported from energy communities, regardless of the type of resources used or stakeholders present. The often-cited benefits include lower energy prices, additional sources of income from power generation and sale, higher penetration of clean energy resources, community-based decision making and increased awareness and education about sustainability (Brummer 2018). However, several barriers and challenges have been identified as the causes of the limited global growth of energy communities. The main barriers include the lack of clear legal frameworks or energy policies, the need for advanced planning and management tools, and limited access to financial resources and technical expertise (Herbes et al. 2017).

As noted earlier, governments and organizations in Europe and North America have been promoting the concept of shared energy communities as a key strategy in the transition to decarbonized economies and, ultimately, in tackling the climate change crisis (European Renewable 2020b; Coughlin et al. 2010; Viardot 2013). However, few actions have been taken in the Kingdom of Saudi Arabia to foster the concept of energy communities. Indeed, in the last two decades, a limited number of feasibility studies have been conducted to evaluate the economic and environmental benefits of these communities for the Kingdom. These studies considered hybrid systems as well as microgrids, including solar and wind power generation systems, to meet the electrical loads of communities located in various regions of Saudi Arabia. Most of the published literature is aimed at designing renewable energy systems for specific locations, remote areas or individual buildings (Amran et al. 2020; Thomas 2020; Shaahid, Al-Hadhrami, Rahman 2014; Mohamed, Eltamaly, and Alolah 2015; Elhadidy 2002; Rehman and Al-Hadhrami 2010; Ramli, Bouchekara, and Alghamdi 2018). Only a few studies of grid-connected Saudi energy communities have been reported in the literature (Ramli, Sennoga, and Alghamdi 2017; Alaidroos, He, and Krarti 2012; Dehwah and Krarti 2019; Rezk, Kanagaraj, and Al-Dhaifallah 2020).

Specifically, Ramli, Sennoga, and Alghamdi (2017) evaluated the cost-effectiveness of a grid-connected hybrid photovoltaic (PV)/wind system to meet the energy demand of two Saudi cities, Dhahran and Yanbu. In their analysis, they assumed that the capital costs of installation would be US$400/kilowatt (kW) for PV systems and US$1,020/kW for wind turbines. They also assumed the grid electricity price would be US$0.032/kilowatthour (kWh) with various sellback-rate scenarios. The analysis indicated that wind turbines are more cost effective than PV systems because of the high wind resources available in both sites. The analysis found that the optimum hybrid wind/PV system could meet the demand load of the community located in Dhahran with a levelized cost of energy (LCOE) of US$0.035/kWh, slightly higher than the grid electricity price (Ramli, Sennoga, and Alghamdi 2017).

Alaidroos, He, and Krarti (2012) performed a cost optimization analysis to design hybrid systems for a grid-connected residential community consisting of 200 houses located in Yanbu. Both PV arrays and wind turbines were considered to meet, fully or partially, the community's electrical demand. The capital costs were set at US$3,995/kW for PV arrays and US$1,540/kW for wind turbines. With a low electricity price of US$0.03/kWh, the authors found that neither PV arrays nor wind turbines are cost effective for on-site electricity generation. The analysis indicated that an optimal carbon-neutral design for the community could be achieved with a cost of energy (COE) of US$0.042/kWh and would include only wind turbines (Alaidroos, He, and Krarti 2012).

Dehwah and Krarti (2019) evaluated the optimal design of hybrid power systems to supply residential communities in Al-Khubar, located in the eastern region of Saudi Arabia. First, they estimated the energy demand of these communities using prototypical models for villas, apartment buildings and one school, designed based on current construction practices. They then assumed that the energy demand of the community has been reduced through the implementation of cost-effective energy-efficiency measures for various building types. These measures include adding thermal insulation in the walls and roofs as well as installing high-efficiency air conditioning systems. Finally, they assumed power is supplied from the grid and/or renewable on-site generation systems consisting of PV arrays and wind turbines. Based on the current electricity production cost of the grid, estimated at US$0.10/kWh, the analysis indicated that PV and wind systems would become cost effective when their capital cost is US$1.600/kW and US$1,480/kW, respectively. Moreover, the analysis found that, when the grid electricity price is increased to US$0.15/kWh and PV and wind capital costs are respectively reduced to US$1,340/kW and US$925/kW, the optimal power generation system (including PV/wind/grid) would result in an LCOE of US$0.126/kWh. With this optimal hybrid design, the residential community could reduce its carbon emissions by 70% (Dehwah and Krarti 2019).

A recent study considered how to design the best combination of PV arrays, fuel cells and batteries to meet the needs of a small community with an electrical load of 500 kWh/day in Neom city (Rezk, Kanagaraj, and Al-Dhaifallah 2020). Neom (meaning new future) city is set to be built along the Red Sea in northwest Saudi Arabia. It will include an urban center, villages, research centers, sports and entertainment venues and tourist destinations. The aim is to attract people from around the world to work there to develop innovative technologies for the future (Neom 2020). Neom city is planned to be 100% powered by renewable energy systems using smart distribution networks, making use of the site's significant solar and wind resources. In a feasibility study by Rezk, Kanagaraj, and Al-Dhaifallah (2020), both standalone and grid-connected Neom communities were considered. The analysis was conducted using the HOMER analysis tool with the following cost data (i) US$1,000/kW for PV systems, (ii) US$500/kW for fuel cells, (iii) US$300/kW for electrolyzers, (iv) US$200/kilogram (kg) for hydrogen storage tanks, (v) US$175 for 360-amp hour (Ah) batteries and (vi) US$500/kW inverters. When the community is considered off the grid, the optimal design includes a 200 kW PV array with 96 360 Ah batteries, 30 kW fuel cell system with 110 kW electrolyzer and 50 kg hydrogen tank, resulting in a COE of US$0.12/kWh. When the community is connected to the grid, the PV/fuel cell (FC) system was found to remain cost effective if the grid extension distance exceeds 30 km, as the cost of connection is estimated at US$10,000/kilometer (km; Rezk, Kanagaraj, and Al-Dhaifallah 2020).

Saudi Arabia has a plan to deploy 60 gigawatts of clean power sources to achieve its 2030 goal of having 30% of the power mix supplied by renewables. This goal will assist the country in meeting its commitment to reduce its carbon emissions by 130 million tonnes by 2030 (Amran et al. 2020; Thomas 2020). This study investigates the role of energy efficiency in achieving carbon-neutral designs for Saudi residential communities and its contribution to the targeted reduction of carbon emissions. Through the comprehensive analysis described in this paper, the best approaches to achieving cost-effective carbon neutrality status for generic residential communities in various Saudi regions are determined. First, the analysis approach is described, including the prototypical housing units used to design the residential communities as well as the renewable power systems considered to achieve carbon neutrality. Then, the analysis results are discussed, including the cost effectiveness of designing carbon-neutral residential communities in various Saudi regions, the impacts of grid electricity prices and the capital costs of renewable power systems.

Analysis Approach

In Saudi Arabia, most residential communities and compounds include villas and apartment buildings (Colliers International 2017). Typically, residential communities include 50 to 200 housing units with a mix of 60% villas and 40% apartments (Colliers International 2017; Klynveld 2016). For this study, communities of 100 housing units are considered, each with 60 villas and 40 apartments. To design carbon-neutral residential communities in various Saudi regions, the following general and systematic analysis approach is used:

i. Define baseline housing prototypes that meet current Saudi energy efficiency standards as components of the residential communities.

ii. Design energy-efficient and net-zero energy villas and apartments using cost-effective energy measures and rooftop PV systems.

iii. Estimate the load profiles for residential communities that include baseline, energy-efficient and net-zero energy housing units.

iv. Optimize the design of carbon-neutral residential communities based on available solar and wind resources as well as capital costs for on-site renewable power systems.

v. Perform a series of sensitivity analyses to assess the impacts of capital costs for renewable power systems.

The following sections outline the analysis approach, including the housing models, types of residential communities and optimization-based design methodology for carbon-neutral communities.

Baseline Energy Models for Housing Units

The baseline Saudi prototypical housing units used to design carbon-neutral communities in this study are based on energy models developed by Krarti, Aldubyan, and Williams (2020). Specifically, the housing units are set to meet the current energy-efficiency standards in Saudi Arabia, including building envelope thermal requirements (Saudi Arabia Standards 2014b) as well as minimum energy performance standards (MEPs) for air conditioners and appliances (Saudi Arabia Standards 2012, 2013, 2014a). Table 1 lists the main features of the baseline energy models for both villas and apartment buildings (Krarti, Aldubyan, and Williams 2020). Renderings of the two energy models are shown in Figure 1.

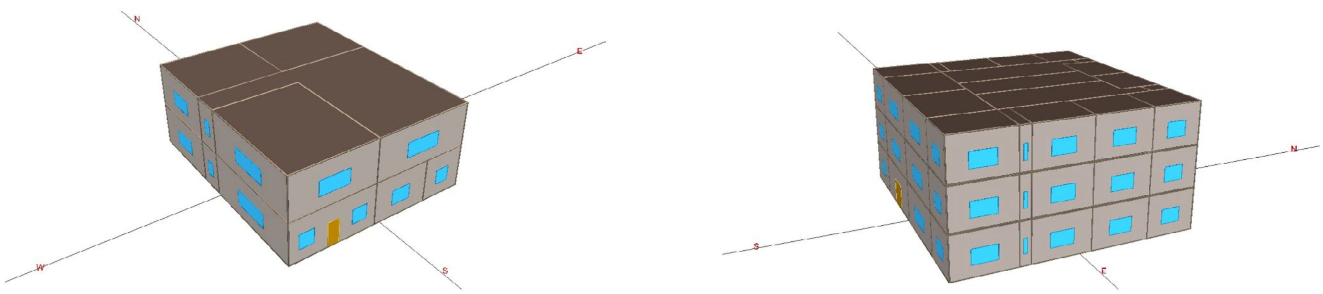
In this study, four Saudi locations are considered, to determine the impact of climate on the design of carbon-neutral communities (Jeddah, Riyadh, Dhahran and Abha). Figure 2 shows the average monthly solar and wind resources as well as dry-bulb outdoor air temperatures for the four Saudi sites. While the four sites have similar solar resources — with Abha having slightly higher global horizontal solar radiation averages — Dhahran has better wind resources throughout the year. It has an average annual wind speed of 4.4 meters (m)/second (s) compared to 3.5 m/s for Jeddah and 3.0 m/s for both Abha and Riyadh. As expected, Abha has the lowest monthly ambient air temperatures, with an annual average of 18.7 degrees Celsius (°C). This is significantly below that of Jeddah (26.7°C) and of Dhahran and Riyadh (26.2°C).

Table 1. Main features of the baseline energy models of villas and apartment buildings.

Building model	Villa	Apartment unit
Number of floors	2	3
Total floor area	525 m^2	1,260 m^2
Wall construction	20 mm plaster outside + 150 mm concrete hollow block + 50 mm polystyrene insulation + 20 mm plaster inside	
Roof construction	10 mm built-up roofing + 100 mm polystyrene insulation + 200 mm concrete roof slab + 13 mm plaster inside	
Floor construction	Ceramic title + 100 mm concrete slab on grade	
Glazing	Double-clear with wood frames	
Window-to-wall ratio	13%	15%
Infiltration	0.8 ACH	0.8 ACH
Cooling set point	23°C	24°C
HVAC system	Split DX	Window AC
EER	9.5	9.5
Occupancy period	24 hours/day	24 hours/day

Source: Authors.

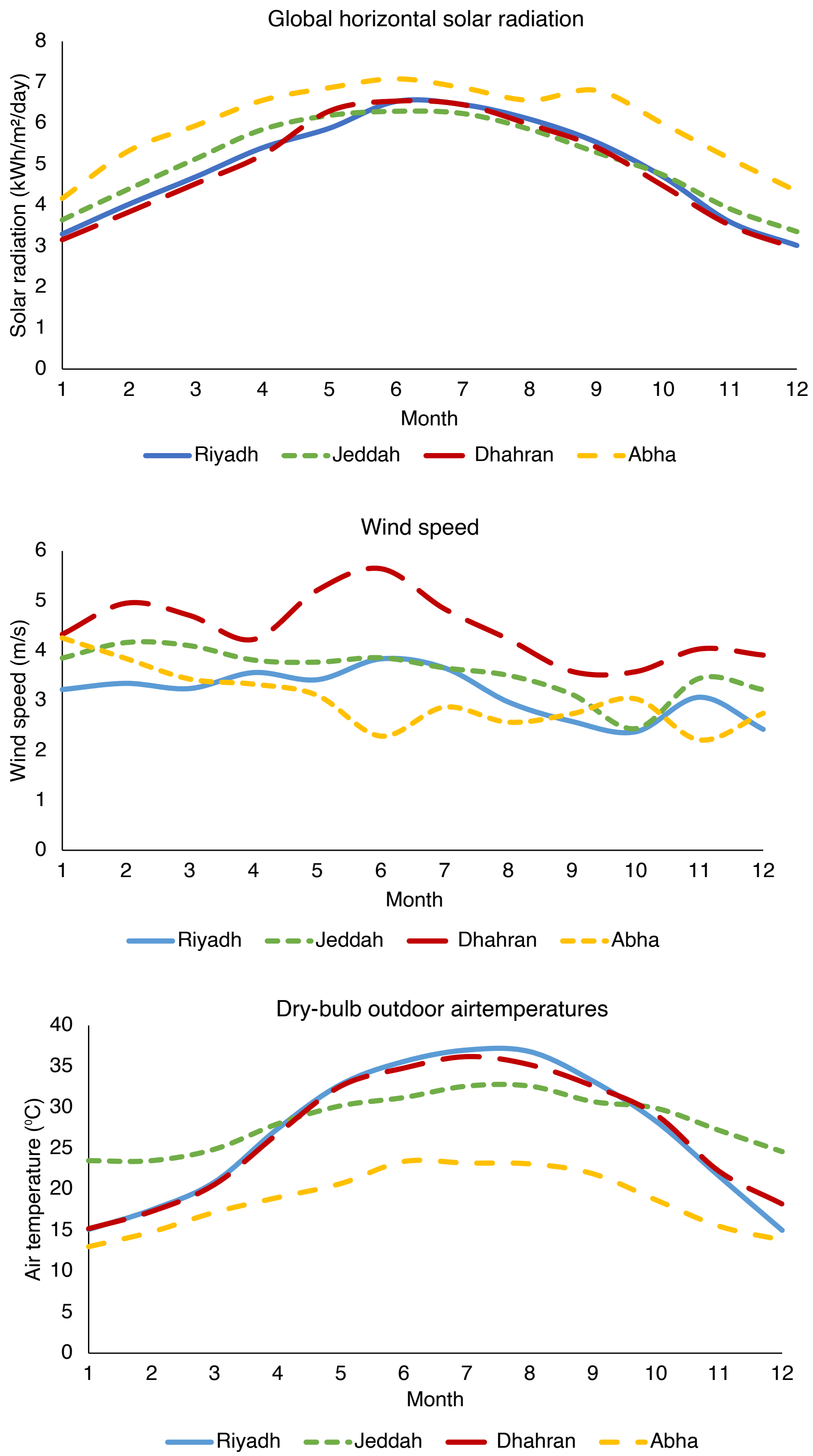
Figure 1. Renderings of energy models for (a) villa and (b) apartment building.



(a) (b)

Source: Authors.

Figure 2. Average monthly (a) global horizontal solar radiation, (b) wind speed and (c) outdoor air temperatures for the four Saudi sites considered in this study.



Source: Homer (2021).

Energy-efficient Housing Units

Based on a life-cycle cost (LCC) optimization analysis, high energy-efficiency housing units are determined as detailed in Krarti, Aldubyan, and Willams (2020). Table 2 summarizes the energy-efficiency measures (EEMs) added to the baseline features of both the villas and apartment buildings in the four Saudi locations considered in this study.

Table 2. List of measures used to design energy-efficient villas and apartment buildings.

Housing type	Location	List of energy-efficiency measures
Villas	Riyadh, Jeddah, Dhahran	Air-inf-75; EE-light; EE-appliances; EER-12; overhangs
	Abha	Air-inf-50; EE-light; EE-appliances; EER-12; overhangs
Apartment buildings	Riyadh, Jeddah, Dhahran, Abha	Cool-roof; air-inf-75; EE-light; EE-appliances; EER-12

Source: Authors.

Note: Air-inf= air infiltration; EE= energy efficiency; EER= energy efficiency rating.

Table 3 lists the specific EEMs used to design the energy-efficient housing units in the four Saudi sites, as indicated in Table 2.

Table 3. EE measures evaluated for Saudi residential building prototypes.

Label	Specifications	Action
Overhang	Add 0.5-m depth overhangs above all the windows	0.5-m overhang
EE-light	Use LED lamps (70% reduction in power density)	70% reduction in LPD*
Air-inf-50%	Reduce air leakage by 50%	ACH = 0.40
Air-inf-75%	Reduce air leakage by 75%	ACH = 0.20
EE-appliances	Use high-efficiency appliances	65% reduction in EPD*
EER-12	Use air conditioners with EER = 12	EER = 12.0
Cool Roof	Use highly reflective coatings on roofs	Roof SR = 0.6

Source: Krarti, Aldubyan, and Willams (2020).

* Note: EPD= Equipment Power Density; LPD= light power density. The EPD and LPD values depend on each housing type and location, as detailed in Krarti, Aldubyan, and Willams (2020).

Net-Zero Energy Housing Units

For this study, the net-zero energy (NZE) designs for both the villas and apartment buildings are obtained by installing rooftop PV arrays atop the energy-efficient housing units outlined in Section 2.2. Indeed, Saudi Arabia has recently approved a regulatory framework allowing small-scale solar distribution systems to be connected to the grid (Electricity 2020). When enacted, the framework will allow for the introduction of net metering, which uses a net-billing mechanism to credit PV-generated electricity exported to the grid at set rates. For instance, households are credited with 0.07 SAR/kWh (US$0.0187/kWh) for any excess electricity generated by their rooftop PV systems. Table 4 lists the PV sizes, expressed in kW, required to achieve NZE status for both the villas and apartments located in the four Saudi sites. Moreover, Table 4 provides the annual yield of electricity generated by a 1kW PV array, depending on an hourly analysis using the optimal tilt angle for each of the four sites (Hybrid Optimization 2021). Moreover, the PV array's performance is estimated using both solar radiation as well as ambient air temperatures, as outlined in Figure 2. The representative PV system used throughout the study consists of crystalline silicon modules with a nominal efficiency of 15% and a temperature coefficient of 0.47%/°C as well as an inverter efficiency of 96% (Solar Advisor Module 2020).

Table 4. Sizes of PV arrays (expressed in kW) needed to achieve NZE design for villas and apartments.

Location	1-kW PV array annual electricity generation (kWh/year)	Villas	Apartments
Riyadh	1,596	12.5	30.0
Jeddah	1,662	18.5	28.5
Dhahran	1,557	20.0	35.5
Abha	2,079	7.5	13.0

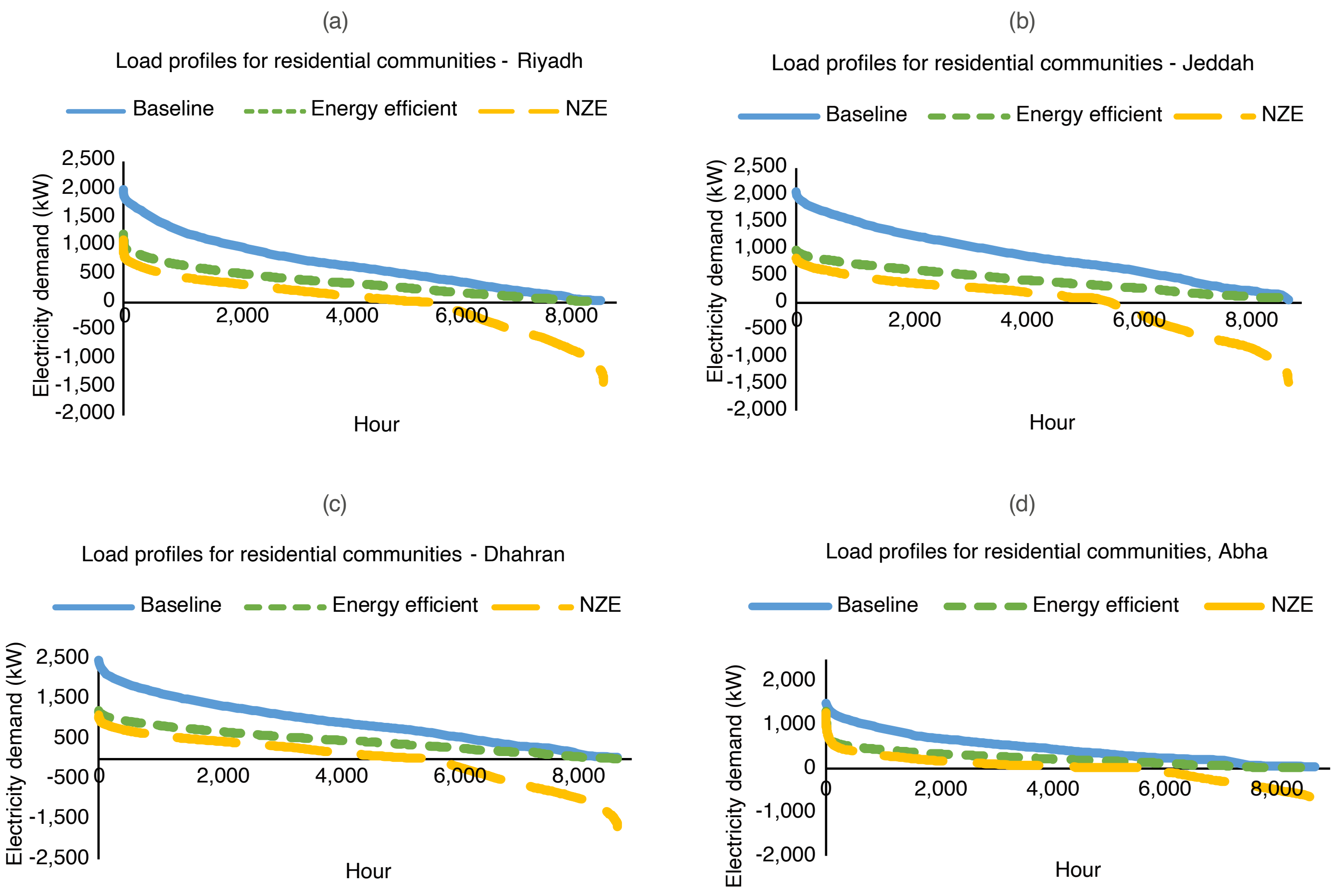
Source: Authors.

Electrical Loads for Communities

As noted earlier, the residential communities considered in this study consist of 100 housing units, including 60 villas and 40 apartment buildings. For the four Saudi locations, Figure 3 illustrates the hourly profiles, expressed in terms of load duration curves, for three residential communities based on three levels of building efficiency — baseline, energy-efficient (EE) and net-zero energy (NZE) housing units. As indicated in Figure 3, the general trend indicates that the electrical demand of the baseline community is the highest followed by the EE and NZE communities in that order. The negative demand in the NZE communities indicates that excess electricity generated on-site is provided to the grid. Aggregated over the entire year, the net annual electricity demand in the NZE community is close to zero for all four Saudi sites, as summarized in Table 5. The annual electrical loads for the baseline communities range from 7,963 megawatthours

(MWh)/year (Dhahran) to 4,071 MWh/year (Abha). For the energy-efficient communities, the electrical loads are reduced by almost 50% compared to the baseline cases and range from 4,030 MWh/year (Dhahran) to 1,961 MWh/year (Abha). The peak and average demands follow the same trends as those observed for the annual loads, with Dhahran having the highest values and Abha exhibiting the lowest demand. The load factors (i.e., ratio of peak to average demand) for both baseline and energy-efficient communities are relatively low and range from 0.17 (Abha) to 0.43 (Jeddah). These low load factors indicate non-uniformity in electrical demand through the year and, ultimately, affect the number and types of power plants used by the grid for power generation.

Figure 3. Duration curves for three communities made up of baseline, energy-efficient and NZE housing units located in (a) Riyadh, (b) Jeddah, (c) Dhahran and (d) Abha.



Source: Authors.

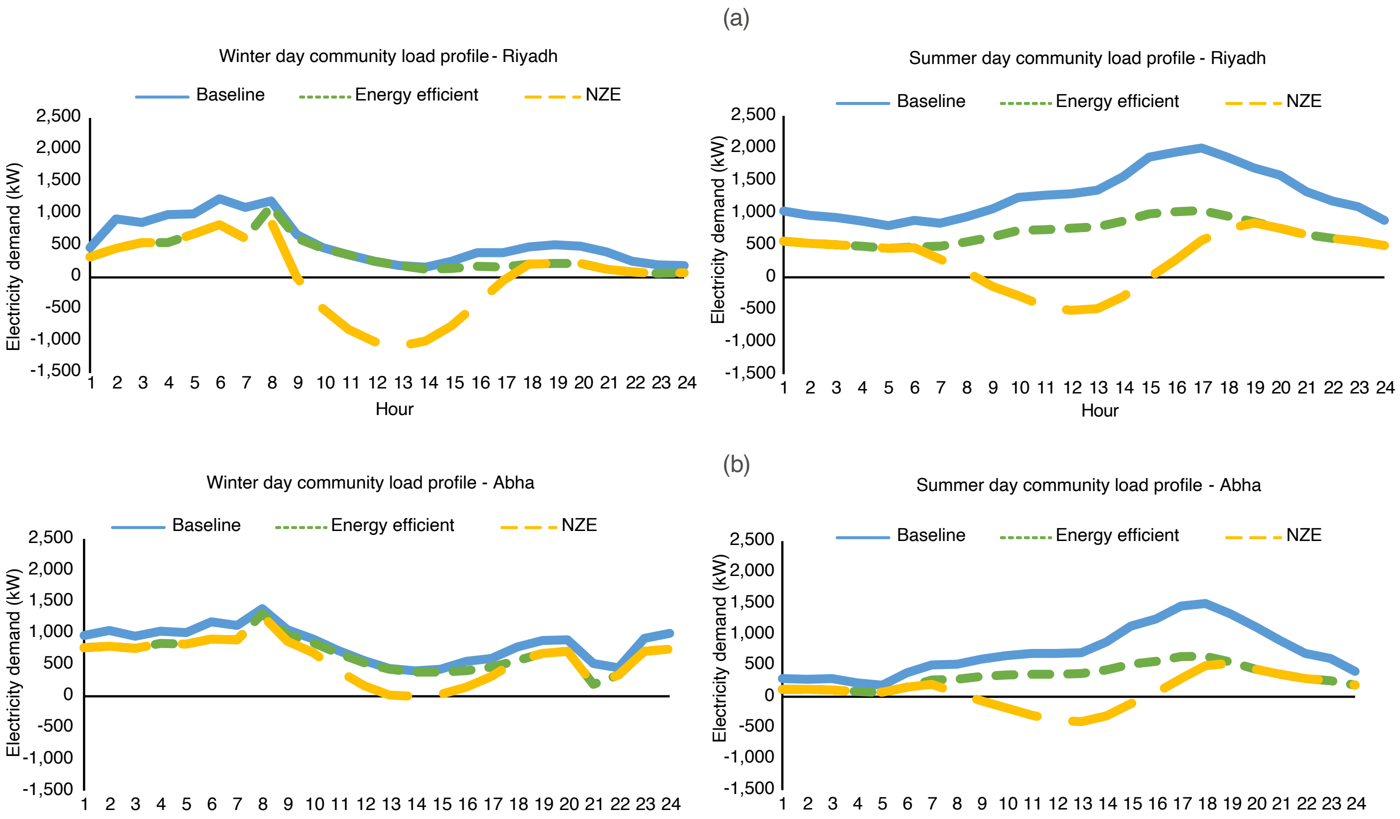
Table 5. Main characteristics of the electrical loads for the residential communities.

Location	Riyadh			Jeddah		
Community type	Baseline	Energy-efficient	NZE	Baseline	Energy-efficient	NZE
Total (MWh/year)	5,881	3,059	-53	7,676	3,707	-32
Peak demand (kW)	2,002	1,217	1,109	2,061	981	833
Average demand (kW)	671	349	-6	876	423	-4
Load factor	0.34	0.29	0.00	0.43	0.43	0.00
Location	**Dhahran**			**Abha**		
Community type	Baseline	Energy-efficient	NZE	Baseline	Energy-efficient	NZE
Total (MWh/year)	7,963	4,030	-48	4,071	1,962	-55
Peak demand (kW)	2,471	1,216	1,101	1,499	1,312	1,281
Average demand (kW)	909	460	-5	465	224	-6
Load factor	0.37	0.38	0.00	0.31	0.17	0.00

Source: Authors.

In all four Saudi locations, the highest electricity demands occur during the summer for the baseline and EE communities. This is because all the housing units require higher air conditioning use in that season to reach the desired thermal comfort level. For the NZE communities, the rooftop PV systems generate sufficient electricity during the daytime hours, which effectively reduces the peak demand, even during the summer months. Figure 4 compares the summer and winter day load profiles for the three types of communities located in Riyadh and Abha. For Riyadh, which has a hot and dry climate, the demand is lower during the winter for all three community types (Figure 4[a]). For Abha, which has a mild climate, the peak demand is similar on both winter and summer days for the baseline and EE communities, even though they exhibit different load patterns (Figure 4[b]). Indeed, the peak occurs in the early morning during the winter period and in the late afternoon during summer months. For the NZE communities, the rooftop PV systems generate more electricity than needed during daytime hours, especially during the summer months, resulting in power supplied to the grid during those hours.

Figure 4. Sample daytime profiles for the three types of residential communities in winter (January 15) and summer (July 15) in (a) Riyadh and (b) Abha.



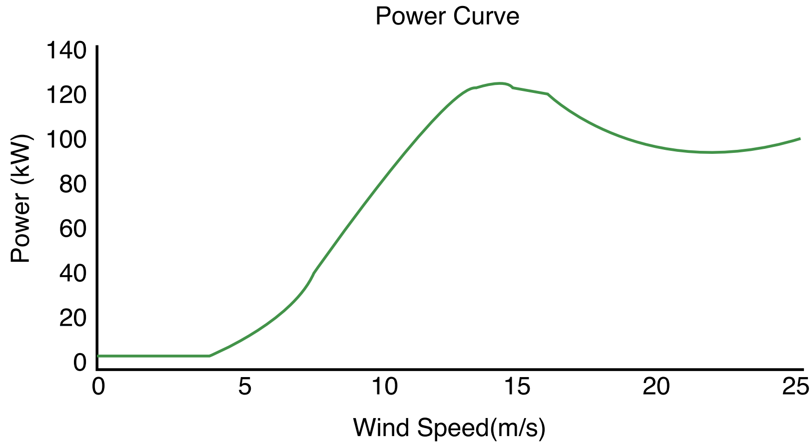
Source: Authors.

Renewable Power Systems

To design carbon-neutral communities, two renewable energy systems are considered in this study: solar PV arrays with DC–AC inverters and wind turbines that can generate AC power directly. The PV module has a rated efficiency of 15%, which changes with ambient temperatures, and the inverter has a rated efficiency of 96% (Solar Advisor Module 2020). The wind turbines consist of 100kW units that have 21-meter rotors with a power curve shown in Figure 5 (Wind Power 2020).

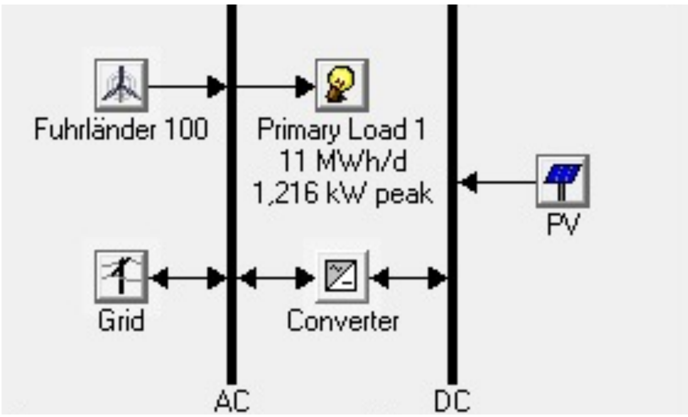
For the design of carbon-neutral communities, the HOMER tool is used throughout this study. The tool utilizes a brute force optimization technique to determine the most cost-effective combinations and capacities of renewable power systems as well as the grid required to meet the electrical loads of the residential communities. It also accommodates any desired constraints, such as a specific renewable fraction or carbon emissions reduction (Hybrid Optimization 2021). Figure 6 illustrates a typical power supply–demand flow between the electrical load of any residential community and the grid as well as the PV-inverter systems and wind turbines.

Figure 5. Power curve for the wind turbine used to design the carbon-neutral residential communities.



Source: Authors.

Figure 6. Power flow between load, grid, PV systems, inverters and wind turbines.



Source: Authors.

The costs for installing as well as operating and maintaining (O&M) PV systems depend significantly on system size, labor costs and the types of inverters and balance of systems (BOS) used (Fu, Feldman, and Margolis 2018). In general, however, the installed cost of PV systems has significantly reduced in the last few years. For instance, the overall installation cost (i.e., including PV modules, labor, BOS and inverter) for residential rooftop PV systems has decreased from US$7.34/watt direct current (W_{DC}) in 2010 to US$2.70/$W_{DC}$ in 2018 — a 63% reduction (Fu, Feldman, and Margolis 2018). For large-scale commercial PV systems, the installation costs, including inverters, are even lower; they are estimated to be US$1.95/$W_{DC}$ for 100kW systems to US$1.72/$W_{DC}$ for 1,000kW capacities (Fu, Feldman, and Margolis 2018). The cost of inverters for large-scale systems is estimated to be US$0.01/$W_{DC}$. For wind turbines as well, the costs have been decreasing in the last decade but at a lower rate than those of PV systems. Based on recently reported data, the installation costs vary depending on the country and region of the world (IEA 2018). For instance, the average cost for wind turbines in Europe is estimated to be US$1,730/kW, whereas it is only US$1,275/kW in Denmark. In the United States, the average installation cost is estimated to be US$1,585/kW, with O&M costs of 44 US$44/kW-year.

Table 6 lists the cost data, including capital, replacement and O&M costs, for the renewable power generation systems considered in this study. In addition, a series of sensitivity analyses is carried out to evaluate the impacts of the installation costs of both wind turbines and PV systems on the designs of the carbon-neutral communities.

Table 6. Cost data used for PV systems and wind turbines in the designs of carbon-neutral communities.

System	Installation cost (US$/kW)	Replacement cost (US$/kW)	O&M cost (US$/kW/year)	Lifetime (years)	Reference
PV arrays	1,640	1,520	18	25	(Fu, Feldman, and Margolis 2018)
Inverters	80	80	0	10	(Fu, Feldman, and Margolis 2018)
Wind turbines	1,585	1,268	44	25	(International Energy Agency 2018)

Source: Authors.

Discussion

In this section, the results of the optimization design analysis for the carbon-neutral communities are presented for all community types and site locations. For the design analysis, the electricity sale rate is set in line with the current Saudi Electricity Company (SEC) tariff structure for residential buildings (i.e., US$0.048/kWh for the first 6,000 kWh/month block and US$0.080/kWh for the remainder (SEC 2020). The sellback rate is set at US$0.0187/kWh for any excess electricity generated on-site (SEC 2020). Moreover, the carbon emissions for the power generated by the grid are estimated as 0.703 kg/kWh, which is based on the latest reported data on emissions intensity for the Saudi power sector (Enerdata 2020).

Carbon-neutral Designs

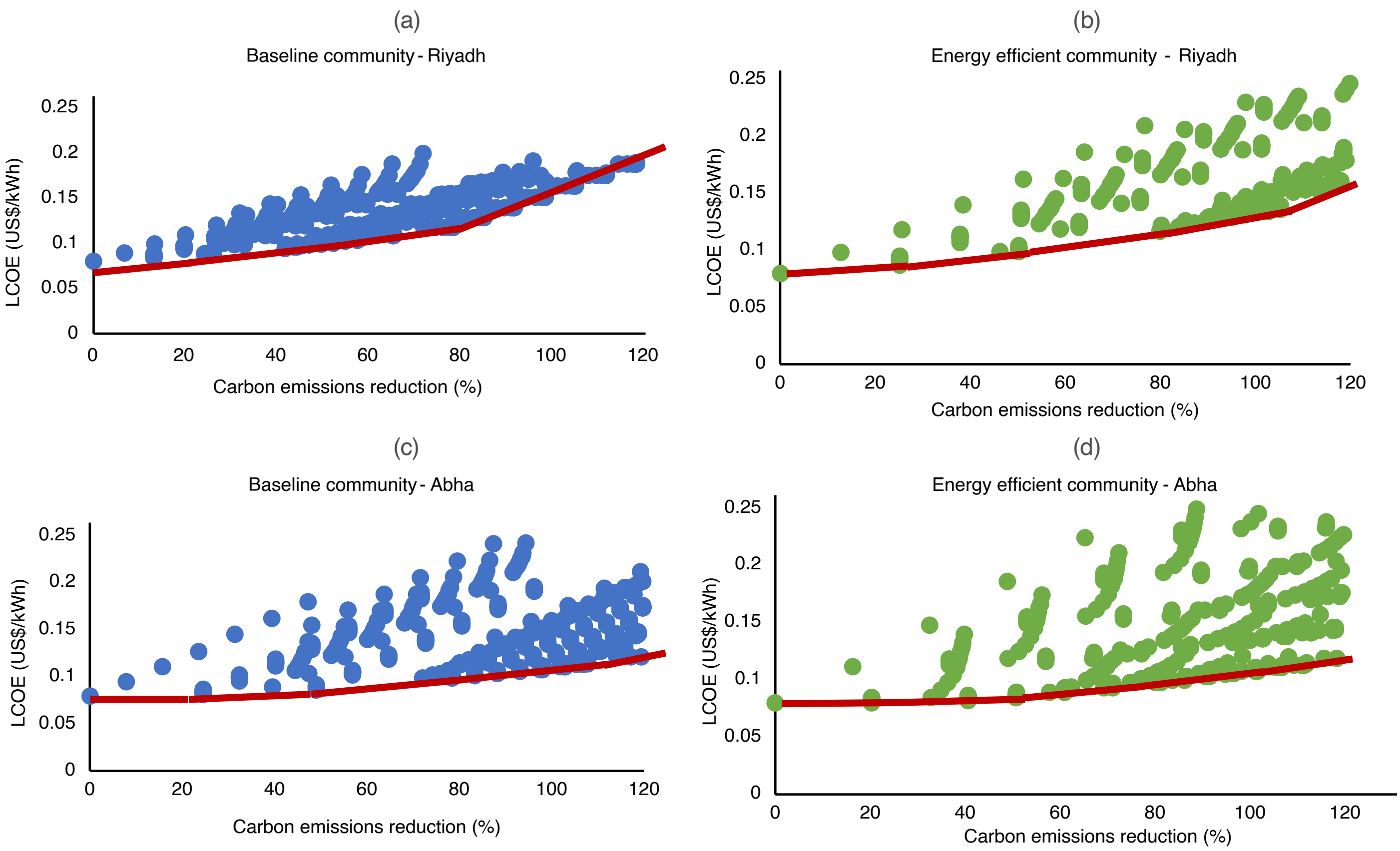
Owing to the low grid electricity costs, the use of any renewable generation system — PV arrays or wind turbines — is not cost effective for the baseline and EE communities in all Saudi locations, as depicted by Figure 7 (Riyadh and Abha). The cost effectiveness of hybrid renewable power systems is typically evaluated using their levelized cost of energy (LCOE) values, which express the price (in US$/kWh) of the power they produce over their lifecycle, assumed to be 25 years in this study. Specifically, Figure 7 shows the variations in the LCOE values with the percentage of carbon reduction relative to the grid-only option for several sizes of PV arrays as well as different numbers of wind turbines, represented by the solid dots. The lower solid lines in Figure 7 indicate the Pareto paths of PV/wind combinations that provide the minimum LCOE values for any desired reduction in carbon emissions. As noted for both the baseline and EE communities in all locations, the LCOE values increase with higher reductions in carbon emissions because of the inclusion of larger capacities of PV arrays and wind turbines used to generate on-site electricity. In particular, a carbon-neutral community is achieved when the reduction in carbon emissions reaches 100%. Table 7 summarizes the capacities of the renewable energy systems as well as the LCOE values needed to achieve carbon neutrality for the two types of communities. As expected, smaller capacities of PV and wind systems are needed to reach carbon neutrality for the EE communities compared to the baseline communities for all the Saudi sites considered in this study. Indeed, the EE communities require less electricity from the grid and thus induce fewer carbon emissions. Moreover, the LCOE values required to reach carbon neutrality are consistently lower for the EE communities than those needed for the baseline communities. A renewable fraction of 0.70 is consistently required to attain a carbon-neutral level in all the communities and sites. Based on the PV sizes needed for all the housing units in the NZE communities listed in Table 4, the PV systems required to reach a carbon-neutral status for the EE communities generally have lower capacities, even though wind turbines may also be required.

Table 7. Capacities of renewable power systems and LCOE values needed to achieve carbon neutrality in the two communities.

Location	Community type	PV size (kW)	Inverter size (kW)	Wind turbine capacity (kW)	LCOE (US$/kWh)	Renewable fraction (-)
Riyadh	Baseline	3,000	1,800	0	0.163	0.70
	Energy-efficient	2,000	1,600	0	0.133	0.67
Jeddah	Baseline	3,000	1,800	2,500	0.142	0.69
	Energy-efficient	1,600	1,000	1,000	0.138	0.70
Dhahran	Baseline	3,000	1,600	2,500	0.136	0.71
	Energy-efficient	1,700	1,700	1,000	0.133	0.71
Abha	Baseline	2,500	1,000	1,000	0.160	0.77
	Energy-efficient	850	600	500	0.135	0.72

Source: Authors.

Figure 7. Optimal paths for carbon-neutral design for (a) baseline community in Riyadh, (b) EE community in Riyadh, (c) baseline community in Abha and (d) EE community at Abha.

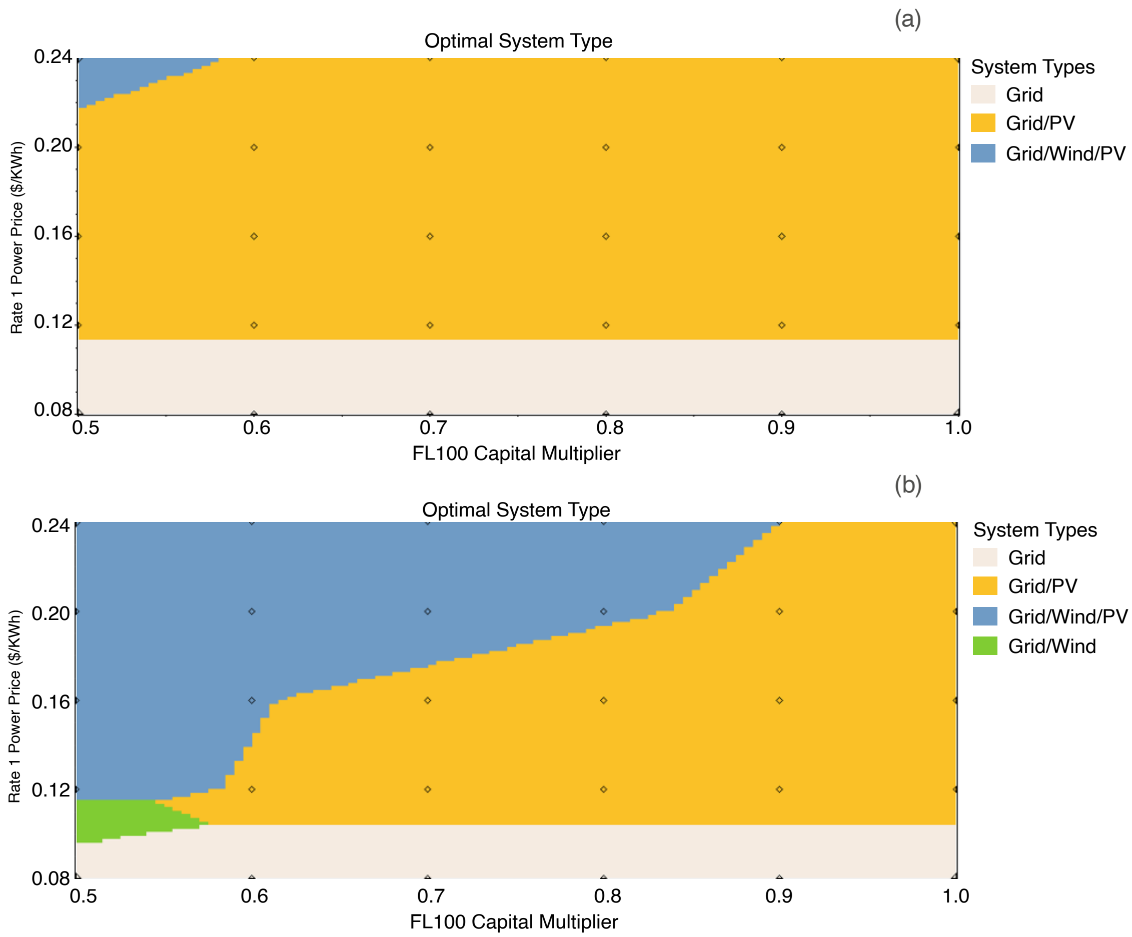


Source: Authors.

Impact of Wind Turbine Costs

The optimization results for the best combinations of PV systems and wind turbines to achieve carbon neutrality at the lowest LCOE values depend significantly on the system installation costs and grid-generated electricity prices. Figure 8 shows the optimal combinations of PV/wind systems that achieve the lowest LCOE values for various grid electricity prices and capital costs of wind turbines, expressed using cost multipliers relative to the reference costs summarized in Table 4. Figure 8, specific to the EE communities in Riyadh and Jeddah, indicates that when the grid electricity prices increase, renewable energy systems become more cost effective. When the wind turbines are installed at capital costs close to those of the reference values (i.e., multipliers close to 1), only PV systems can be cost effective when the grid electricity price exceeds US$0.10/kWh in Jeddah and US$0.115/kWh in Riyadh. Both PV and wind systems can be cost-effectively installed only when there are both high grid electricity prices and low wind turbine installation costs. Specifically, when the EE community is located in Jeddah, the optimal hybrid system includes both PV arrays and wind turbines only if the grid electricity rate is higher than US$0.12/kWh and the installation costs are 40% lower than those listed in Table 4.

Figure 8. Effect of grid electricity price and wind turbine cost on the optimal system selection for EE communities located in (a) Riyadh and (b) Jeddah.

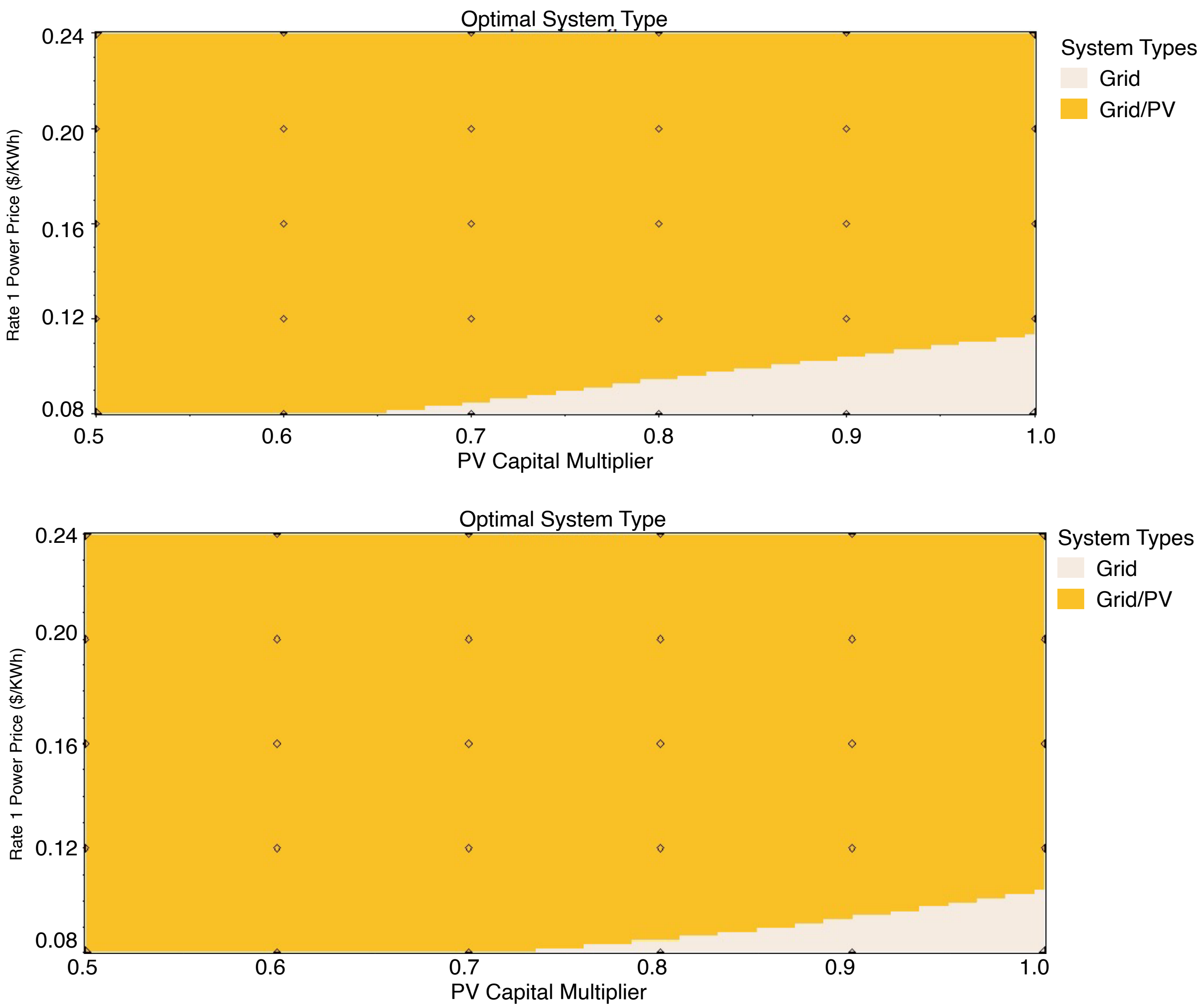


Source: Authors.

Impact of PV System Costs

Figure 9 illustrates the optimal combinations of PV/wind systems with the lowest LCOE values for various grid electricity prices and PV-array installation costs for the EE communities located in Riyadh and Jeddah. Cost multipliers are used for the PV systems, expressed relative to the reference costs summarized in Table 4. In particular, Figure 9 indicates that PV systems become cost effective at the current grid electricity rates only when the PV costs are reduced by 35% (i.e., a cost multiplier of 0.75) for Riyadh and 25% (i.e., a cost multiplier of 0.65) for Jeddah. When PV costs remain at the current levels (refer to Table 4), the grid electricity price must be US$0.11/kWh in Riyadh and US$0.10/kWh in Jeddah in order for the PV arrays to become cost effective as on-site generation systems for the EE communities.

Figure 9. Effect of grid electricity price and PV system cost on the optimal on-site PV/wind systems for EE communities located in (a) Riyadh and (b) Jeddah.



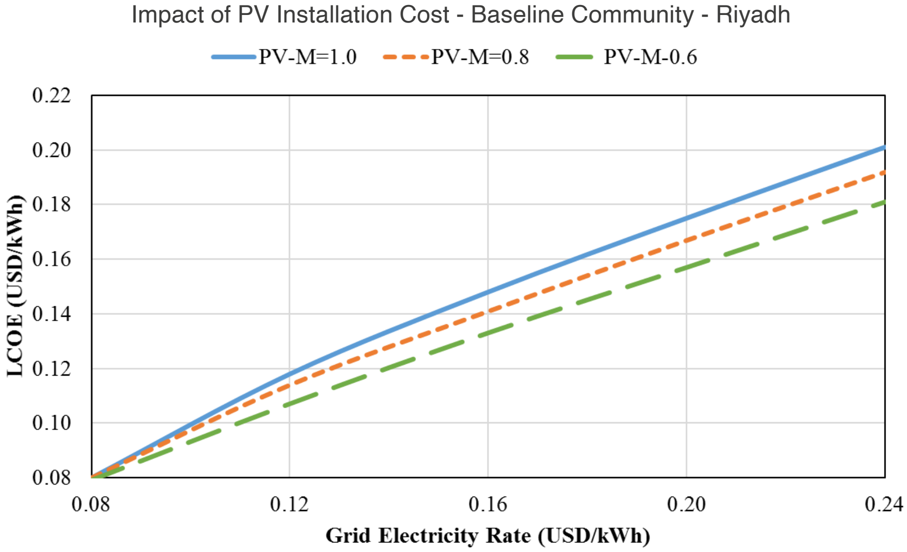
Source: Authors.

Impact of Grid Electricity Prices

The results shown in figures 10 and 11 clearly indicate that grid electricity prices substantially affect the cost effectiveness of both PV systems and wind turbines as on-site power generation options for Saudi residential communities. The effects of grid electricity prices on the optimal LCOE values needed to meet the electricity demands of baseline communities located in Riyadh are illustrated in Figure 10 for various PV-system cost levels. As expected, when the electricity prices are higher, the PV systems become more cost effective, especially if their installation costs are lower (i.e., having lower cost multipliers). The cost-effective inclusion of PV systems as an on-site power generation option for the communities results in lower LCOE values when compared to the grid electricity prices. The impacts of higher grid electricity prices and lower PV costs on the design of carbon-neutral residential communities are illustrated in Figure 11. The figure shows the Pareto paths to carbon neutrality for the baseline community located in Riyadh (Figure 11[a]) and for the EE community located in Jeddah (Figure 11[b]). These are shown specifically when the grid electricity rate is set at US$0.16/kWh and the PV installation costs are reduced by 20% (i.e., with a cost multiplier of 0.80) relative to the reference costs in Table 4. Unlike the case in Figure 7, the Pareto paths have optimal LCOE values as carbon emissions increase. For the baseline community in Riyadh, the optimal LCOE value is US$0.140/kWh for a 44% reduction in carbon emissions. For the EE community in Jeddah, the optimal LCOE value is US$0.143/kWh, with a 43% reduction in carbon emissions.

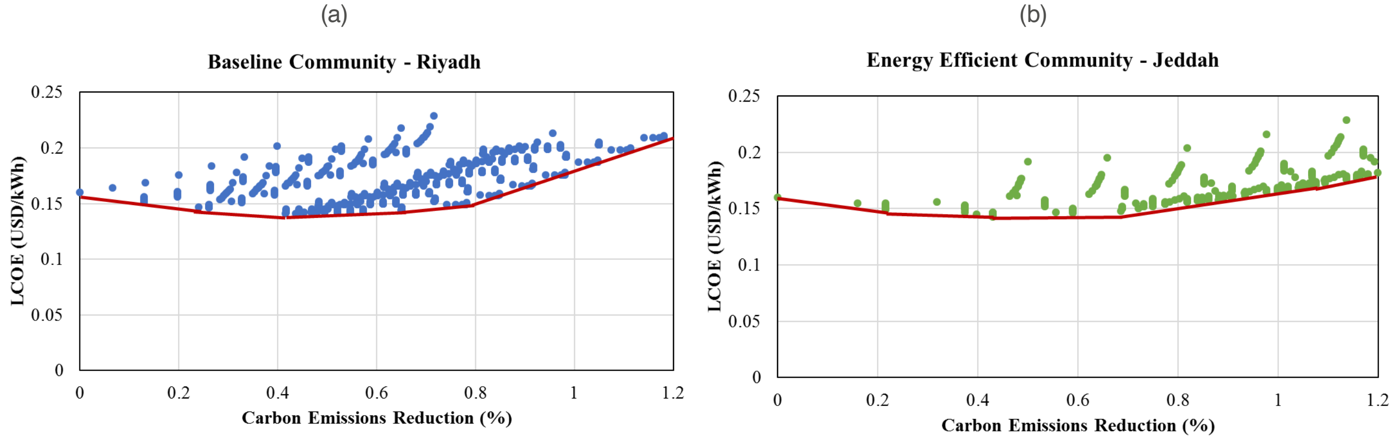
Table 8 summarizes the composition of the renewable power systems in the carbon-neutral cases. These are shown for a grid electricity price of US$0.16/kWh and a 20% reduction in PV capital costs relative to the reference levels for the baseline community in Riyadh and the EE community in Jeddah. Compared to Table 7, the LCOE values in Table 8 have increased relative to the reference electricity prices and PV costs to achieve a carbon-neutral status for both communities. This price increase can be attributed to two factors: (i) a higher price for electricity from the grid, which meets 30% of the electricity needs of the communities, and (ii) the inclusion of more on-site PV systems and wind turbines, especially for the baseline community in Riyadh.

Figure 10. Effect of grid electricity price and PV capital costs on optimal LCOE values for baseline communities in Riyadh.



Source: Authors.

Figure 11. Optimal paths for carbon-neutral design for (a) the baseline community in Riyadh and (b) the EE community in Jeddah.



Source: Authors.

Table 8. Capacities of renewable power systems and LCOE values required for the two communities to achieve carbon neutrality.

Location	Community type	PV size (kW)	Inverter size (kW)	Wind turbine capacity (kW)	LCOE (US$/kWh)	Renewable fraction (-)
Riyadh	Baseline	3,000	1,700	2,000	0.187	0.70
Jeddah	Energy-efficient	1,600	1,000	100	0.166	0.70

Source: Authors.

Summary and Conclusions

This study investigated the cost effectiveness of designing carbon-neutral communities in four Saudi locations. The optimization results of the design analysis indicate that, while it is feasible to design carbon-neutral residential buildings in Saudi Arabia, their cost effectiveness depends on several factors:

The energy-efficiency level of the housing units within the residential communities has a significant impact on the costs and the cost effectiveness of the carbon-neutral designs. Specifically, reducing the electrical demands of the communities through proven energy-efficiency measures can significantly reduce the capital costs and capacities of the renewable energy systems needed to reach a carbon-neutral status. For instance, when energy-efficiency measures are implemented in a residential community located in Abha, the annual electrical demand is reduced by 51%, the PV size needed to reach carbon neutrality is decreased by 66% and the number of wind turbines is lowered by 50%.

Grid electricity prices are crucial to the cost effectiveness of any on-site renewable power system. At the current energy prices, neither PV systems nor wind turbines are cost effective to install on site to produce electricity for residential communities. For instance, based on the current capital costs for renewable power systems, the grid electricity price must be US$0.10/kWh in Jeddah for the PV arrays to become cost-effective on-site generation systems.

The capital costs of PV arrays and wind turbines influence both the cost effectiveness and the appropriate mix of on-site renewable power systems. At current grid electricity prices, PV installation costs must be reduced by 35%, relative to reference costs, to become cost effective in partially meeting the demand of an energy-efficient community in Riyadh. For an energy-efficient community in Jeddah, the installation costs for wind turbines must be lowered by 40% relative to the reference costs and combined with higher grid electricity prices of at least US$0.12/kWh for both PV arrays and wind turbines to become cost-effective options.

Based on the results of this study, the main recommendations for fostering a carbon-neutral design for residential communities in Saudi Arabia include combinations of energy policies. These policies primarily involve energy price reforms to increase the grid electricity prices. Policy solutions also include the deployment of incentive programs to foster the installation of PV systems and/or wind turbines, depending on the site resources, and implementing feed-in tariffs and/or net-metering policies for the residential sector.

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Notes

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About the project

This study is part of the **Modeling Residential Energy Demand and Energy Efficiency in Saudi Arabia** project, which aims to accurately model the country's entire residential building stock. The project's key goals are (i) to better understand the current status of the Kingdom's housing sector in terms of its energy consumption, and (ii) to assess the potential of different energy efficiency programs and demand-response management to reduce electricity demand from the perspective of both households and the government.

More broadly, the project aims to help KAPSARC conduct technical, economic, and environmental assessments of residential demand-side management options, and in turn to support policymakers seeking to design impactful energy strategies for Saudi Arabia's housing sector.

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