A comparative analysis of renewable and non-renewable energy generation to relegate CO₂ emissions and general costs in household systems

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Abstract
Ensuring adequate implementation of solar energy for providing environment-friendly energy to the household sector, which can considerably abate pollutants in the environment and make power industry structure sustainable, is necessary for developing countries. Comparison in terms of environmental and cost impacts of renewable energy (hybrid solar system) with non-renewable energy sources, water and planning development authority (WAPDA), and diesel generators (DGs) has been examined in the household sector of Pakistan. Primary data of hybrid solar systems have been obtained from 10 different households segregated them into two categories according to their income as medium-income households (MIHs) and lower income households (LIHs) containing 5 kW and 3 kW of hybrid solar energy systems, respectively. While operating with a hybrid solar energy system instead of a non-renewable energy system, in terms of average generated power and average running load, carbon dioxide (CO₂) emissions can be reduced up to 8,446.6 kg CO₂ and 6,131.725 kg CO₂, respectively, in the next 25 years. Comparison of costs indicated that renewable energy has a comparatively low cost per electric unit. It can pay back its total installation cost in just 8 years and can save a sum of $4,936.4375, along with many more ecological, economic, and societal benefits. Pakistan can efficiently utilize solar energy to relegate CO₂ emissions and general costs as it has distinct geographical features to access sunlight in most days of the year.

Keywords CO₂ emissions · Energy efficiency · Renewable energy · Hybrid solar · Household comparison · Cost analysis

Introduction
The management of energy consumption and CO₂ emission continued to be a major issue throughout the COVID-19 epidemic. The lack of public research to solve this real-time issue effectively was a big challenge as the previous literature could rarely help (Mohsin et al. 2021). The air pollution resulting from increased energy consumption has now become a global phenomenon. COVID-19 is declared to be a carrier of SARS-CoV-2 (Wen et al. 2022). Anthropogenic activities like fossil fuel burning, cement production, and deforestation escalated the CO₂ emissions into the atmosphere and should be fetched to zero to overcome one of the most significant environmental issues called global warming. The longer it takes to do so, the warmer the globe will become (Pierrehumbert 2019). Carbon dioxide’s (CO₂) atmospheric concentrations were recorded at the highest level in the last two million years, reported in Sixth Assessment Report (AR6) by Intergovernmental Panel on Climate Change (IPCC). Since the late 1800s, CO₂ emissions have crossed 2400 billion tonnes. Human activities are mainly blamed for this exponential increase by the consumption of fossil fuels. The human interventions resulted in a warmer climate at an accelerated rate over 2,000 years. It is believed that the last decade has seen the hottest environmental temperature in global history recorded in the past 125,000 years. This temperature rise triggered many climatic factors like rising sea levels, droughts, extreme precipitation, rapid glacier melting, receding snowline, and extreme heat (IPCC 2019). In the global economic and social advancements, energy has always played a fundamental role. However, extensive
energy usage has caused exceeding levels of air pollution and global warming, which is mainly produced through fossil fuel combustion (Zhang et al. 2019). The contribution to the global GHG emissions of the energy sector is approximately 75%, and the ever-increasing global energy demand has led to the multiplication of GHG emissions (Zaidi et al. 2018).

To mitigate the impacts of global warming, energy conservation is a very crucial tool for the household sector which consumes nearly 20% of energy worldwide, grabbing the interest of academia and government departments worldwide (Liu & Sun 2019). A similar scenario can be observed in Pakistan making the household sector lucrative for solar PV adoption, as this sector consumes nearly 48% of electricity produced in the country (Survey 2018–19). Due to increasing energy demands, the energy sector in Pakistan is the main recipient of governmental subsides (Kessides 2013), pressurizing the economic and social sectors extensively. Practical measures to shift the household sector from fossil fuel energy to off-grid energy can provide alternative energy production sources which are environment friendly and reduce power outages (Qureshi et al. 2017). Pakistan is blessed with landscapes and areas with vast direct and natural reception of solar energy, which are not affected by the seasonal variations (Sadiqa et al. 2018). Despite having vast natural potential, the generation of solar energy is quite low in Pakistan, and its inclusion in the energy mix is nominal (Khalil & Zaidi 2014). A total of over 50% of electricity is produced by consuming fossil fuels in Pakistan, and these fuel combustions lead to massive GHG emissions, which is a precursor of climatic change (Tareen et al. 2018). The majority of the experts consider solar energy generation as a source to eradicate carbon-inclusive energy production to guarantee a sustainable and secure future (Hussain et al. 2018, 2019). In all the major power-consuming sectors like household, commercial, agricultural, and industrial, operational activities are gravely disturbed by frequent power outages, which could be avoided by deploying the latest technologies such as solar photovoltaic (PV) (Qureshi et al. 2017). A comprehensive assessment of the efficiency of the green economy and a comparative analysis of emission reductions are vital in achieving sustainable green economic development. The environmental aspects have been frequently ignored in most studies for the assessment of energy efficiency. However, the concept has been extensively used in the past (Hou1 et al. 2019).

Therefore, to overcome the power shortage and reduction of CO2 emissions, the deployment of PV in all sectors of life is vital. In the current research study, the PV application in the household sector is targeted. The investigation into household behaviors and norms is primarily conducted through household consumption and expenditure surveys (HCEs), which can play a vital role in achieving carbon reduction targets (Yuan et al. 2019). Like many developing countries, Pakistan has a large growing population with the generation of a significant amount of CO2 emissions in the atmosphere. An energy-based HCE can be the most effective way of presenting the findings on energy consumption and expenditure of households. In our previous study, we took an organization as a sample of study and discussed cost comparison, output analysis, and different properties of solar energy and non-renewable energy. This exclusive study presents a comprehensive comparison of CO2 emissions among renewable energy sources (hybrid solar energy systems) with non-renewable energy sources and their economic and climatic impacts on the household sector.

The main purpose of this research project is to present a realistic picture of measures to reduce CO2 emissions by providing analysis and comparisons in terms of efficiency and cost of deploying a hybrid solar system in Pakistan’s household sector for green and clean Pakistan. Similarly, the application of probability simulation presented in this study will enable the researchers to forecast the future of solar energy while casting pleasant impacts on the community and atmosphere. The global impact of this study is that it frames the outlines to reduce non-renewable energy usage, decrease long-term costs of energy generation costs, and minimize GHG emissions altogether for sustainable development of society.

**Research methodology**

**Study area**

The household sector was taken as a sample for this research study, as 48% of the energy in Pakistan is consumed by households and is considered the main consumer of electricity (Survey 2018–19). To compete with the economic powers of the world, Pakistan also has to promote non-fossil fuels and renewable energy sources as measures are being carried out to generate electricity from these renewable sources across the globe. The higher the consumption of electricity by households, the higher the CO2 emissions, causing extensive adverse climatic impacts. The seasonal variations and geographical location of Pakistan present a promising potential to generate electricity from renewable energy sources (Sadiqa et al. 2018). A total of 4,500 kWh/m² and 2,500 to 3,500 kWh/m² tilted solar radiations received by 60% and 40% of the country respectively per annum (Ashfaq & Ianakiev 2018). About 95% of Pakistan’s total stretch of land is the recipient average irradiation of 5–7 kWh/m² per day (Solangi et al. 2011) which indicates the potential for harvesting solar energy to meet household energy needs.
Data collection

Following a mixed-method approach, primary and secondary data collection sources were utilized for energy system evaluation in Pakistan, particularly hybrid energy systems. To achieve research objectives, preliminary data was attained from 10 households from different regions of the Punjab province of Pakistan, as the province is the recipient of direct sunlight almost throughout the year. The selected households were further subdivided into two different categories based on their income, i.e., lower income households (LIHs) and medium-income households (MIHs). The comparison and evaluation showed that MIHs use more electricity (nearly double of LIHs) as these households use high energy-consuming electric appliances such as air conditioners, irons, and deep freezers. On the other hand, LIHs consume a lower level of electricity through low-power-consuming appliances such as fans, refrigerators, and televisions. The preliminary data was useful in densifying the study with accurate readings of energy usage, building micro-comparisons, and ensuring the authenticity of the research.

A typical hybrid solar energy system, presented in Fig. 1, was chosen to be presented as the ideal solar energy generation tool for households due to its enhanced efficiency, low cost, reduced emissions, and high reliability (Ingole & Rakhonde 2015). This hybrid solar energy system combines the on-grid solar system (GTSS) and off-grid solar system (OGSS) which are powered through solar heat. The produced energy is directly fed into the main grid, and firstly charges the battery power bank; when this power bank is full, the excessive power is fed into the main grid with net metering (Ingole & Rakhonde 2015; Sultan et al. 2018). As displayed in Fig. 1, an excessive amount of electricity produced by solar panels would reduce the power input from other energy sources including WAPDA and DG. Since the hybrid solar energy system can provide accurate readings of generation and usage from each of the energy sources, the study was able to present a comprehensive comparison which is discussed in the latter part of this study. Furthermore, careful considerations were taken in the selection of the hybrid energy based on the validity and reliability of each system and associated system spheres including high-quality reliable solar plates, well-tamed manpower, wire quality along with connection, and solar rays tilting angle.

The medium-income households and low-income households carefully installed the hybrid energy systems containing 5 kW and 3 kW hybrid inverters respectively along with installed solar panels that can power up nearly 3 and 1.5 kW, respectively. In the 5-kW system, 12 solar modules were connected in two strings containing 6 modules each in the series, and both strings were connected parallelly with four batteries of 220amp/12 V connected for backup. Similarly, in the 3-kW system, a string having 6 modules in series was connected with two backup batteries 220amp/12 V. Furthermore, the class of solar panels used in the system enabled the power of each panel at 250 W with each solar module having 8.1 amp and 31 V. Grade A (highest quality) polycrystalline solar modules were installed with the help of blocks that are easily moveable on the top of the roof in cubic meters as shown in Fig. 2. Since the efficiency of polycrystalline solar modules is much higher at high temperatures than monocrystalline solar cells, a pure sine wave solar inverter with an output power of 1, called Axpert V Off-Grid Inverter, was deployed. The power from solar panels was fed into the grid inverter where maximum power point tracking (MPPT) charge controller was used with a direct connection (DC) to a pure copper wire of 10 mm for longevity and sustainability of the hybrid energy system. The installed inverter came with premier functionalities including an optional anti-dusk kit, cold start function, overload, short circuit protection, auto restart while AC is recovering, wide DC input range, and selectable input voltage range for home appliances and personal computers (Kit & Kit 2019).

The solar system, displayed in Fig. 2a and b, was installed at specified angles, normally at 30–45°, to maximize the power generation output and electricity generation, which heavily depends on the intensity of heat. These types of energy-efficient hybrid solar energy systems are being promoted in Punjab where mercury can cross 40 °C during summer (Sajjad et al. 2015). However, due to landscape indifferences and seasonal variations, the solar modules and
structural integrity can be moved towards an optimized angle (Rehman et al. 2012). The considerable point in these systems is that the angle should be set where maximum solar output lies and moved appropriately.

Calculations

The record of daily energy generation and consumption readings in kilowatt-hour (kWh) from 7 am to 5 pm for 15 days enabled us to obtain energy data from these solar hybrid energy systems. There is an app and a monitoring system to monitor the solar system provided by the inverter companies. The data presented in this study was obtained by the monitoring system. The aforementioned calculations have been derived from data obtained from the Axpert V Off-Grid Inverter (Tesla produced inverter) in June 2020. The data logger is basically generated by the data collection, which is connected with hardware. The data logger is further connected with the inverter, which updates the data on the cloud and is connected to MATLAB. MATLAB provides access to the data for analysis. The obtained data is real and correct, attained from the inverters connected online through WiFi devices. Hence, there is no chance of any biases in the data as the data is received online on MATLAB and further analyzed. The model of probability simulation enabled us to determine the energy contribution from the solar hybrid systems, after calculating the average daily and yearly energy contribution. Following the preliminary calculations, the projection of CO₂ emissions caused by WAPDA, DG, and hybrid solar energy for the coming 25 years was made by applying a probability-based simulation model. Additionally, detailed efficiency and cost comparisons were made by
applying the cost–benefit ratio formula. To develop a precise understanding of emissions, costs, and efficiency, online resources were used to collect the secondary data including Google Scholar, Web of Science, Science Direct, and the online library of the university.

The main objective to obtain the preliminary facts (primary data) was to understand the ground realities regarding all the sources of energy in households, particularly the impact of solar energy. Comprehensive comparisons and analysis of already available secondary data enabled us to have a critical understanding of the energy spectrum of emissions, cost, and efficiency in this research project. The findings of this study will advocate securing a future of sustainable energy development by exploring crucial options like solar energy through awareness and disseminating its broader understanding. In addition to the probability-based simulation model and cost–benefit ratio, frequency analysis and descriptive analysis were also applied for presenting data analysis and comparisons through Microsoft Excel, MATLAB and Origin Pro 9.0.

Result and discussion

Energy generation, usage, and backup from hybrid solar system

The study sample of middle-income households and lower income households contained 5 kW and 3 kW hybrid inverters with the installed solar panels powering nearly 3 kW and 1.5 kW respectively. In accordance with the suggested load, the solar energy supplied by the solar panel for the sake of this study is presented in graphical form in Figs. 3 and 4. The mentioned figures also indicate the consumed energy distributed with the contribution of other energy generation resources. As mentioned earlier, the daily energy in kWh was calculated from 7 am to 5 pm for continuous 15 days and the entire data set of 10 systems is illustrated in Figs. 3 and 4 which displays the maximum energy generation, average running load, and saving backup. In system I, the average energy generation of MIHs and LIHs turned out to be 2.235 kW and 1.143 kW respectively, average running load 1.658 kW and 0.80 kW, while the average backup was 0.578 kW and 0.343 kW respectively. In the case of LIHs, the 6th and 13th day displayed negative saving backup which meant that energy consumption was much higher on those specific days and/or bad weather was experienced causing low generation of energy. In system II, the average energy generation of MIHs was found to be 2.315 kW and of LIHs to be 1.151 kW, the average running load was 1.664 kW and 0.674 kW, and the average backup was 0.651 kW and 0.478 kW respectively. In the case of MIHs, average energy generation was comparatively high as compared to other systems with the highest energy saving on the 8th day, and in case of LIHs, the 1st, 7th, 10th, 11th, and 15th days usage and backup were consistent. In system III, the average energy generation of MIHs which was 2.289 kW and LIHs which was 1.133 kW, average running load was 1.662 kW and 0.585 kW, and the average backup was 0.627 kW and 0.548 kW. As we can see in the case of LIHs, in the majority of the days 1, 2, 4, 5, 7, 9, 10, 11, and 15, the average backup is higher as compared to the average running load which means this house used energy efficiently, as displayed in Fig. 1.

The average energy generation in system IV, for MIHs, was 2.249 kW and LIHs 1.180 kW, which is comparatively higher from other houses; the average running load was about 1.596 kW for MIHs and 0.639 kW for LIHs; and average backup is 0.653 kW and 0.541 kW respectively. In this system, in case of LIHs, energy generation is comparatively high from all systems on all the days. In the last system V, average energy generation of MIHs was 2.286 kW and LIHs 1.108 kW, the average running load was 1.568 kW and 0.639 kW, and the average backup was 0.718 kW and 0.469 kW respectively. In this system, in the case of LIHs, energy generation is comparatively low from all systems on all days, whereas in the case of MIHs, average backup is comparatively high from all systems on all days. As we can see that in both MIHs and LIHs, for all the systems on day 6th, 7th, 13th, and 14th, the average running load on weekends skyrocketed as a result of increased use of electric home appliances such as water pump, irons, and washing machine. Focusing on peak hours, maximum radiation is delivered by the sun, and there is also maximum load shedding. However, according to the literature, during this period, the energy contribution by the solar panel is increased compared to the other domestic resources (Sultan et al. 2018). Table 1 represents the combined average generated powers, running loads, and backups of MIHs and LIHs after applying a 25-year probability simulation model. The average saving backup reduces over time due to overload and inefficient usage of power in the household. As the efficiency of the solar panel reduces after 10 years, 1% of each year till 25 years, the simulation accounted for such losses and inefficacies to calculate the total generated power, so in case of no backup, households should increase solar power.

CO₂ emissions generated by solar system and WAPDA energy sources

The main objective of this study was to calculate and compare the most environment-friendly energy source by comparing a projection of 25 years of energy generation from three energy sources in households (WAPDA, hybrid solar,
Fig. 3  Energy (kWh/day) generated, average running load, and saving backup of hybrid solar system from 7 am to 5 pm for 15 days for 5 medium-income households.
Fig. 4 Energy (kWh/day) generated, average running load, and saving backup of the hybrid solar systems from 7 am to 5 pm for 15 days for 5 lower income households.
and DG) to determine the most efficient energy source for electricity generation. WAPDA is the main energy supplier of electricity in the country; we accounted for only non-renewable energy sources in case of WAPDA, which are nearly 87% of total energy production in Pakistan as shown in Table 2.

Table 2 also displays the greenhouse gas emissions, specifically CO₂, from various energy resources (WAPDA and hybrid solar). The unit used for calculating carbon emissions in official records was grams of carbon dioxide per kilowatt-hour (gCO₂/kWh) as displayed in Table 2. For further evaluations, the emission factor equation (Avert 2018) was taken under consideration and was converted to kilogram carbon dioxide per kilowatt-hour (kgCO₂/kWh) (Levihn 2014). The emission factor equation in metric and imperial systems is provided below.

For converting pound to gram (imperial system).

\[ 1 \text{lbsCO}_2/\text{kWh} = 0.454 \text{gCO}_2/\text{KWh} \]

For converting gram to kilogram (metric system).

\[ 1 \text{gCO}_2/\text{kWh} = 0.001 \text{kgCO}_2/\text{kWh} \]

As you can see in Table 2, in the case of average generated power, the emissions generated by hybrid solar and WAPDA were 598.9 kg CO₂ and 9045.5 kg CO₂, and in the case of average running load, it was found to be potentially 434.8 kg CO₂ and 6566.525 kg CO₂ each for the next 25 years. Therefore, in case of average generated power, while using the hybrid solar system, we can reduce emissions up to 8446.6 kg CO₂ and in the case of average running load, 6131.725 kg CO₂ emissions in the next 25 years. It is evident from the data that the inclusion of solar energy in the energy mix of Pakistan would exponentially reduce carbon emissions as compared with other energy sources. Even though carbon emissions would not be absolute zero due to lack of modern infrastructure, updated systems, and frequent quality inspections, the emissions would decrease to a much reasonable level in accordance with the goals suggested by United Nations (Guo 2011). This amount of emissions reduction is only predicted at a small scale of 10 households which was our sample size. If our model is applied to the whole country, or at least only in the remote areas which have very little to no access to electricity and are away from the grids, it would result in very low-scale CO₂ emissions by energy generation and eventually may also benefit the economy. As most of the power generated by WAPDA is through oil and gas which ultimately affects our economy, for example, the government of Pakistan paid 9 billion US dollars to import the crude oil to fulfill the energy needs during the fiscal year 2008–2009 that placed a heavy burden on national budget (Kamran 2018). Furthermore, power sector has been plagued; prompted by blatant dependence on thermal power and subsidies which caused an uptick in circular debt, resultantly, these factors are hindering its operational capacity (Shah and Longsheng 2020). This is one of the primary reasons behind the disturbed social and economic conditions the nation had ever seen (Qureshi et al. 2017). Shah and Solangi (2019) took comprehensive overview of power situation in Pakistan. On annual basis, Pakistan requires more than 9% energy. It is estimated that power demand in Pakistan will increase eightfold by 2030, and in 2050, it will mark 20-fold (Noureen 2014). Heavy reliance on thermal resources for energy production is the main reason of energy crisis in Pakistan. Economic jolts of COVID-19 to its already struggling economy also require more power supply for post COVID-19 economic revival which is a matter of concern. Multiple alternative power generation sources must be adopted in order to save our environment (Shah et al. 2021). Only 0.3% of Pakistan energy consumption comes from environment-friendly energy sources which is terribly low (Irfan et al. 2019). Therefore, the diversification of power generation sources, especially induction of solar PV in the energy mix, will open new avenues of research work, job opportunities, and reduction in CO₂ emissions. It will also cause the emergence of promising new markets. Solar power was also to be a vital source for the development of hydrogen economy in Pakistan (Shah 2020).

### Table 1

| Description         | Average generated power | Average running load | Average saving backup |
|---------------------|-------------------------|----------------------|-----------------------|
| MIHs                | 19,177,620,39           | 14,941,145.8         | 6,010,409             |
| LIHs                | 10,065,895.16           | 6,289,517.8          | 4,154,482.4           |
| Average (MIHs + LIHs)/2 for 25 years | 14,621,757.775         | 10,615,331.85        | 5,082,445.7           |
| 1 year (kWh)        | 584,870.311            | 424,613.272          | 203,297.828           |
| 1 year (kWh)        | 584,870311.kWh         | 424,613272 kWh       | 203,297828 kWh        |
Table 2 CO₂ emissions generated by hybrid solar system and WAPDA for 25 years

| Description               | Emission rate (gCO₂) | Energy share | Average generated power (kgCO₂) | Average running load (kgCO₂) |
|---------------------------|----------------------|--------------|--------------------------------|----------------------------|
| WAPDA                     |                      |              |                                |                            |
| Coal                      | 975<sup>ab</sup>     | 12.7%        | 795×584.870311 gCO₂            | 413,997 kgCO₂              |
|                           |                      |              | 570,248 gCO₂                   | 413,997 kgCO₂              |
|                           |                      |              | (570,248×12.7/100) 72.421 kgCO₂ |                            |
| Gas + Imported LNG        | 608<sup>ab</sup>     | 34.6%<sup>d</sup> | 608×584.870311 gCO₂            | 413,997 kgCO₂              |
|                           |                      |              | 355,601 gCO₂                   | 413,997 kgCO₂              |
|                           |                      |              | (355,601×43.3/100) 154 kgCO₂   |                            |
| Oil                       | 742<sup>ab</sup>     | 31.2%        | 742×584.870311 gCO₂            | 413,997 kgCO₂              |
|                           |                      |              | 355,601 gCO₂                   | 413,997 kgCO₂              |
|                           |                      |              | (355,601×43.3/100) 154 kgCO₂   |                            |
| Total emission for 1 year |                      |              | (72.421 + 154 + 135.399)=361.82 kgCO₂ | 52.577 + 111.785 + 98.299=26.61 kgCO₂ |
| Total average emissions of 10 households for 25 years | 361.82×25=9045.5 kgCO₂ | 262.66×25=6566.525 kgCO₂ |
| Solar photovoltaic        | Solar energy         | 40.96<sup>e</sup> | 40.96×584.870311 gCO₂         | 17.392 kgCO₂               |
|                           |                      |              | 23,956.287 gCO₂                | 17.392 kgCO₂               |
|                           |                      |              | (23,956.287×12.7/100) 361.82 kgCO₂ |                            |
| Total average emissions of 10 households for 25 years | 23.956×25=598.9 kgCO₂ | 17.392×25=434.8 kgCO₂ |

<sup>a</sup>Hernandez et al. (2014)
<sup>b</sup>Varun et al. (2009)
<sup>c</sup>Amponsah et al. (2014)
<sup>d</sup>Survey (2018–19)

**CO₂ emission generated by diesel generator**

Table 3 explains the variety of rated power generators with their fuel consumption and greenhouse gas emissions. This study proposes a constant output demand (P<sub>out</sub>) of 1.05 kW per hour of diesel generator for producing electricity which is consistent with previous literature (Jakhrani et al. 2012). As the average load shedding of electricity in Pakistan varies upon the factors of geographical location, seasonal change, and authoritative regulations, this study determines the amount to be an average of 3 h a day. Upon such selection, per day power output demand can be calculated as (P<sub>out</sub>×hour)=(1.05×3)=3.15 kWh. The efficiency of the generator is predicated on the power output demand and is calculated as P<sub>out</sub>/P<sub>in</sub>, as can be seen in Table 3.

In order to calculate fuel consumption, the quality and efficiency of the generator play a significant role. However, in accordance with the previous literature, a linear model for predicting fuel consumption per hour (Messenger 2018; Skarstein and Uhlen 1989) can be expressed as F = (0.246 × P<sub>out</sub>) + (0.08415 × P<sub>i</sub>). Fuel consumption per day (L/day) was calculated by multiplying fuel consumption per hour (L/hour) with the average number of hours, the generator is expected to run (3 h), whereas fuel consumption per kilowatt-hour was calculated by dividing fuel consumption per day (L/day) with power output demand per day (3.15 kWh) as shown in Table 3.

In order to find the greenhouse gas emissions generated from diesel generators, the emission factor of carbon and carbon dioxide had to be taken under consideration. Several studies have hinted at determining the emission factor for diesel generators which ranges from 2.4 to 3.5 kg CO₂/L (Alsema, 2000; Dufo-López et al. 2011; Fleck and Huot 2009). Therefore, this study considers the emission factor for the diesel generator to be 3 kg CO₂/L as indicated by Jakhrani et al. (2012) due to the similarity of research background. The greenhouse gas emissions per hour (kg/hour) were calculated by multiplying the fuel consumption per hour (kg/hour) with an average number of hours. The generator is expected to run (3 h) as shown in Table 3. Finally, the greenhouse gas emissions per kilowatt-hour were calculated...
by dividing greenhouse gas emissions per day (kg/day) with power output demand per day (3.15kWh) as displayed in Table 3.

### Cost of energy-generated sources

#### Cost of solar panel–generated energy consumption

As mentioned previously, the daily energy in kilowatt-hour was calculated from 7 am to 5 pm for continuous 15 days. The solar panels produced about 585kWh of energy in a year and contributed nearly 33% of the total running load with a daily average contribution of 1.6kWh. In this way, during its life cycle, its total power generation and contribution to the powerhouse in a total of the next 25 years would stand at 1,022,000kWh. The suggested typical hybrid solar system has a capital cost of $1,962.5 on average and an estimated cost of $0.0625 per unit (Sultan et al. 2018). After the first 10 years, 1% loss of energy occurs every year increasing the inefficiency of solar panels which is also accounted for in the results. The aforementioned calculations have been derived from the data received from the Axpert V Off-Grid Inverter (Tesla inverter) in June 2020. The derived findings reveal that the current hybrid solar system will return its capital cost after 8 years of functioning at 60% capacity. Operating for 7 h a day is considered normal efficiency of a good solar system which sums up to 1,705kWh per day. According to the 25-year prediction model, the contribution of energy will cost nearly $6387.5 for the next 25 years and the amount is saved up would be $4,936.4375 as can be seen in Table 4.

#### Cost of WAPDA-generated energy consumption

If we factor in the same WAPDA-generated number of units to the cost equation, then it will cost a total of $11,069.5375 in the next 25 years. The initial cost of the WAPDA connection for the same load is about $156.25 including the wiring and connection charges. Hence, this study compared the WAPDA-generated power with solar panels with an assumption of the life span of 25 years (Kneifel et al. 2016).

The total cost of the same WAPDA-generated units for a year including the cost of connection and wiring stands at $599.03125 and it becomes $11,225.7875 for the next 25 years. After including the extra amount of $98.147375 and accounting for 1% hike in taxes and levies, the total cost of WAPDA for the next 25 years becomes $11,323.9375 as can be seen in Table 5. This comparison indicated that the cost of energy generated with a hybrid solar system is almost half of the cost of energy generated by WAPDA. Already conducted research studies show that solar power is the best renewable power option for Pakistan in terms of life span, cost, and maintenance as well as operation cost (Irfan et al. 2019).

#### Cost of generator produced energy consumption

Table 6 displays that the energy production by generator for 12 months was found to be 4,088 kWh, with an average cost per unit which is $0.1875. According to the literature, a generator’s average life span is 12 years with a working capacity of 6 to 7 h per day (Benton et al. 2017). Therefore, a generator’s cost for the next 25 years will be $19,162.5 as shown in Table 6.

### Table 3: Greenhouse gas emissions (CO2) generated by diesel generator

| Rated power of generator in kW ($P_i$) | Efficiency of diesel generator | Fuel consumption | Greenhouse gas emissions (CO2) |
|--------------------------------------|--------------------------------|-----------------|------------------------------|
|                                       |                                | (L/hour) (L/day) (L/kWh) (kg/hour) (kg/day) (kg/kWh) |
| 2                                     | 0.52                           | 0.43            | 1.29                        | 0.41                        | 1.29                        | 3.87                        | 1.23                        |
| 3                                     | 0.35                           | 0.51            | 1.53                        | 0.49                        | 1.53                        | 4.59                        | 1.46                        |
| 4                                     | 0.26                           | 0.60            | 1.80                        | 0.57                        | 1.80                        | 5.40                        | 1.71                        |
| 5                                     | 0.21                           | 0.68            | 2.04                        | 0.65                        | 2.04                        | 6.12                        | 1.94                        |

### Table 4: Mathematical values of the solar energy contribution

| Metric                                      | Rate                |
|----------------------------------------------|---------------------|
| Average production of LIHs and MIHs per year  | 585 kWh             |
| Single day generation                        | 1.6 kWh             |
| Number of units generated in single day      | 11.2 kWh            |
| Total units produced in life cycle           | 102,200 kWh         |
| Price per unit                               | $0.0625*            |
| Average capital cost                         | $1962.5             |
| Total amount of generated energy in life cycle| $6387.5             |
| Number of units produced in a calendar year  | $4088 kWh           |
| Capital cost will be returned in 8 years according to cost–benefit ratio formula | $2044               |
| Amount which will be saved                   | $4936.4375          |

*Sultan et al. (2018)
Efficiency and cost comparison

By conducting a 25-year prediction simulation, the study was able to determine that the projected cost of energy generation by WAPDA and DG accounted for a total of $11,323.9375 and $19,162.5 respectively. These are compulsory regular expenses to be paid by a consumer apart from hiked levies and inflation. In their life span, hybrid solar energy panels cost up to $6,387.5 proving that the per unit cost of energy generation by solar panels is far less than the two other energy sources. Furthermore, solar panels are more efficient as an energy-generating tool since their life span is also 25 years. Previous study also indicates that the development of technology and novel inventions in the energy sector can decrease the cost and increase the efficiency of renewable energy generation (Anser et al. 2020). Additionally, these solar panels have nominal extra maintenance costs while the public utility WAPDA and diesel generator have comparatively higher maintenance costs. A properly installed solar panel seldom requires maintenance during its life span except for the costs of accidental damage. Some of the causes of interruption in energy generation arise merely from interruption of the inverter, wire repairing, and monitoring (ASNE 2015). Keeping in view the environmental friendliness, efficiency, and cost-effectiveness, and easy maintenance, solar energy can be deduced as the best option over the other sources of power generation in developing countries. It has been suggested after thorough research studies such as Shah et al. (2018) and Xu et al. (2019) and feasibility analysis of solar power, across Balochistan and Sindh have been spotted as best places to be electrocuted by alternative power source, i.e., solar energy. Moreover, solar energy is one of the good choices for the generation of green hydrogen energy in the country (Chien et al. 2021). From the above results and discussion, it is clear that a hybrid solar system is much more efficient than non-renewable energy sources to be widely deployed across Pakistan.

Conclusion and future recommendations

Based on the detailed data analysis and comprehensive discussions regarding hybrid solar systems installed in the various households, we can draw the following recommendations and conclusions:

Lower income households and medium-income households have a daily average power generation of nearly 1,145 kWh and 2,275 kWh, respectively; however, the fluctuations may occur under different weather conditions, i.e., winter and summer. In the selected 15-day period, about 667 kWh and 1,630 kWh were the daily average loads for lower income households and medium-income households along with 476 kWh and 645 kWh backup, respectively. A few numbers of systems that cause a reduction in saving backups over time are caused by the inefficient use of energy in the households and overload surges. However, households with no power backups can increase the power of solar to have an uninterrupted flow of energy. In terms of average produced energy, the emissions caused by WAPDA and hybrid solar systems were 9045.5 kg CO$_2$ and 598.9 kg CO$_2$ respectively, and in terms of average running load, 6566.525 kg CO$_2$ and 434.8 kg CO$_2$ respectively for the predicted next 25 years. Replacing the traditional sources of power generation with a hybrid solar energy system can abate carbon emissions up to 8,446.6 kg CO$_2$ as per average generated power. Considering the average running load, over 6131.725 kg CO$_2$ of carbon emissions can be reduced in the next 25 years whereas diesel generator has a higher rate of carbon emissions than WAPDA. The data analysis shows that the inclusion of a hybrid solar energy system in Pakistan’s energy mix would have a significant cut in carbon emissions as compared to the other sources of energy. Some of the long-term hurdles such as the absence of up-to-date systems, modern infrastructure, and frequent quality checkups will not be able to bring down the carbon emissions to zero. However,
through solar hybrid energy systems, these carbon emissions can be reduced up to a considerable level.

Furthermore, the cost of the diesel generator is the highest among the two other energy sources with a total of $19,162.5 in the predicted next 25 years, whereas WAPDA will cost the households nearly $11,323.9375 for the predicted next 25 years. A properly installed hybrid solar energy generating at a capacity of 60% for 7 h a day will return its capital cost in merely 8 years and save up to a sum of $4,936.438. Additionally, the level of reliability of a hybrid solar energy system is much more than other non-renewable energy sources as it has the net metering feature and can add additional energy to the grid causing minimal wastage. This research study indicated that the problem of power outages can be uprooted by integrating the current power generating sources with a hybrid solar energy system. Therefore, we can conclude that solar energy has a bright future in Pakistan due to the country’s distinctive geographic position and access to direct sunlight most days of the year.

This study emphasizes the external influencing factors to household energy generation through the hybrid solar system such as quality manpower for installation, product quality, geographic position, and other quality parameters necessary for solar energy generation. The most efficient way of energy generation through a hybrid solar system considers some parameters including optimal angle to catch solar radiation, the intensity of light, standard wire, temperature, grounding of solar panels, and dust. Furthermore, replacing standard AC wire with DC wire can achieve quality output, and an updated power monitoring system should be in place to attain accurate readings. Moreover, replacing the AC aluminum wire with copper wire and wrapping separately with different insulating tapes instead of plastic tape will reduce the chances of any short-circuiting and accidents. Seasonal variations may bring changes in the direction and angle of sunlight. Therefore, for optimum output, the adjustment of angle plays an important role during winters and summers. Some of the pre-requisites to avoid the hybrid solar energy system’s power losses are proper positioning and keeping the system dust-free. Lastly, a multi-connector should be used for quality connections and replace the direct insertion of the floor frame with moveable blocks up to 1 m² to ensure the quality output.

Author contribution Dr. Mudassir Hussain: The author generated fundamental research idea, formed research objectives, developed approaches and methods for conducting this study, and wrote the first draft of the manuscript.

Manzoor Sultan: The author contributed to the study design and data organizing and evaluation.

Dr. Faiza Uzma: The author contributed in data evaluation and provides assistance in writing.

Prof. Cheng Longsheng: The author spearheaded the research and provided a supervising role in conducting the research.

Dr. Muhammad Yousaf Malik: The author formulated data analysis plan and provided a comprehensive interpretation of the data.

Abdul Rahman Butt: The author developed graphical representation of the data and formed figures and tables.

Aqsa Sajjad: The author developed statistical representation of the data and reviewed the first version of the manuscript.

Ijaz Younis: The author assisted in data collection and arrangement. Muhammad Imran: The author assisted in data collection.

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Declarations

Ethics approval This is a genuine work with properly cited resources. All the data is provided within the article with authors’ resources and no client involved, so this section is not applicable.

Consent to participate Not applicable.

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