Cleaner Energy Systems 8 (2024) 100110

Contents lists available at ScienceDirect

Cleaner Energy Systems

journal homepage: www.elsevier.com/locate/cles

Assessment of prosumer-based energy system for rural areas by using TRNSYS software

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ARTICLE INFO

Keywords:
Prosumer
Electrification
Digitalization
Renewable energy
Energy trade

ABSTRACT

The prosumers are the new performers progressing towards a low-carbon future. Renewable-based power generation is essential, even in rural areas, to pave a path toward sustainable development. This study establishes a simulation model for two identical residential buildings to assess the prosumer's impact on future local (standalone) energy systems. According to the climate condition of Pakistan, the technical, economic, and environmental performance of the standalone system is evaluated using TRNSYS software. Assumptions and modeling of different components, photovoltaic (PV) panels, and batteries are also discussed. This study provides the starting point of a real-time framework of energy trade between two rural houses connected with a common microgrid. Both houses are medium-sized family houses with almost identical electricity demands. One house has PV mounted on the rooftop, with the battery as an optimal energy storage option. Attention is given to peak demand management and surplus energy during enough production hours. A dynamic energy management approach between two buildings is proposed based on TRNSYS and blockchain. Simulation results show that the real-time implementation of local energy production and energy trading at the household level facilitates achieving the dual benefits of reducing consumer costs and maximizing self-consumption.

Introduction

Motivation

Energy consumption practices are undergoing essential reforms to cope with growing energy demand and severe climate challenges. According to the International Renewable Energy Agency tracking SDG7 report, the global electricity access rate improved progressively from 83 % to 91 % during 2010 to 2020. Due to the potential impact of COVID-19, the annual growth rate of electrification has slowed, and around 733 million people remained unserved in 2020. At the present rate of progress, the world will meet only 92% of electrification by 2030 (IRENA, 2022a). Consistent efforts are required to accelerate electrification, particularly for countries currently being left behind. Today's energy production relies on fossil fuels, which is detrimental to the environment. A wide range of renewable energy (RE) technologies and their progressive placement exhibit affordable and clean energy for all. Generally, RE integration is increasing rapidly, contributing to 90 % of the total power capacity growth in 2020 (IEA, 2020).

Scientists and engineers are working actively to explore alternate implementation strategies of RE sources by highlighting the importance of green energy (Lin and Li, 2022), developing sustainable energy technologies with RE sources (Abas et al., 2014), and emphasizing RE integration in urban areas (Saavedra et al., 2022), as well as rural areas with microgrid installation (Kamal et al., 2022) and maximizing utilization of existing grids (Ranjbar et al., 2022). Technical, economic, social, environmental, and infrastructural factors affect the choice of suitable and affordable technologies for particular circumstances (González and Connell, 2022). Solar energy is one of the attractive options among all the RE sources due to its abundance and sustainable availability across the globe (Gao et al., 2022). Solar power experienced significant growth with a 21-fold increase during 2010–2021, resulting in substantial cost reduction, technological advancement, and supportive financing models (IRENA, 2022b).

Related work

Solar power has enough potential to play an essential role in clean energy supply compared to finite fossil fuel sources. Seasonal availability of sun reduces its effectiveness in domestic and commercial use. To deal with the inherent intermittency of solar energy, enormous

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https://doi.org/10.1016/j.cles.2024.100110
Received 2 February 2023; Received in revised form 17 October 2023; Accepted 21 February 2024
Available online 29 February 2024

Nomenclature

Acronyms

DEGS	Diesel Engine Generator set
DOD	Depth of discharge
FSOC	Fractional state of charge
LCOE	Levelized cost of electricity
MPPT	Maximum power point tracker
NEPRA	National electric power and regulatory authority
PSH	Peak sunshine hours
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RE	Renewable energy
RES	Renewable energy sources
SOC	State of charge
SOH	State of health
TRNSYS	Energy simulation software package

Fixed variables and parameters

C_{bat}	Capacity of battery in ampere-hour
Ct	Capital cost
Dr	Degradation rate
dr	Discount rate
Et	Annual rated energy produced by PV system
FiT	Feed-in tariff
N_a	Number of autonomy days
OMt	Operation & maintenance cost
P_{load}	Energy used in a day
P_{pv}	Size of PV panels in KW power
Rt	Replacement cost

approaches with promising results are available such as energy storage technologies (Lai et al., 2017), hydrogen energy storage (Liu et al., 2019), flywheel energy storage (Li and Palazzolo, 2022), pumped hydro energy storage (Ma et al., 2014), supercapacitor energy storage (Ma et al., 2015), electric vehicle's battery (Akbari et al., 2019) etc. PV systems, grid-connected (Mokhtara et al., 2021) or standalone (Das et al., 2021), have been extensively used for several types of applications worldwide. A standalone PV system requires sufficient solar panels and battery capacity to ensure the system's reliability. Deterministic and stochastic methods are used for PV system sizing. Peak Sun Hour (PSH) is a simple deterministic approach that can be used to determine PV system sizing (Al-Riza and Gilani, 2014).

Currently, the building sector comprises around 20–40 % of total energy consumption in developed countries (Liu et al., 2019). Extensive applications of solar energy have shown remarkable growth in recent years. Solar energy can be easily combined with existing structures, making it more favorable, especially in remote areas. An optimization algorithm is proposed for the flexible market in distributed generation with clustered microgrids considering any bidding strategy to promote peer-to-peer energy trading (Dudkina et al., 2022). To develop sustainable communities, implementing renewable energy requires robust planning and policies. Because of several techno-commercial challenges, solving a problem through extensive experiments is complicated. Modeling and simulation are more promising alternatives to reduce the number of repetitive and iterative testing in long-run experimentation (Shrivastava et al., 2017). TRNSYS acronyms TRaNsient SYStem is a well-known energy simulation program and deals with transient systems such as electrical systems, thermal behavior of buildings, solar energy applications etc. (Kenai et al., 2021).

Numerous studies investigated residential energy demand and supply statistics with rooftop PV by using TRNSYS software. Energy demand for a detached family house is analyzed in different climate zones with the help of TRNSYS (Rashad et al., 2022). An overview of the design and optimization of hydrogen production with solar power using TRNSYS and GenOpt was carried out for different climate conditions in Turkey (Karacavus and Aydın, 2020). Performance analysis of PV and thermal energy demand of single-family buildings and mechanical ventilation is carried out with TRNSYS (Góra et al., 2021). The energy-saving index of a building shaded by PV panels in different climate zones of India is studied (Bhuvad and Udayraj, 2022). An integrated model for solar space and water heating system for a laboratory building within an academic institution is developed using TRNSYS, and the effect of variation of optimum solar collector tilt, collector size and storage tank volume is analyzed (Farooq and Zhang, 2022). A model was developed and simulated with TRNSYS to analyze the near-to-net zero energy building performance of Iraq's hot and dry climate (Abdul-Zahra & Al Jubori, 2021). TRNSYS-based simulations are performed for hybrid photovoltaic-thermal (PV/T) solar panels that co-generate electricity and hot water for local use in tropical climates (Maoulida et al., 2023).

A parametric analysis of different solar collector integration options is studied in a single-family detached house in Thessaloniki, Greece. TRNSYS software is used to estimate the seasonal storage tank volume, optimize the system design, and achieve a seasonal combined solar fraction of at least 39 % (Antoniadis and Martinopoulos, 2019). To improve the overall performance of heat exchangers in energy-efficient buildings, a low-level waste heat recovery method is studied with TRNSYS software (Brough et al., 2021). Heat gains/losses on the energy demand of a three-zone building are focused on year-round analysis in TRNSYS. With the proper selection of renewable energy sources, the exact energy requirement of the building and the lowest installation cost are determined (Rashad et al., 2022). EnergyPlus and TRNSYS-16 software are used to analyze the annual energy consumption and production by PV and wind and show that it is theoretically possible to design zero-energy buildings in new cities (Zahedi et al., 2022). Green energy alternatives are provided at a community level to ensure the sustainability of the environment. The thermal behavior of attached solar greenhouse gas connected with rock-bed storage is investigated using TRNSYS software (Asad et al., 2019). Borehole energy storage is a viable option for seasonal solar thermal energy storage for large communities; a case study of 52 homes solar community heating was developed using TRNSYS and active hourly simulations of thermal loads conducted over five years (Rad et al., 2017).

Energy trading networks improve the environmental sustainability, reliability, and economic patterns of energy systems. Based on existing sustainability goals and principles, the scope of domestic energy trade cannot be compromised. However, there are some social and regulatory barriers in addition to technical and economic hindrances to implementing energy trading. In recent years, the increasing use of renewable energy sources has encouraged producers to sell excess electricity to nearby consumers to promote collective self-consumption (Reis et al., 2022). Adequate rules and specialized trading technologies, such as peer-to-peer (blockchain), are substantial (Tushar et al., 2021). Energy trading problems like privacy breaches, miscommunication, and network speed are more challenging to overcome in conventional centralized systems (Yap et al., 2023). Therefore, early renewable platforms evolved as decentralized energy distribution systems. Numerous algorithmic studies are being conducted to optimize market mechanisms (Ping et al., 2023), coordinate supply and demand, improve trading efficiency, and reduce market manipulation (Tkachuk et al., 2023). Blockchain technology is used to enhance the security of hybrid microgrids because of its technical and economic advantages over conventional grids (Li et al., 2023). The struggles and challenges the energy sector faces to promote P2P energy trading enabled by blockchain technology in a developing country are highlighted (Gupta et al., 2023).

The above literature studies the use of TRNSYS software for multi-objective investigation of energy systems with various constraints to provide ideas for energy management solutions. Considering the proposed strategies, an advanced approach with minimum common grid dependence is proposed for residential buildings. Our study highlights rural electrification by microgrids. The rural area is selected from Pakistan. Due to the extensive latitude range from north to south, it experiences a diversified climate. Pakistan is located in the Sunbelt and has vast solar power potential, estimated at around 2 900 GW (Rafique et al., 2020). Productive use of this potential would lead to economic growth and emission reduction. PV power generation is the best option to reduce the fossil fuel import of the country.

Steps and contributions

This study aims to excite the conversion of traditional electricity consumers into electricity prosumers (individuals who both consume and produce), even in rural areas. Extensive technical analysis is provided to effectively highlight energy trade between buildings. Economic analysis is done to support the forecast. This paper discusses a case study of two rural houses with similar electricity demands.

The main steps include (1) the Daily energy demand of a residential house is calculated based on real-time data, and section (2.1) explains a typical residential house, (2) PV and battery size are calculated by the Peak Sun Hour method, (3) Simulation data for TRNSYS is set according to calculated and selected data sheet values, (4) The technical, economic, and environmental performance of the system is evaluated based on TRNSYS simulation results, (5) The same simulation is run again with the demand of two houses to solve for the surplus energy produced by the RE and the prosumer capacity is estimated, (6) Real-time framework of energy trade between two rural houses connected with a common microgrid is proposed.

This study's main contribution includes technical evidence to support the energy trade between two buildings in a cost-effective way. To the best of author's knowledge, none of the previous studies properly considered TRNSYS software to model the energy trading among rural houses as a viable option. This study bridges this gap and makes the model more systematic and proficient. Validation of technical and economic analysis results supports the forecast of the study.

Materials and methods

Photovoltaic Geographical Information System (PVGIS) tool is used to track down the highest solar radiation area. Quetta City of Pakistan, is selected to analyze the essential impact of solar energy sharing. After estimating the actual energy demand of a typical two-bedroom house, the PV system is sized with the PSH method. With all calculated and assumed parameters, the TRNSYS model is developed for a microgrid-connected residential house, which includes rooftop-mounted PV and battery. Two cases are investigated with the same simulation model. Details of all parameters and assumptions are discussed in the following.

Buildings characteristics

A typical two-bedroom with one living room house is selected from a rural area of City Quetta, Pakistan. The estimated number of people living in this house is 3 to 4, and only one person remains in the house during the daytime. Table 1 shows the list and number of appliances installed in the typical house. Table 2 comprises the power consumption of each appliance and estimation data of appliance usage based on time hour.

Based on the above data, the energy demand is 8005.1 Wh/day. But it is quite possible that two or more appliances are turned on at the same time, so keeping in mind some miscellaneous loads and a quite unusual usage time of 10 kWh/day is the estimated maximum demand of this house. Since the chosen home is from a rural area, assuming the homeowner has limited capital to invest heavily in modern heating and cooling equipment. This study does not consider building heating and cooling demand as electricity consumption. Heating and cooling can be served traditionally, such as wood firing or biogas.

System components and production data

Photovoltaic: It is essential to determine the availability of solar energy for the site and energy demand per day to size the PV system. The

Table 2
Total usage time in hours and power consumption per day.

Appliance	Power, W	Quantity × Hours used	Energy per day, Wh/day = (Quantity × Hours used × Power)	Data sheet Source
Ceiling fan, hall	82.5	1 × 17	1 402.5	(HunterFan, 2023)
Ceiling fan, room	82.5	2 × 12	1 980	(HunterFan, 2023)
Light small	8	3 × 7	168	(Energetic, 2023)
Light big	25	2 × 7	350	(Energetic, 2023)
Light porch	25	1 × 3	75	(Energetic, 2023)
TV	39	1 × 16	624	(Sharp, 2023)
Table fan	42.5	–	0	(Ecocost, 2023)
Washing machine	423	1 × 0.5	211.5	(Panasonic, 2023a)
Exhaust	18.3	1 × 3	54.9	(Maxx Air, 2023)
Water pump	100	1 × 4	400	(Ato, 2023)
Refrigerator	93.3	1 × 24	2 239.2	(Orient, 2023)
Iron	1000	1 × 0.5	500	(Panasonic, 2023b)
Total Energy			**8 005.1**	
After adding miscellaneous load			**10,000**	

Table 1
Installation and power consumption of appliances.

Appliances	References	Porch	Living /Dining	Kitchen	Bathroom/ Toilet	Room1	Room2
Ceiling fan, hall	CFH	0	1	0	0	0	0
Ceiling fan, room	CFR	0	0	0	0	1	1
Light small	L1	0	0	0	1	1	1
Light big	L2	0	1	1	0	0	0
Light porch	LP	1	0	0	0	0	0
TV	TV	0	1	0	0	0	0
Table fan 12″	TF	0	0	0	0	0	0
Washing machine	WM	0	0	1	0	0	0
Exhaust fan	EF	0	0	1	0	0	0
Water pump	WP	0	0	0	1	0	0
Refrigerator	RF	0	0	1	0	0	0
Iron	IR	0	0	0	0	1	0

load demand of a typical two-bedroom residential building is explained in the previous section, around 8 kWh/day. However, we assumed the total energy used in a day (Pload) as 10 kWh by including some miscellaneous loads. The average peak sunshine hours (PSH) of Quetta are 4.26 (Ahmed et al., 2021). System efficiency (Ƞsystem) is 80%, including connection losses and dust factor.

$$\text{Ppv} = \frac{\text{Pload}}{(\text{P.S}.H \times \eta\text{system})}(\text{kW}) \tag{1}$$

PSH = Peak sunshine hours of Pakistan, Pload = Total Energy used in a day, Ƞsystem = Efficiency of the system.

Simulation has been carried out for the selected PV size, and the solar panel used in the simulation is Jinko Solar JKM 400 M–72H, with a rating of 400 W (Jinko, 2022) . Table 3 shows the specifications of this 400 W solar panel.

Battery: The PV system is designed with one autonomy day, making it cost-effective. Normally, a depth of discharge (DOD) greater than 80 % should be avoided. The "sweet spot" (optimum DOD for the greatest amount of power produced over the service life) is between 20 % and 60 % on average.

$$\text{Cbat} = \frac{\text{Pload} \times \text{Na}}{(\text{DOD} \times \text{Vrated} \times \eta\text{system})}(\text{Ah}) \tag{2}$$

C_{bat} is the battery capacity in ampere-hours (Ah), and Na is the number of autonomy days (a day with minimum solar irradiation) required consecutively. V_{rated} is the voltage of the system in volts. The Nissan Leaf AESC LiNM battery (Nissan, 2023)is used in the simulation and Table 4 lists the specification of the battery.

Simulation parameters

The electricity demand of the sample residential house on a typical working day is used and estimated the energy consumption of a two-bedroom house is 10 kWh/day as explained in Section 2.1. TRNSYS Type9c is used to simulate the load demand, and Fig. 1 depicts the results for one day.

A 3.5 kWp PV system (Jinko Solar JKM 400 M–72H with a rating of 400 W) is simulated with Type103b. According to the calculation, a total of 8 panels each of 400 W power are assumed to be installed at the rooftop of the building, with a slope of 28° The input to this model is provided with Quetta's Type15–6 weather data file. Fig. 2 depicts the total horizontal radiation on the slop of the PV panel for one year in hourly resolution.

Power production of the PV panel flows into the Inverter/Charge controller. The Type48b Inverter/Charge controller model is designed to interact with the Type47a battery. A 30-kW battery (2014 Nissan Leaf AESC LiNM battery) is simulated with a control algorithm implemented in Type48b. The battery is charged during enough production hours. If the battery's state of charge is high, load demand is served by the input power from renewable energy. If the input power is not enough to meet the load, power is drawn from the battery to meet the load demand until the lower limit of the battery is approached. At this point, Type48b stops further discharging of the battery, and the required amount of power is met with a backup source. In this case, the Type120a Diesel Engine Generator set (DEGS) is modeled as a backup source with 1 kW rated power because PV and battery are usually sufficient to meet the load demand in this specific case. A parameter for the charge-to-discharge limit on the fractional state of charge (FSOC) should be controlled carefully to prevent the battery from getting stuck at the lower charge limit. The battery can be discharged to 10%, then recharged to 30 % before discharging again.

Table 3
Jinko Solar JKM 400 M–72H solar panel specifications.

Attribute	Value	Attribute	Value
Maximum Power	400Wp	Cell type	Mono PERC
V_{MP}	41.7 V	No. of half cells	144 (6 × 24)
I_{MP}	9.60 A	Dimensions	2008 × 1002 × 40 mm
Voc	49.8 V	Weight	22.5 kg
Is	10.36 A	Front glass	3.2 mm tempered glass
Efficiency at STC	19.88%	Frame	Anodized Aluminum Alloy

Table 4
Battery specifications.

Attribute	Value
Battery Type	REVB (Li NM)
Model	2014 Nissan Leaf AESC LiNM battery
Cell Rating	7.5 V 65Ah (488 Wh)
Self-discharge	5.7% per month @ 21 C
Cost	90$/ kWh
Initial State of SOH	70 %
End-of-life SOH	50 %
Initial round trip efficiency at 100 % SOH, 0–100 % SOC	98 %
Round trip efficiency at 60% SOH 0–100% SOC	83 %
Overall round-trip efficiency for	98 %

Results and discussion

Mainly in this section, two cases are discussed; in the first case, a detailed model of the electricity system of a residential building is analyzed, and in the second case, a basic framework of the utilization of surplus energy is proposed to highlight the prosumer impact on the overall electricity system. In both cases, the same model is used with the respective demand of the buildings. Fig. 3 shows the layout of the electricity model in TRNSYS.

Analyzed case

According to the sized and estimated parameters for one residential building, as shown in Fig. 4, the renewable energy-based system is simulated with TRNSYS-18 from October 1 to 8 with hourly resolution. As Fig. 5 depicts, the estimated power is enough for one residential building to meet the load demand. During the daytime, PV production is enough to meet the load demand and charge the battery. When PV is unavailable at night, the battery starts discharging to fulfill demand. The battery did not reach its lower limit despite being discharged the whole night. Fig. 6 shows the fraction state of charge of the battery and its capacity for the same period of 7 days from October 1 to 8. In this case, DEGS does not supply any power because the PV and battery efficiently serve the whole demand. A backup source is required only when both PV and battery are insufficient to fulfill the load demand. This case is precisely according to our assumptions. Energy security is completely accomplished in this case to address the economic aspect; another case is discussed in the 3.2 section.

Economic analysis

Appropriate economic analysis is essential to understanding the profitability of the investment in the PV system. Due to small-scale projects, operating costs like replacing faulty cables and cleaning panels can be ignored. Table 5 presents average values of components and their cost.

Based on electricity consumption data, a typical house consumes 3650 kWh/a. The resulting data derived from the TRNSYS simulation listed in Table 6 shows that total electricity production from a 3.5 kWp PV system is 6000 kWh/a. It is evident that the generated electricity can easily fulfill the energy requirements of the homeowner, and the excess energy can be sold to the power grid.

If the total electricity demand is fulfilled from the conventional grid supply, per unit cost of electricity is followed by the government's

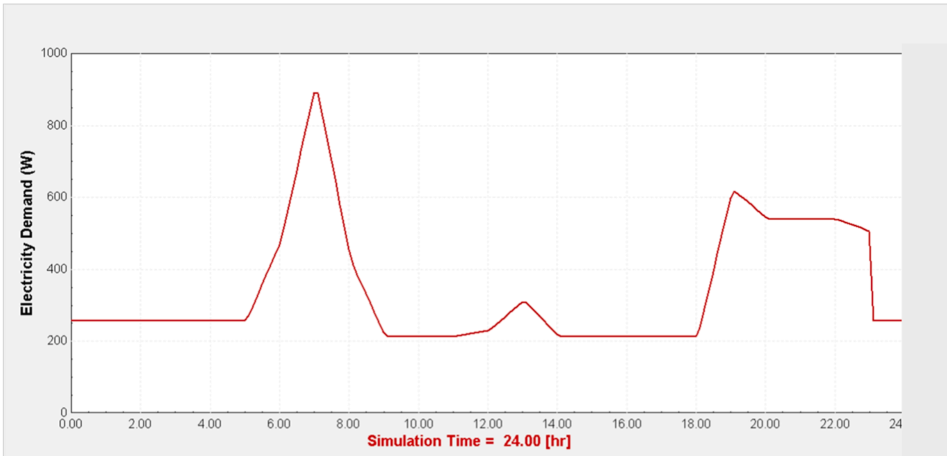

Fig. 1. Hourly electricity demand for one day.

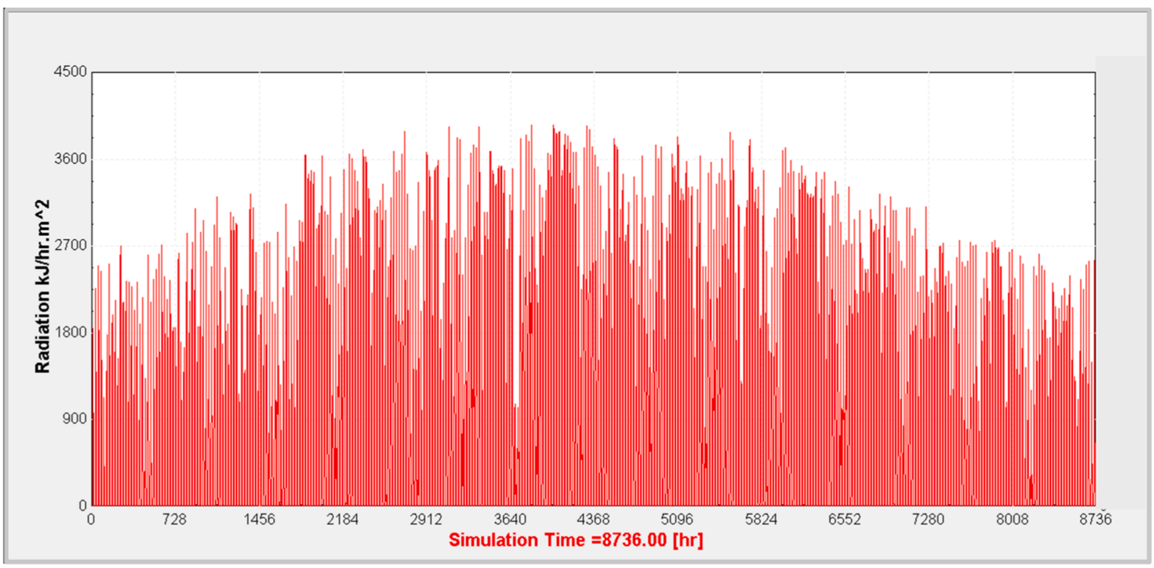

Fig. 2. Annual solar radiation.

official website, National Electric Power and Regulatory Authority (NEPRA) (NEPRA, 2022). According to the NEPRA report, the cost of electricity is 0.08 $/kWh. Return on investment depends upon annual energy production from the system, and it can be calculated from annual energy saving using the following equation.

$$\text{Annualsaving} = \text{Annualenergyinjectedintogrid} \times \text{FiT} \tag{3}$$

According to the result data from the TRNSYS simulation, this specific model has 2350 kWh of excess energy. The feed-in tariff (FiT) is selected at 0.09 $/kWh (NEPRA, 2022) to calculate annual savings from the solar plant.

For the second case, a cost-based metric known as the Levelized cost of electricity (LCOE) (Ameur et al., 2020) of the PV system is calculated using Eqs. (4) and (5). LCOE estimates for solar PV tend to be fairly high than the alternatives based on common assumptions (Branker et al., 2011).

$$\text{LCOE} = \frac{\text{Total lifetime cost}}{\text{Total lifetime output}} (\$;\ /\ \text{kWh}) \tag{4}$$

$$\text{LCOE} = \frac{\sum_{n=0}^{N} \frac{Ct+OMt+Rt}{(1+dr)^n}}{\sum_{n=1}^{N} \frac{Et*\ (1-Dr)^n}{(1+dr)^n}} (\$;\ /\ \text{kWh}) \tag{5}$$

According to the datasheet of this particular PV panel, a lifespan of 20 years is considered. Ct, OMt, and Rt are the capital, operation & maintenance, and replacement costs of the PV panel and maximum power point tracker (MPPT), respectively. The annual rated energy produced by PV is represented with Et. Additionally, dr is the discount rate, and Dr is the degradation rate. A monocrystalline solar cell has an average annual degradation of 0.3 % (Rajput et al., 2017).

Finally, the cost comparison of conventional source and PV-based system is presented in Table 7 to signify the energy trade potential. The unit cost of electricity in a conventional system is 0.08 $/kWh, which can be reduced to 0.027$/kWh by installing a PV system. Yet, the cost reduction potential is available with additional energy trading to neighboring customers.

Environmental analysis

Consumption of nonrenewable electricity for households contributes indirectly to emissions. Power generation emissions are considered equivalent to CO_2 emissions. The Climate Transparency Report published that Pakistan's emission factor is 359 g CO_2-e/kWh (Climate transparency report, 2020). According to this emission factor, the 6000 kWh PV electricity production reduces 2154 kg equivalent CO_2

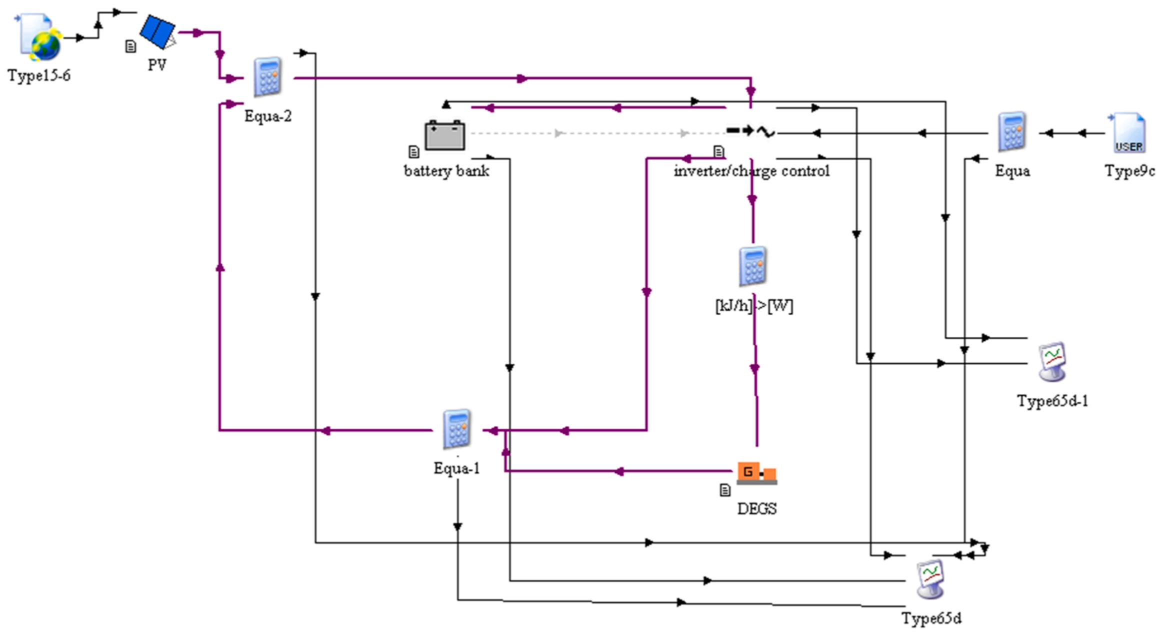

Fig. 3. The layout of the electricity model in TRNSIS-18.

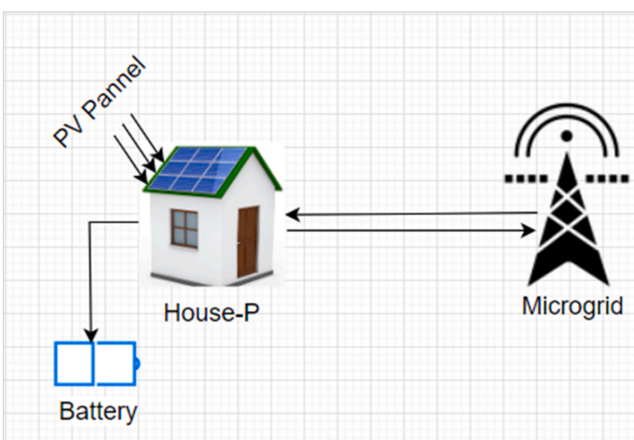

Fig. 4. One House (Prosumer building).

emission.

Proposed case

In this case, we modeled the same plan for two identical houses, as shown in Fig. 7. The same microgrid connects both houses. One house is equipped with a PV and battery storage system and acts as a prosumer. At the same time, the other house depends on grid power and the surplus energy produced by the prosumer during enough production hours. Now, the total energy demand is 20 kWh/day. Just 3.5 kWp panels are mounted on the roof of house one. Fig. 8 depicts the simulation results reflecting that the grid is turned on to meet the demand. Fig. 9 shows that battery discharges more as compared to only one house case. FSOC of the battery also clearly indicates the state of the battery.

From these simulation results, we can assume that we can trade electricity by incorporating blockchain technology between two buildings. With this prosumer and consumer strategy, we move one step closer to a low-carbon future.

Digitalization of electricity system with blockchain

Introducing blockchain technology into the power sector is a potential market with increasing applications. Blockchain is a decentralized, digital transaction technology that authorizes secure business performance in peer-to-peer networks. Blockchain is a distributed technology with many unique advantages, such as secure data storage, fault tolerance, data that cannot be modified, high computing capacity, low cost, and audibility. Digitalizing power systems with blockchain integration includes smart contracts, smart meters, and Renewable Energy Sources (RES) bids.

With blockchain technology, the whole trading is done in a decentralized manner. All transactions include buyer and seller only. Both parties decide the price and conditions of trade. This is opposite to the conventional centralized distribution system, where the whole power generated by different utility companies and independent power producers is regulated by state authority. Transformers control voltage regulations according to load utility, and power are transmitted to distant consumers by high-tension transmission lines. Thus, consumers pay via banks according to their consumed power.

Any electricity system has its generation, transmission, and distribution constraints. It is evident that transmission systems involve the parallel transmission of both power and price, alongside multiple fixed and variable losses such as load losses, hysteresis losses, eddy current losses, series losses, transmission line losses, and some non-technical losses, like power theft. Though these losses are handled with the installation of respective devices to improve the transmission profile, adding this equipment increases overall transmission cost. This leads to decentralized distribution's advantage in avoiding unnecessary transmission costs. With the rising share of RES, managing the central grid is becoming more complex, which develops into distributed grid management. For reliable electricity flow, appropriate scheduling and robust control infrastructure are still challenging for the energy sector. Blockchain technologies with smart infrastructure are a promising solution for decentralized systems. Economic and policy barriers should be tackled before integrating blockchain technology into the power sector. Many international companies are developing blockchain pilot projects in the energy sector after witnessing the successful implementation of blockchain in other sectors. Developed RE technologies and smart meters made this job relatively easy. Numerous strategic models for

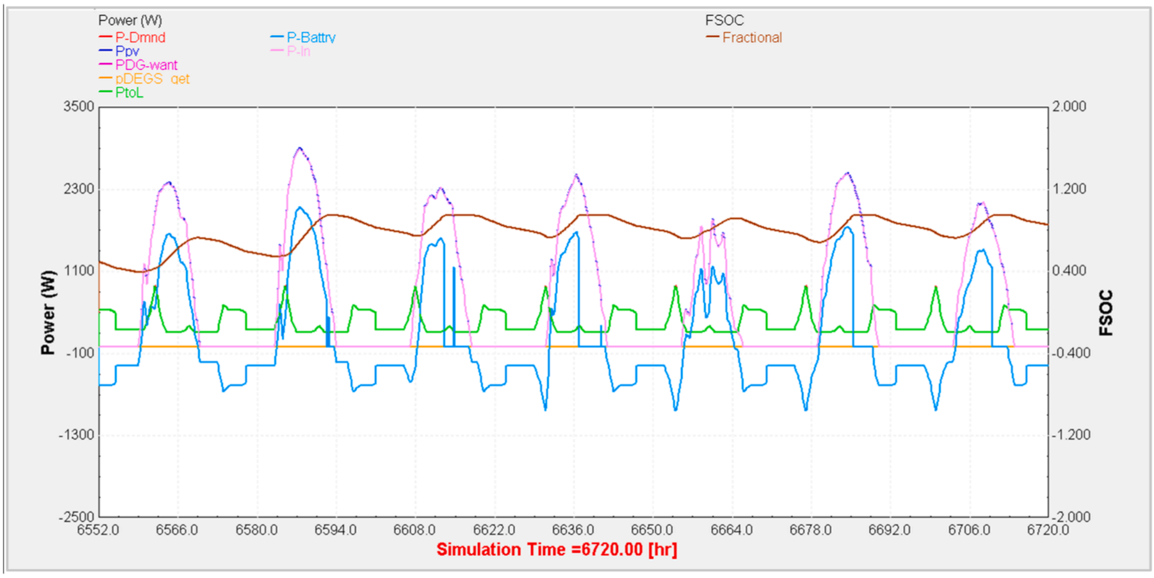

Fig. 5. Power state Oct1–8 (One house).

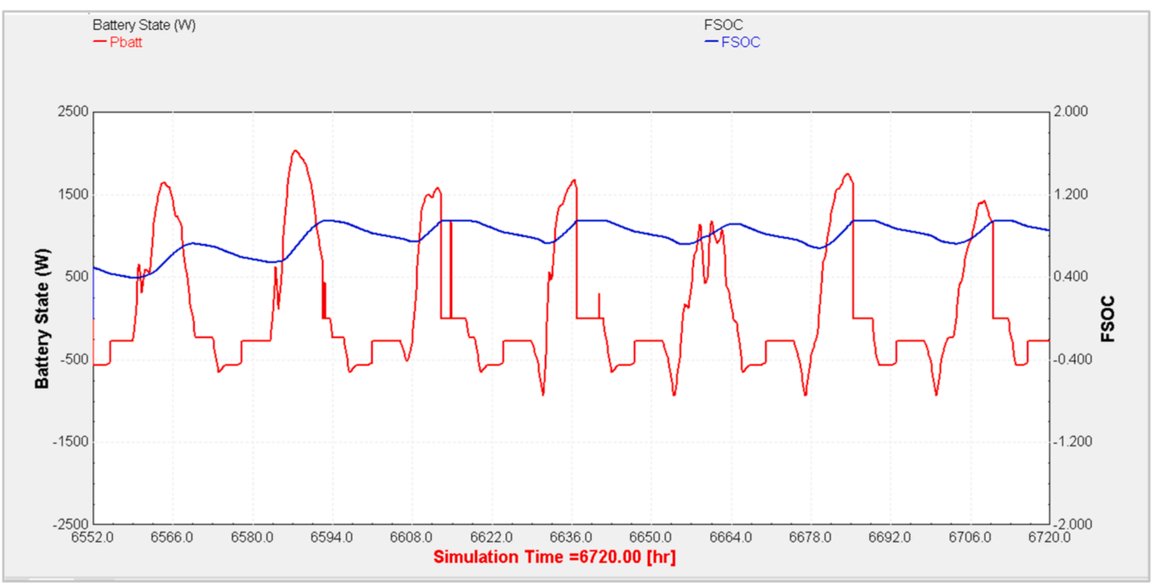

Fig. 6. Battery state Oct1–8 (One house).

Table 5
PV system parameters.

Parameters	Components	Value for one	Total
Capital cost	PV array ($/kWp)	350	1225
	PV array MPPT controller ($/kW)	100	350
	Battery ($/kWh)	90	2250
Replacement cost	Battery ($/kWh)	90	
Maintenance cost	PV array ($/kWp/year)	9	31.5
	PV array MPPT controller ($/kW/year)	2	7
	Battery ($/kWh/year)	18	540
Annual interest rate (%)		2	
Annual inflation rate (%)		1.2	
Degradation rate (%)		0.3	
Discount rate (%)		–	

Table 6
Data derived from simulation results.

Attribute	Value
Average production from 3.5kWp PV system per year	6000 kWh
Average requirement per year	3650 kWh
Total bills for a household for one year	295.6 $
Annual saving	211.5 $

implementing Blockchain with RES have been established with remarkable advantages.

Fig. 10 is a graphical representation of our TRNSYS model. It shows that House-P, equipped with PV and one-day battery storage, has enough capacity to meet its energy demand and can easily share surplus energy with House-C or the Microgrid. Surplus energy trade to the neighboring consumer is more profitable for the prosumer and beneficial for the utility grid as it reduces the peak demand.

Table 7
Cost Comparison.

Type	Attribute	Value
Conventional source	Average electricity requirement per year	3650 kWh
	Total bills for a household for one year	295.5 $
PV based system	PV installation cost	1575 $
	Yearly maintenance cost	38.5 $
	Life span (years)	20
	Average electricity production from 3.5kWp PV system per year	6000 kWh
	LCOE	0.027 $ / kWh
Trade potential	Annual surplus energy	2350 kWh
	Annual savings	211 $

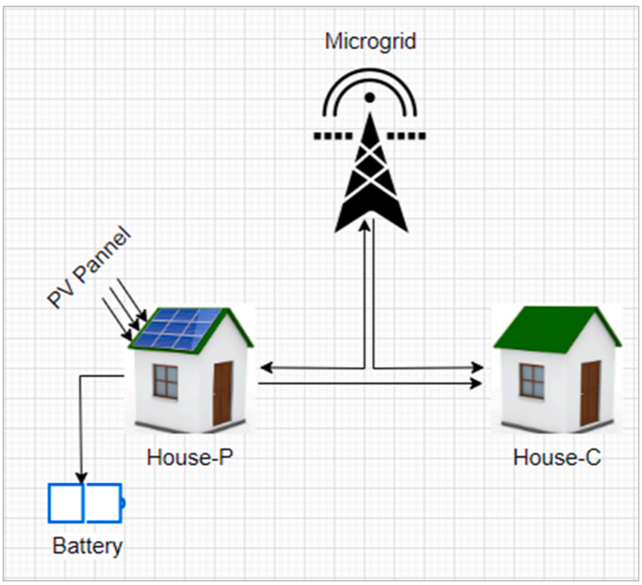

Fig. 7. Two Houses.

Conclusion

In this research, the daily energy demand of a typical residential building is calculated according to the regional condition of rural areas of Pakistan. The peak sunshine hour method is used to determine the appropriate PV size. The results show that a 3–4-person family house has 10 kWh of electricity demand daily. A 3.5 kWp PV panel is required to meet this demand efficiently. A 30-kWh battery is installed as an energy storage unit for excess production. The results came from a TRNSYS simulation. Simulation shows that the system performance is satisfied according to design parameters. The resulting data show that a prosumer house can save 295.6 $ in annual electricity bills and sell surplus energy to the neighboring consumer or grid with 211 $ annual income.

Energy trade with blockchain technology is considered a suitable option, making a more economical microgrid system for abandoned areas. This study provides the starting point of a real-time framework of energy trade between two rural houses connected with a common microgrid. Even though in this study, blockchain is not implemented pragmatically to analyze the behavior of prosumer and consumer, two identical building case is technically tested. Simulation results for this case show that neighboring prosumers also easily cover more than half the demand for a second house. Selling electricity to nearby consumers is more profitable for both the prosumer and the grid.

The study paves a path toward sustainable development and outlines the potential significance of energy trading mechanisms that help build a sustainable environment through a circular economy to empower consumers and prosumers. Simulation results are provided to emphasize the implementation of local energy generation and energy trading at the household level to achieve dual benefits. This study highlights the huge scope for developers to explore this research domain. Consideration of energy trading mechanisms and the power consumption of multiple buildings, including heating and cooling demand, could be a future study.

Funding

The research is part of the Ph.D. study supported by TEMPUS in the frame of Stipendium Hungaricum.

CRediT authorship contribution statement

Aqsa Rana: Conceptualization, Supervision, Writing – review &

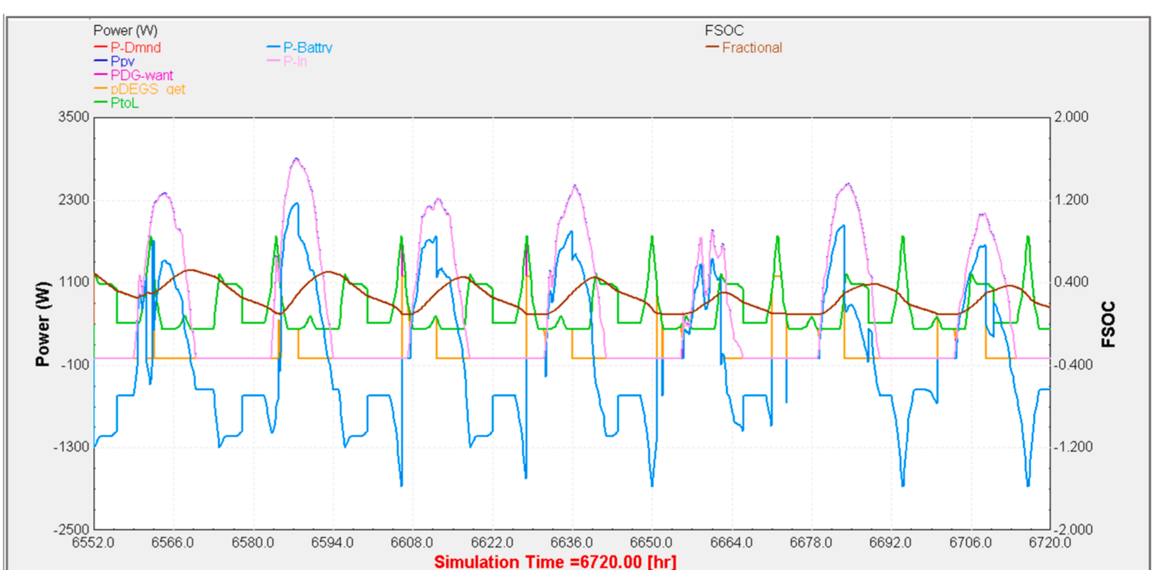

Fig. 8. Power state Oct1–8 (Two houses).

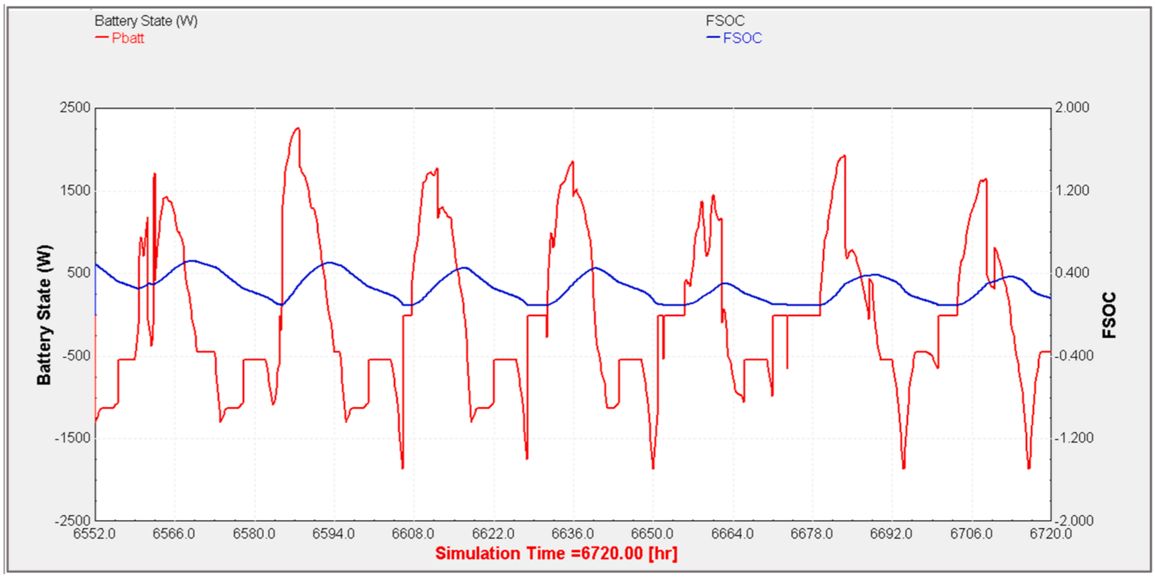

Fig. 9. Battery state Oct1–8 (Two houses).

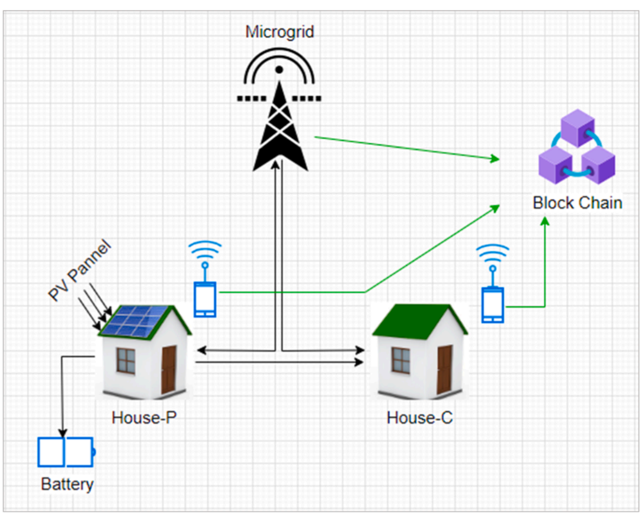

Fig. 10. Two Houses layout with blockchain.

editing. **Gyula Gróf:** Visualization, Methodology, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data sources are mentioned accordingly, and all definite sources are also listed in the references.

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