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RESEARCH ARTICLE

P2P Energy Trading: An Optimal Solution for Energy Shortage in Pakistan

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ABSTRACT Green energy can help in protecting the environment. Moreover, its continuous supply increases the quality of life and indeed the economic development of a country. The power sector in Pakistan is continuously under stress due to the imbalance between the demand and supply of energy. Pakistan has abundant renewable energy resources, i.e., solar, hydro, wind, etc., which are the main elements of green energy. This study first evaluates the existing power sector in Pakistan. Then, we proposed a peer-to-peer energy trading framework that helps in reducing the stress on the power sector in Pakistan by meeting the local energy demands of the consumers with the help of local energy generation. In the proposed peer-to-peer energy trading market, a novel method for determining the uniform energy trading price is proposed. This proposed pricing method increases the utilities of the market participants i.e., saving in energy bills for consumers and profitability for the sellers. The proposed study assumes that solar energy is provided from the energy producer side. Solar energy penetration on various ratios starting from 14% to 35% is tested on environment and consumer satisfaction levels. We conducted comprehensive experiments to validate the proposed method and the results suggest that a 35% penetration of solar in each subdivision can be helpful to decrease the current stress on Pakistans' power sector. Furthermore, it also helps in reducing the carbon emission footprint.

INDEX TERMS Energy trading, transmission and distribution losses, energy shortage, solar energy.

I. INTRODUCTION

The availability of energy is correlated with rising GDP and also helps to enhance the quality of life [1]. Meanwhile, Pakistan is suffering from a severe shortage of energy due to failure to meet the growing demand from an increasing population and the development of industries and agriculture [2]. To overcome this energy shortage, several reforms were made in the late 90s to develop a stable energy system that ensures reliable access to energy. These reforms involved structural transformations, organizational innovations, and regulatory developments [3]. Under structural transformation, a state-owned enterprise became vertically unbundled, resulting in the transfer of business structures, i.e., the change from a monopoly system to a single buyer model.

In contrast, organizational innovations led to the creation of administrative institutions such as market operators and regulators [4]. Despite all these struggles and reforms, the energy sector in Pakistan is still under stress. According to the World Bank reports, Pakistan is still facing an energy shortage [5]. For this reason, urban domestic consumers have to face an energy outage(Load shedding) ranging from 8 to 12 hours on a daily basis [5], [6]. The problem of energy shortage in Pakistan is more devastating in rural areas where people face energy outages for about 15 to 16 hours per day [7].

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TABLE 1. Nomenclature.

P_i	Energy Producer i	LESCO	Lahore electric supply company
GENCO	Generation companies	DISCO	Distribution companies
WAPDA	Water and power development authority	m_i	Circle
SD	Sub-division	M	Energy market
D	Division	NTDC	National transmission and dispatch company
C_i	Consumer i	NEPRA	National electric power regulatory authority
ζ	Need for energy factor	TP	Trading price
P2P	Peer-to-peer	T_{poff}	Offered trading price
SL	Satisfaction level	H	Annual solar radiation
A	Solar panel area	r	Solar panel efficiency
E_{dem}	Energy demand of a consumer	E_{sur}	Surplus Energy of a producer
δ	Transmission and distribution losses	PR	Performance ratio
AQI	Air quality index		

This massive energy shortage results in increasing tariffs, increase in circular debt and deterioration of the quality of life [8], [9]. Besides these effects, it also severely affects the overall performance of the energy sector and creates an alarming situation for economic growth [10], [11]. The consequences of the upsurge of energy shortages have been immense for industrial, retail, and agricultural consumers. The economy of Pakistan has been virtually paralyzed. Only in the textile sector, about 40% of its manufacturing jobs have been badly affected [12].

Various factors such as inappropriate planning, obsolete power plants with inefficient transmission systems, and poor governance are some of the leading causes behind the collapse of Pakistan's energy sector [13], [14], [15]. Besides these factors, political influence, instability, and absence of substantial investments create a lot of hindrance in deploying the hydro projects and increase reliance on the other expensive sources of energy such as imported fuels and natural gas reserves which are also one of the root cause for this energy crisis and increase in energy tariff [16], [17]. The high dependability on fuels and natural gas combustion for the generation of energy also creates many problems with health issues and increases the pollution level in Pakistan. According, to the Air quality index(AQI), Pakistan is the fifth most polluted country globally with an annual PM2.5 average of $74.3\mu g/m^3$ [18]. Moreover, according to the World Bank report, the current utilization ratio of fuel and natural gas reservoirs in the generation of energy will lead to the elimination of these reservoirs by the end of the year 2025 and By the year 2030, Pakistan will run out of natural gas [5]. Moreover, deviant activities such as bribes, corruption, and bureaucratic influence cannot be ignored in the delay or energy crisis [19]. These activities also lead to the result of a poor rate of energy bill recovery [20].

Public awareness is very critical in energy conservation, and sometimes the incentives found will contribute to the effective management of existing resources [21]. National Electric Power Regulatory Authority (NEPRA) also proposed reforms to support public awareness policies such as Net metering, financial incentives, and carbon pricing [22]. Under the proposed net metering policy of NEPRA, an energy consumer is encouraged to generate his energy by employing renewable energy resources and can sell it to the national grid under the mutual agreement and thereby offering them a seamless energy option to their consumers [23], [24]. Geographically Pakistan is abundant in distributed renewable energy resources, i.e., wind, and solar. Proper utilization of such resources can prove an excellent solution to overcome the current energy shortage in Pakistan.

Several studies have been carried out to analyze the energy crisis in Pakistan. The author in [25] estimates that the magnitude of the direct rebound will affect residential electricity consumption. In his proposed work, he used time-series data from the year 1973 to 2016. By deploying the co-integration econometric technique and error estimation, he found that the magnitude of the direct rebound effect is 69.5 percent in the long run, and 42.9 percent in the short run. However, his proposed work does not consider the transmission losses and installed system capacity. In [26] authors presented a detailed review of energy planning and policy formulation in Pakistan.

Zakaria and Noureen [27] used a long-range alternate energy planning model to analyze the structure of the electric power sector in Pakistan. In their proposed work, they used historical data for electricity demand and supply. Their results demonstrate that fuel cost is one of the most dominant factors that influence the overall cost. However, the proposed work was evaluated with the fixed-line loss rate. Another study using stochastic frontier to analyze the cost-effectiveness of energy distribution utilities in Pakistan has been found in [28]. This proposed study evaluated eight distribution utilities having data for the year 2003-2013. The result of this study reveals that distribution companies are 27.5% cost-inefficient. Moreover, studies found in [2], [3], [21], and [29] provide a general overview of the energy shortage in Pakistan. However, according to the authors' best knowledge, the effect of solar penetration and P2P energy trading is not addressed on Pakistans' premises.

Peer-to-Peer (P2P) energy trading is a new paradigm shift from unidirectional centralized to bi-directional decentralized energy trading markets [30], [31], [32], [33]. Several countries have deployed their pilot projects to transform their existing energy infrastructure [34], [35], [36], [37]. In the P2P energy trading markets, renewable energy sources are used as the main resources to generate green and healthy energy such as solar panels, wind turbines, etc., Renewable energy conversion through artificial photosynthesis has proved an environment-friendly route to harness green energy from sunlight. The processes to convert solar light into useful fuels comprised of photocatalysis, photovoltaic, etc., which rely on the utilization of semiconductors as active photocatalysts and sunlight absorbers for photovoltaic [38]. Photovoltaic devices as renewable alternatives are well explored and can be the best contenders in the energy marketplace. To date, several kinds are introduced and commercialized including amorphous and crystalline silicon (c-Si), a thin film based

(CdTe, CIGS, etc), dye-sensitized, and the latest evolution of perovskite solar cells. The current market is dominated by the c-Si solar cells due to their elongated lifetimes (25 years) but they are expensive as compared to other counterpart technologies [39]. Perovskite solar cells (PSCs) are cheaper as compared to the market occupier c-Si, and their power-per-weight ratios (PSC; 23WKg^{-1}) are far better than c-Si solar cells (0.1WKg^{-1}) [40]. Moreover, c-Si is very expensive as compared to perovskite semiconductors as the latter can be synthesized through a facile chemical process involving the alkali-metals such as cesium, lead, methylammonium, etc. In terms of power conversion efficiency, PSCs (25.7%) are comparable to c-Si (26.1%) but the long-term stability and lifetime of PSCs are just a few thousand hours, which are still under experimental investigations but are going to be commercialized in near future [41]. A series of optimizations are reported to enhance the PCE and stability of PSCs including the dopants, organic polymers as moisture resistant, and thin-layered organic interlayers to prevent intrinsic electrical losses such as hysteresis. The action of the organic moiety is always to address the ion migration from where the current-voltage (I-V) hysteresis usually arises. So, the progressive research to place PSCs near commercialization standards [42] is still underway, and PSCs would be the next photovoltaic market occupiers in near future.

In this context, this study is aimed to evaluate the effect of solar penetration in the East region of Pakistan. This study discusses the energy shortage and proposes a structured framework within the existing infrastructure for energy distribution among consumers. The proposed framework helps to reduce the effect of energy outages on consumers. Also, a uniform pricing method is proposed which increases the revenues of the energy sellers and reduces the energy bills for the consumers. The rest of this paper is organized as follows: Section 2 discusses the existing infrastructure. Section 3 presents the proposed energy trading and distribution infrastructure. In Section 4, the discussion is extended toward the energy market clearing mechanism. The results are discussed in Section 5, followed by a conclusion in Section 6.

II. EXISTING ENERGY INFRASTRUCTURE

The energy sector entities under the governance of the Government of Pakistan are encapsulated in Fig. 1 From this figure, it can be seen that Pakistan has four primary Public and Private energy producers, i.e., Water and Power Development Authority (WAPDA), Pakistan atomic energy commission, Independent Power Plants(IPPs), and Karachi Electric Supply Company (KESC). All energy generation companies (GENCO) utilize energy generation sources, i.e., water, fuel, natural gas, etc., to generate energy according to their installed and operating capacities. After energy generation, the National Transmission and Dispatch Company (NTDC) services are deployed to transmit it to the distribution companies (DISCO). Further distribution companies are responsible for transmitting and distributing the energy at the provincial, regional, and consumers' doorsteps.

TABLE 2. Category-wise number of consumers.

Year	Domestic	Commercial	Industrial	Agricultural	Public Lighting
2014	3052697	524702	75006	57313	2154
2015	3228511	542738	77277	58382	2227
2016	3403443	561030	79588	59136	2338
2017	3556800	576691	81640	59664	2424
2018	3848417	602268	84183	60621	2547

TABLE 3. Category-wise energy demand of consumers(MW).

Year	Domestic	Commercial	Industrial	Agricultural	Public Lighting
2014	4606.00	1420.00	3767.00	584.00	113.00
2015	4912.00	1482.00	3915.00	596.00	112.00
2016	5225.00	1558.00	4112.00	607.00	113.00
2017	5525.57	1638.61	4294.52	615.92	113.11
2018	6074.75	1735.78	4521.90	637.46	115.45

This study is limited to the eastern region of Pakistan which is served by LESCO. From now we only discuss the energy facts and figures related to the LESCO.

For the eastern region, Lahore Electric Supply Company (LESCO) is the leading energy supplier. It provides energy to Lahore, Kasur, Okara, Nankana, and Sheikhupura civil districts. This company was founded in 2001 after the vertical integration of the WAPDA scheme, previously known as the Lahore Area Electricity Board (AEB), and its distribution network consisted of sixty-eight 132-kV and fourteen 66-kV sub-stations. Presently, it has one hundred thirty-four 132-kV and seven 66-kV substations [43].

LESCO is divided into nine circles. Each circle is responsible for the transportation of energy to several divisions. Each division is further divided into subdivisions to distribute the energy to the consumers' doorstep. Fig. 2 presents the layout of the LESCO and its interconnected substations. LESCO distributes the consumers into different categories such as domestic, commercial, industrial, agricultural, and public lighting. According to the report [20], the number of consumers in each category is increasing every year. Table 2 presents the 5-year comparisons of category-wise increase in the number of consumers.

With the increasing number of consumers, the consumers' energy demand is also increased exponentially. Table 3 presents the category-wise demand of consumers.

To satisfy the energy demand of consumers, LESCO purchased energy units from several GENCO through NTDC. Table 4 presents the difference in units purchased by LESCO to the sold units along with percentage losses.

In Table 4 units sold column represented the number of units consumed by the consumers along with the lost units due to loss. However, the recovery of the energy bills consumed by the consumers also plays a vital role in the financial condition of LESCO. Energy theft and non-recoverable energy bills also deteriorate the financial condition of LESCO. According to the report [20], the average collection of energy bills by domestic consumers is 98.26% compared to 86.09% for agricultural consumers.

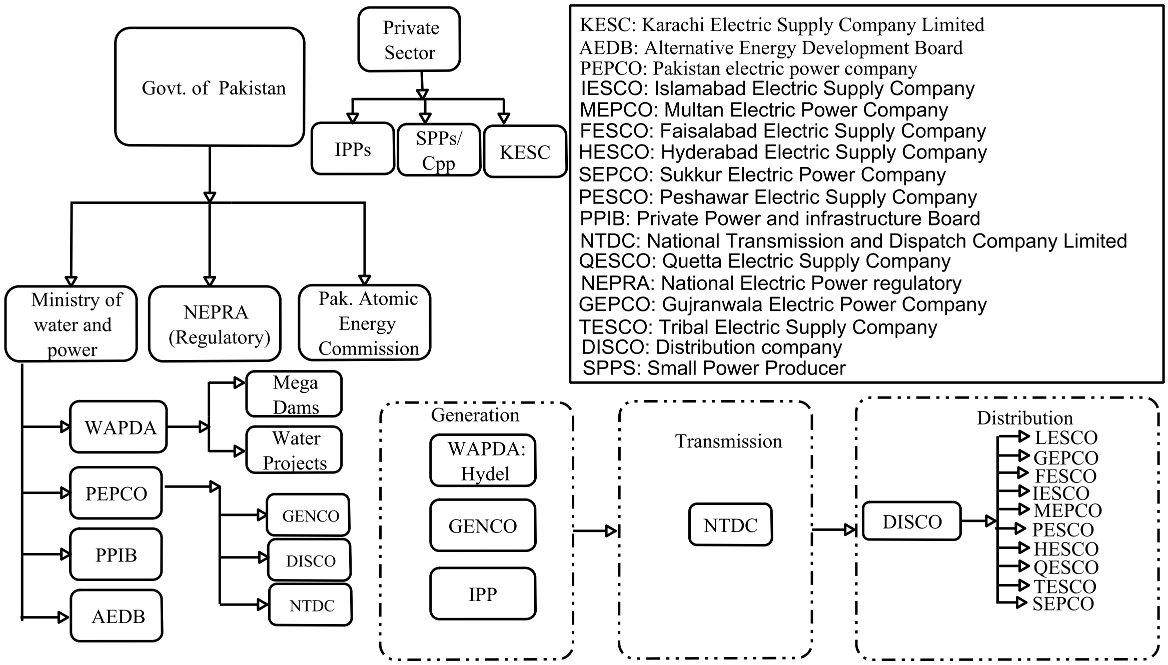

Govt. of Pakistan
Private Sector
IPPs
SPPs/ Cpp
KESC
KESC: Karachi Electric Supply Company Limited
AEDB: Alternative Energy Development Board
PEPCO: Pakistan electric power company
IESCO: Islamabad Electric Supply Company
MEPCO: Multan Electric Power Company
FESCO: Faisalabad Electric Supply Company
HESCO: Hyderabad Electric Supply Company
SEPCO: Sukkur Electric Power Company
PESCO: Peshawar Electric Supply Company
PPIB: Private Power and infrastructure Board
NTDC: National Transmission and Dispatch Company Limited
QESCO: Quetta Electric Supply Company
NEPRA: National Electric Power regulatory
GEPCO: Gujranwala Electric Power Company
TESCO: Tribal Electric Supply Company
DISCO: Distribution company
SPPS: Small Power Producer
Ministry of water and power
NEPRA (Regulatory)
Pak. Atomic Energy Commission
WAPDA
Mega Dams
Water Projects
PEPCO
GENCO
DISCO
NTDC
PPIB
AEDB
Generation
WAPDA: Hydel
GENCO
IPP
Transmission
NTDC
Distribution
DISCO
LESCO
GEPCO
FESCO
IESCO
MEPCO
PESCO
HESCO
QESCO
TESCO
SEPCO

FIGURE 1. Existing energy infrastructure.

TABLE 4. Units purchased sold summary.

Year	Units Pur-chased(GWh)	Units Sold(GWh)	Losses	
			GWh	%age
2013-14	18424.98	15948.29	2476.69	13.44
2014-15	19009.00	163828.36	2680.64	14.10
2015-16	20151.92	17341.98	2809.94	13.94
2016-17	20621.54	17782.81	2838.73	13.77
2017-18	23731.24	20448.50	3282.74	13.83

TABLE 5. Transmission and distribution losses.

Year	No. of complaints	Losses	
		Allowed%	Actual%
2013-14	25,504	9.01%	13.40%
2014-15	8,363	11.75%	14.10%
2015-16	17,631	11.76%	13.94%
2016-17	10,887	11.76%	13.77%
2017-18	3,303	11.76%	13.83%

In contrast, the recovery ratio from the commercial and industrial consumers is 98.64% and 93.88% respectively. The overall percentage of recovery for the fiscal year 2016-17 was 99.20% this percentage dropped to 95.93% for the fiscal year 2017-18 due to energy theft cases.

Transmission and distribution losses in LESCO are also increasing every year, leading to complaints about the nominal voltage regulation. Table 5 presents the number of complaints along with percentage transmission and distribution losses over the five years from 2013 to 2018.

As described earlier in Section I, there are 8 to 12 hrs energy outages per day which deteriorates the quality of life. To manage the energy outage, each division cuts the energy supply in subdivisions according to the outage plan of the circles. However, to reduce the energy outage and support a green energy environment, LESCO introduces net metering. Under this concept, each consumer through renewable energy sources can generate their energy, and in the case of excess, they can inject energy into the system. To promote and facilitate this opportunity. LESCO reserves some capacity for net metering in some of its connected divisions [43].

Furthermore, each division also deploys the net metering paths with its connected subdivisions. Using these paths, each consumer in subdivisions generates their energy and injects the excess energy into the subdivisions. This energy is aggregated and distributed at the divisional level with the other subdivisions where it is needed. When subdivisions do not require energy, this energy is injected into the circle where other circles use it or injected into the national grid. The amount of energy injected by the consumers depends on the consumers who use renewable energy sources, i.e., solar, wind, biomass, etc. This is along with the line capacity available for net metering. Fig. 3 and Fig. 4 show the numbers of consumers in each subdivision along with the capacity available for net metering.

III. PROPOSED ENERGY INFRASTRUCTURE AND ITS MODELING

The proposed energy infrastructure is shown in the Fig. 5.

It can be seen that LESCO is considered an energy market M. This energy market M is segmented into several segments m_i such that $m_i \subseteq M$. A segment m_i can be referred to as a circle. A circle m_i is further divided into several divisions D_j such as $D_j \subseteq m_i$. Each division D_j is further divided into several subdivisions SD_k such that $SD_k \subseteq D_j$. There are several consumers C who demand energy in each subdivision, and there are several producers P who have the capacity and

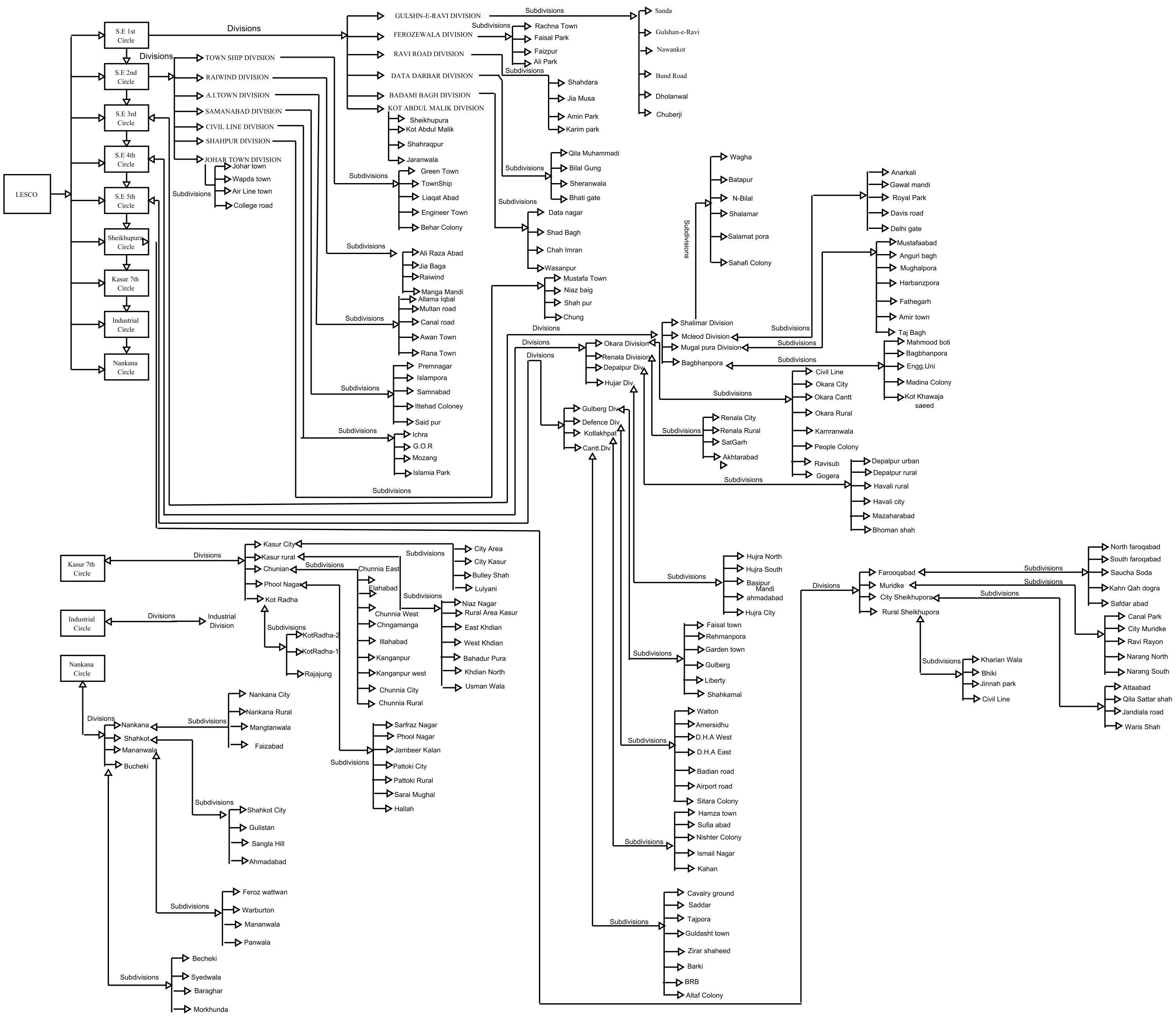

LESCO
S.E 1st Circle
S.E 2nd Circle
S.E 3rd Circle
S.E 4th Circle
S.E 5th Circle
Sheikhupura Circle
Kasur 7th Circle
Industrial Circle
Nankana Circle
Divisions
GULSHN-E-RAVI DIVISION
FEROZEWALA DIVISION
RAVI ROAD DIVISION
DATA DARBAR DIVISION
BADAMI BAGH DIVISION
KOT ABDUL MALIK DIVISION
Sheikhupura
Kot Abdul Malik
Shahraqpur
Jaranwala
Subdivisions
Sanda
Gulshan-e-Ravi
Nawankot
Bund Road
Dholanwal
Chuberji
Rachna Town
Faisal Park
Faizpur
Ali Park
Shahdara
Jia Musa
Amin Park
Karim park
TOWN SHIP DIVISION
RAIWIND DIVISION
A.I.TOWN DIVISION
SAMANABAD DIVISION
CIVIL LINE DIVISION
SHAHPUR DIVISION
JOHAR TOWN DIVISION
Johar town
Wapda town
Air Line town
College road
Green Town
TownShip
Liaqat Abad
Engineer Town
Behar Colony
Qila Muhammadi
Bilal Gung
Sheranwala
Bhati gate
Data nagar
Shad Bagh
Chah Imran
Wasanpur
Mustafa Town
Niaz baig
Shah pur
Chung
Ali Raza Abad
Jia Baga
Raiwind
Manga Mandi
Allama Iqbal
Multan road
Canal road
Awan Town
Rana Town
Premnagar
Islampora
Samnabad
Ittehad Coloney
Said pur
Ichra
G.O.R
Mozang
Islamia Park
Wagha
Batapur
N-Bilal
Shalamar
Salamat pora
Sahafi Colony
Anarkali
Gawal mandi
Royal Park
Davis road
Delhi gate
Mustafaabad
Anguri bagh
Mughalpora
Harbanzpora
Fathegarh
Amir town
Taj Bagh
Mahmood boti
Bagbhanpora
Engg.Uni
Madina Colony
Kot Khawaja saeed
Shalimar Division
Mcleod Division
Mugal pura Division
Bagbhanpora
Okara Division
Renala Division
Depalpur Div
Hujar Div
Civil Line
Okara City
Okara Cantt
Okara Rural
Kamranwala
People Colony
Ravisub
Gogera
Renala City
Renala Rural
SatGarh
Akhtarabad
Depalpur urban
Depalpur rural
Havali rural
Havali city
Mazaharabad
Bhoman shah
Gulberg Div
Defence Div
Kotlakhpat
Cantt.Div
Hujra North
Hujra South
Basipur Mandi
ahmadabad
Hujra City
Faisal town
Rehmanpora
Garden town
Gulberg
Liberty
Shahkamal
Walton
Amersidhu
D.H.A West
D.H.A East
Badian road
Airport road
Sitara Colony
Hamza town
Sufia abad
Nishter Colony
Ismail Nagar
Kahan
Cavalry ground
Saddar
Tajpora
Guldasht town
Zirar shaheed
Barki
BRB
Altaf Colony
Farooqabad
Muridke
City Sheikhupora
Rural Sheikhupora
North faroqabad
South faroqabad
Saucha Soda
Kahn Qah dogra
Safdar abad
Canal Park
City Muridke
Ravi Rayon
Narang North
Narang South
Attaabad
Qila Sattar shah
Jandiala road
Waris Shah
Kharian Wala
Bhiki
Jinnah park
Civil Line
Kasur 7th Circle
Kasur City
Kasur rural
Chunian
Phool Nagar
Kot Radha
City Area
City Kasur
Bulley Shah
Lulyani
Chunnia East
Elahabad
Chunnia West
Chngamanga
Illahabad
Kanganpur
Kanganpur west
Chunnia City
Chunnia Rural
Niaz Nagar
Rural Area Kasur
East Khdian
West Khdian
Bahadur Pura
Khdian North
Usman Wala
KotRadha-2
KotRadha-1
Rajajung
Sarfraz Nagar
Phool Nagar
Jambeer Kalan
Pattoki City
Pattoki Rural
Sarai Mughal
Hallah
Industrial Circle
Industrial Division
Nankana Circle
Nankana
Shahkot
Mananwala
Bucheki
Nankana City
Nankana Rural
Mangtanwala
Faizabad
Shahkot City
Gulistan
Sangla Hill
Ahmadabad
Feroz wattwan
Warburton
Mananwala
Panwala
Becheki
Syedwala
Baraghar
Morkhunda

FIGURE 2. LESCO archirecture.

installed infrastructure for the generation of energy using renewable energy sources, i.e., solar and wind.

From the above information, the general mathematical formulation of LESCO can be represented as:

$$LESCO = \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\left(m_i + D_j + SD_k\right) \tag{1}$$

The proposed system assumes that in each subdivision SD_k, there is a sub-divisional coordinator, a virtual system. The energy consumers and producers can interact with each other through the sub-divisional coordinator. The main objective of the sub-divisional coordinator is to handle and monitor the energy trading activities inside the subdivision only. Energy trading activities of the sub-divisional coordinator include keeping a record of the energy demand requested by the consumers and energy supply by the producers. One more key responsibility of the sub-divisional coordinator includes determining the participants' energy trading price and making sure the accessibility of the energy according to his decision in the case when there is no energy availability from the grid. However, in the case of grid availability, the sub-divisional coordinator makes sure that energy supplied by the energy producers can be traded with the other peer subdivisions.

To avail this opportunity, each energy consumer or producer first registers him/herself in the sub-divisional system. For registration as an energy consumer, a consumer C_i should submit the required information, i.e., name, address, balance of energy tokens in their wallet, to the sub-divisional coordinator. When registering as an energy producer names and addresses are proposed. Energy token is just like a virtual currency that can be purchased from sub-divisional offices after making payments. One energy token is used for one-kWh energy trading.

Smart meter technology is an efficient way to keep a record of energy demand and energy supplied by the participants [44], [45]. Therefore, in the proposed system, it is assumed that both energy consumers and producers will have smart meters at their premises. At any time t an energy consumer C_i is supposed to submit the information about his demand E_{dem}, whereas an energy producer P_i is supposed to submit the amount of energy E_{sur} he/she is willing to trade with others along with the offered price Tp_{off}.

Due to stochastic and seasonal variation of renewable energy sources, i.e., solar the supply capacity of energy producers is limited; it is impossible to meet all the consumers' energy demand (E_{dem}). To handle this challenge, the sub-divisional coordinator instructs the energy consumers to submit their demand and the need for energy factor ξ. This need for energy parameter ξ can vary ranging from 0 to 1. From the reported values of energy factor, ξ three types of energy users are identified by the sub-divisional coordinator as (i) Low demand consumers, (ii) Medium demand energy consumers, and (iii) High demand energy consumers. Based on the gathered information sub-divisional coordinator will determine the energy trading price *TP* which will be discussed briefly in Section IV-A and distribute the energy among the consumers.

Both energy consumers and producers under the proposed system use LESCO's infrastructure for the transmission and distribution of renewable energy. Therefore, each sub-divisional coordinator will impose some fee (ϕ) in terms of service charges for managing and transportation of energy. Half of this service fee ϕ applies to energy consumers and the other half is imposed on energy producers. However, rationality and false reporting about the demand of consumers cannot be ignored. Therefore, handling this challenge and restricting false reporting sub-divisional coordinator imposes some extra fee θ rather than the service charges on those energy consumers who report high energy factor ξ. By doing this, the proposed system reduces the effect of false reporting and treats everyone equally. The proposed system gives high preference to those energy consumers whose need for energy factor ξ is high. Giving preference to those consumers is based on the fact they are paying more than the other consumers, and it is most beneficial for the sub-divisional revenue gathering terms.

IV. MARKET CLEARING MECHANISM

Market clearing plays a significant role in the energy trading platform as it incentivizes the participants to participate in energy trading activities. Time of usage of energy also has a dominant effect on the market clearing mechanism. Many researchers proposed several methods to determine the market-clearing price, such as a mixed-integer-based linear method proposed in [47] to determine the market-clearing price. In [48] Benders-like decomposition method is proposed for determining the market-clearing signal. Bi-level modeling is used in [49] to determine the market-clearing signal. Competition is an effective way to increase the trust level in the energy trading platform and motivates the participants to participate in energy trading activities that have not been addressed in these studies.

Considering the effects of competition, several researchers used a double auction mechanism in their studies to find the pricing signal [50], [51], [52], [53]. In these studies, a producer offered price should be less than the grid selling price. Although it is an effective technique to increase consumers' savings because consumers' purchase prices will be less than the grid selling price. However, it is not always a good option for energy producers to offer their prices less than the grid selling prices. Especially in the case when there is an uninformed outage from grid supply. This situation creates an opportunity for energy producers to generate high revenue.

In this context, we proposed a novel method inspired by MinMax method [54] which incorporates the competition among the energy producers to select the market-clearing signal.

A. PROPOSED MARKET CLEARING MECHANISM

As stated in Section III, each producer will inform the sub-divisional coordinator about the amount of energy

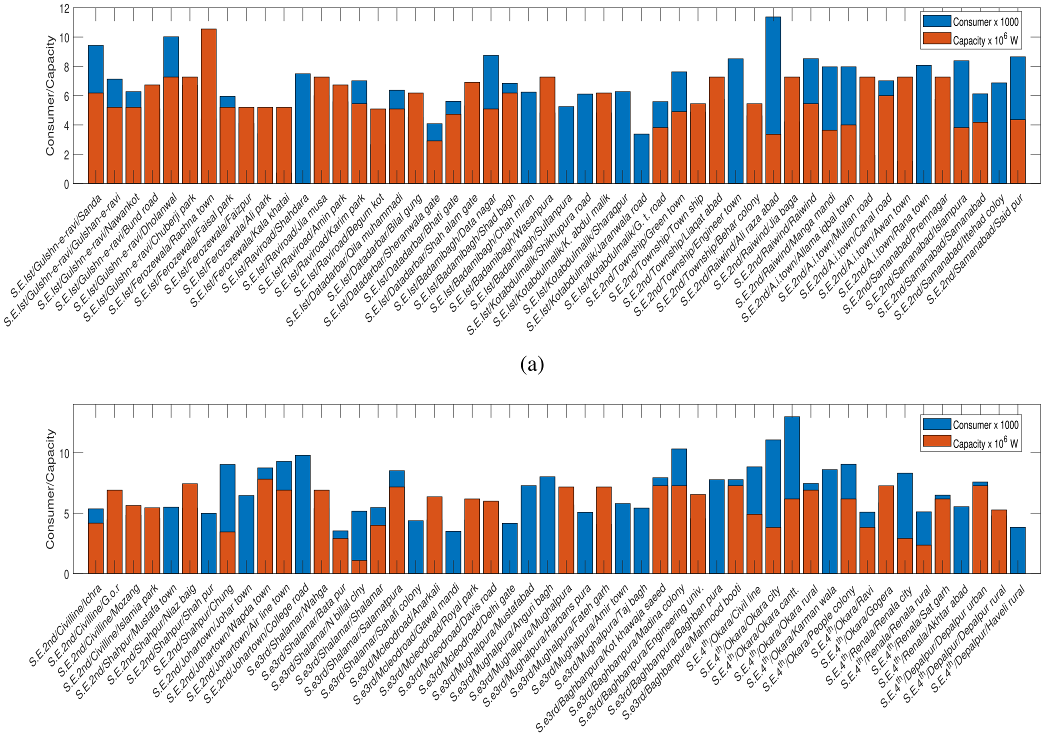


FIGURE 3. Number of consumers and capacity available for net-metering-1. The graph is split into two parts for better readability.

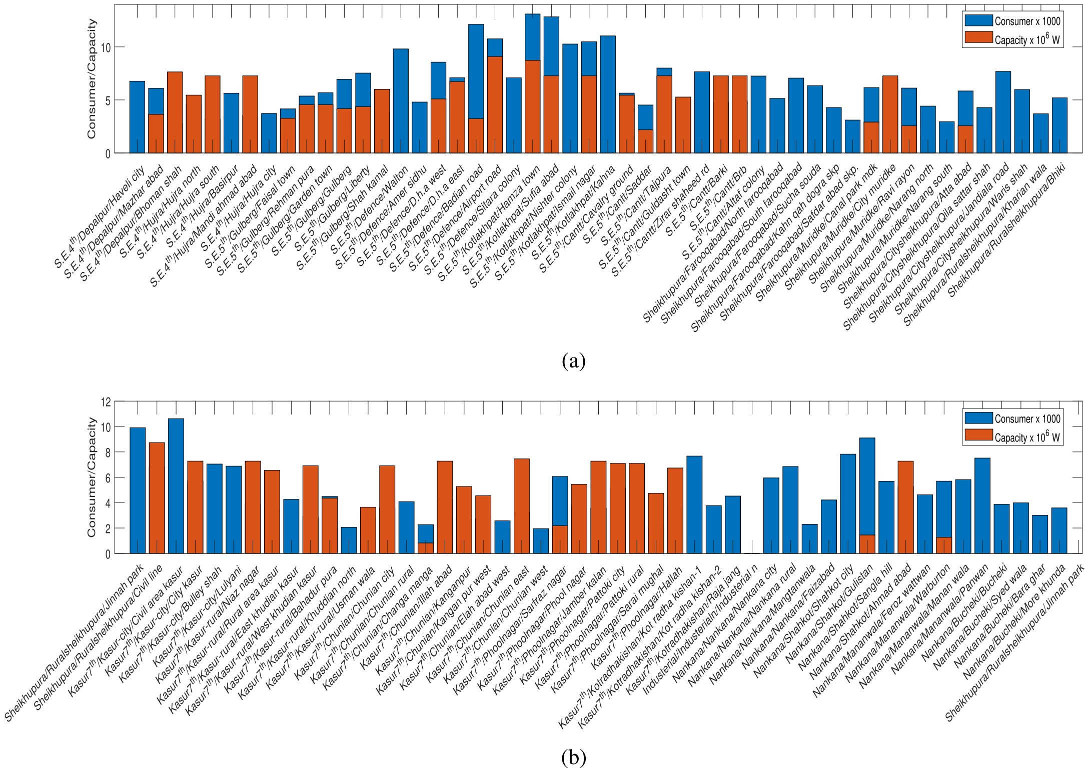


FIGURE 4. Number of consumers and capacity available for net-metering-2. The graph is split into two parts for better readability.

τ he is willing to trade with others along with the offered price Tp_{off}. Based on the amount of energy E_{sur} sub-divisional coordinator will make sets for the producers such as:

$$\begin{aligned} E_{sur} &= \{P_i, P_{i+1}, P_{i+2}, \ldots, P_{i=n}\} \\ Price &= \{Tp_i, Tp_{i+1}, Tp_{i+2}, \ldots, Tp_{i=n}\} \end{aligned} \tag{2}$$

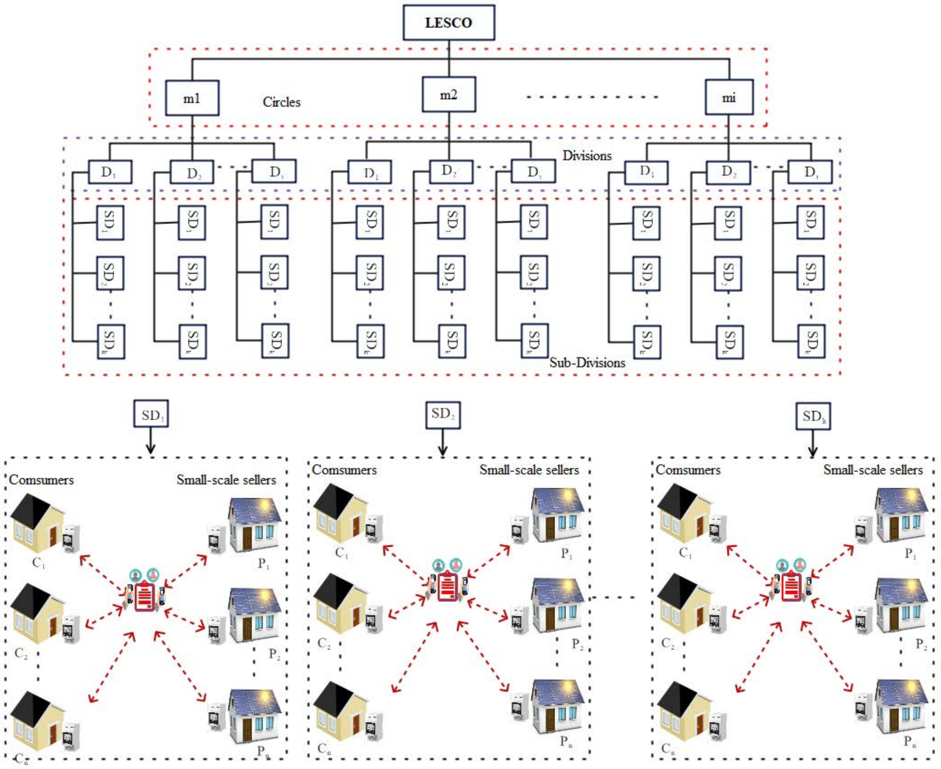


FIGURE 5. **Overview of the proposed model.**

where P_i represents a producer who contributes more energy compared to the others and TP_i is associated with his/her offered price. Similarly, each consumer also informs the sub-divisional coordinator about the energy factor ξ, which determines how much energy an energy consumer needs. At the time (t), when all consumers and producers submit this information to the sub-divisional coordinator need to find out the number of consumers who requested high energy levels among the available consumers. From the sub-divisional point of view, a consumer having high ξ has a strong energy demand; for this type of consumer price of energy does not matter. Such consumers' selection reflects that they put the high energy supply producers at the topmost front compared to the other producers who are offering low energy. Whereas a consumer having a small value for ξ is considered more sensitive to the price of energy. In such types of consumers, they give high preference to such producers who offered the lowest price among the others. In this manner, the sub-divisional coordinator computes the score for all energy producers.

Let us suppose that $SC(P_1, P_2)$ represents the pairwise score for producer P_1 against producer P_2 then the producer P_{win} is selected as the winner by the MinMax method given as:

$$P_{win} = \arg\min_{P_1}\left(\max_{P_2} SC(P_2, P_1)\right) \tag{3}$$

As the sub-divisional coordinator uses ranked pairs among the available producers, there are three variants: winning votes, Margin, and Pairwise opposition are used in the proposed method to determine the winner producer. Based on sub-divisional evaluation let $d(P_1, P_2)$ be the number of consumers who rank P_1 over P_2. These variants define the number score $SC(P_1, P_2)$ for energy producer P_1 against P_2 as:

$$SC(P_1, P_2) := \begin{cases} d(P_1, P_2), & d(P_1, P_2) > d(P_2, P_1) \\ 0 & \textit{otherwise} \end{cases} \tag{4}$$

Eq. (4) represents the number of consumers' preferences P_1 over P_2, in the case when the score increases the number of consumers who prefer P_2 over P_1. If not, then the score for P_1 against P_2 will be zero. This variant is known as winning votes.

$$SC(P_1, P_2) := d(P_1, P_2) - SC(P_2, P_1) \tag{5}$$

Eq. (5) is known as the margin variant which defines the number of consumers preferences P_1 above P_2 minus the number of consumers preferences P_2 over P_1.

Eq. (6) describes the third variant which is called pairwise opposition and it is defined as the number of consumers' preferences P_1 over P_2 regardless that more consumers prefer P_1 over P_2 or vice versa.

$$SC(P_1, P_2) := d(P_1, P_2) \tag{6}$$

In the proposed market clearing mechanism, a sub-divisional coordinator will select an energy producer P_i as a winner who satisfies either all three variants or at least two.

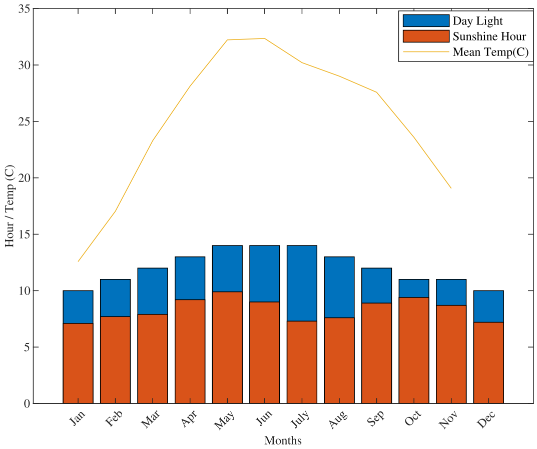


FIGURE 6. Lahore average temperature and sunlight duration.

V. PROPOSED SYSTEM OBJECTIVES

1) CONSUMERS' OBJECTIVES

Every consumer expects that there would not be an outage in the supplied energy so that he/she can run the daily routine life activities uniformly. Moreover, the energy price should be low so that he/she does not face any financial burden while using energy. However, in the case of limited energy supply and uninformed energy outages from the grid, it creates many problems to run their daily routine activities. In this case, the price of energy dominates over the availability of energy; hence consumers' first objective is to procure the energy on a prior basis when there is no energy supply from the grid. For this reason, a consumer has a higher price tolerance if the system ensures the supply of energy to them. If ω is the factor that measures the availability of energy to the consumers, then consumers' satisfaction level SL_{con} will be equal to 1 if $\omega = 1$ and will be 0 otherwise. From the consumers' perspective, the objective function of a consumer can be written as:

$$F_{con} = max(SL_{con}) \tag{7}$$

2) PRODUCERS' OBJECTIVES

Energy producers' are the entities that generate their energy using renewable energy sources. This produced energy is meant for their usage along with trading with others in the case of surplus. Suppose an energy producer generates an amount of E_{gen} by employing renewable sources, and $E_{selfcon}$ is the self-consumption of a producer. In that case, the surplus energy he/she can trade with others can be found as:

$$E_{sur} = E_{gen} - E_{selfcon} \tag{8}$$

While trading this surplus energy, a producer prefers to sell it at a high price to increase his/her revenue. In terms of revenue, the objective function of an energy producer can be expressed as:

$$F_{Pro} = max(Revenue) \tag{9}$$

TABLE 6. LESCO 1st circle attributes.

Division	Sub-division	Consumers#	Net Metering capacity (MWh)	Line losses(%)
Gulshan-ravi	Sanda	9428	6.18	14.43
Gulshan-ravi	Gulshan	7128	5.2	14.43
Gulshan-ravi	Nawankot	6257	5.2	14.43
Gulshan-ravi	Bund Road	5097	6.73	14.43
Gulshan-ravi	Dholanwal	10019	7.27	14.43
Gulshan-ravi	Chuberji	6712	7.27	14.43
Ferozewala	Rachana	4413	10.55	22.03
Ferozewala	Faisal park	5951	5.22	22.03
Ferozewala	Faizpur	4104	5.22	22.03
Ferozewala	Ali park	3403	5.22	22.03
Ravi Road	Shahdra	7493	6.2	14.19
Ravi Road	Jia Musa	6000	7.27	14.19
Ravi Road	Amin park	5584	6.73	14.19
Ravi Road	Karim park	2659	6.2	14.19
Data Darbar	Qila M.	6373	5.09	14.19
Data Darbar	Bilalgung	5415	6.18	14.19
Data Darbar	Sheranwala	4084	2.91	14.19
Data Darbar	Bhatigate	5615	4.73	14.19
Badamibagh	Data nagar	8747	5.09	9.18
Badamibagh	Shadbagh	6840	6.18	9.18
Badamibagh	Chahimran	6241	N.A	9.18
Badamibagh	Wasanpur	4823	7.27	9.18
Kot Abdul	Sheikhupora	6108	N.A	15.93
Kot Abdul	K.Abdul	4826	6.18	15.93
Kot Abdul	Sharqpur	6276	N.A	15.93
Kot Abdul	Jaranwala	3376	N.A	15.93

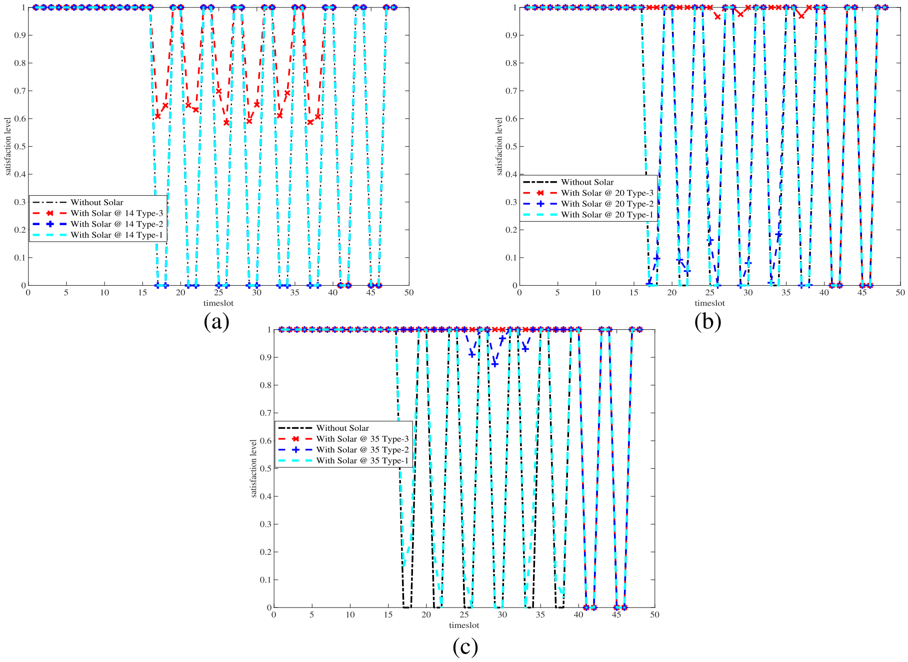
TABLE 7. Determining the winner producer.

		A		
		Type-1	Type-2	Type-3
B	Type-1	-	A=[66.66%] B=[33.33%]	A=[33.33%] B=[66.66%]
	Type-2	A=[33.33%] B=[66.66%]	-	A=[33.33%] B=[66.66%]
	Type-3	A=[66.66%] B=[33.33%]	A=[66.66%] B=[33.33%]	-
Pair wise score (W-T-L)		0-0-2	2-0-0	0-0-2
Pair wise defect		50%	0%	50%
Margin		50%	0%	50%
Worse pair opposition		50%	0%	50%

To achieve high revenue, the amount of energy a producer can produce plays a significant role. In the proposed study, we only consider that the producer uses a solar panel on their rooftop to generate clean energy. In the production of solar energy, the environment also plays an important role.

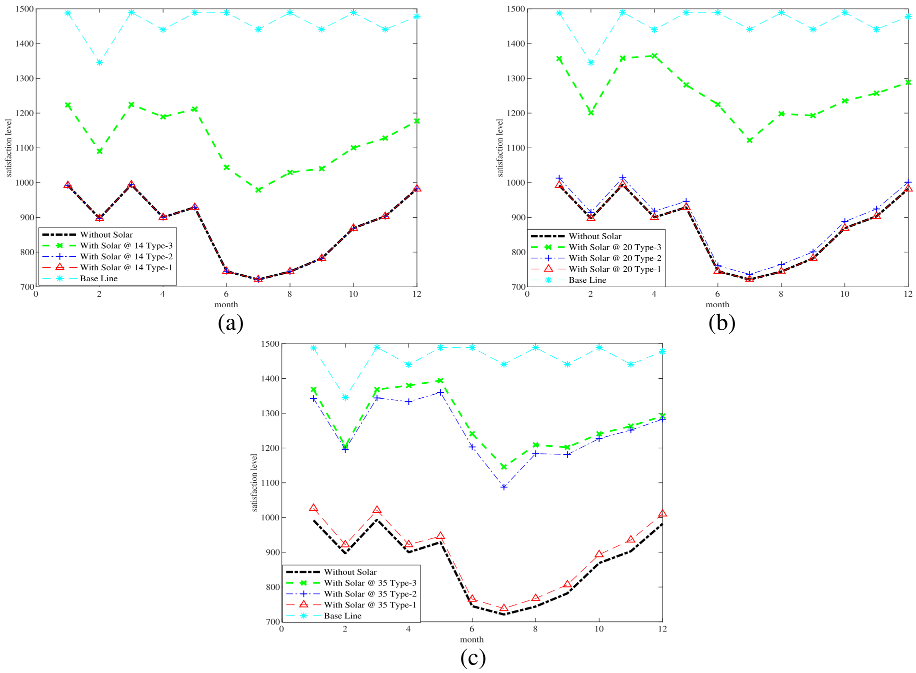
The proposed study is on the premises of the East region of Pakistan called Lahore. This region is one of the most feasible places in Pakistan for deploying solar panels due to its workable temperature range and sunlight duration. Based on the data gathered from [46] Fig. 6 shows the average temperature range along with the sunlight duration throughout the year 2018.

Besides the weather condition, the installed system capacity and its associated losses are essential factors for determining the accurate estimation of the generated solar energy.



(a) (b) (c)

FIGURE 7. Consumers'satisfaction for one-day Data nagar.



(a) (b) (c)

FIGURE 8. Consumers'satisfaction for one-year Data nagar.

For assessment of the generated solar energy, the proposed method uses the following equation for solar energy generation given as:

$$E_{Estimated} = A \times r \times H \times PR \tag{10}$$

where A represents the total solar panel area measured in (m^2), r is the solar panel efficiency, H is the annual solar radiation, and PR is the performance ratio. To achieve a more accurate estimation of solar energy, inverter losses, temperature losses, DC and AC wire losses are also considered.

3) SUB-DIVISIONAL COORDINATORS' OBJECTIVES

In the proposed system, the objectives of the sub-divisional coordinator include energy trading among the participants keeping in view the existing power system reliability and efficiency. If E_{dem} and E_{sur} are the total demand requested

TABLE 8. Data nagar solar penetration effect.

Month		Satisfaction			Without solar	Base line	% change w.r.t without solar			$\%age$ change w.r.t base line		
		@14%	@20%	@35%			@14	@20	@35	@14	@20	@35
1	Type-1	992	992	1026.794	992	1488	0	0	3.50	-33.33	-33.33	-30.99
	Type-2	992	1012.949	1342.538	992	1488	0	2.11	35.33	-33.33	-31.92	-9.77
	Type-3	1223.42	1356.848	1368.597	992	1488	23.33	36.77	37.96	-17.77	-8.81	-8.02
2	Type-1	897	897	921.7646	897	1345	0	0	2.75	-33.30	-33.30	-31.46
	Type-2	897	914.5386	1195.635	897	1345	0	1.95	33.29	-33.30	-32	-11.10
	Type-3	1089.933	1200.965	1205	897	1345	21.50	33.88	34.33	-18.96	-10.70	-10.40
3	Type-1	994	994	1020.903	994	1490	0	0	2.70	-33.28	-33.28	-31.48
	Type-2	994	1013.996	1344.114	994	1490	0	2.01	35.22	-33.28	-31.94	-9.79
	Type-3	1224.721	1358.132	1368.3	994	1490	23.21	36.63	37.65	-17.80	-8.85	-8.16
4	Type-1	900	900	922.115	900	1440	0	0	2.45	-37.5	-37.5	-35.96
	Type-2	900	918.0085	1333.297	900	1440	0	2.0	48.14	-37.5	-36.24	-7.40
	Type-3	1185.201	1361.807	1380	900	1440	31.68	51.31	53.33	-17.69	-5.43	-4.16
5	Type-1	929	929	949.1377	929	1489	0	0	2.16	-37.60	-37.60	-36.25
	Type-2	929	946.1383	1359.917	929	1489	0	1.84	46.38	-37.60	-36.45	-8.66
	Type-3	1211.501	1381.072	1394	929	1489	30.40	48.66	50.05	-18.63	-7.24	-6.38
6	Type-1	744	744	765.1514	744	1489	0	0	2.84	-49.96	-49.96	-48.61
	Type-2	744	760.7264	1203.021	744	1489	0	2.24	61.69	-49.96	-48.91	-19.20
	Type-3	1043.665	1225.132	1241	744	1489	40.27	64.66	66.80	-29.90	-17.72	-16.65
7	Type-1	720	720	738.3239	720	1441	0	0	2.54	-49.96	-49.96	-48.76
	Type-2	720	736.0578	1087.478	720	1441	0	2.23	51.03	-49.96	-48.96	-24.53
	Type-3	978.952	1121.772	1145.618	720	1441	35.96	55.80	59.11	-32.06	-22.15	-20.49
8	Type-1	745	745	767.2664	745	1489	0	0	2.98	-50.03	-50.03	-48.47
	Type-2	744	764.2124	1183.889	745	1489	0	2.57	58.91	-50.03	-48.67	-20.67
	Type-3	1029.31	1198.148	1209	745	1489	38.16	60.82	62.28	-30.87	-19.53	-18.80
9	Type-1	783	783	806.8054	783	1441	0	0	3.04	-45.73	-45.73	-44.01
	Type-2	783	800.6833	1181.234	783	1441	0	2.25	50.86	-45.73	-44.43	-18.02
	Type-3	1040.172	1192.799	1202	783	1441	32.84	52.33	53.51	-27.81	-17.22	-16.58
10	Type-1	869	869	893.361	869	1489	0	0	2.80	-41.63	-41.63	-40.00
	Type-2	869	887.9096	1227.119	869	1489	0	2.17	41.21	-41.63	-40.36	-17.58
	Type-3	1100.266	1235.117	1241	869	1489	26.61	42.13	42.80	-26.10	-17.05	-16.65
11	Type-1	903	903	935.5109	903	1441	0	0	3.60	-37.33	-37.33	-35.07
	Type-2	903	924.2539	1251.675	903	1441	0	2.35	38.61	-37.33	-35.86	-13.13
	Type-3	1128.114	1257.071	1263	903	1441	24.92	39.21	39.86	-21.71	-12.76	-12.35
12	Type-1	982	982	1010.417	982	1478	0	0	2.89	-33.55	-33.55	-31.63
	Type-2	982	1001.358	1282.901	982	1478	0	1.97	30.64	-33.55	-32.24	-13.20
	Type-3	1177.259	1288.38	1292	982	1478	19.88	31.19	31.56	-20.34	-12.82	-12.58

by the consumers and total energy supplied by the producers respectively, then the power balance equation can be written as:

$$F = E_{dem} - (E_{sur} - \Delta) \tag{11}$$

where Δ represents the transmission and distribution losses. At the time (t) after gathering the information about the consumers' energy factor ξ and producers' injected energy E_{sur} sub-divisional coordinator first determines the market clearing signal TP as described in Section IV-A. At any time interval, t the positive value of Eq. (11) represents the case when there is excess in demand, and less supply is available. In such a case, when the market-clearing signal is less than the grid selling price, then the sub-divisional coordinator will distribute the energy demand among the consumers so that their energy bills can be reduced. The difference in energy will be imported from the grid so that consumers' satisfaction level which is measured in terms of the availability of energy in the proposed study, can be maximized. The objective function of the sub-divisional coordinator can be expressed as:

$$\begin{aligned} Y = max(\sum_{i=1}^{n} SL_{con_i}) \\ s.t\ E_{supplied} = E_{supplied_{P1}} + E_{supplied_{P2}} \\ + E_{supplied_{P3}} + \ldots + E_{supplied_{Pn}} = 0 \end{aligned} \tag{12}$$

However, when the market-clearing signal value is higher than the grid selling price and grid supply is also available, the sub-divisional coordinator will make sure that the offered energy will be traded with his peer sub-divisional coordinator or injected into his division. In this case, if grid energy is not available sub-divisional coordinator will distribute the offered energy to their energy consumers to maintain the power balance equation Eq. (11). In the case when the local sub-divisional generated energy is insufficient to meet the energy demand sub-divisional coordinator will import the energy from his peer sub-divisional coordinator to maintain the power balance in Eq. (11) or try to keep the minimum difference between the demand requested by energy consumers and their supplied energy. In limited energy availability, a sub-divisional coordinator will first distribute the energy to the high energy demand consumers before filling the others.

VI. DISCUSSION OF THE RESULTS AND SUGGESTION

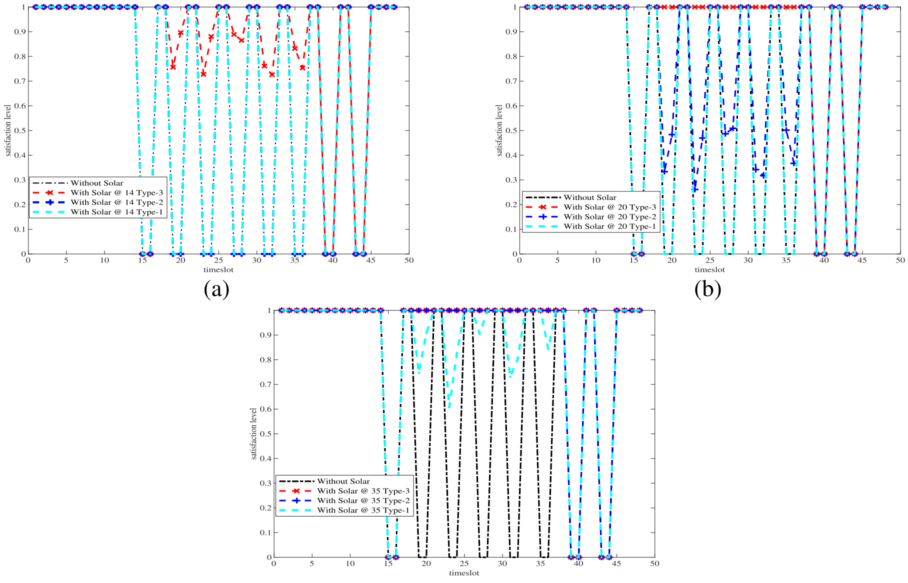
In this section, we present the results of the proposed model and provide suggestions. For this purpose, we used the eastern city of Pakistan, i.e., Lahore, where LESCO operates as DISCO. LESCO is divided into nine circles having thirty-nine total divisions and each division having multiple sub-divisions. This proposed model is evaluated on the Lahore 1st circle which is divided into six divisions and twenty-six subdivisions. The data includes energy consumers' demand, the number of consumers, the capacity of the net metering path, transmission , and distribution losses in each subdivision taken from LESCO officials and NTDC websites. The temperature data used to calculate solar energy generation is obtained from Climate Change Knowledge Portal [46]. The CO_2 emission values produced by the coal and natural gas-driven power plants are used as 0.55kg per kWh [57].

For energy demand data, we equally distribute the total population in a subdivision into three types to classify energy consumers. From this, we get three types of energy consumers (i) Low energy demand consumers having demand from ($2.5kWh$ to $\leq 3kWh$) (ii) medium energy demand consumers ($3kWh$ to $\leq 4kWh$) and (iii) high energy demand consumers ($demand \geq 4kWh$). Losses that have been considered in this work such as Ac and Dc cable losses, inverter losses, and temperature losses are selected according to the guidelines provides in [55], [58], and [59]. The effect of temperature on solar energy generation is taken from [59]. The efficiency of the inverters is assumed to be 95%. For the sake of simplicity, we assumed that the low energy demand consumers have a low energy factor $0 \leq \xi \leq 0.4$. Energy need factor for medium energy users varies from $0.4 \leq \xi \leq 0.7$ and the value of ξ varies from $0.7 \leq \xi \leq 1$ for high energy demand consumers.

For solar generation, we first take 14% of the population in a subdivision and divide the energy producers into three types (i) Low-level energy producers who use solar panels of capacity $3.3kWh$ (ii) Medium-level energy producers who use a solar panel of capacity $5kWh$ and (iii) High-level energy producers who use a solar panel of capacity $7kWh$ then we increase the solar penetration up to 20% and 35% of the population size in the subdivision. Furthermore, in the proposed work, we do not consider the effect of storage elements, i.e., batteries. This selection is made intentionally as the authors assumed that setup required with storage elements is expensive due to battery cost, and battery degradation cost and also has a very long payback period [56]. The consumers' energy demand and producers' solar-generated energy are sampled over a 30-minute time interval for a year.

Grid selling price is considered as $4¢/kWh$. Service charges for all types of consumers are considered as $1¢/kWh$ and additional charges imposed only on high energy demand, and medium energy demand consumers are $2¢/kWh$ and $1¢/kWh$ respectively. The proposed model is evaluated by measuring the consumers' satisfaction level, which increases with the availability of energy supply in the case when grid supply is not present. For this purpose, we first considered the solar penetration of about 14% of the total population in a subdivision and discussed the total percentage utilization of the net metering path capacity. Then solar penetration level is increased from 14% to 20% and 35%, and with this increase, some suggestions will be provided in the context of a recommended net metering capacity path by evaluating the consumers' satisfaction level. Table 6 presents the LESCO 1st circle facts and figures about the number of consumers, available capacity for net metering, along with line losses.

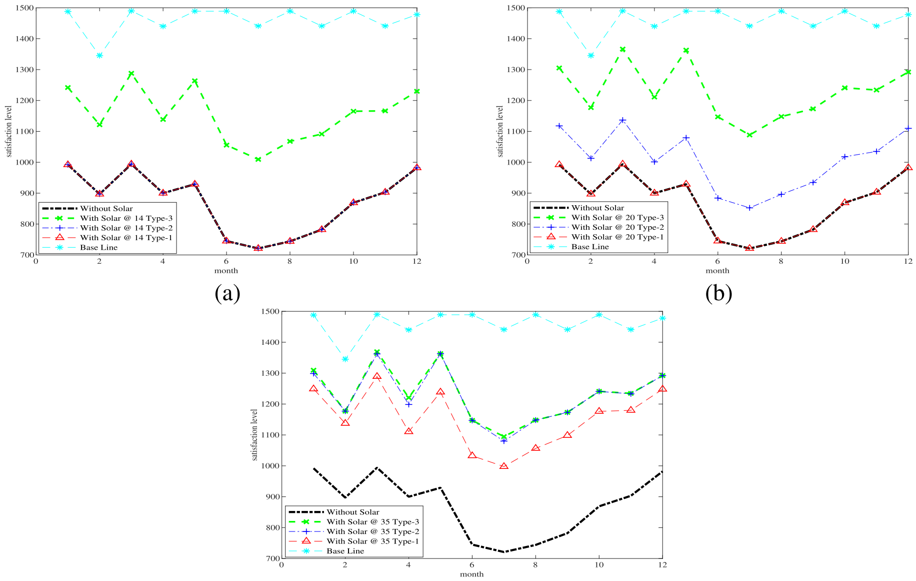
From Table 6, it can be seen that some of the subdivisions do not have a dedicated net metering path. For such types of



(a) (b)

(c)

FIGURE 9. Consumers'satisfaction for one-day Shadbagh.



(a) (b)

(c)

FIGURE 10. Consumers'satisfaction for one-year Shadbagh.

subdivisions in the proposed work, we assumed the value as 6.18 (MWh).

LESCO will maintain the balance between the demand and limited supply of energy. An energy outage has occurred at the subdivisional level. To experiment, we assumed that if a division consists of N subdivisions, then at time t only $N/2$ subdivisions will avail the energy from his divisions. Moreover, if grid supply is available at subdivision i then his peer subdivision j will face the energy outage from the grid. On these bases, the experiment is performed over the data of one year.

To demonstrate the working of the proposed model, we first take a random division (Badamibagh) and its associated subdivisions from Table 6 and explain how our proposed model is working. There are four subdivisions associated with the Badamibagh division named Data Nagar, Shadbagh, Chahimran, and Wasanpur. From this information proposed model makes two pairs of peer subdivisions as pair-1($Datanagar \longleftrightarrow Shadbagh$) and pair-2 ($Chahimran \longleftrightarrow Wasanpur$). So in these pairs, if grid supply is available in one subdivision, then there will be no grid availability in the second subdivision.

TABLE 9. Shadbagh solar penetration effect.

Month		Satisfaction			Without solar	Base line	% change w.r.t without solar			% change w.r.t base line		
		@14%	@20%	@35%			@14	@20	@35	@14	@20	@35
1	Type-1	992	992	1248.916	992	1488	0	0	25.89	-33.33	-33.33	-16.06
	Type-2	992		1117.87	1287.98	1488	0	12.68	30.92	-33.33	-24.87	-12.71
	Type-3	1241.873	1305.227	1309.522	992	1488	25.18	31.57	32.0	-16.54	-12.28	-11.99
2	Type-1	897	897	1137.329	897	1345	0	0	26.79	-33.30	-33.30	-15.44
	Type-2	897	1012.728	1177	897	1345	0	12.90	31.21	-33.30	-24.70	-12.49
	Type-3	1121.54	1177	1177	897	1345	25.03	31.21	31.21	-16.61	-12.49	-12.49
3	Type-1	994	994	1289.13	994	1490	0	0	29.69	-33.28	-33.28	-13.48
	Type-2	994	1136.65	1362.652	994	1490	0	14.35	37.04	-33.28	-23.71	-8.57
	Type-3	1287.90	1366.35	1369.21	994	1490	29.56	37.46	37.74	-13.56	-8.29	-8.10
4	Type-1	900	900	1110.40	900	1440	0	0	23.37	-37.5	-37.5	-22.88
	Type-2	900	1001.28	11198.52	900	1440	0	11.25	33.16	-37.5	-30.46	-16.76
	Type-3	1138.63	1211.16	1220.8	900	1440	26.51	34.57	35.64	-20.92	-15.89	-15.22
5	Type-1	929	929	1238.63	929	1489	0	0	33.32	-37.60	-37.60	-16.81
	Type-2	929	1079.21	1363	929	1489	0	16.16	46.71	-37.60	-27.52	-8.46
	Type-3	1263.69	1363	1363	929	1489	36.02	46.71	46.71	-15.13	-8.46	-8.46
6	Type-1	744	744	1032.47	744	1489	0	0	38.77	-50.03	-50.03	-30.65
	Type-2	744	844.17	1147	744	1489	0	18.84	54.16	-50.03	-40.61	-22.96
	Type-3	1055.52	1147	1147	744	1489	41.87	54.16	54.16	-29.12	-22.96	-22.96
7	Type-1	720	720	997.58	720	1441	0	0	38.53	-50.03	-50.03	-30.77
	Type-2	720	852.44	1080	720	1441	0	18.39	50.0	–50.03	-40.84	-25.05
	Type-3	1009.33	1088.37	1094.65	720	1441	40.18	51.16	52.03	-29.95	-24.47	-24.47
8	Type-1	745	745	1056.41	745	1489	0	0	41.80	-49.96	-49.96	-29.05
	Type-2	744	896.21	1148	745	1489	0	20.29	54.09	-49.96	-39.81	-22.90
	Type-3	1061.71	1148	1148	745	1489	42.51	54.09	54.09	-28.69	-22.90	-22.90
9	Type-1	783	783	1098.24	783	1441	0	0	40.26	-45.66	-45.66	-23.78
	Type-2	783	934.53	1173	783	1441	0	19.35	49.80	-45.66	-35.14	-18.59
	Type-3	1091.35	1173	1173	783	1441	39.38	49.80	49.80	-24.26	-18.59	-18.59
10	Type-1	869	869	1176.27	869	1489	0	0	35.35	-41.63	-41.63	-21.0
	Type-2	869	1017.80	1241	869	1489	0	17.12	42.80	-41.63	-31.64	-16.65
	Type-3	1165.14	1241	1241	869	1489	34.07	42.80	42.80	-21.75	-16.65	-16.65
11	Type-1	903	903	1179.63	903	1441	0	0	30.63	-37.33	-37.33	-18.13
	Type-2	903	1035.14	1233	903	1441	0	14.63	36.54	-37.33	-28.16	-14.43
	Type-3	1166.38	1233.84	1233.84	903	1441	29.16	36.63	36.70	-19.05	-14.37	-14.33
12	Type-1	982	982	1247.97	982	1478	0	0	27.08	-33.55	-33.55	-15.56
	Type-2	982	1109.78	1292	982	1478	0	13.01	31.56	-33.55	-24.91	-12.58
	Type-3	1229.72	1292	1292	982	1478	25.22	31.56	31.56	-16.79	-12.58	-12.58

Take random time slot $t = 17$ in daylight the energy consumers in the Data Nagar subdivision submit information about the demand for energy to the sub-divisional coordinator along with the need for energy factor ξ. The total energy demand of energy consumers at the sub-divisional coordinator is $E_{dem} = 30.5614\ MWh$. This demand includes the energy demand for type-1 consumers having $\xi = (0 - 0.4)$, type-2 having $\xi = (0.4{-}0.7)$ and type-3 having $\xi = (0.7{-}1)$. As we equally distribute the total population into three equal parts, each type of energy consumption is about 33.33% of the total population. All energy producers also submit the amount of surplus E_{sur} they have along with the offered prices Tp_{off}. The total surplus energy available at the Data Nagar with 14% solar generation including line and other losses such as inverter losses, AC and DC wire losses, Temperature losses is $E_{surplus} = 4.3348\ MWh$. The grid availability at this time slot $t = 17$ is found to be 0 at the Data Nagar subdivision. For the sake of simplicity, we assumed that the energy producer of Type-1 offered their prices at $5¢/kWh$ the offered prices of type-2 and type-3 are assumed to be $5.4¢/kWh$ and $6¢/kWh$ respectively. The same prices are also assumed in other subdivisions. From this information, the sub-divisional coordinator firstly determines the market-clearing price TP.

Since we equally distribute the total population into three types of consumers so in this way each type of consumer i.e., type-1 to type-3 are each representing 33.33% of the total population of Data Nagar. Based on this, the sub-divisional coordinator first makes a list that reflects the selection of energy producers for each type of energy consumer. The selection list of energy producers can be represented as:

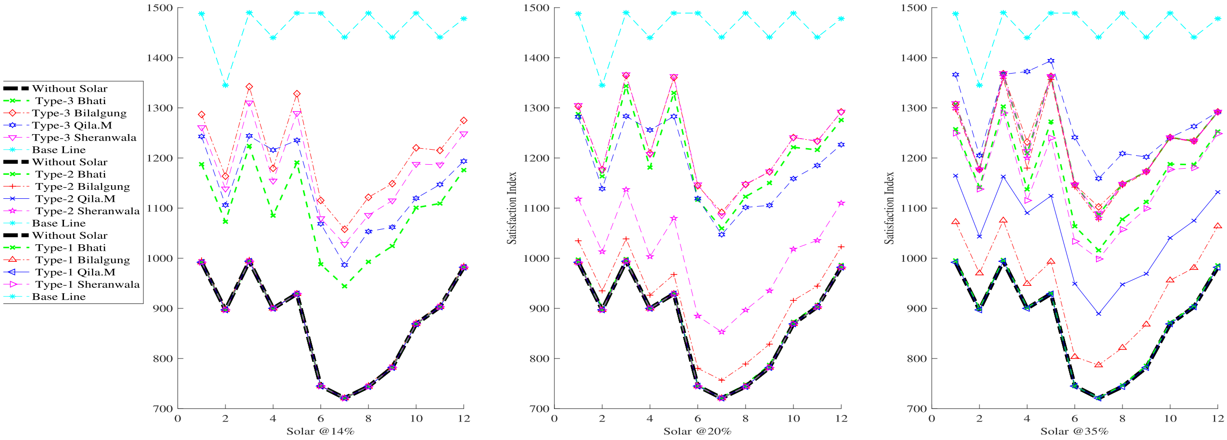
$$\begin{aligned} Type-3\ Consumers'\ Selection &= Type-3 \\ &> Type-2 > Type-1 \qquad (13) \end{aligned}$$

$$\begin{aligned} Type-2\ Consumers'\ Selection &= Type-2 \\ &> Type-1 > Type-3 \qquad (14) \end{aligned}$$

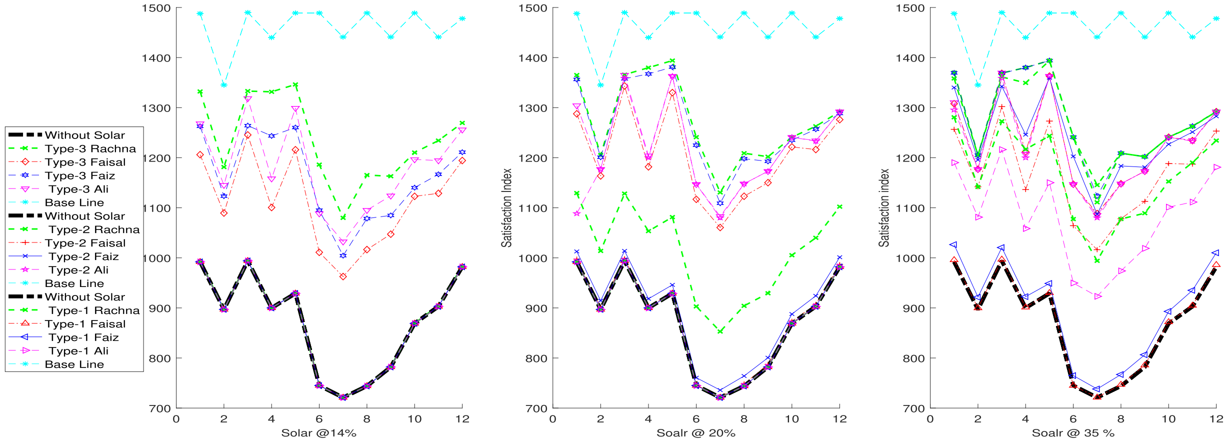
$$\begin{aligned} Type-1\ Consumers'\ Selection &= Type-1 \\ &> Type-2 > Type-3 \qquad (15) \end{aligned}$$

From Eq. (13), it can be seen that type-3 energy demand consumers highly prefer high energy producers because they want to fulfill their energy on a prior basis and for this, they initiated the high energy producers to inject their energy into the system so that the consumer energy needs can be fulfilled. Whereas low-demand energy consumer-prefer type-1 producers because their prices are low. The Table uses Eq. (4) to Eq. (6) to find out the winning energy producers so that his offered price will be selected as the trading price T_p.

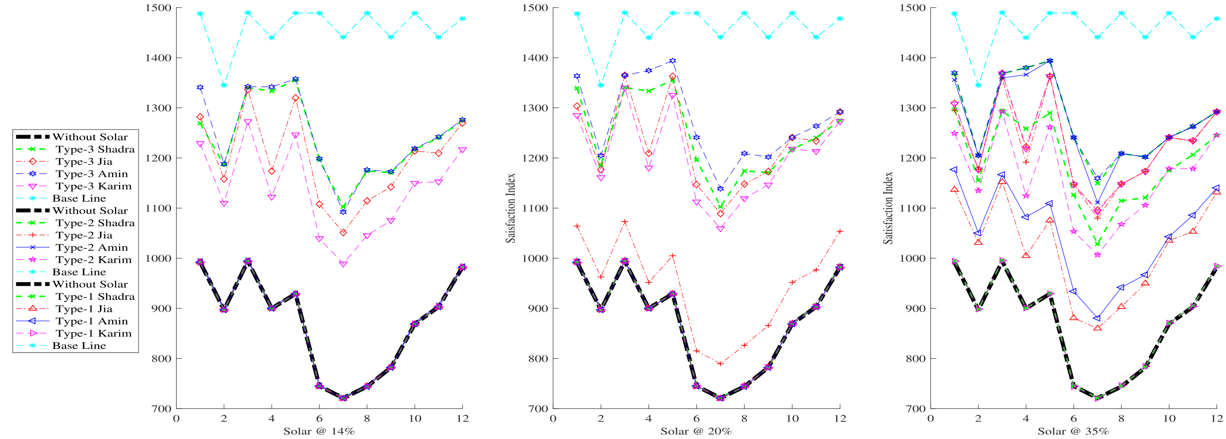
In Table 7, 'A' represents the energy consumers who prefer the energy producer listed in the column to the energy



(a) Data darbar Div.



(b) Ferozewala Div.

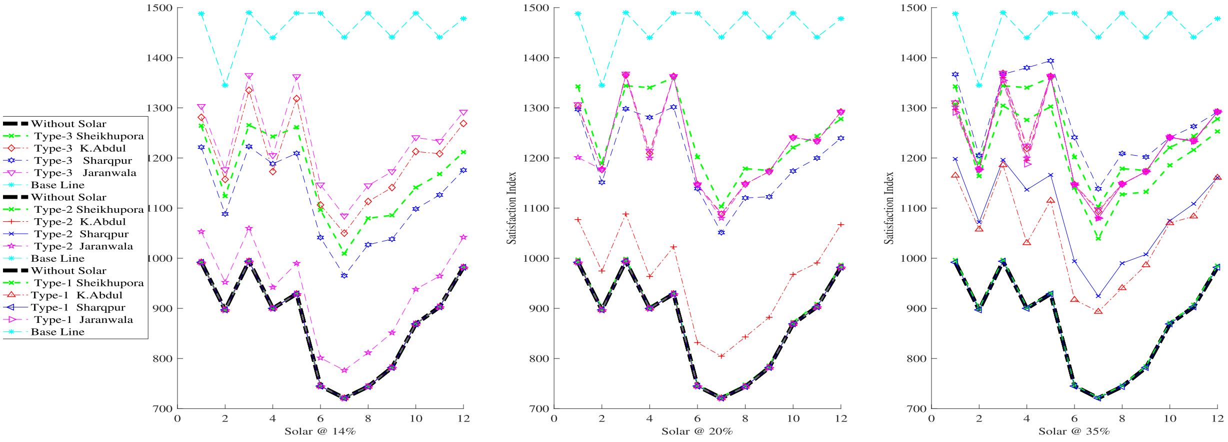


(c) Ravi Div.

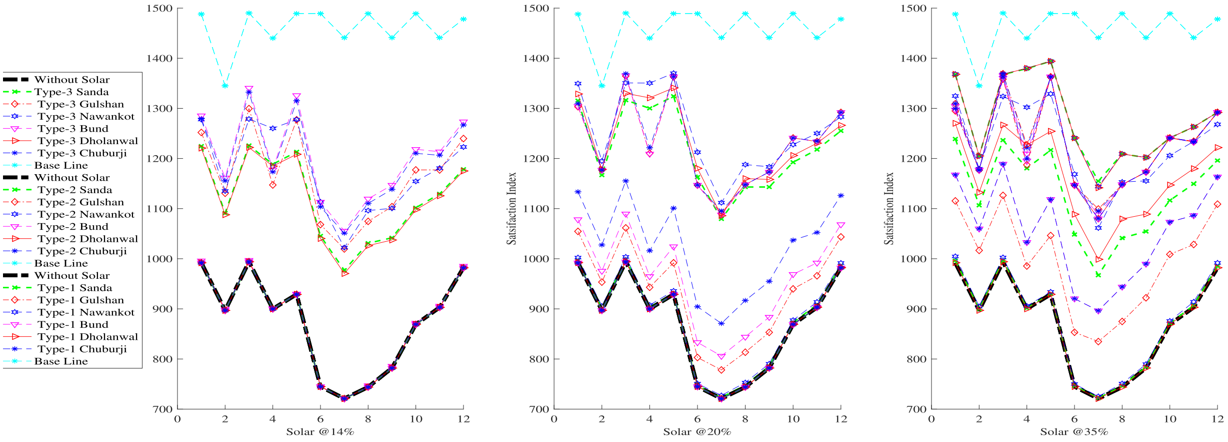
FIGURE 11. Solar penetration effects in other divisions-1.

producers listed in a row. 'B' represents the consumers who prefer the energy producer listed in the row to the energy producer in the column. From Table 7, it can be seen that the energy producer of type-2 is winning the most in all variations described in Eq. (4) to Eq. (6). Therefore sub-divisional coordinator will use their offered price as the market-clearing price *Tp*.

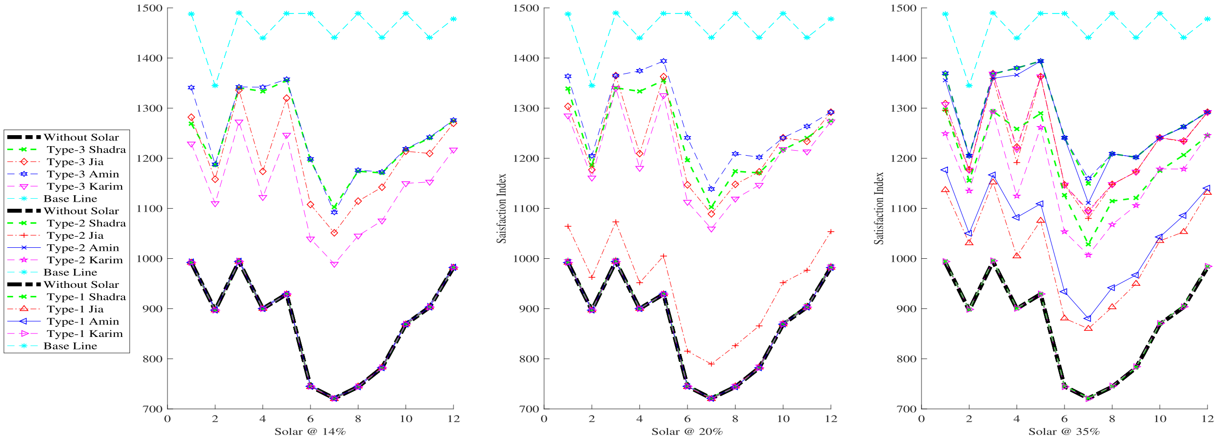
Now, the total surplus available at the sub-divisional coordinator is $E_{sur} = 4.3348\ MWh$, but the total demand requested by energy consumers is $E_{dem} = 30.5614\ MWh$. About these two values, the deficit between the demand and available surplus is 26.2266 MWh. As grid supply is not available, the sub-divisional coordinator will import the energy with his peer sub-divisional coordinator Shadbagh.



(a) Kot Abdul Div



(b) GulshanRavi Div.



(c)

FIGURE 12. Solar penetration effects in other divisions-2.

In Shadbagh, grid supply is available; therefore, energy generated by the producers can be sold in his peer subdivision. The total available surplus at Shadbagh subdivision at 14% solar penetration is found to be 4.2777 MWh.

By importing this amount of energy, the energy difference between demand and supply at Data Nagar will reduce from 26.2266 MWh to 21.9489 MWh. However, there is still a large difference between the requested demand and the available surplus that is not fulfilled as there is no source available from where the energy can be imported. For distributing this energy the sub-divisional coordinator first considers type-3 consumers as they are paying more. After fulfilling the type-3

TABLE 10. Suggested net metering line capacity.

Division	Sub-division	Existing net Metering capacity (MWh)	Suggested net Metering capacity (MWh) at 35% solar penetration	Utilization(%)
Gulshan-ravi	Sanda	6.18	9	90.40
Gulshan-ravi	Gulshan	5.2	8	90.88
Gulshan-ravi	Nawankot	5.2	7	91.43
Gulshan-ravi	Bund Road	6.73	6.73	77.25
Gulshan-ravi	Dholanwal	7.27	10.5	97.35
Gulshan-ravi	Chuberji	7.27	8	85
Ferozewala	Rachana	10.55	10.55	86
Ferozewala	Faisal park	5.22	7.5	97.21
Ferozewala	Faizpur	5.22	5.5	95.99
Ferozewala	Ali park	5.22	5.2	85.71
Ravi Road	Shahdra	6.2	701	99.91
Ravi Road	Jia Musa	7.27	8.2	98.80
Ravi Road	Amin park	6.73	7.6	98.55
Ravi Road	Karim park	6.2	7	96.74
Data Darbar	Qila M.	5.09	5.8	96. 39
Data Darbar	Bilalgung	6.18	6.18	92.58
Data Darbar	Sheranwala	2.91	5.5	94.82
Data Darbar	Bhatigate	4.73	7.1	98.75
Badamibagh	Data nagar	5.09	8	97
Badamibagh	Shadbagh	6.18	6.6	94
Badamibagh	Chahimran	N.A	6.9	97
Badamibagh	Wasanpur	7.27	7.27	72
Kot Abdul	Sheikhupora	N.A	6.8	98
Kot Abdul	K.Abdul	6.18	6.18	98
Kot Abdul	Sharqpur	N.A	7	99
Kot Abdul	Jaranwala	N.A	5	87

consumers if some energy will be left it will be distributed among type-2 and type-1 consumers respectively. The same process is repeated with an increase in penetration of solar from 14% to 20% and 35%. Based on the findings, Fig. 7 presents the satisfaction level of the energy consumers for one day in these three solar penetration ratios.

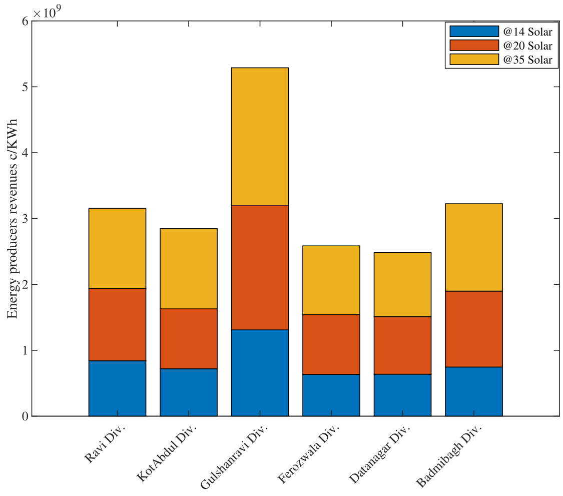
From Fig. 7(a), it can be seen that by deploying the solar at 14% only partial need for energy demand for consumer type-3 is fulfilled. Whereas if the solar penetration is increased from 14% to 20%, most of the demand for consumer type-3 is fulfilled. However, if a further increase is made from 20% to 35% energy demand of type-3 consumers is 100% fulfilled whereas the energy demand for the type-2 consumer is also fulfilled as shown in Fig. 7(b)(c). Moreover, in some instances, the energy consumption of type-1 also gets the energy from the proposed system.

By using the solar penetration of 14% total 99.75% line capacity of net metering will be used. However, if the solar penetration is increased from 14 to 35%, the recommended line capacity for net metering is 8-MWh with a utilization factor of 97%. The proposed model is evaluated on one-year data. Fig. 8 presents the satisfaction level of energy consumers for one year. From Fig. 8(a), it can be seen that by using solar penetration at 14%, the satisfaction level for type-3 consumers is increased from 992 to 1223.44, which presents a 23.33% increase in the satisfaction level. However, compared with the baseline value of 1488, there is a reduction in satisfaction level of about 17.7795%. This is because the proposed system is not using the storage devices which provide energy in the absence of solar light. Table 8 compares the total satisfaction level for one-year data of all types of consumers by using the solar penetration from 14% to 35% in the Data Nagar subdivision.

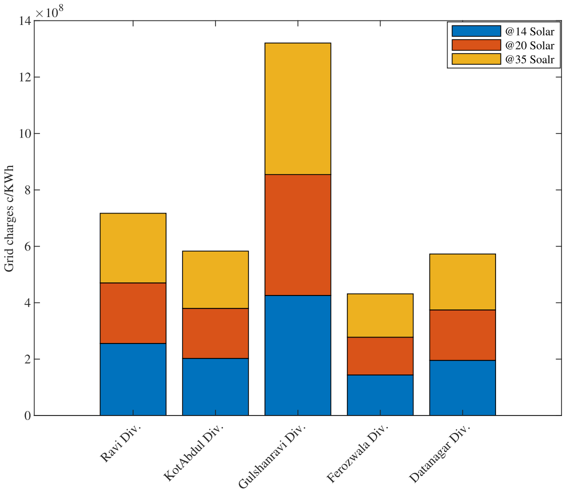
A similar process is carried out at time slot $t = 19$ when there is no grid supply at the Shadbagh subdivision. At this time, Data Nagar will provide its surplus energy. Fig. 9 presents the satisfaction level for consumers at subdivision Shadbagh for one day.

From Fig. 9(c), it can be seen that 35% solar penetration affects more on all types of consumers. The solar penetration and its effect on consumers' satisfaction level over one year are presented in Fig. 10. The percentage change in satisfaction level of consumers for one other solar penetration can be observed in Fig. 10 and Table 9.

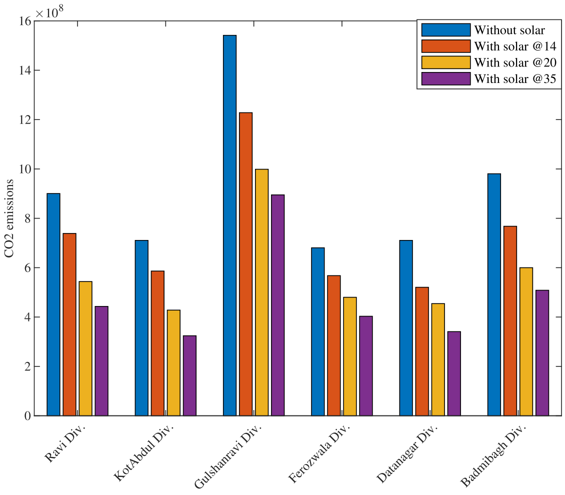
Solar penetration effects on other divisions are presented in Fig. 11 and Fig. 12. From these figures, it can be well



(a) Energy producers revenues.



(b) Grid revenue.



(c) CO_2 emissions.

FIGURE 13. **Energy producers revenue and grid earnings.**

observed that solar penetration at the rate of 35% has a significant impact on the energy consumers' satisfaction level as it meets all the energy demand for the type-3 and type-2 energy consumers along with partially fulfilled demand for energy type-1 consumers. Regarding 35% solar penetration Table 10 provides recommended capacity for net metering at each subdivision with its percentage utilization factor.

Based on the trading price *TP*, the total revenue earned by the energy producers after paying grid charges is shown in Fig. 13(a). Fig 13(b) and (c) are presenting the grid revenues and reduction in CO_2 by using solar energy. It can be seen that the 35% utilization of solar energy not only increases the consumers' satisfaction level but also reduces CO_2 emissions.

VII. CONCLUSION

Continuous energy supply is mandatory for a better quality of life and also for economic development in any country. In this paper, we consider Pakistans' current energy shortage as a case study. Since 1990, there are about 8 to 12 hours of energy outages in a day. Therefore, this creates a lot of problems for the people in Pakistan and is a great hindrance to the countrys' economic growth. For this problem, we first evaluate the existing energy infrastructure of Pakistan. Then keeping in view the present challenges and issues, a peer-to-peer energy trading model is proposed. In the proposed peer-to-peer energy trading platform, we proposed a novel method for determining the uniform pricing for energy trading among participants. The proposed pricing scheme brings fairness to an energy market by promoting competition among the energy sellers and increases the utilities of the market participants i.e., reduction in energy bills for consumers and an increase in profitability for sellers. In the proposed work, the energy producers are assumed to deploy solar panels for their energy production. Moreover, the generated energy is traded with others through the sub-divisional coordinator. Different solar penetration starting from 14% to 35% is tested, and the finding reveals that 35% solar penetration helps a lot to meet the energy demand of the consumers during the daytime. Also, this 35% solar penetration has remarkable effects on the reduction in CO_2 emissions. In the proposed work some factors have not been discussed so far which may have significant effects such as batteries and storage constraints, financial and participants' privacy concerns, etc. Further, blockchain can be deployed in the proposed work to make a tamper-proof financial transaction system. These factors will be considered in future work to make the proposed system more effective.

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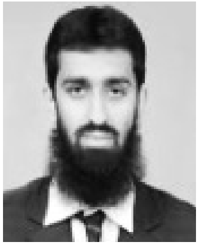

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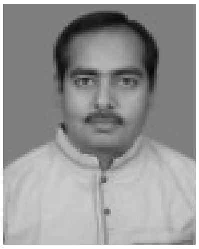

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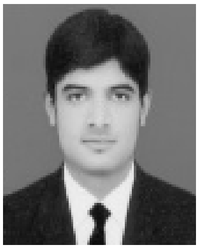

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