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Increasing the Role of Solar and Wind Energy in CO_2-neutral Electrification of Developing Countries

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Ph.D. Dissertation

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Declaration

Independent Work and Indicating References

I, the undersigned, Aqsa Rana, declare that the current PhD dissertation is my work, and only the sources referred have been used in the document. Each part, used literally or taken over and paraphrased from other sources, has been indicated by identifying its source.

Budapest, April 3, 2024

Aqsa Rana

Preface

The principal subject of this Ph.D. research is CO_2-neutral electrification in developing countries. The continuous increase in population and growing expansion of the industrial sector are the reasons for the ever-increasing demand for electricity, which directly burdens the central grid. The continuous development cannot be imagined without high electricity utilization, but it is impossible to sustain it in an environmentally friendly way based on traditional energy sources (fossils). In developing countries, the problem is twofold. On the one hand, a national grid system suffers from many problems, such as simultaneously increasing the electricity and supply area while reducing the use of fossil fuels.

On the other hand, there are substantial rural areas without electricity (grid), but this does not mean that people living there do not use electricity. They use, but sources are small generators that run on different fuels, which causes specific CO_2 emissions. The world is striving hard to mitigate climate challenges, reduce carbon emissions, and reduce dependence on swiftly depleting fossil fuel sources. The integration of renewable energy sources into electricity generation can be a solution to reduce greenhouse gas emissions that trigger climate change. Therefore, intensive use of carbon-neutral energy sources is paramount to achieving sustainable development goals. Thus, renewable energy penetration is apprehended, but the inherent intermittency of renewable energy makes it complex to accommodate at the grid level and requires the solution of several additional tasks. Nevertheless, energy storage technologies tackle power fluctuation and facilitate meeting peak demands.

However, the last few decades have proved that renewable energy is the future of the global energy supply system. The scientific community is analyzing and resolving technical, social, and economic issues related to widespread applications of distributed renewable energy. Adopting renewable energy in distributed networks prevents the expansion of transmission lines and lowers the pressure of establishing fossil fuel power plants. Electrification of remote areas through decentralized generation using renewable energy sources has emerged as a low-cost and practically viable solution. Domestic-level energy trading makes the system more cost-effective. In practice, energy trading at the domestic level is a sustainable option with significant benefits, such as reducing the load on the shared grid and reducing consumer costs. The idea of energy trade potential assessment with system optimization is new, bridges the gap between renewable energy sources integration and excess energy utilization, and upgrades the energy consumption behavior of general household users. The prosumers (individuals who both consume and produce electricity) are the new performers progressing towards a low-carbon future. In recent years, the increased use of renewable energy sources has encouraged producers to sell excess electricity to nearby consumers, promoting domestic energy trading. Residential energy trading networks lead toward the objectives of cost minimization and self-consumption maximization to improve the environmental sustainability, reliability, and economic patterns of energy systems. However, there are some social and regulatory barriers in addition to technical and economic hindrances to

implementing energy trading at the domestic level. Based on current sustainable development goals (SDGs) and principles, the scope of collective energy consumption cannot be compromised. Appropriate rules and specialized trading technologies, such as peer-to-peer (blockchain), are substantial due to their technical and economic advantages over traditional trade.

The integration of renewable energy worldwide is increasing rapidly as a proven route to achieving sustainable social goals. Solar and wind energy sources can serve as solutions to the problems mentioned earlier. That is why this Ph.D. study reports on how the potential of solar and wind energy can be maximized for the national grid (Part I) and supply electricity for rural areas (Part II).

Keywords: Sustainable development, Energy system planning, Distributed generation, Prosumer, Electrification, Decentralized energy trade

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Abbreviations

Acronyms

AE	Alkaline electrolyte
BaU	Business as usual
CHP	Combined heat and power
CSC	Collective self-consumption
DEGS	Diesel engine generator set
DHW	Domestic hot water
DOD	Depth of discharge
DRP	Demand response program
EH	Energy hub
EREC	European Renewable Energy Council
ES	Energy storage
FiT	Feed-in tariff
FSOC	Fractional state of charge
GAMS	General algebraic modeling system
GDP	Gross domestic product
GHG	Greenhouse gas
GRC	Grid reinforcement cost
HLM	Home load management
IRENA	International Renewable Energy Agency
LCOE	Levelized cost of electricity
MPPT	Maximum power point tracker
NEPRA	National Electric Power and Regulatory Authority
NPC	Net present cost
O&M	operation and maintenance cost
PEM	Polymer electrolyte membranes
PSH	Peak sunshine hours
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
P2P	Peer-to-peer
P2H	Power-to-hydrogen
RE	Renewable energy

RES	Renewable energy sources
SDG	Sustainable development goal
SHS	Solar home systems
SOC	State of charge
SOH	State of health
TRNSYS	TRaNsient SYStem
TOU	Time of use
VRE	Variable renewable energy

Nomenclature

Fixed variables and parameters

bm	The first hour of allowable operation interval for appliances m
bn	The first hour of allowable operation interval for appliances n
C_{batt}	Capacity of battery in ampere-hour
C_{CHP}^{max}	Maximum allowable natural gas input of CHP
Ct	Capital costs
dr	Discount rate
Dr	Degradation rate.
E(t)	Electricity at the hub input at hour t
E_{app} (t)	Energy consumption of electrical appliances at hour t
E_{app}^{R} (t)	Energy consumption of responsive appliance at hour t
E_{app}^{NR} (t)	Energy consumption of non-responsive appliances at hour t
E_{CHP} (t)	The CHP unit provides electrical power at hour t
E_{ch}^{s} (t)	Charging energy of battery at hour t
E_{dch}^{s}(t)	Discharging energy of battery at hour t
E_{grid} (t)	Electrical power is provided by the grid at hour t
E_m	Energy consumption of appliance m at each operating hour t
E_m (t)	Energy consumption of appliance m at operating time t
En	Total energy consumption of appliance n in its operational interval
E_n^{min} (t)	Minimum allowable energy consumption of appliance n at hour t
E_n^{max} (t)	Maximum allowable energy consumption of appliance n at hour t
Epv	Energy produced by PV

E_{RES} (t)	RES provides electrical power at hour t
Es	Emission saved
Fr	Fuel required
Fs	Fuel saved
G (t)	Natural gas received at energy hub input at hour t
H_{CHP} (t)	Heat provided by CHP unit at hour t
H_d (t)	Household heat demand at hour t
Im	The last hour of allowable operation interval for appliances m
In	The last hour of allowable operation interval for appliances n
M	Set of hourly on-off controlled appliances
m	Index of M-type appliances
Md	CO_2-equivalent per kWh by diesel generator
Mpv	CO_2-equivalent per kWh by PV system
N	Set of consumption extent-controlled appliances
n	Index of N-type appliances
N_a	Number of autonomy days
P_{load}	The total load for a typical residential home in a day in kWh
P_{pv}	Size of PV panels in kW power
P(u)	Power generated by wind turbine
Rt	Replacement costs
SOC_{min}	Minimum state of charge
Temp	Temperature
t	Time in hour
Um	Required operation time of appliance m in day
V (t)	Dispatch factor of natural gas at hour t
η_{ch}^{s}	Efficiency of battery charging
η_{dch}^{s}	Efficiency of battery discharging
$\eta_{DC/AC}$	Efficiency of DC/AC converter
η_{gapp}	Efficiency of heat appliances
$\eta_{g\text{-}e}$	Gas to electricity conversion efficiency
$\eta_{g\text{-}h}$	Gas-to-heat conversion efficiency

1. Introduction

Sustained growth requires an abundant energy supply to meet residential, industrial, and commercial energy needs. Energy production and consumption practices are undergoing essential reforms to cope with growing energy demand and severe climate challenges. In contrast, most existing power plants in the conventional energy system are based on fossil fuels. They are currently the primary sources of balancing the supply/demand dynamics of the global energy system. However, the problem is that fossil fuel sources are not being supplied at the rate at which they are being used up, which means we must reduce our dependence on them to sustain the long-term energy system. Another major concern is that every stage of the fossil fuel life cycle, from extraction, processing, and transportation to combustion, causes toxic pollution, especially greenhouse gas (GHG) emissions that trigger the global climate crisis [1]. Fossil fuels are primarily responsible for global warming as fossil fuel combustion accounts for 85% of CO_2 emissions [2].

Specifically, United Nations Sustainable Development Goal 7 (SDG7) states, “Ensure access to affordable, reliable, sustainable and modern energy for all”. Therefore, the threat of phasing out fossil fuels in the future and detrimental environmental consequences give rise to using renewable energy sources (RES). The latest energy trends show that the world is not on track to meet SDG7 goals, so SDG custodian agencies emphasize the need for more substantial and concrete commitments to clean energy access [3]. Annual clean energy investment has grown much faster than investment in fossil fuels over this period, comparing the projections for 2023 with the 2021 data (24% vs. 15%) [4]. According to the International Renewable Energy Agency (IRENA) tracking SDG7 report, the global electricity access rate improved progressively from 83% to 91% from 2010 to 2020. Due to the impact of COVID-19, the annual electrification rate has slowed, and around 733 million people remained unserved in 2020. At the current growth rate, the world will cover only 92 % of electrification by 2030 [3].

The world is working hard to mitigate climate challenges, and integrating renewable energy (RE) is greatly helping achieve green energy goals. RE is clean, environmentally friendly, and safer than traditional burning fossil fuels that negatively impact our environment. Growing environmental concerns have made using RE to meet energy needs imperative. Using RE in areas with sufficient potential can reduce the load on the central grid, providing a safer and more reliable energy supply option. However, RES is clean energy, but it is challenging to predict because it depends on weather conditions. Thus, the variable nature of RES introduces new tasks in the operation and management of continuous energy supply [5]. Since rebuilding a complete grid infrastructure for RES is quite complex, many small and large RES-based projects are installed independently for local use or integrated into the global central grid. The scientific community is analyzing and solving technical, social, and economic issues related to widespread applications of distributed RES. Adopting RES in distributed networks prevents the expansion of transmission lines and lowers the pressure to establish fossil fuel power plants. The last few decades have proved that RE is the future of the global energy supply system. Advancement of RE systems in terms of multi-generation systems such as electricity, heat, hydrogen, and cooling power may lead to further efficiency improvement [6]. According to a 2020 report by the International Energy Agency, hydro, solar, bioenergy, and wind power sources will account for nearly 40 percent of the global electricity supply by the end of 2030. Solar energy is the most acceptable option among all RES due to its abundant availability, significant cost reduction, technological advancements, and supportive financing models [7].

Even after recognizing the significance of RES, the world is still coping with an energy crisis, especially developing countries facing three major problems: (a) providing access to electricity for all, (b) contributing to the global goal of a low-carbon energy system and (c) making access to electricity economically viable. Despite huge RE potential, lack of quality information about RE resources and wrong policies lead South Asian countries to unbalanced energy supply and demand or high-cost power generation with severe environmental damage. Timely planning for alternative RES is essential for developing countries to achieve new social and economic development goals. Additionally, RE is an inevitable choice for South Asian countries due to the region's growing focus on mitigating greenhouse gases.

Modernizing existing infrastructure and entering the digital age address energy system challenges successfully. The possibility of selling surplus energy during periods of sufficient production provides a starting point for local energy trading. However, appropriate energy distribution rules must be developed for proper energy trading, and special trading technologies such as peer-to-peer (P2P) blockchain can be introduced. The transformation of energy systems has a long-term impact and involves extraordinary costs at the societal level. Energy policymakers should, therefore, develop programs to ensure social acceptance of energy policy efforts through appropriate training and information tools. Conventional centralized systems have more difficulty overcoming energy trading problems like privacy breaches, miscommunication, and network speed. Therefore, early renewable platforms evolved as decentralized energy distribution systems. Numerous algorithmic studies are being conducted to optimize market mechanisms, coordinate supply and demand, improve trading efficiency, and reduce market manipulation.

As energy systems continue to evolve, so do their challenges and complexities. Moreover, timely energy planning is essential to meet the upcoming challenges. Therefore, there is a need for intensive planning and policies to implement RE for the development of sustainable communities. Because of the numerous techno-commercial challenges, solving a problem through extensive experimentation is complex. Modeling and simulation are more promising alternatives to reduce the number of repetitive and iterative tests in long-term experiments. Different energy modeling tools are available with specific purposes and features, and no individual tool is specialized enough to address all energy system constraints. Choosing a particular tool depends on many factors; the energy analyst's choice is one.

1.1. Scope of the research

The main scope of the research presented in this dissertation is to develop a comprehensive plan of the electricity model according to demand and supply balance for extensive technical analysis. The EnergyPLAN modeling tool was employed to work out a more ambitious variable renewable energy (VRE) integration scenario to determine the technically most feasible alternative scenario for a specific South Asian country. Considering all the significant challenges, long-term planning for RE development is suggested for a diverse population and dispersed geographical location. The results may be adapted and supported in developing more sustainable power generation serving 1,787 million people in South Asian countries. However, there are many similarities and differences in the electricity supply systems of these countries. Absence and remoteness from the central grid make off-grid power generation the most reliable source of electricity to meet the needs of peripheral areas. Electrification of remote areas through decentralized generation using RES has emerged as a low-cost and practically viable solution. Domestic-level energy trading further reduces the shared grid load and consumer costs. This new idea of local energy trade potential assessment with system optimization bridges the gap between RES integration and excess energy utilization.

1.1.1. Aims

This thesis aims to modernize existing infrastructure and provide rural electrification by entering the digital era through the progressive use of RES to ensure a continuous and abundant energy supply to achieve sustainable and secure energy system goals.

1.1.2. Thesis statement

To analyze the ways to support energy systems for higher renewable share and self-consumption to accelerate electrification practices in developing countries. Integrating RE, such as solar and wind, to move towards a low-carbon economy, considering digitization with decentralization to empower the power sector.

1.1.3. Research objectives

Global energy consumption practices are undergoing essential reforms to cope with growing energy demands and severe climate challenges. Actually, we are facing a double challenge. On the one hand, we must increase the power capacities and, on the other hand, reduce CO_2 emission. Our first objective is to provide an extensive energy plan with the progressive use of RES to ensure a continuous and abundant energy supply as a significant target towards a sustainable and secure energy system. Our second objective is to assess the prosumer's impact on future energy systems. Progression to low carbon future leading towards RE prosumers even in the rural areas. A dynamic approach of energy trade between prosumer and consumer by blockchain and beyond.

Accomplished objectives

- An evaluation of the energy problems of South Asian countries related to the transition to less carbon-intensive power generation;
- Recommending suitable energy policy tailored for South Asian countries serving transition towards a sustainable power generation by high-level RES integration;
- Development of country-level long-term simulation model of electricity system;
- Technical and economic aspects of energy storage (ES) during excess production hours to enhance the system resilience;
- Power to Hydrogen (P2H) is a significant part of the work (EnergyPLAN software helps to optimize surplus energy and calculate the practically feasible potential for P2H conversion);
- Assessment of the most appropriate sector where hydrogen as an alternative fuel offers high environmental benefits at as low cost as possible;
- Decentralized distribution system Blockchain-based local grid cost calculation, more detailed socio- economic and technical study related to us already for the recommended prototype rural areas of Pakistan;
- A novel dynamic simulation model was developed with TRNSYS software to optimize energy system layout, including domestic-level Photovoltaic (PV) installation scenarios to build long-term cost-saving alternatives;
- A dynamic framework of energy trade between prosumer and consumer, especially at a community level, by using HOMER-Pro software.

1.2. Outline of dissertation

This dissertation is composed in the following way: Chapter 1, intruding brief context, the scope of this research, and major achieved objectives. In addition, a detailed literature review of the preceding research in this field and the focus of this study is presented. Next, in Chapter 2, an overview of the methods and analysis tools required for energy modeling, planning, and optimization is briefly introduced. Chapter 3 explained data-tailoring, long-term energy system planning, and simulation in the EnergyPLAN tool, considering all practical limitations. Consequently, the utilization of surplus production with an appropriate scheme is proposed to enhance overall system reliability. In Chapter 4, renewable energy-based rural electrification is discussed, and the system component, used methodology, and research results with novel scientific contributions are presented. Finally, Chapter 5 summarizes the key findings concluded in the dissertation and potential future opportunities. Lastly, the leading scientific contribution and related publications, summarizing the new scientific contribution of the research works addressed in Chapters 3 and 4 as eight theses, along with their list of corresponding publications.

1.3. Literature review

1.3.1. Renewable energy integration

The Paris Climate Change Agreement was established in 2015 to address the root causes of climate change. Climate change due to global warming due to GHG emissions is an urgent global challenge of our time that directly affects the planet and people. Many countries are legally obliged to implement plans to reduce greenhouse gas emissions. The goal is to limit global warming to below 2°C, preferably 1.5°C, compared to pre-industrial levels. Today's energy production relies on fossil fuels, which is detrimental to the environment. However, the continued increase in carbon dioxide (CO_2) emissions is a concern, especially for countries that rely heavily on fossil fuels for economic growth. These countries, often characterized as developing countries with limited technological progress, have prioritized economic gains at the expense of the environment. According to Global Burden of Disease Research, 6.7 million deaths worldwide in 2019 were attributed to indoor and outdoor pollution, and 4.3 million of them died prematurely due to outdoor air pollution [8]. The world is striving hard to mitigate climate challenges, reduce carbon emissions, and reduce the dependence on swiftly depleting fossil fuel sources.

The integration of RE (biomass from plants, geothermal energy, hydropower, solar energy, and wind energy) across the globe is increasing rapidly as a proven route to achieving sustainable society goals. A wide range of 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 [9]. The last few decades have proved that RE is the future of the global energy supply system. Energy consumption practices are undergoing essential reforms to cope with growing energy demand and severe climate challenges. Scientists and engineers are working actively to explore alternate implementation strategies of RE sources by highlighting the importance of green energy [10], developing sustainable energy technologies with RE sources [11], and emphasizing RE integration in urban areas [12], as well as rural areas with microgrid installation [13] and maximizing utilization of existing grids [14]. Technical, economic, social, environmental, and infrastructural factors affect the choice of suitable and affordable technologies for particular circumstances [15]. Solar energy is one of the attractive options among all the RE sources due to its abundance and sustainable availability across the globe [16]. Solar power experienced significant growth with a 21-fold increase during 2010-2021, resulting in substantial cost reduction, technological advancement, and supportive financing models [17].

RES typically have low power generation capacity and are installed close to end-users in the distribution system, ultimately reducing transmission costs and line losses. However, due to the uncertain nature of VRE sources through single-line out-of-work, many loads face blackouts, which raises a significant question about the overall stability and reliability of the power supply network. The most appropriate solution to tackle the probabilistic uncertainty of RES is to incorporate ES systems such as batteries. The inherent variability of RES critically imposes the addition of flexible sources to enhance the system’s overall resilience [18]. Conventional microgrids face several challenges due to the intermittent nature of RES and the lack of efficient energy management systems. Decentralized distribution based on blockchain technology is a promising technique for microgrids to provide a secure, stable, dynamic energy management framework for sustainable power generation to meet the UN SDG (SDG7, SDG11, and SDG13) [19]. Various methods can optimize the optimal location and backup size for proper RES generation. The advancement of multi-generation energy systems such as electricity, heat, hydrogen, and cooling power may improve efficiency. However, multiple energy infrastructures such as electricity and gas, combined heat, and power (CHP) units are the best complement to distributed generation to smooth RES oscillations. Efficient utilization of heterogeneous energy sources improves the system's reliability, stability, and operational efficacy and lowers energy costs and emissions.

1.3.2. Energy system planning /modeling

Consistent efforts are required to accelerate electrification, particularly for countries currently being left behind. The development of sustainable communities requires intense planning and policies to implement RE. Transition in the energy sector is one of the priority tasks for sustainable development. Financial, technical, and social management are essential, as well as targeted policies and innovative legislation, which are complementary to be adopted for sustainable energy planning. Energy planning is based on meeting forecasted energy demand over a specific period. Long-term energy planning models typically feature a broad scope and a low level of temporal detail to prevent this exercise from becoming computationally inefficient [20].

Lack of information, data, and local expertise are significant challenges for the future widespread use of RE in developing countries. There is a demand for interdisciplinary, tool-based approaches to enable solution-based energy planning considering location-specific conditions. Because of the numerous techno-commercial challenges, solving a problem through extensive experimentation is complex. Modeling and simulation are more promising alternatives to reduce the number of repetitive and iterative tests in long-term experiments [21]. Different modeling tools with multiple details are used according to the requirement to optimize the extent of RES's integration in any specific power system. More than 85 adequate modeling and simulation tools are available to design energy system models on different planning horizons and scales, including types of generation technologies used, time frames, range of demands, construction types, investment magnitudes, and geographic coverage [22]. Most of the models assist in planning the sustainable integration of RES into the national energy system. The selection of a specific model depends on the prime objective, analytical approach, data availability, time horizon, underlying assumptions, and sectoral coverage [23]. Various research has adopted MESSAGE, LEAP, IAM, OSeMOSYS, EnergyPLAN, EPPA, MARKAL, and others to build an optimal energy system planning and simulation model.

1.3.3. Energy trade

The subsequent significant development in energy management systems is enabling local energy trading. However, energy trading has always occurred in national electricity markets, where power producers, grid operators, retailers and suppliers, and major energy companies buy and sell electricity. Due to the continued penetration of new affordable technologies such as PV systems, it is important to include prosumers in storing and trading energy in future energy markets to ensure a stable grid. Currently, prosumers are not yet part of the energy trade, mainly due to their small size and the unregulated nature of their local energy production. Energy trading networks improve energy systems' environmental sustainability, reliability, and economic patterns. Based on existing sustainability goals and principles, the scope of domestic energy trade cannot be compromised [24]. 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 RES has encouraged producers to sell excess electricity to nearby consumers to promote collective self-consumption [25]. Adequate rules and specialized trading technologies, such as P2P blockchain, are substantial [26]. Energy trading problems like privacy breaches, miscommunication, and network speed are more challenging to overcome in conventional centralized systems [27]. Therefore, early renewable platforms evolved as decentralized energy distribution systems. Numerous algorithmic studies are being conducted to optimize market mechanisms [28], coordinate supply and demand, improve trading efficiency, and reduce market manipulation [29].

1.3.4. Blockchain technology

Significant technological innovations and the progressing use of RES reinforce every consumer's demand for a sustainable, continuous, and abundant energy supply. As an emerging technology, Blockchain promises to provide tamper-proof, secure, transparent, and decentralized energy trading mechanisms that help provide sustainable environmental solutions by circulating the economy to empower consumers and prosumers. The rapid development of blockchain technology has gained interest from energy start-ups, innovation developers, finance suppliers, academic institutions, and the government. Although the substantial renewable potential is an opportunity to implement blockchain technology, financial management, innovative technology development, and acceptance of decentralized technology are still the most significant obstacles.

In the Internet world, blockchain is a secure distributed data storage application with point-to-point transmission, encryption algorithms, consensus mechanisms, and many other computer applications [30]. Information is stored in data sets called blocks and verified using cryptographic hashes. Participants can join or leave the blockchain network at any moment without impacting the system's operation significantly, and it is challenging for external attackers to gain control of the blockchain [31]. Blockchain is a computing paradigm whose core attributes are the decentralization of shared databases, higher-order distribution, and co-maintenance. From a technical viewpoint, it is a higher-order background database maintaining a public distributed ledger. The blockchain framework realizes a transfer of value and assets between individuals without any intermediate, replacing the traditional transaction confirmation systems. Blockchain technology is a P2P process in which records are not kept/updated by a single authority but distributed across the whole network so that all computer nodes have the same information. This configuration adds a new record as a new information block, explaining why this technology is called "blockchain." Adding a new block of information in the distributed ledger requires cryptographic validation. Hence, a "hash algorithm" key validates the new transaction, sending information to all network nodes. Briefly, on each transaction, two programs are executed; one generates the new block, and the other algorithm validates this newly added block. The whole record is accessible to all members in blockchain-based technology, but no one can exchange or alter the recording process. Hence, this immutable feature removes corruption and can help empower the community through sustainable infrastructure.

Based on architecture, blockchain technology is categorized into three main types: private, public, and consortium. The innovative functionality of blockchain technology is rapidly applied to an increasing number of processes. ***Figure 1*** shows the major application areas of blockchain technology.

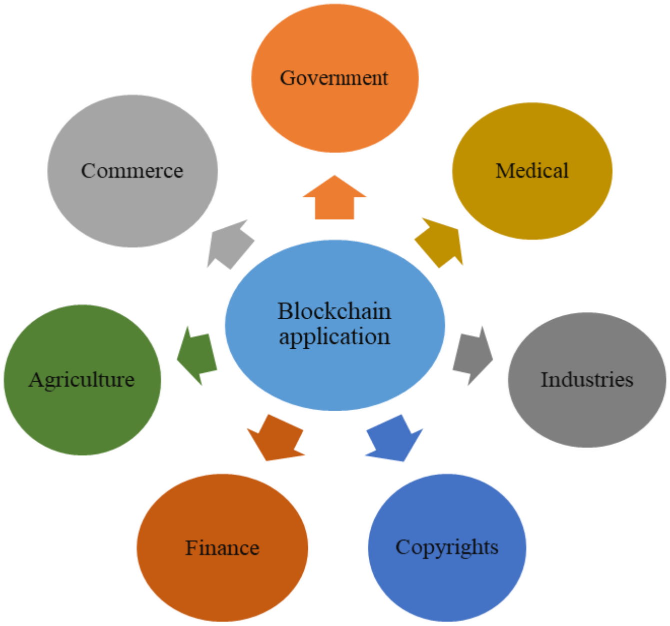


Figure 1. *Application areas of blockchain technology*

The first blockchain application was the decentralized payment of instruments [32], which expanded from one currency to multiple assets. Since blockchain technology has transparency and reliability, it has attempted to decentralize the entire market through transaction recording, smart contracts, and decentralized autonomous enterprises. Similarly, when blockchain technology is applied to distributed energy resources, the distributed energy resources system becomes more responsive, efficient, and less costly in energy supply services [32]. Blockchain technology applications in the energy distribution system automatically provide promising rectifications in the energy market [33]. Blockchain provoked an essential change in the energy market in which clients can control, convey, and sell utilities. So, prosumers can easily refer their excessive essentials to other customers inside their framework. In this way, blockchain bloomed the economic and social advantages in the energy system with better energy generation, accurate energy consumption, and transparent data tracking. Growing RE generation promoted the energy system's decentralization by including smart and microgrids. In the forthcoming distributed energy system, power buyers and sellers can contact each other directly in the P2P-enabled framework of blockchain technology [34].

Blockchain is a game-changer technology with diverse applications in various grey areas, having several built-in essential features that can augment several traditional and imminent applications in the energy sector. Blockchain has enormous energy system applications due to its socio-economic and consumer-centric influences. Until the middle of 2017, only 3% of blockchain technologies were used in energy-related areas [35]. Blockchain can reinforce three major energy trends: digitalization, decarburization, and electrification [36]. There are numerous energy system use cases where blockchain technology is applicable. Potential applications and aspects in which blockchain technology might affect the operation and management of the energy system are listed below:

- **Resource Sharing:** Blockchain offers common source sharing among multiple users, like sharing charging units for e-vehicles, energy packaging information for energy commodity trading, and many more.
- **Transparency:** Unchangeable records and transparent procedures are among the best features of blockchain technology. Further, it assists in auditing and regulating the system.
- **Billing:** Smart metering of blockchain assures automated billing for consumers and prosumers. The smart contract provides convenience in installment invoices to utility companies.
- **Competitive nature:** Smart contracts enhance trouble-free and secure switching of energy suppliers that mobilize the market with increasing competition, ultimately reducing energy tariffs.
- **Trading:** Blockchain-based trading platforms have tremendous potential to shake typical market infrastructure due to the inclusion of green certification, commodity trading transactions, risk management, and trading without intermediates.
- **Market estimation:** The energy market depends upon the supply and demand profile. The market fluctuates according to consumer preferences, environmental concerns, and individual energy practices. Blockchain technology identifies demand patterns and stimulates the market to provide a specific product.
- **Security:** Cryptographic techniques safeguard the transaction process. Blockchain secures confidential data, maintains privacy, and is reliable for identity management.

- **Automatic control:** Decentralized distribution significantly improves control of the energy grid. Behind-the-meter activities based on blockchain notably speed up the system.
- **Grid management:** Blockchain could potentially manage a decentralized grid network efficiently. Blockchain could assist in optimizing flexible alternative sources, which, as a result, affect revenue for network use.
- **Swift communication & data transfer:** Blockchain could be used for data transmission and storage through intelligent devices. Apart from data transfer, data standardization is also enabled in blockchain technology.

1.3.5. Regional energy resources and policies for going green

South Asia encompasses 3.4 % of the world's land, while the region accommodates almost one-fourth of the world's total population [37]. Such massive population growth in South Asian countries has amplified the energy demand and environmental degradation. The region's general electrification is 74% [38]. South Asian countries face energy security issues due to high dependence on a single source for electricity production that varies from country to country. South Asian governments have realized that appropriate schemes are necessary for the normal functioning of domestic and industrial activities. Several developing South Asian countries like Pakistan, India, Sri Lanka, Afghanistan, and Nepal are looking for alternate energy sources such as solar, wind, hydro, and biomass for sustainable power generation to promote enough electricity with a possible low CO_2 emission. ***Table 1*** shows the current energy mix of these countries. South Asian countries have initiated significant efforts to reduce overdependence on fossil fuels and move towards alternative energy types, specifically RE, to manage the growing demand. Geographically, South Asian countries have different climatic conditions and have easy access to various RES. ***Table 2*** offers a brief description of RE potential.

Table 1. *Electricity generation status in South Asian countries*

Country	Yearly electricity consumption kWh/capita (2018)	Yearly electricity generation TWh (2018)	Coal	Natural gas	Oil	Hydro	Renewable sources	Nuclear
			% of total					
Pakistan	600	136.3	13	34.6	16	28	4.6	3.8
India	1000	1 558.7	55	6.7	0.1	13.5	24.7	1.8
Sri Lanka	700	16.2	31	-	24	41	3.4	-
Afghanistan	-	1.12	-	-	-	-	-	-
Bangladesh	500	89.7	7.1	69.3	22.7	0.7	0.2	-
Nepal	200	6	-	3	-	96	1	-

Sources: [38], [39], [40], [41], [42].

Table 2. *The renewable energy potential of South Asian countries*

Country	Solar power kWh/(m^2·day)	Hydropower (GW)	Wind power (GW)
Pakistan	5.3	59	132
India	5	150	102
Sri Lanka	5	2	24
Afghanistan	6.5	25	158
Bangladesh	5	0.3	30
Nepal	4	83	-

Sources: [38], [40].

South Asian countries face numerous energy challenges despite having huge RE potential. Lack of quality information about RE resources and erroneous policies lead South Asian countries to unbalanced energy demand and supply or high-cost electricity generation, causing severe environmental damage. Suppose timely planning for alternate energy sources is not started. In that case, a significant gap arises between the potential of fossil fuel supply and the energy demand to achieve new social and economic development targets of South Asian countries. Further, RE is an inevitable choice for South Asian countries due to increasing attention on greenhouse gas mitigation in that region. Many researchers have scrutinized the energy systems of South Asian countries. Extensive energy planning is essential for the region's social and economic development. The primary issue in India related to power generation is the abundance of coal utilization that adversely deteriorates environmental quality. India ranked 177 out of 180 nations in the Environment Performance Index 2018 [43]. A comprehensive “National Action Plan on Climate Change” was launched in 2008 to reduce carbon emissions and increase the share of solar energy. Nepal does not have coal, natural gas, or petroleum products; there is a high dependence on traditional energy sources [44]. However, being rich in water resources and having a diverse geography, Nepal meets its energy needs principally through hydropower generation [45]. Still, the Nepalese government must spend much of its gross domestic product (GDP) to import electricity, mainly from India, especially during the dry season. The Nepalese government planned to promptly increase RE integration share from less than 1% to at least 10% and elevate this target from 10% to 30% within the next 20 years [46].

RE integration has already started in Bangladesh according to various plans. The flow of many Bangladeshi rivers has not hit its target (because of its death), making the hydro project's growth tentative. Small renewables, particularly Solar Home Systems (SHS), give an array of hope for the country's RE development goals [47]. However, SHS is not very satisfying with various problems, especially during monsoon season, when severe issues erupt. Sri Lanka plans to have 100% renewable-based generation by 2050 [48].

On the other hand, in Afghanistan, due to the damaged energy generation infrastructure, the transmission and distribution of the country's energy sector is still the least developed in the region; almost 80% of grid power is imported from neighboring countries [49]. The Afghan government has set the target to generate 5000 MW RE-based domestic power generation by 2032, equivalent to meeting 95% of the country's electricity demand [50]**.** Pakistan has plentiful energy resources, mainly RES, but unfortunately, a significant proportion of these resources are unexploited. Presently, VRE contributes less than 5% of Pakistan's' total power generation. The total installed capacity of wind power is 1 086 MW against the 100-150 GW available wind power potential.

Similarly, 430 MW solar power generation capacity is installed while the considerable potential of 100 GW is present [51]. Pakistan has enormous potential for bioenergy, being an agricultural country, covering 25% of the country's total GDP. The annual Energy Development Board reported that considering all the possible bioenergy production sources, 4 – 6 GW potential is available [52]. The overall hydropower potential in Pakistan is almost ~ 60 GW [53]. The government of Pakistan set a target to contribute 30% VRE of the country's total power generation by 2030. The European Renewable Energy Council (EREC) projected in 2018 that RES must meet at least 50% of the world's energy needs in 2040 [54]. Hence, developing countries like Pakistan should comply with this strategy to pursue global development goals.

Sufficient information on alternative energy sources and energy efficiency for competent policies have become essential for South Asian countries due to continuously depleting fossil fuel sources. South Asian countries' capacity limitations for RE integration and analysis of current energy statistics with targeted RE development projects are listed in ***Table 3***.

Table 3. *Current and prospective energy statistics of South Asian countries*

South Asian countries and RE planning	Total population [millions]	Population lacking electricity [millions]	Population electrified [%]	Rural population electrified [%]
Country	Pakistan			
	197	57	71	63
Renewable Energy Targets	• 25% of generation capacity from alternative and RE technologies by 2025, including solar, wind, geothermal, biomass, biogas, syngas, waste-to-energy, storage systems, ocean/tidal, and hybrids • 30% from alternative and RE technologies by 2030 • 30% large-scale hydro (more than 50 MW) in total generation			
Plans related to achieving those targets	○ Renewable Energy Policy 2019 (draft)			

Country	India			
	1 339	93.7	93	89
Renewable Energy Targets	• 40% of installed power generation capacity from clean energy sources by 2030 • 175 GW from RES by 2025, including 100 GW solar, 60 GW wind, 10 GW bio-power, 5 GW small-scale hydro			
Plans related to achieving those targets	○ Announcements in line with the country's Intended Nationally Determined Contribution ○ Ministry of new and renewable energy (MNRE) Year-End Review 2018			
Country	Sri Lanka			
	21.4	no data	98	99
Renewable Energy Targets	• 20% from non-conventional renewables by 2020; 50% by 2030 (except large-scale hydro) • Meet the total power demand from renewable and other indigenous energy resources by 2030 (energy self-sufficiency)			
Plans related to achieving those targets	○ Long-Term Electricity Generation Plan 2018-2037 (draft)			
Country	Bangladesh			
	164	31.3	88	81
Renewable Energy Targets	• 10% renewable generation by 2020			
Plans related to achieving those targets	○ Power System Master Plan 2016			
Country	Afghanistan			
	38	no data	98.7	98
Plans related to achieving RE targets	• Power generation from renewable and other indigenous energy resources, especially hydro-power			
Country	Nepal			
	28	no data	93	93.4
Plans related to achieving RE targets	• Long-Term RE Plan			

Sources: [55], [56], [57], [58].

2. Method, Data, and Analysis Tool

2.1. Techniques of energy system planning modeling and optimization

Developing sustainable communities requires vital planning and policies to implement RES [59]. Energy system models can provide essential analytical benefits and have a long history of supporting decision-making at national and international levels [60]. The choice of a particular energy modeling tool depends on many factors; however, various models currently address long-term energy system capacities and operational planning, such as PLEXOS, PyPAS, EnergyPLAN, OSeMOSYS, and GenX [61]. EnergyPLAN software tool developed at Alborg University in Denmark simulates national long-term energy planning scenarios [62]. It results in a shorter time using high-resolution analytical programming (hourly). According to resource availability and conversion technologies, this tool simulates the system to obtain an alternate energy system with the highest RES penetration.

The International Energy Agency estimates that 30% of the world's final energy is used in residential buildings [63]. Assessing building energy performance through modeling and simulation is a more promising approach to solving complicated problems. Several building simulation tools, such as TRNSYS, EnergyPlus, ESP-r, and Design-Builder, are used to estimate the energy performance of the building. TRNSYS, the acronym TRaNsient SYStem, is a well-known energy simulation program that deals with transient systems such as electrical systems, thermal behavior of buildings, solar energy applications etc. [64]. TRNSYS was developed at the Solar Energy Laboratory at the University of Wisconsin-Madison [65]. Community-scale energy planning with considerations such as local supply sources, storage facilities, climate conditions, and user involvement is receiving increasing attention. Hybrid Optimization of Multiple Electric Renewable Sources (HOMER-Pro) software is a community-scale energy planning tool originally developed to support the design of off-grid electrical energy systems but extended to model grid-connected and thermal systems. HOMER-Pro is used to optimize hybrid system size using an hourly energy balance and minimum net present cost (NPC) as an objective function [66].

A wide range of computer tools allows users to model and analyze energy systems at the national and regional levels to help design transition pathways. These models are often very different from one another, and therefore, decision-makers and researchers should choose the most suitable energy system modeling tool depending on the specific purpose and objectives of their analysis.

2.2. Software and data analysis tools

The entire research in this dissertation was developed and analyzed using various software and specific modeling tools. The results are generated by data processing and simulation. A list of tools and software used is shown below:

1) Microsoft Excel

2) EnergyPLAN

3) TRNSYS

4) HOMER-Pro

2.2.1. How does EnergyPLAN work?

The main objective of EnergyPLAN is to support the design of national energy planning strategies with economic and technical analyses of various alternate options and investment choices. EnergyPLAN uses analytical programming instead of establishing a series of balance equations. EnergyPLAN works purely on a deterministic approach without stochastic elements and only simulates user-defined systems. EnergyPLAN is programmed and maintained in Delphi Pascal. EnergyPLAN simulates a leap-year period as a whole. EnergyPLAN simulates the energy system at an hourly resolution level for one year.

EnergyPLAN comes with a graphical user interface in which the user can type in inputs and refer to the aspects of an energy system, such as energy demands, energy production units, resources, simulation, and operation, including technical limitations and costs (fuel costs, exchange of electricity and gas, taxes, variable and fixed operational costs, and investment costs). The outputs generated by EnergyPLAN are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs, including income from the exchange of electricity. With a temporal resolution of 1 hour, results can also be presented down to this resolution. The export facility can import the results into a spreadsheet for further investigation or illustration.

2.2.2. How does TRNSYS work?

TRNSYS simulations are constructed by connecting individual components. Each of the components in the system is a separate block (called 'Type') in which the parameters can be defined according to system requirements. These components represent a piece of equipment that a system of equations can represent to calculate its performance. Each of the input and output of the components can be interconnected so that they can communicate with each other in the TRNSYS environment, similarly to how they would be connected in real life. When a simulation is started, the TRNSYS kernel determines which Types are included in the simulation by reading the input file. It also checks the input file for syntax errors and whether all Types included in the simulation can be found in the available DLLs. If this is all correct, TRNSYS initiates the simulation. At each time step of the simulation, the kernel calls the Type routines once in the order that the Types appear in the input file. It then checks the inputs to the Types and re-calls each Type that inputs have changed from the previous call. This process continues until the inputs for all types no longer change. Then, it moves to the next time step and repeats the process. When a simulation is complete, TRNSYS writes an error log file and any output files that have been set up for the simulation. The error file contains the simulation's notifications, warnings, and error messages.

2.2.3. How does HOMER-Pro work?

HOMER-Pro, an optimization model, facilitates the design evaluation of off-grid and grid-connected power systems for various applications. HOMER-Pro requires inputs such as technology options, component costs, and resource availability to estimate a particular system. HOMER-Pro uses these inputs to simulate various system configurations and produces results as a list of feasible configurations sorted by cost parameter. HOMER-Pro simulates system operation by calculating energy balances at each phase of the year and calculating these for each system configuration. It then determines whether a configuration is feasible and estimates the cost of installing and operating the system over the project's life. HOMER-Pro repeats the optimization process for sensitivity analysis for each specific sensitivity variable. Simulation results are displayed in various tables and graphs that help to compare configurations and evaluate them based on their economic and technical merits. These tables and graphs can be easily exported in reports and presentations.

Designing a power system requires many decisions about its configuration: what components does it make sense to include in the system design? How many and what size of each component should we use? The wide range of technology options, changes in technology costs, and the availability of energy resources make these decisions difficult. HOMER's optimization and sensitivity analysis algorithms make evaluating the many possible system configurations easier.

3. Long-term Energy System Planning

3.1. Introduction

Climate change and global warming are undoubtedly the most pressing threats to human and ecosystem existence. CO_2 emissions are a major cause of the mentioned problems. A common trend is that natural resources and sustainability concerns are directly related. Due to technological progress and proper planning, developed countries are more capable of dealing with risk, while developing countries suffer the most due to violations of environmental laws. The impact of low-carbon electricity generation on energy system infrastructure is clear after understanding the harmful effects of polluting energy sources. The integration of RE plays an important role in the energy supply system, provides enormous environmental benefits, and can improve the structure of the global power system. Although increasing the use of RES to ensure a continuous and abundant energy supply is a significant goal for a sustainable and secure energy system, appropriate schemes are necessary for proper integration. Various modeling tools are available for long-term or short-term power system planning. The choice of a particular modeling tool depends on many factors, such as the primary objective, analytical approach, data availability, time frame, underlying assumptions, sectoral coverage, planning horizon, types of generation technologies used, range of demands, and scale of investment. Moreover, any planning tool we apply is only white canvas; we must make the picture.

The fluctuating nature of RE generation makes it complex to adjust at the grid level. ES is a valid option to ensure grid stability. Typically, ES systems include a range of technologies such as batteries, flywheels, pumped hydro, compressed air energy storage, supercapacitors, and superconducting magnetic energy storage. However, these technologies are quite expensive and require additional precautions. Moreover, some of them are immature. With the increasing potential of RE, the addition of ES systems has become crucial. Hydrogen is suitable for renewable ES for various reasons, such as the highest chemical energy density and high ignition temperature. It can be stored permanently and directly end-used in various industries.

This chapter presents a comprehensive long-term energy plan at the country level, considering a low-carbon strategy that integrates the most technically feasible RES into the national energy system. Energy planning and optimization are general methodologies in future energy system research. These methods' reliability and successful application depend on initial data, like the **reliable load function**, **realistic demand**, and **generation profiles**. A straightforward approach is developed to determine the hourly load function, while only workday load, non-workday load, and monthly electricity need are known. The Photovoltaic Geographical Information System (PVGIS) tool was used to develop a profile of solar power generation. The EnergyPLAN modeling tool was applied to simulate different scenarios for Pakistan, assessing the approximate extent of RES integration with relevant outcomes. The surplus energy is utilized to produce hydrogen during excess energy production hours to enhance the operational flexibility of an optimized energy system. A complete technical assessment of the power-to-hydrogen (P2H) operation of future energy system scenarios is analyzed according to the results of the EnergyPLAN. The inherent intermittent nature of VRE challenges power system stability, and the integration cost of VRE is another significant penalty. A realistic estimate of integration cost provides the electricity system planners and policymakers with the foresight to investigate such "additional" costs quantitatively. A detailed technical analysis of the maximum penetration potential of RES for the national power system was modeled according to the methodology discussed in section 3.2.

3.2. Methodology

Figure 2 depicts the methodology used to work out the EnergyPLAN Pakistan country model to analyze the technically feasible extent of RES integration based on the supply and demand balance and its impact on the power system.

The proposed method consists of several steps that can be summarized as follows:

1. Data collection: hourly load function generation, extraction of solar data for particular locations using PVGIS tool, and production of hydro dams according to monthly rain variation;
2. Model pre-processing: Modeling of EnergyPLAN tool with actual data provided in different but authentic (domestic or international) sources to simulate alternative future scenarios according to reference year;
3. Model validation: The reference model is validated using actual data in EnergyPLAN software to perform technical analysis;
4. RES potential estimation: RES's most appropriate technical penetration level is investigated considering CO_2 emissions, total system cost, and other practical limitations;
5. P2H conversion: RES penetration is apprehended, but to tackle the problem of inherent intermittency of RE, P2H operation of future energy system scenarios analyzed according to EnergyPLAN;
6. A realistic estimate of the cost of VRE integration and the limitations of installing VRE capacity in the power system.

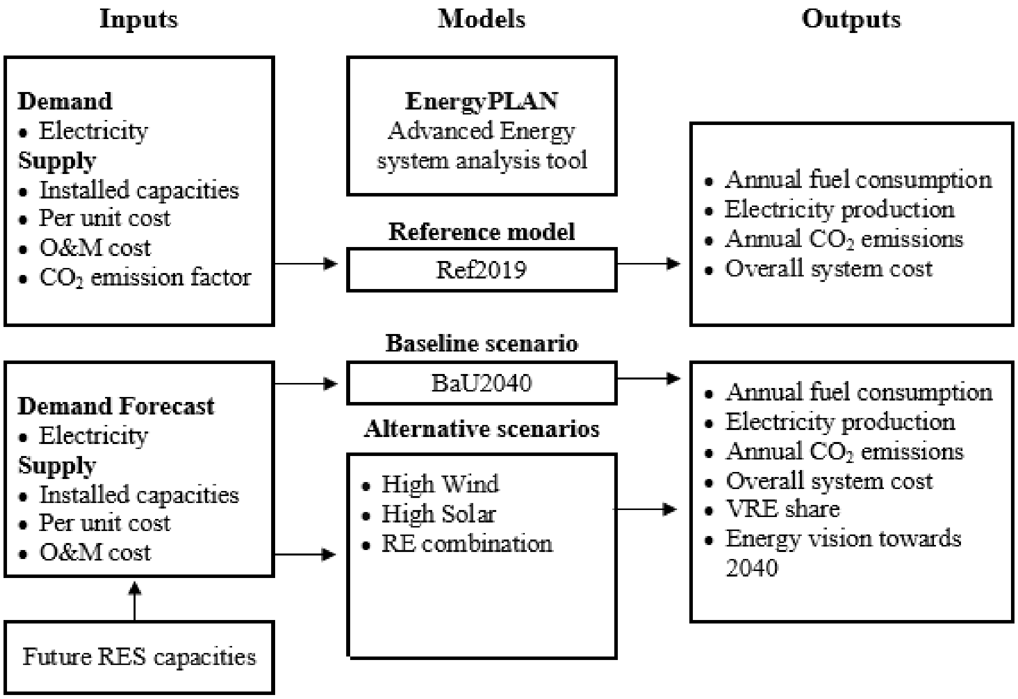


Figure 2. *Structure of the electricity model of Pakistan in EnergyPLAN*

3.2.1. Hourly load profile

An hourly load function was one of the main input data requirements for the EnergyPLAN tool. I developed a strategy to determine the hourly load function when only the workday load, non-workday load, and monthly electricity are known (see ***Figure 3***). Dividing the entire year into 52 weeks as they have working days and non-working days, including holidays. According to the monthly variation in electricity needs, a weekly increasing/decreasing trend was determined. A typical week (5 workdays +2 non-workdays) serial average was determined. The series of needed weekly standards were determined to meet monthly electricity needs for the entire year. The workdays and non-workday patterns were added (+/-) to the week's day. I developed a demand profile on the database provided in the report [67]. The seasonal workdays' and weekend days' hourly profiles were modified and merged to meet every month's electricity demand. According to the calendar, the workdays and non-workdays follow each other, so the typical pattern is set for each day, and when the load is summarized, the monthly summation and monthly variation are according to the official National Electric Power and Regulatory Authority (NEPRA) data, as shown in ***Figure 4*** below.

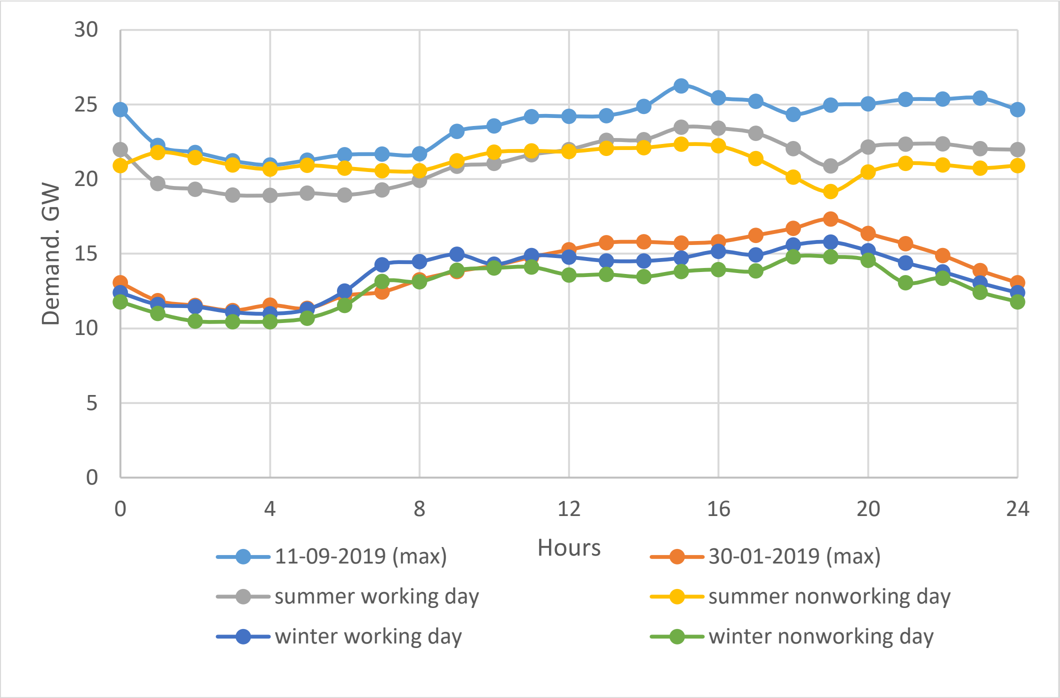


Figure 3. *Available load profiles for different days of the reference year 2019*

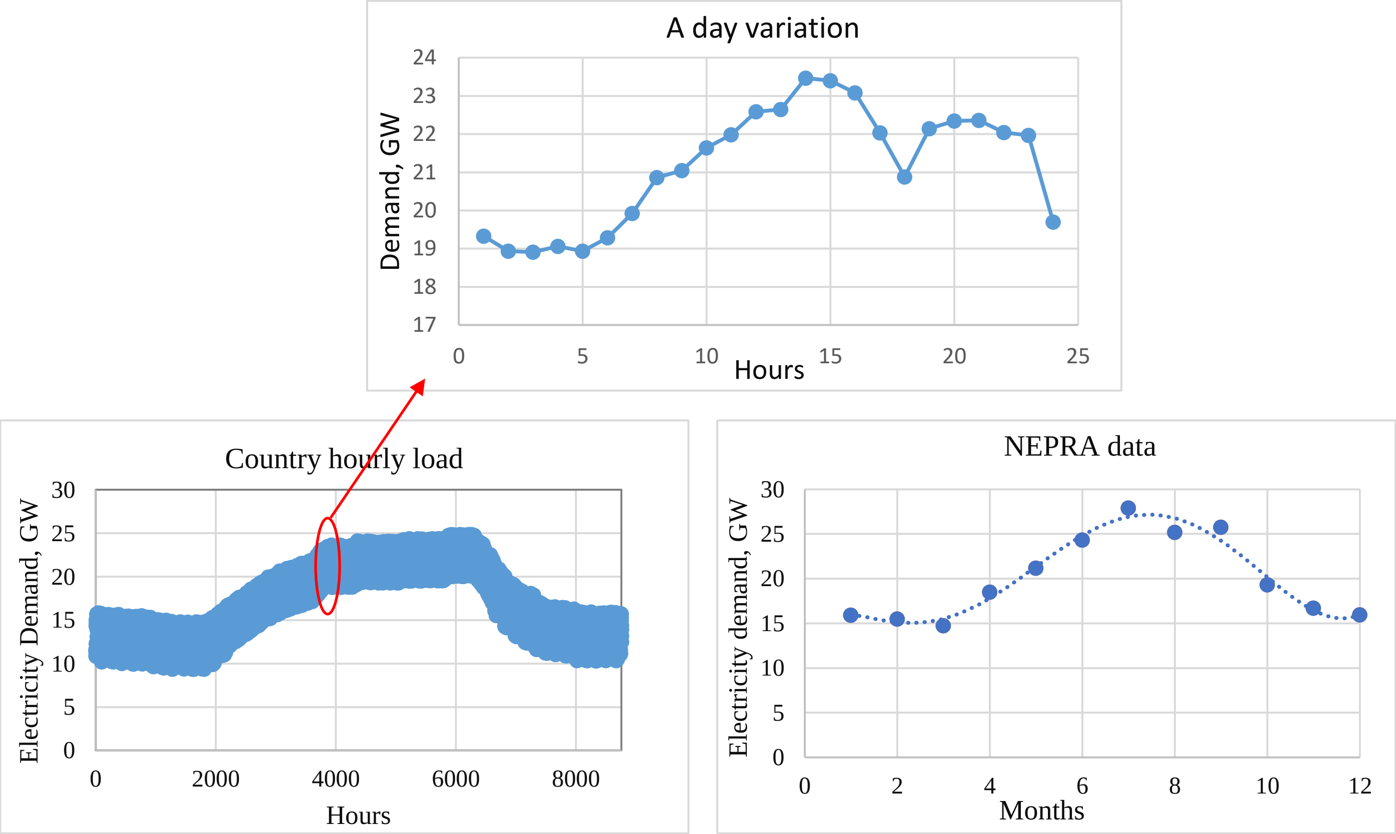


Figure 4. *Whole year hourly load variation curve and monthly averages*

3.2.2. Hourly renewable generation profiles

A summary is provided here, and the appendix contains further details about generating needed profiles.

Solar generation profile:

The EnergyPLAN software for calculating solar energy production needs a time series for an entire year that describes the actual generation by a value between 0 – 1, where 0 means no solar generation and 1 means the installed solar capacity produces power equivalent to the nominal power. Such a time series was not available. The generation profiles for solar energy were worked out on the base of the PVGIS software. PVGIS provides information on solar radiation PV system performance and helps calculate how much energy different types of PV systems can produce at almost any location in the world [68]. The hourly production curve results in the needed values if one defines the 1 kW solar power capacity (peak) for any location. A PV model calculation is needed to produce complete year data since only the typical yearly data is available for the hourly base. An alternative way to get the needed time series is if the PVGIS monthly representative day's production and solar data are used to determine the actual month's hourly data. They can merge data from a whole year. ***Figure 5*** provides the solar locations.

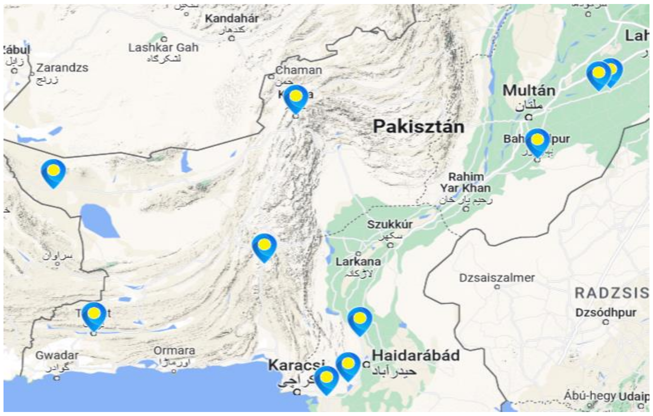


Figure 5. *Solar energy locations*

Wind generation profile:

The EnergyPLAN software for calculating the wind energy production needs a time series for an entire year that describes the actual generation by a value between 0 – 1, where 0 means no wind generation and 1 means the installed wind capacity produces power equivalent to the nominal power. Such a time series was not available. The time series construction in point is based on Pakistan's wind data and wind power generation characteristics. An early work [69] is about the wind data for Quetta, Pakistan, based on the autoregressive moving average processes (ARMA) model. The energy yield of wind turbines in Pakistan was analyzed in [70]. At that time (2009), only a few wind projects were finalized; they provided wind data only for Gharo, and the machine performance for Suzlon was 950 kW and 1250 kW, and Westas was 1500 kW. Later on, a renewable energy atlas was provided in [71]. Not only the renewable data but also some electrical-grid power time series were provided for the year 2016. The time series generated for the EnergyPLAN model in this study satisfies that introduced in [71]considering Pakistan's three years of development. Updated wind energy potential assessment and characteristics are provided in [72], where representative sites are introduced to describe the country's wind energy potential. The chosen sites for the weighted average were chosen following the [72] work. The considered areas have different capacity potentials, that is, the weighted base, and have different wind characteristics that determine the rate of the produced power of the nominal values. ***Figure 6*** provides the wind energy locations.

Figure 6. *Wind energy locations*

Hydroelectricity profile:

Calculating hydroelectric power generation requires a time series similar to those used for solar or wind generation. The hydroelectric power production profile was constructed as shown in ***Figure 7*** by considering Pakistan's dam capacity, the future developments reported in [61], the rain frequency, and the melting of the glaciers as reported in [73].

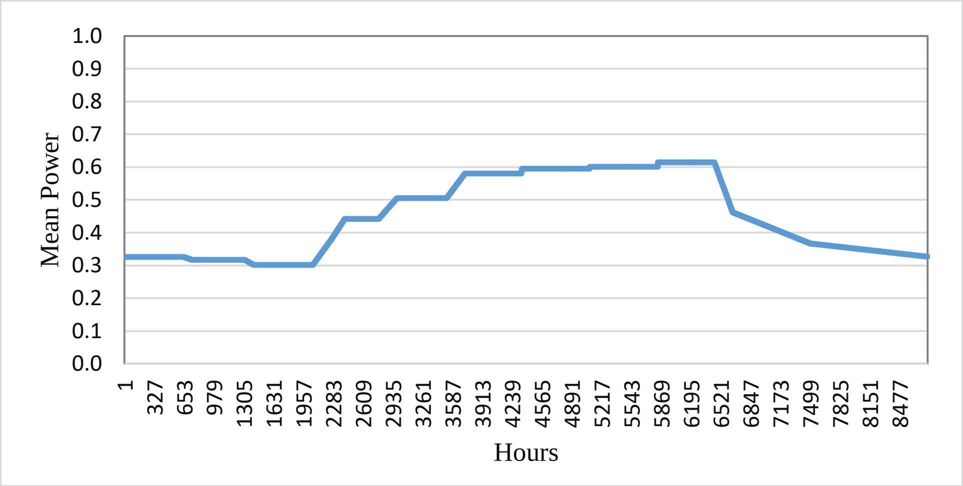


Figure 7. *Resulting hydroelectric power generation profile*

3.2.3. Thermal power generation

The EnergyPLAN can calculate different thermal power generation. ***Table 4*** provides the thermal power capacities that were considered in the calculations.

Table 4. *List of thermal and nuclear capacities in MW*

Type - installed (MW)	2019/2020	2039/2040 BaU	2039/2040 RE
Gensets heavy fuel oil combined cycle	1 793	195	195
Gensets heavy fuel oil	247	147	147
Gensets imported LNG	41	11	11
OCGT existing	0	0	0
OCGT candidate	0	16 861	16 861
OCGT existing domestic gas	3 965	747	747
OCGT existing imported LNG	6 988	4 907	4 907
OCGT committed to importing LNG	1 242	1 242	1 242
OCGT candidate imported LNG	0	0	0
ST Regasified liquefied natural gas	589	0	0
ST heavy fuel oil	3 784	0	0
ST domestic gas	180	0	0
ST Coal existing domestic coal	830	600	600
ST Coal existing imported coal	3 799	3 672	3 672
ST Coal committed to domestic coal	0	2 725	2 725
ST Coal committed to imported coal	0	1 487	1 487
ST Coal candidate domestic coal	0	1 5067	5 073
Bagasse	369	1 606	1 607
Total thermal	23 827	49 268	39 274
Nuclear existing	1 330	1 330	1 330
Nuclear committed	0	3 177	3 177
Nuclear candidate	0	0	0
Total nuclear	1 330	4 507	4 507

3.2.4. Validation of the model

EnergyPLAN requires specific inputs to calculate particular results, and the system must be validated against the actual data sets. The reference model dataset is derived based on electricity data for the year 2019. Despite the enormous RE potential, the country's renewable share in total power generation is approximately 5%. This input set is called the **Reference model (Ref2019).** Before generating future scenarios, system reliability is tested to ensure the absolute certainty of the model. Model validation involves comparing actual and modeled data to confirm whether the model responds satisfactorily to the natural environment. In this case, the reference model is developed using data from 2019.

The model's validity is checked by comparing the annual emission and the power production/consumption. Emission comparison: Data from other studies conducted by the LEAP and the TIMES models have been selected for comparison with EnergyPLAN data since no emissions data were available for the country after 2015. Actual power-related CO_2 emissions for the reference year 2019 by EnergyPLAN are 68 Mt, while [67] predict 80 Mt for 2020 and [72] 70 Mt for 2019. The monthly electricity demand was compared with the actual demand reported in the State of Industry Report 2020, and ***Table 5*** contains the results. The slight difference occurred because EnergyPLAN is a long-term planner, so minimal differences are evident if we develop a short-term model; however, results remain within the limits defined by the country's annual report. Another reason was that hydropower generation is tailored to the demand instead of the steady operation as the installed capacity and the yearly hydroelectric power generation data are required. The generation profile is constructed by considering today's and future dams' capacities and the yearly rain periodicity. The effect of the zoom-out of time is visualized in ***Figure 8*** to follow the results shown in ***Figure 9*** and ***Figure 10***.

Table 5. *Electricity demand validation – average monthly power demands*

Month	Calculated (MW)	Actual [67] (MW)	Difference (MW)	Difference %
Jan	15 399	15 938	-539	3.4
Feb	14 753	15 489	-736	4.8
Mar	14 841	14 746	95	0.6
Apr	18 543	18 516	27	0.1
May	21 697	21 191	506	2.4
Jun	24 329	24 349	-20	0.1
Jul	25 094	24 927	167	0.7
Aug	25 368	25 198	170	0.7
Sep	25 448	25 753	-305	1.2
Oct	19 735	19 328	407	2.1
Nov	16 413	16 704	-219	1.3
Dec	15 667	15 973	-306	1.9
Annual Average	19 786	19 842	56	0.3

Figure 8. *The effect of the zoom-out of the time scale in Figure 9 and Figure 10*

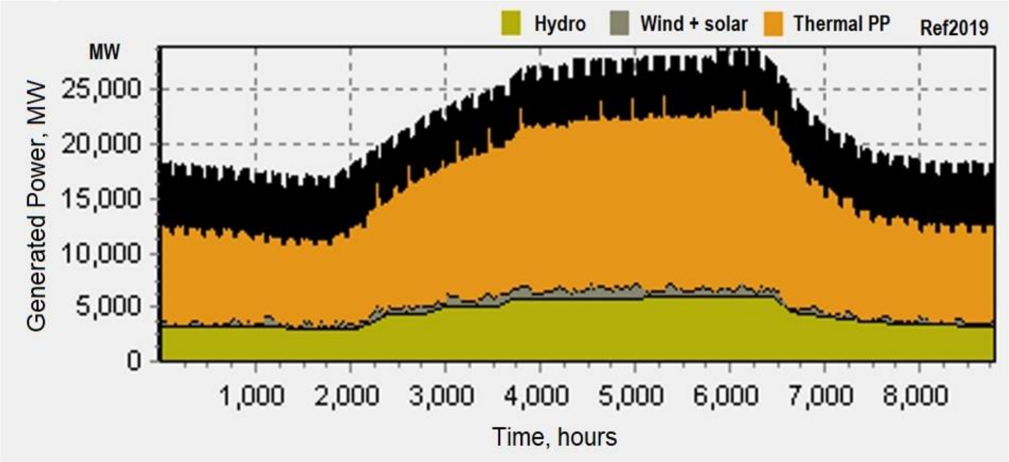


Figure 9. *Ref2019. Electricity demand and production in 2019, according to EnergyPLAN*

The Ref2019 results prove that Pakistan's EnergyPLAN country model input set is determined accordingly and suitable for assessing future scenarios.

3.2.5. Investigated scenarios

The baseline scenario 2040 was developed based on forecast data from the World Bank 2020 Annual Report. The baseline scenario is a **BaU2040** scenario. Still, there is a margin for changes in resource shares in this scenario. Moreover, the **BaU2040** simulation results can also serve to judge the reliability of my country model in point for the long-term scale. The energy mix structure (hydro, thermal, nuclear, and renewable) was determined according to the World Bank's forecast. Still, the specialists of the World Bank applied a different model approach for determining the electricity status in 2040. The basic outline of the **BaU2040** is that the calculated demand harmonizes with the national and international institutions' forecasts. The following three main scenarios are analyzed to estimate the technically feasible share of RES in the national plan, considering the same demand for all derived future scenarios.

HW2040 Scenario: Based on the BaU2040 scenario, the EnergyPLAN determines the maximum technically feasible wind capacity with minimum total system cost. The results and discussion section provides more details about high wind.

HS2040 Scenario: The same applies to solar energy; based on the BaU2040 scenario, the EnergyPLAN calculates the maximum technically feasible solar capacity with minimum total system cost. The results and discussion section explains more details about High solar.

RE2040 Scenario: This scenario is not only based on BaU2040; it combines “high wind” and “high solar” scenarios, considering integrating RES into the national electricity system. In addition, more bioenergy, nuclear reduction, and thermal fuel limitations are also considered as inputs to develop this scenario. The results and discussion section describes all relevant measures implemented to develop this final RE mix scenario for 2040.

The annual export capacity is estimated according to the most feasible RES integration range in practice. The ES option is considered to increase the overall system's flexibility and use surplus energy to produce hydrogen during excess production times, as “hydrogenation” benefits the community. VRE integration cost calculation methods differ in the literature because the power system pays when VRE is added to the generation mix by replacing thermal fuel, which depends on the research goal and system limitations. There are two main types of VRE integration costs: estimates from the market price of VRE and estimates from power system modeling [74]. I investigated VRE capacity constraints with no operational market, so my calculations follow a power system modeling approach.

3.3. Results and discussion

3.3.1. High wind scenario

Wind supply accounted for only about 3.2 percent of the country's total electricity generation in 2019. Based on the BaU2040 scenario, the maximum technological penetration of wind by 2040 is calculated using EnergyPLAN. I varied the installed wind capacity from 25 GW to 275 GW in 25 GW steps, and the total system costs were calculated. Total system cost values decrease until 150 GW of wind is penetrated, then increase with a further increase in wind capacity. Therefore, ~150 GW is technically the maximum feasible wind capacity, which accounts for 32 640 million USD as a total annual cost of the overall system.

3.3.2. High solar scenario

Solar supply accounted for only about 1.27 percent of the country's total electricity generation in 2019. Based on the BaU2040 scenario, the maximum technological penetration of solar by 2040 is calculated using EnergyPLAN. I varied the installed wind capacity from 25 GW to 275 GW in 25 GW steps, and the total system costs were calculated. I varied the installed solar capacity from 25 GW to 275 GW by the 25 GW steps, and the overall system costs were calculated. Total system cost values decrease until 125 GW of solar is penetrated, then increase with further increases in wind capacity. Therefore, ~125 GW is technically the maximum feasible wind capacity, which accounts for 46 146 million USD as a total annual cost of the overall system.

Table 6. *Electricity supply sources for different scenarios in MW (installed capacities)*

Sources (MW)	Ref2019	BaU2040	HW2040	HS2040	RE2040
Hydro	9 861	37 559	37 559	37 559	37 559
Thermal	23 827	49 268	49 268	49 268	39 274
Wind	1 248	13 494	150 000	13 494	35 000
Solar	430	35 397	35 397	125 000	65 000
Nuclear	1 330	4 507	4 507	4 507	4 507
Total	36 534	140 125	276 631	229 728	178 063
VRE capacity	4.6 %	34.5 %	67 %	60.3 %	56.2 %

3.3.3. RE combination scenario optimization

To plan the optimal VRE scenario for the country's overall electricity system with an active share of each source (renewable and non-renewable), I considered all the key results of the previous scenarios along with maximum biomass and bagasse addition and reduction of thermal fuel according to the country's current policies. To calculate the RE combination scenario, I considered some realistic constraints. I considered the hydropower potential the same as in the BaU2040 scenario. ***Table 6*** shows the reduction of thermal fuel; thermal power production was subsequently reduced to avoid further greenhouse gas emissions. The amount of bagasse was increased according to resource capacity as Pakistan currently has only 273 MW of installed capacity of bagasse while bioenergy is a major energy source, contributing 44% of total RES worldwide. This scenario includes 4407 MW of nuclear; no further increase is predicted due to high operation and maintenance costs. A total of 39,274 MW of thermal fuel was added to the final model to maintain system reliability. The VRE share was appropriate for total electricity production in this RE2040 scenario. There is no doubt that further expansion is possible. More storage capacity coupled with excess RE is required at higher penetration to reduce overall system costs.

Wind and solar sources in RE2040 are 35 GW and 65 GW, respectively. The inclination towards solar energy generation for power systems is due to many factors. One of them is the high operation and maintenance cost of wind power shown in ***Table 8***, and the small proportion of wind reduces the cost of grid integration. Based on all these logical assumptions, the RE2040 scenario is performed with EnergyPLAN, and the results are concluded. Total CO_2 emissions in this scenario are 139 Mt with an annual system cost of 47 181 million USD without GRID integration costs. The monthly electricity demand for 2040 is calculated by EnergyPLAN, as shown in ***Table 7***, and the per-year electricity demand and production for 2040 with the RE2040 model are shown in ***Figure 10***. The system balance includes imported electricity, which can be reduced by increasing hydro capacity on the one hand and the other, assuming that developed regional cooperation can sustain it in the future.

Table 7. *Monthly average electricity demand in MW – calculated by EnergyPLAN for RE2040*

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
62 023	59 421	59 775	74 683	87 386	97 987	101 068	102 174	102 494	79 486	66 105	63 101
Annual Average						79 690					

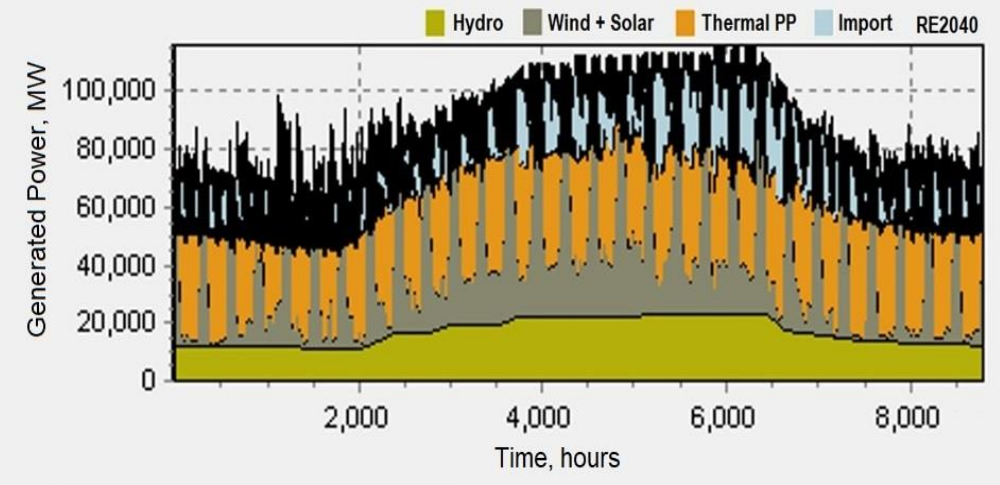


Figure 10. *RE2040. Electricity demand and production in 2040 by the EnergyPLAN*

3.3.4. **Technical analysis of electricity production scenarios**

After completing the simulation for all five scenarios (Ref2019, BaU2040, HW2040, HS2040, and RE2040) in EnergyPLAN, the results of the comparison based on two technical points: 1) CO_2 emission and 2) total system cost are listed in

Table 10. Overall system costs per unit fuel price and operation and maintenance costs for 2019 and 2040 are calculated, as shown in ***Table 8*** and ***Table 9***. The model's cost is based on the IRENA database [22], the database used for the HeatRoad4 EU project EnergyPLAN model [62], and the National Power System statistic [75]. I constructed the hourly load profile based on the workday and weekend day demands reported by NEPRA [67]. The wind and solar production hourly data were generated by calculating the region's weighted mean potentials following the HeatRoad4 EU project reports.

Table 8. *The cost parameters used in EnergyPLAN*

	Model 2019			Model 2040		
Source	Investment USD/kW	Years	O&M %	Investment USD/kW	Years	O&M %
PP+	1.8	40	1.96	1.75	40	1.96
Nuclear	4.164	60	2.4	3.36	60	2.1
Wind	0.924	27	3.84	0.876	30	3.99
Solar	0.828	35	1.57	0.624	35	1.56
Hydro	2.508	60	1.5	2.56	60	1.5

Table 9. *The used fuel cost parameters in EnergyPLAN*

Fuel type	Fuel price (USD/GJ)
Heavy fuel	12.8
Natural gas	10.77
Coal (Imported)	5.52
Uranium	0.99

Table 10. *The calculated annual costs and CO_2 emissions for different scenarios*

Name of scenario	Annual cost (MM USD)	CO_2 emissions (Mt)
Ref2019	15 001	70
BaU2040	55 018	206
HW2040	33 943	61
HS2040	46 745	145
RE2040	47 181	139

(Not including the grid integration costs)

3.3.5. Limitations of VRE capacity installation

Replacing the existing thermal sources with VRE has become inevitable due to the depletion of the oil and gas reserves. VRE is undoubtedly the most appropriate alternative energy source, but a high share of VRE challenges the power system due to inherent intermittency and uncertainty. The additional integration cost is another significant penalty for the power system and consumers when coping with VRE temporal fluctuation and geographical dispersion. The appropriate estimation of integration costs provides foresight for power system planners and policymakers. The quantitative investigation of such integration costs is challenging because it is “additional.”

The additional cost of VRE integration is stated by different terms like “hidden cost,” “variability cost,” and “balancing cost”; however, the term integration cost is widely used. Similarly, calculation methodologies of VRE integration costs differ in the literature because the power system pays when VRE is included in the generation mix by replacing thermal fuel, depending on the research target and system boundaries. There are two main categories of VRE integration costs: estimates from the market price of VRE and estimates from power system modeling [74]. My study investigates the limits of the VRE capacity; while there is no operational market, my calculations follow the power system modeling way. In developed economies where the VRE integration has reached a significantly higher level than in South Asian countries, the VRE integration cost modeling follows estimates from the market prices and the system modeling applied in the earlier state of renewable energy penetration. South Asian countries’ power systems nowadays in the transition towards this VRE integration level justify following the methodologies used, for example, investigating electricity systems in EU countries earlier [76]. The VRE integration costs apply to both the supply and demand sides, and the costs increase with the VRE penetration level. However, solar power has less integration costs than wind power due to more consistent power outputs.

The following are the essential components that require significant attention while calculating the grid integration costs.

- Defining the boundaries of each category.
- Grid costs are primarily specific to the systems and projects, and the general and typical costs have a more significant margin of inaccuracy.
- Future grid expansion parameters.
- Room for new and planning with low-cost approaches.

As mentioned above, the cost of VRE integration is project-specific. I found that if the market share is 30–40% for wind, the integration cost is 30–42 $/MWh [77]. With 10% penetration of onshore wind power, the integration cost reduces to 11–15.6 $/MWh. Similarly, for solar integration, the cost is 32–38.4 $/MWh [78]. However, according to the current estimations, these results vary widely. As per the studied literature, VRE integration values are slightly different on the supply and demand sides; they range from 2.3–12.1 $/MWh for 5–30% wind penetration, and for a similar level of solar penetration, they range from 5.5–7.1 $/MWh. Meanwhile, the demand side costs are much higher, almost 7.3–18.6 $/MWh [74].

According to the GreenNet model in [78], the two-step model contains 1) the assumptions on the extra grid reinforcement cost and 2) short-term system balancing. The author believes that applying only the extra grid reinforcement cost in the long-term planning period is enough to derive additional criteria in determining the limits of the VRE integration. The grid reinforcement costs related to the solar and wind penetration from [77], [74], [76], and [78] were collected into an Excel sheet. Two formulae were assessed for estimating the Grid Reinforcement costs: a power function used in the literature and a second-order function. I found that the power function has an

R^2=0.98 value while the introduced second-order function has an R^2=0.996 value in the range where the related data were found. So, considering the above, I applied the second-order polynomial function for the investigated power range to calculate that specific cost.

$$GRC = ap^2 + bp + c \qquad (3.1)$$

Grid Reinforcement Cost (GRC) in USD/MWh, and p means wind or solar penetration in terms of the generation ratio of the total production, a, b, and c terms are specified as the solar or wind power generation is in point:

Solar power generation: a=17.4, b= 0.31, c=5.4

Wind power generation: a=161, b=-16, c=2.5.

Wind capacity:

Calculating the wind-related grid reinforcement cost according to equation **(**3.1), my estimation function results in, for example, if p=0.1, 0.2, and 0.3, then *GRC*=2,5, 5.7, and 12.2 USD/MWh, respectively.

Applying equation **(**3.1) elaborates on the natural trend that increasing wind energy production means a more significant increase than linear dependence. The BaU2040 reference includes 13.49 GW of wind and 35.4 GW of solar power. When I investigate the maximum rate for wind power, the additional ("penalty") wind production is subject only to the calculation. ***Table 11*** illustrates the details of the calculation.

The total cost is seen as empirical results, and with a second-order estimation, the absolute maximum (limitation) for wind power capacity is 57.86 GW with a total yearly cost of 45 903 million USD.

Table 11. *Variation of the total cost for wind capacity, including the grid integration cost*

Installed Wind Power	Units	(GW)			
		25	50	75	100
Total Annual cost	MM USD	51 057	44 449	39 733	36 347
Wind Generated Electricity	GWh	73 060	146 120	219 180	292 240
Penetration Ratio	-	0.10	0.21	0.31	0.42
Surplus production	GWh	33 625	106 685	179 745	252 805
Grid Reinforcement Cost	USD/MWh	2.6	6.2	13.3	23.9
Additional Cost	MM USD	269	2 042	7 397	18 716
Total Cost	MM USD	51 326	46 491	47 130	55 063

Solar capacity:

Maximum (limitation) capacity is followed similarly to the wind for solar power. ***Table 12*** summarizes the results. The surplus production is calculated over 35.4 GW production as this value is in BaU. Calculating the solar-related grid reinforcement cost according to equation (3.1), my estimation function results in, for example, if p=0.1, 0.2, and 0.3, then GRC=5.6, 6.2, and 7.1 USD/MWh, respectively.

The total cost is seen as empirical results, and with a second-order estimation, the absolute maximum (limitation) for solar power capacity is 95,3 GW with a total yearly cost of 50 419 million USD.

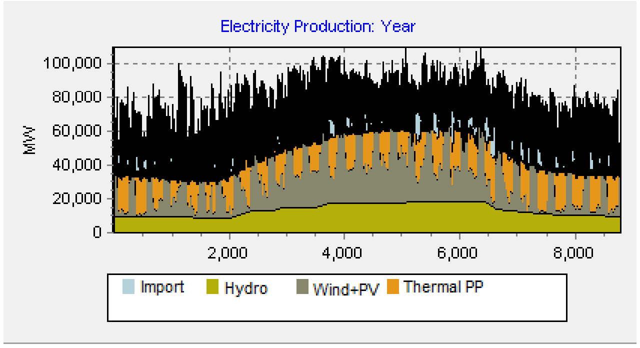
Table 12. *Variation of the total cost for solar capacity, including the grid integration cost*

Installed Solar Power	Units	(GW) 50	75	100	125	150
Total Annual cost	MM USD	52 197	48 889	47 230	46 745	46 248
Solar Generated Electricity	GWh	108 997	163 495	217 994	272 492	326 991
Penetration Ratio	-	0.156	0.234	0.311	0.389	0.467
Surplus production	GWh	31 834	86 332	140 831	195 329	249 828
Grid Reinforcement Cost	USD/MWh	5.9	6.5	7.2	8.2	9.4
Additional Cost	MM USD	583	1 729	3 153	4 961	7 260
Total Cost	MM USD	52 780	50 618	50 383	51 706	53 508

3.3.6. Power to hydrogen option

Assessing the power to hydrogen conversion as one of the promising approaches of ES, energy planning is done for a bit shorter term. Detailed energy planning of the Pakistani electricity system for 2030 is done with the EnergyPLAN software tool. I developed a more intensive scenario, considering the system integration costs associated with increased RES share. Electricity demand and production, along with the estimated amount of surplus production for 2030 by the EnergyPLAN, are shown in ***Figure 11*** and ***Figure 12***.

Simulation results for the RES-2030 scenario showed an export capacity of 50TWh/year. If we use this energy to produce hydrogen, electrolysis is the best procedure to feed it with RES to produce emission-free hydrogen. Two promising electrolyzer types are alkaline electrolytes (AE) and polymer electrolyte membranes (PEM). Based on current technologies, AE and PEM have 50kWh/kgH_2 electricity consumption [66], which will probably be further reduced with technological advancement. According to his conversion factor of 50TWh/year, electricity can produce 1Mt H_2 annually. According to our calculation, 1Mt hydrogen equals 2.89Mt diesel fuel, which can be substituted as a green transportation fuel and results in 0.72 Mt CO_2 emission reduction. Potential outputs in different hydrogenation sectors are shown in ***Table 13***. Though hydrogen has tremendous utilization potential in numerous fields, public transportation is most appropriate.



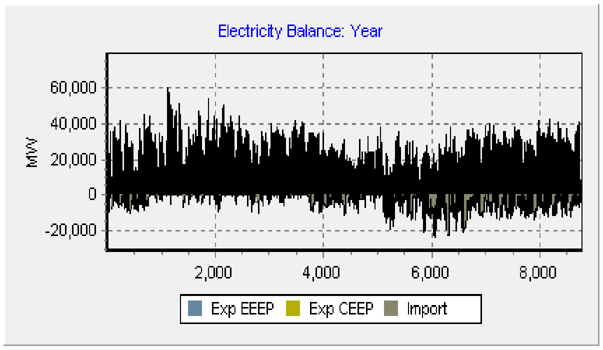


Figure 11. *Electricity demand and production in 2030 by the EnergyPLAN*

Figure 12. *The surplus and import needs in 2030 by the EnergyPLAN*

Table 13. *Potential outputs in different sectors of the hydrogenation*

Sector	Diesel fuel performance	Hydrogen performance	Specific CO_2 reduction	1Mt H_2 distribution	Output	CO_2 reduction
Passenger urban (bus)	60 pass-km/kg	173.4 pass-km/kg	0.004 kg/pass-km	25%	$4.34 \cdot 10^7$ pass-km	$1.81 \cdot 10^5$ ton-CO_2
Passenger Rail	210 pass-km/kg	607 pass-km/kg	0.0012 kg/pass-km	10%	$6.07 \cdot 10^7$ pass-km	$0.723 \cdot 10^5$ ton-CO_2
Freight Rail	15.62 ton-km/kg	45.1 ton-km/kg	0.016 kg/ton-km	30%	$1.35 \cdot 10^7$ ton-km	$2.17 \cdot 10^5$ ton-CO_2
Freight Road	4.25 ton-km/kg	12.3 ton-km/kg	0.059 kg/ton-km	35%	$0.43 \cdot 10^7$ ton-km	$2.53 \cdot 10^5$ ton-CO_2
				100%		$7.23 \cdot 10^5$ ton-CO_2

3.4. Summary

RES integration in long-term energy planning is crucial to cope with growing energy crises and future energy challenges. Although VRE is recommended as the most suitable alternative energy source, the level of penetration of VRE in the planning phase is entirely dependent on geographical location and resource potential. With the help of an energy modeling tool, a more realistic insight is provided to investigate the limit of VRE integration capacity in the national power system. Considering the system integration costs associated with increased VRE share, the EnergyPLAN tool develops a more intensive scenario than the official national plan. Alternative scenarios were formulated, such as the increased level of renewable energies and their combination regarding the national plan as the BaU scenario to simultaneously set more appropriate but ambitious targets.

Intermittent supply from RES makes it mandatory to have a backup energy source, which could store energy from RES during excess production hours. Energy storage technology is in the development phase, and P2H conversion is one of the promising approaches of ES. The results show that this plan is effective and can be extended to other regional countries. The long-term energy planning method helps countries achieve their sustainable climate goals.

I focused on the generation side and considered areas connected to electricity, but I did not deal with areas not connected to electricity. I see the electrification of these areas as feasible rather than expanding the electricity network, with a technological leap of sorts, in line with the views of many other researchers, where small and medium-sized local networks are created in cooperation with new market methods like blockchain technology. I see the need to develop long-term planning further to include these new technologies in the design toolkits.

The new scientific findings of the **Chapter 3** are summarized in the following theses.

Preface of Thesis 1, Thesis 2, and Thesis 3:

Developing a model of a country's entire electricity system is usually a complex task. The complexity depends on the content and scope of the model. During the PhD study, the depth of the developed model of the Pakistani electricity system is suitable for conducting medium- and long-term technical and economic studies. The proposed method is based on the **available public data**; in the same way, any country model can be generated when similar data are available.

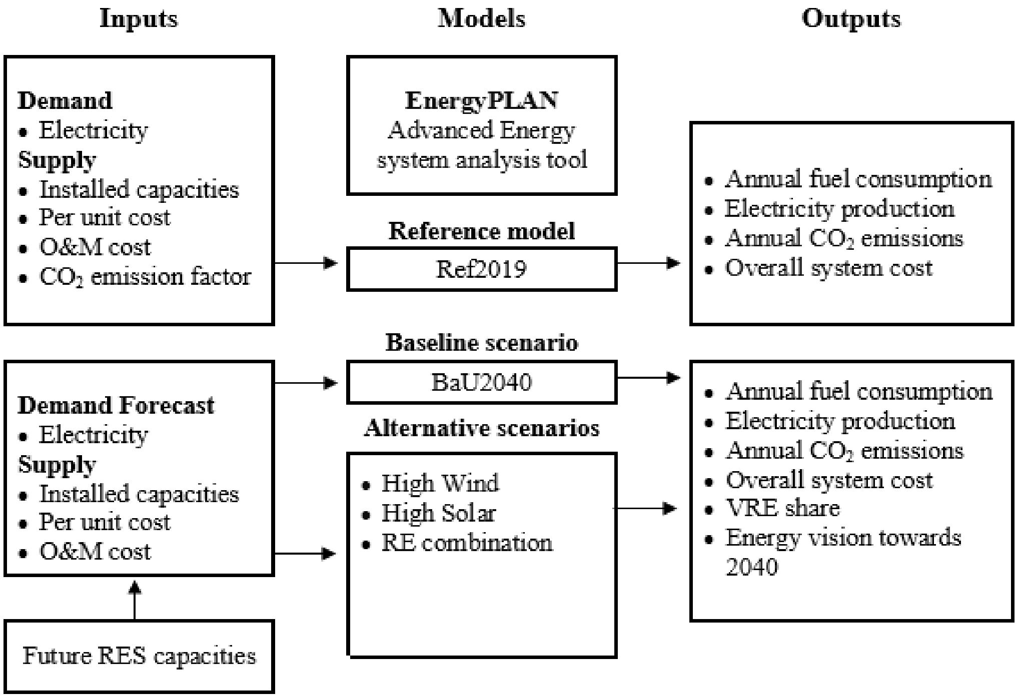
Thesis 1:

According to the requirements of the EnergyPLAN framework, a model of Pakistan's electricity system has been developed. The implementation of the model involves the development of the following main steps:

1. Based on monthly aggregated energy demand, knowing the consumption curves of winter and summer seasonal working days and weekend days, the energy demand profile is generated for the entire year (8760 hours).
2. Thermal power plants are not considered individually but with a power plant characterized by average efficiency.
3. The hourly output curve of photovoltaic power plants (0..1) takes into account the location of power plants already installed in Pakistan and planned expansions so that the solar potential of each area is determined as the weighted proportion of the capacity in that area.
4. The hourly output curve of wind turbines (0..1) takes into account the location of wind farms already installed in Pakistan and the planned expansions so that the potential of each area favorable to wind energy is determined as the weighted proportion of capacities that can be considered in that area.
5. The hourly power curve of hydroelectric power plants (0..1) takes into account the geographical location of existing and planned hydroelectric power plants and the rainfall of the given area.

6. Validation is made by two steps: (1) is based on the present (2019) real power generation and consumption data, and (2) the projection calculated by another method (e.g., World Bank's projection) is re-modeled.

The following figure summarizes the content of the Thesis 1:



Thesis 2:

The Grid Reinforcement Cost (GRC) for Asian countries can be calculated as $GRC = ap^2 + bp + c$, where for solar power generation: *a*=17.4, *b*= 0.31, *c*=5.4, and for wind power generation: *a*=161, *b*=-16, *c*=2.5 and p means the penetration ratio, calculated as the yearly generated power by solar or wind relative to the whole yearly power production.

Thesis 3:

Using the Pakistan electricity system model implemented in the EnergyPLAN framework, with the introduced Grid Reinforcement Cost formulae, the solar and wind capacities can be optimally utilized if 95 GW of solar capacity and 58 GW of wind power capacity are installed.

4. Renewable Energy-based Rural Electrification

4.1. Introduction

Undoubtedly, the growing population will increase the global demand for fossil fuels in the coming years as the need for secondary energy sources will continue to increase, requiring systemic solutions that can contribute to the sustainable development of the global energy system. On the other hand, it is widely known that the effects of climate change intensify with the use of fossil fuels. Abnormal variations in weather patterns are caused directly or indirectly by human activities and the release of greenhouse gases into the atmosphere from burning fossil fuels, necessitating a shift from fossil fuel use to renewable sources.

RE is the future of the global energy supply system, as the full utilization of carbon-neutral energy sources is crucial to achieving sustainable development goals. The increased use of RES has encouraged producers to sell excess electricity to nearby consumers, promoting domestic energy trading. Decentralized electricity generation from RES is the most promising alternative to direct fossil fuel burning as a common practice in rural areas without disrupting services. The development of decentralized generation is strongly linked to the emergence of energy communities, which have broader positive techno-economic and social objectives than conventional RE production.

Optimal consumption management improves the flexibility of power systems, provides customer comfort, and enhances overall system security. Demand-side management provides flexibility to consumers by changing their load usage patterns to participate in energy sharing. I investigated the optimal operation of a multi-carrier energy hub (EH). The HLM approach is proposed to help the customer actively participate in energy management by shifting the energy demand from peak to off-peak hours. Further, to address the surplus energy production from RES during enough production hours, an ES is integrated, and charging and discharging of the ES are scheduled according to the hub demand. Domestic-level energy trading options without grid involvement are investigated in economic terms.

Energy utilization methods are undergoing numerous updates to meet increasing energy demand and severe climate challenges. An energy-sharing model is simulated for two identical residential buildings to estimate the impact of prosumers on future local (stand-alone) energy systems. The system's technical, economic, and environmental performance are evaluated using TRNSYS software. A dynamic energy management approach based on TRNSYS and blockchain for real-time energy sharing between two buildings is proposed. Simulation results demonstrate that RES-based local energy production and household-level energy trading facilitate the dual benefits of reducing consumer costs and maximizing self-consumption. An ever-growing population and industrialization cause a continuously increasing electricity demand, directly burdening the central grid. The unavailability or remoteness of the central grid makes off-grid power generation the most reliable source of electricity to meet the needs of peripheral areas [79]. RES-based electrification of remote areas through decentralized generation has emerged as a low-cost and practically viable solution, as grid expansion is expensive [80]. HOMER-Pro software is used to determine the optimal RES-based hybrid energy system. Based on the optimized system, a new system was proposed and developed using HOMER-Pro software to investigate the energy trading potential.

Notably, the grid extension requires uniform strength development of the complex system (an increase of power plant, transmission line, and distribution capacities). Otherwise, partial grid extension will sooner or later lead to significant malfunctions. The feasibility of electrification without grid extension must be assessed in this context. While the local electricity system (micro-grid) is smaller than the country grid by several magnitudes, similar steps must be taken to work out a reliable model: assessing the load and the resources. Moreover, the local energy systems have more options for configuring and optimizing the system. The following chapters introduce the evolution of modeling rural electrification solutions from one house to the whole village approach.

4.2. Home energy system

4.2.1. Selected site

A typical residential village is selected from a rural area in the Quetta district of Baluchistan province, Pakistan. This village is situated at 30.17º N and 66.97º E of Pakistan, as shown in ***Figure 13***. The target site was chosen for obvious reasons, such as (1) 72% of the total population of the province lives in rural areas, (2) Electricity is still not available in 64% of Baluchistan areas; in other words, only 36% of Baluchistan has access to electricity (3) Due to the scattered population in rural areas, it is quite impossible to provide electricity to all areas in the current economic situation of the country (4) Significant power generation potential from RES, particularly tremendous solar power potential in the selected region [81].

Figure 13. *Selected site from Pakistan*

4.2.2. Electrical demand

The number of appliances and the energy consumption by each appliance per hour must be known [82] to calculate the energy demand of the entire household. Energy used per day is calculated using the equation (4.1). Usually, the appliance's power is denoted by P, how many appliances are installed is denoted by Q, and the number of hours used by h.

$$Energy\ per\ day = P \cdot Q \cdot h\text{ , Wh/day} \tag{4.1}$$

In each study, the energy demand is changed according to the desired scenario; for one house, a typical two-bedroom house with one living room is selected from rural areas. The estimated number of people living in this house is 3 to 4, and only one person stays home during the day. Another above-average type of household is selected to show the impact of responsive appliances. That is why load profiles are slightly different according to the case study is in point. Additionally, the load to the rural residential community is assessed based on daily electricity consumption. Further, load assessment is extended to the entire rural residential community based on daily electricity consumption. Subsequent sections provide the complete details.

4.2.3. PV modeling

Rooftop PV systems are general and accepted distributed generation technology that enhances household self-sufficiency and reduces the burden on traditional power plants. The inherently intermittent nature of the PV system causes output uncertainty. The safest way to deal with this risk is to forecast the amount of energy the PV system generates. Day-ahead scheduling is a reasonable choice due to the high precision of weather for the next 24 hours, but it is not a subject of this Ph.D. study. The PV system must be sized according to the energy demand and availability of solar energy for specific sites. A typical residential house's total daily load is expressed as P_{load}. The kW power's PV size (PV) can be calculated using equation **(**4.2**)** [83].

$$P_{PV} = \frac{P_{load}}{(\text{P.S.H} \cdot \eta\text{system})}\text{ , kW} \tag{4.2}$$

Quetta's peak sunshine hours (P.S.H) are 4.26h [84]. The system efficiency (η_{system}) is 80%, including connection losses and a dust factor. Jinko Solar JKM 400 M–72H, with a rating of 400 W_p, are assumed to be installed on the house's rooftop at a 28º slope [85]. ***Table 14*** shows the specifications of the selected solar panels.

Table 14. *Specifications of 400 W power solar panel (Jinko Solar JKM 400 M–72H)*

Attribute	Value	Attribute	Value
P_{max}	400 W	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
V_{oc}	49.8 V	Weight	22.5 kg
Is	10.36 A	Front glass	3.2 mm tempered glass

4.2.4. Battery characteristics

Since the power generated by the RES is not constant throughout the day, an ES system is essential for system stability in dealing with the fluctuating supply. A battery is used as an ES system to improve load reliability. The ampere-hour (Ah) capacity of the battery (C_{batt}) with one autonomy day is calculated using equation (4.3) [83].

$$\text{Cbatt} = \frac{P_{load} \cdot N_a}{(\text{DOD} \cdot V_{rated} \cdot \eta_{battery})}, \text{Ah} \tag{4.3}$$

The typical residential load in a day is P_{load}, and N_a is the number of autonomy days (a day with minimum solar irradiation) required consecutively. A depth of discharge DOD greater than 80% should be avoided, and the optimum DOD is usually between 20% and 60% on average. Also, V_{rated} is the voltage of the system in Volts. $\eta_{battery}$ is the efficiency of the battery. Nissan Leaf AESC LiNM battery is assumed to be installed in the house as this battery choice supports the high user demand [86], and ***Table 15*** provides the battery's specifications. Using electric car batteries means a "second life" or extended life for the car batteries. Extending battery life has a strong positive impact from an environmental perspective, as proven by several research studies [87], [88].

Table 15. *Battery specifications*

Attribute	Value
Battery type	REVB (Li NM)
Model	2014 Nissan Leaf AESC LiNM
Self-discharge	5.7% per month @ 21 C
Cost	90 $/ kWh
The initial state of SOH	70%
End-of-life SOH	50%
Overall round-trip efficiency for SOC operating range	98%

4.3. Prosumer-based rural electrification using TRNSYS software

The prosumers are the new performers progressing towards a low-carbon future. Renewable-based power generation is essential to pave a path toward sustainable development. Since two neighboring houses are the basic elements of the local micro grid system, the first research step establishes a simulation model for two identical residential buildings to assess the prosumer's impact on future local (standalone) energy systems. According to Pakistan's climate conditions (see ***Figure 14***) [89], the standalone system's technical, economic, and environmental performance is evaluated using TRNSYS software. The suggested approach provides the starting point of a real-time framework of energy trade between two rural houses connected with a common micro grid. 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 ES 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.

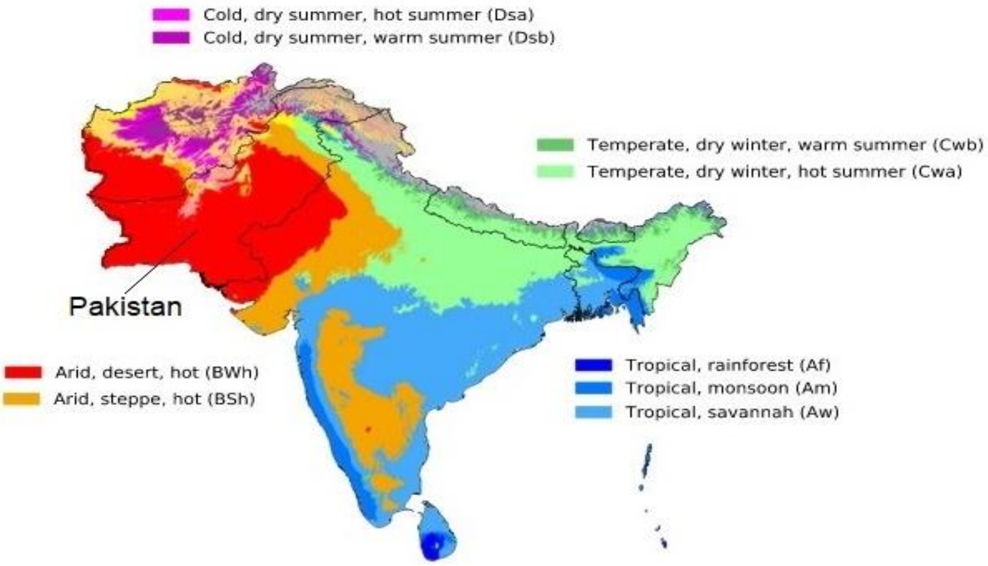


Figure 14. *The climate classification of South-Asia*

4.3.1. Methodology

To empower the conversion of traditional electricity consumers into electricity prosumers, even in rural areas. Extensive technical analysis is provided to highlight energy trade between buildings effectively. Economic analysis is done to support the forecast.

The proposed method consists of several steps that can be summarized as follows:

1. The daily energy demand of a residential house is calculated based on real-time data.
2. The PV system is modeled for a two-bedroom house serving the residential load.
3. Estimated and calculated results are tested using transient simulation software TRNSYS-18.
4. The system's technical, economic, and environmental performance is evaluated.

The Photovoltaic Geographical Information System (PVGIS) tool tracks the area with the highest solar radiation. Quetta City, Pakistan, was 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 using the PSH method. With all calculated and assumed parameters, the TRNSYS model is developed for a micro grid-connected residential house, which includes rooftop-mounted PV and battery. Two cases are investigated using the same simulation model. Details of all parameters and assumptions are discussed in the following.

Building characteristics:

A typical two-bedroom house with one living room was selected from a rural area of City Quetta, Pakistan. ***Table 16*** shows the list and number of appliances installed in the typical house. ***Table 17*** comprises the power consumption of each appliance and estimation data of appliance usage based on time hour.

Table 16*. 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	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

Table 17. *Total usage time in hours and power consumption per day*

Appliance	Power (W)	Quantity × Hours used	Energy	Data sheet Source
Ceiling fan, hall	82.5	1 × 17	1 402.5	[90]
Ceiling fan, room	82.5	2 × 12	1 980	[90]
Light small	8	3 × 7	168	[91]
Light big	25	2 × 7	350	[91]
Light porch	25	1 × 3	75	[91]
TV	39	1 × 16	624	[92]
Table fan	42.5	-	0	[93]
Washing machine	423	1 × 0.5	211.5	[94]
Exhaust	18.3	1 × 3	54.9	[95]
Water pump	100	1 × 4	400	[96]
Refrigerator	93.3	1 × 24	2 239.2	[97]
Iron	1000	1 × 0.5	500	[94]
Total Energy			8 005.1	
After adding miscellaneous load			10,000	

Based on the above data, the energy demand is 8005.1 Wh/day. However, two or more appliances may be turned on simultaneously, so keep in mind that there may be some miscellaneous loads and quite unusual usage times of 10 kWh/day, the estimated maximum demand for 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. Building heating and cooling demand was not considered as electricity consumption. Heating is as traditional as wood or biomass firing [98]. Air conditioning is not standard; traditionally, only the fans provide comfort in hot periods.

Photovoltaic: The load demand of a typical two-bedroom residential building is explained in the previous section, around 8 kWh/day. However, by including some miscellaneous loads, I assumed the total energy used in a day's P_{load} would be 10 kWh. According to the calculation, 3.5 kW peak power solar panels, Jinko Solar JKM 400 M–72H with a rating of 400 W, are assumed to be installed on the house's rooftop at a 28° slope [85]. Eight solar panels, each with 400 W peak power, are assumed to be installed to satisfy the 10 kWh/day household demand.

Battery: The PV system is designed with one autonomy day, making it cost-effective for 10kWh P_{load}. The Nissan Leaf AESC LiNM battery, with a 500 Ah rating, 50% DOD, 83% efficiency, and 48 V rated voltage, is selected for this case. So, seven cells, each of 7.5 V, are connected in series, forming a module, and nine such modules are connected in parallel to obtain the optimum battery capacity.

Simulation Parameters: The electricity demand of the sample residential house on a typical working day is simulated as load demand using Type9c in the simulation studio of TRNSYS, and ***Figure 15*** depicts the results for one day.

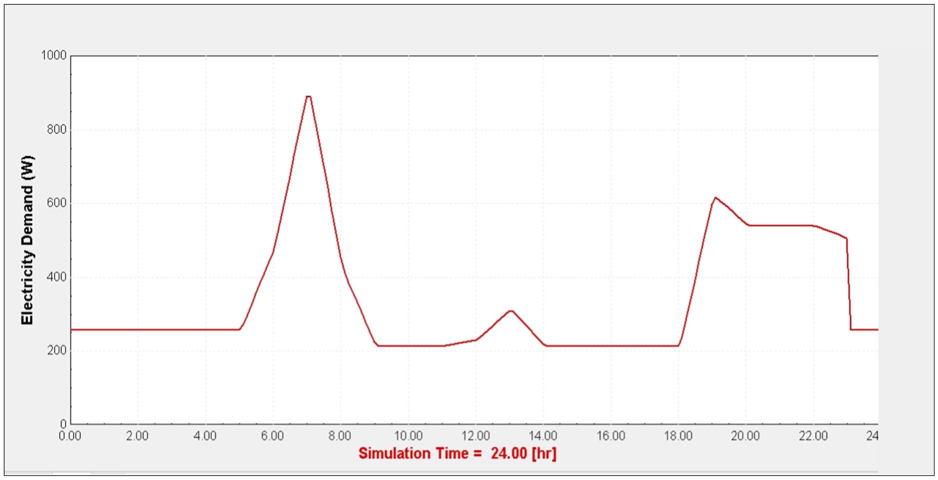


Figure 15. *Hourly electricity demand for one day*

A 3.5 kW PV system is simulated with Type103b. The input to this model is provided with Quetta's Type15-6 weather data file. ***Figure 16*** depicts the total horizontal radiation on the slop of the PV panels for one year in hourly resolution.

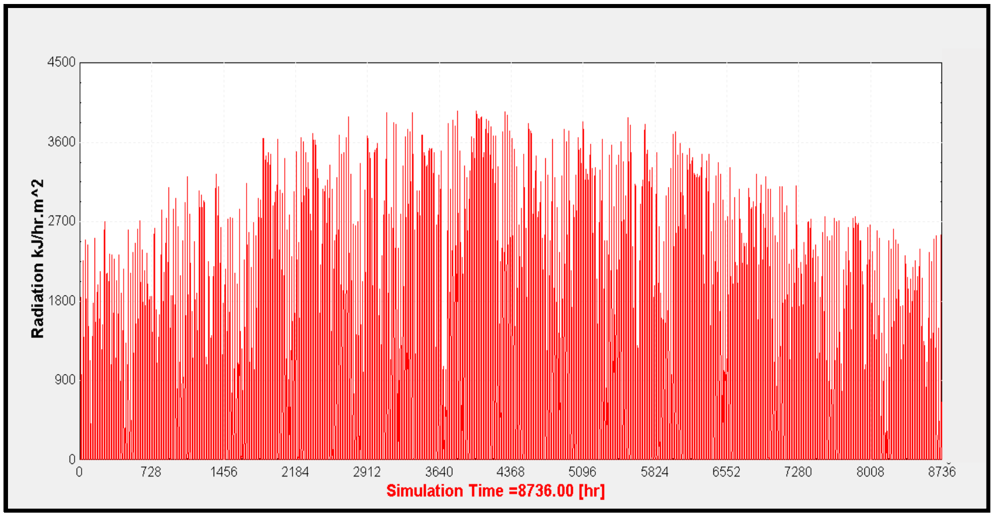


Figure 16. *Annual solar radiation*

Power production of the PV bank flows into the Inverter/Charge controller. The Type48b combined Inverter/Charge controller interacts with the Type47a battery. A 30-kWh 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 RE. 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 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 1kW rated power because PV and battery are usually sufficient to meet the load demand in this specific case. Such unit application is common in rural areas in Pakistan without PV and batteries, serving very minimum electricity [98]. 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 discharge.

4.3.2. Result and discussion

This section discusses two cases: 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 for the respective demands of the buildings. ***Figure 17*** shows the layout of the electricity model in TRNSYS.

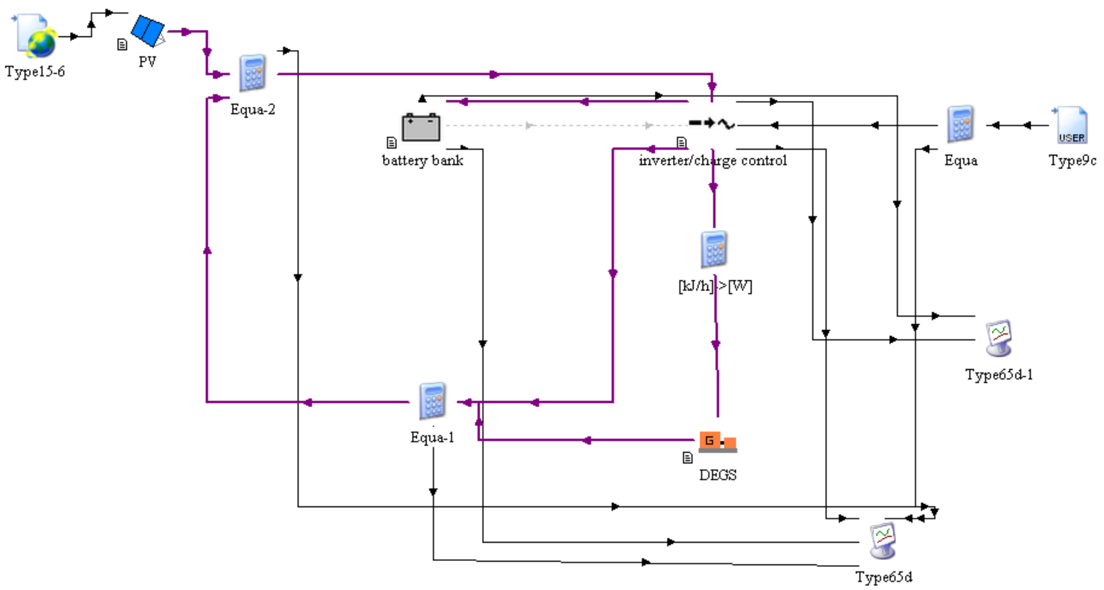


Figure 17. *The layout of the electricity model in TRNSIS-18*

4.3.2.1. Case 1

According to the sized and estimated parameters for one residential building, as shown in ***Figure 18***, the RE-based system is simulated with TRNSYS-18 from October 1 to 8 with hourly resolution. ***Figure 19*** depicts that 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 is discharged to fulfill demand. The battery did not reach its lower limit despite being discharged the whole night. ***Figure 20*** 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 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.

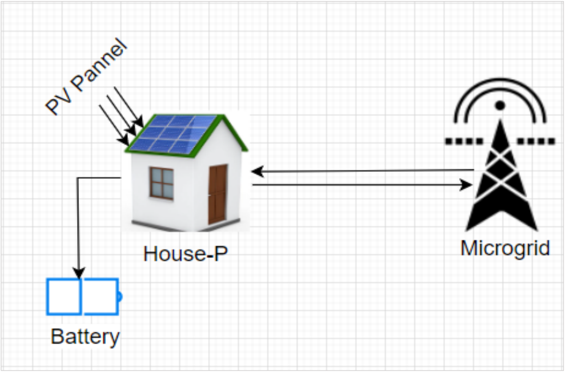


Figure 18. *One house (prosumer building)*

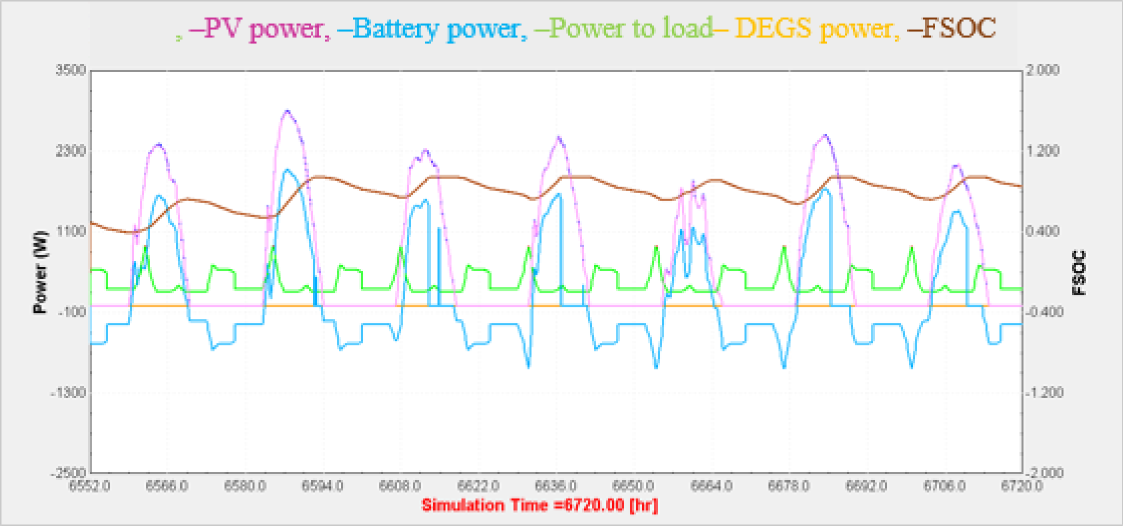


Figure 19. *Power state Oct1-8 (one house)*

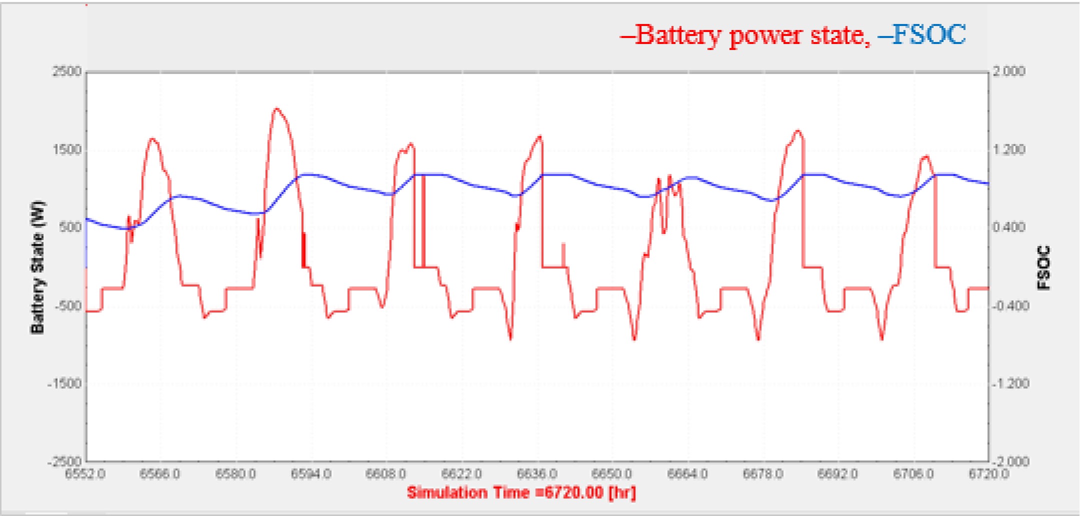


Figure 20. *Power state Oct1-8 (one house)*

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 18*** presents the average values of components and their cost.

Table 18. *PV system parameters*

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

Based on electricity consumption data, a typical house consumes 3650 kWh/a. The resulting data from the TRNSYS simulation in ***Table 19*** shows that total electricity production from a 3.5 kW 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.

Table 19. *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 $

If the total electricity demand is fulfilled from the conventional grid supply, per unit cost of electricity is followed by the government's official website, NEPRA [99]. 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 (4.4).

$$\text{Annual saving} = \text{Annual energy injected into grid } \times \text{FiT} \tag{4.4}$$

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 [99] to calculate annual savings from the solar plant.

For the second case, a cost-based metric known as the Levelized cost of electricity (LCOE) [100] of the PV system is calculated using equations (4.5) and (4.6). LCOE estimates for solar PV tend to be fairly higher than the alternatives based on standard assumptions [101].

$$\mathrm{LCOE} = \frac{\text{Total lifetime cost}}{\text{Total lifetime output}} \text{, (\$/kWh)} \tag{4.5}$$

$$\mathrm{LCOE} = \frac{\sum_{n=0}^{N} \frac{Ct+OMt+Rt}{(1+dr)^{n}}}{\sum_{n=1}^{N} \frac{Et*(1-Dr)^{n}}{(1+dr)^{n}}} \text{, (\$/kWh)} \tag{4.6}$$

According to the datasheet of this particular PV panel, a lifespan of 20 years is considered. *Ct*, *OMt*, *Rt*, and MPPT are the capital, operation & maintenance, and replacement costs of the PV system and maximum power point tracker, 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% [102].

Table 20. *Results of* ***c****ost comparison*

Type	Attributes	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	20 years
	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 \$

Finally, the cost comparison of conventional sources and PV-based systems is presented in ***Table 20*** to illustrate 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:

The consumption of nonrenewable electricity by 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 [103]. According to this emission factor, the 6000 kWh PV electricity production reduces 2154 kg equivalent CO_2 emission.

4.3.2.2. Case 2

In this case, I modeled the same plan for two identical houses, as shown in ***Figure 21***. The same microgrid connects both houses. One house is equipped with a PV and battery storage system and is 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 kW panels are mounted on the roof of house one. ***Figure 22*** depicts the simulation results reflecting that the grid is turned on to meet the demand. ***Figure 23*** shows that the battery discharges more than only one house case. The FSOC of the battery also clearly indicates its state.

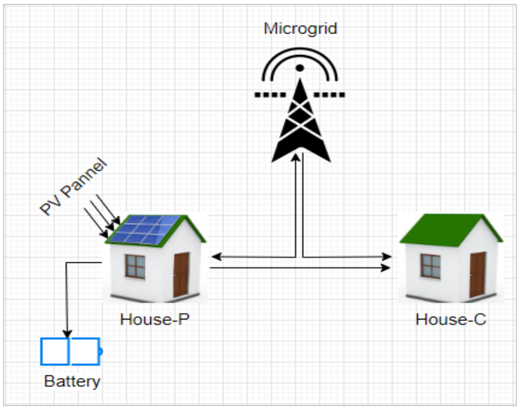


Figure 21. *Two houses (consumer and prosumer building)*

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

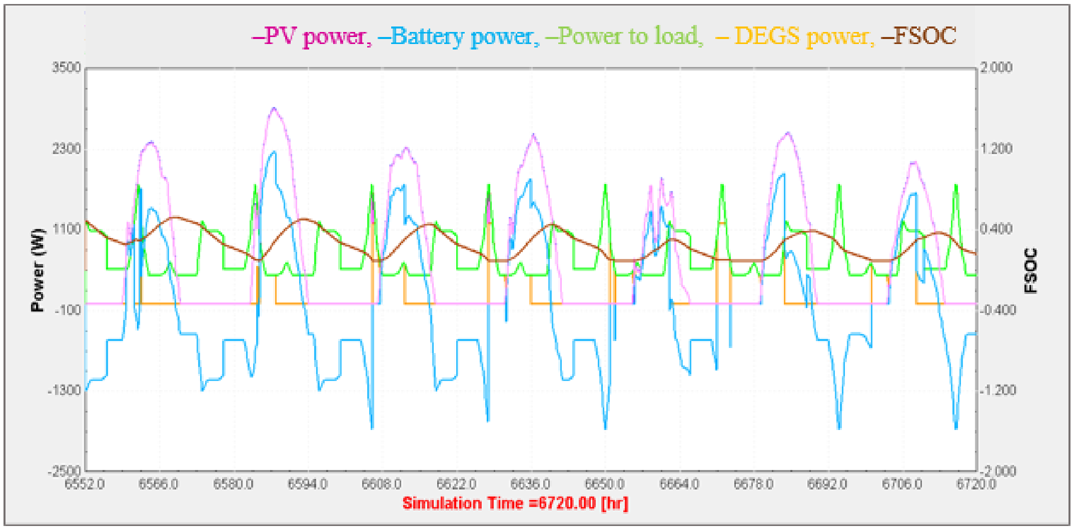


Figure 22. *Power state Oct1-8 (two houses)*

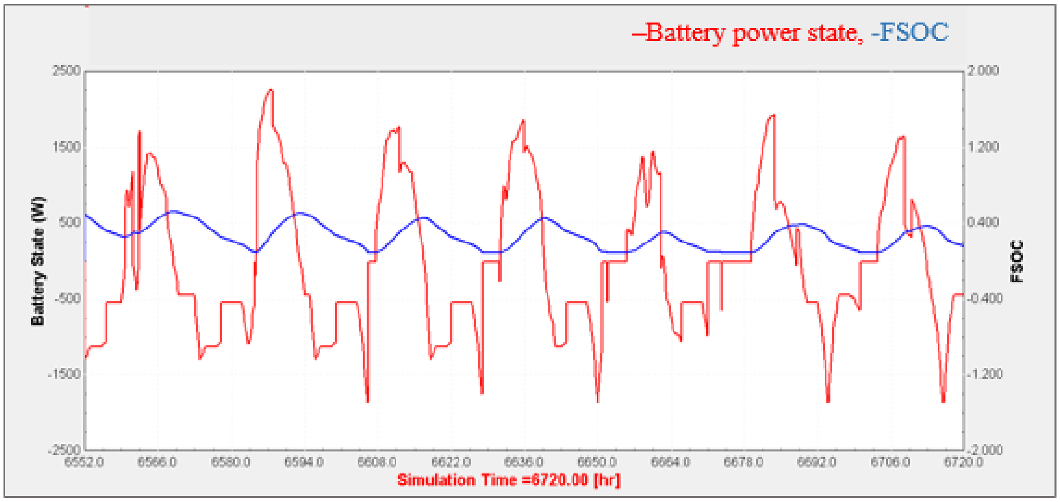


Figure 23. *Battery state Oct1-8 (two houses)*

Digitalization of electricity system with blockchain:

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 the advantage of decentralized distribution in avoiding unnecessary transmission costs. With the rising share of RES, managing the central grid is becoming more complex and has developed into distributed grid management. Appropriate scheduling and robust control infrastructure are still challenging for the energy sector regarding reliable electricity flow. 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 successful implementation in other sectors. Developed RE technologies and smart meters made this job relatively easy.

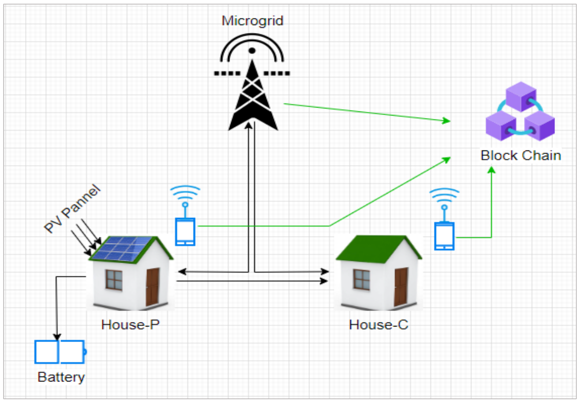


Figure 24. *Two houses layout with blockchain*

Figure 24 is a graphical representation of the basic unit of the proposed local electricity trade 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.

The scientific finding of the Chapter 4.3 summarized as follow:

Preface for Thesis 4: 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 determines the appropriate PV and battery size. The results show that a 3–4-person family house has 10 kWh of electricity demand daily. A 3.5 kW PV system is required to meet this demand efficiently. A 30-kWh battery is installed as an energy storage unit for excess production.

Thesis 4:

The TRNSYS simulation results validate that the system performance is satisfied according to design parameters, and 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. Considering the local energy trade, the simulation proved that the prosumer can cover more than half the demand for the neighboring household. Selling electricity to nearby consumers is more profitable for the prosumer and the grid.

At that point, the natural continuation of the research is extending the number of actors in the local energy trade system. Before extending the model to the whole village level, the basic unit of local electricity – energy flow between the neighboring houses and the micro grid is assessed by the EH concept, providing a more comprehensive analysis.

4.4. Residential energy hub concept for assessment of local energy trade potential

Optimal consumption management improves the flexibility of power systems and provides customer comfort. This point can be considered in the possible local energy trade system by applying the EH concept. Energy consumption statistics show that the building sector alone accounts for 36% of total energy consumption worldwide and almost 39% of total CO_2 emissions [104]. This huge amount of energy consumption is the key reason for promoting energy-efficient building design. Shifting electricity consumption times reduces peak demand. Demand response programs (DRP) have been proposed to manage household energy consumption in smart residential buildings equipped with control devices and communication channels [105]. A DRP application tool helps the customer to actively participate in energy management by shifting the energy demand from peak to off-peak hours. Home load management (HLM) programs are designed to ease the implementation of DRP. Household appliances are responsive or non-responsive, based on time-varying energy prices [106]. In HLM, controllers automatically control the manageable loads of homes according to price changes. The energy sources and responsive demands should be coordinated to maximize the benefits. Integrating different energy carriers makes the energy system analysis slightly more complicated. EH, modeling is an influential approach to coordinating and utilizing different energy sources. The EH unit receives the defined inputs from different sources and decides to transmit, convert, or store them according to the minimum cost operation. Typically, the EH receives common energy carriers such as electricity and gas at input ports and then decides when and what technology should operate to supply heat and electricity at the output ports [6]. Next, the electricity input comes from the local grid, and the gas from the biogas generator or gas storage tank. The small-scale biogas generators are ubiquitous in South Asian suburban regions [107]. The EH concept was initially applied when the electricity and natural gas pipe grids were available. Based on the abovementioned assumptions, this concept is appropriate for assessing energy systems in rural areas, as the following subchapters introduce.

4.4.1. Methodology

The residential EH framework is designed to optimize the operational mode of a multi-carrier EH. Solar panel generation and the charge/discharge schedule of the ESS are coordinated with controllable appliance demand. Hence, HLM is proposed considering time-varying electricity prices. The proposed method consists of several steps that can be summarized as follows:

1. Household load is managed by managing the energy consumption of responsive appliances.
2. Scheduling of responsive appliances was optimized according to time-varying tariffs.
3. Solar panels and battery operation are coordinated with household demand response to minimize the customer cost and maximize self-consumption
4. HLM in the smart home considers the energy trade a viable option.

Regarding the development of rural areas, modern appliances seem to be entirely up-to-date. However, it might be assumed that a technological jump in electrification might happen, as in the telecommunications industry, which happened with mobile phones: phone line technology was jumped over by mobile technology.

The renewable-based residential energy hub model:

Figure 25 shows an overview of the RES-based residential EH model. Electricity and natural or biogas are the main inputs that meet electrical and heat demands. The local electric grid and RES are the sources of electric input, while gas can provide the heat demand. The CHP unit balances a part of the electric demand and meets part of the heat demand. The electric demand consists of appliances and battery charging.

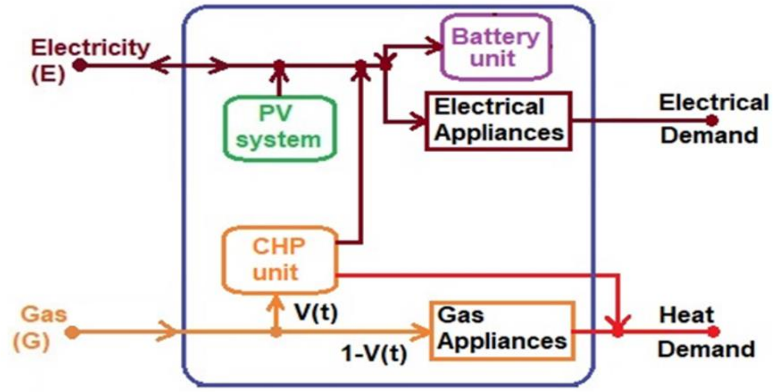


Figure 25. *Residential energy hub*

The mathematical expressions describing the power flow of the residential EH are provided below.

$$\mathrm{Egrid}\ (t) + \eta\mathrm{DC/AC} \cdot \mathrm{ERES}\ (t) + \mathrm{ECHP}\ (t) + \eta^{s}_{dch} \cdot E^{s}_{dch}(t) = \mathrm{Eapp}\ (t) + (\frac{1}{\eta^{s}_{ch}})\, E^{s}_{ch}\ (t) \qquad (4.7)$$

$$(1 - V\ (t)) \cdot (\frac{1}{\eta\mathrm{gapp}}) \cdot G(t) + \mathrm{HCHP}\ (t) = \mathrm{Hd}\ (t) \qquad (4.8)$$

$$\mathrm{ECHP}\ (t) = V\ (t) \cdot G\ (t) \cdot \eta\mathrm{g\_e} \qquad (4.9)$$

$$\mathrm{HCHP}\ (t) = V\ (t) \cdot G\ (t) \cdot \eta\mathrm{g\_h} \qquad (4.10)$$

$$V\ (t) \cdot G\ (t) \leq C^{max}_{CHP} \qquad (4.11)$$

In equation (4.7), t shows the time in hours, Egrid is the electrical energy provided by the grid at hour t, and $\eta_{DC/AC}$ is the efficiency of the DC/AC converter. E_{RES} (t) and E_{CHP} (t) are the electrical energy the RES and the CHP unit provide at hour t. Eapp (t) is the energy the electric appliance consumes at hour t E^{s}_{ch} (t) and $E^{s}_{dch}(t)$ are respectively the charged and discharged energy of the ESS at hour t, where η^{s}_{ch} and η^{s}_{dch} are the charging and discharging efficiencies of the ESS, respectively. Gas received at the hub input port supplies the heat demand and the CHP unit. The value of dispatch factor V decides the extent of dispatch between the CHP and direct heat demand. In equation (4.8), V (t) is the dispatch factor at hour t, G (t) is the gas received at the input port of the EH, and ηgapp is the efficiency of gas-consuming appliances. H_{CHP} (t) and E_{CHP} (t) are the

CHP's heat and electric outputs, respectively. $\eta_{g\text{-}e}$ and $\eta_{g\text{-}h}$ are the gas-to-electric and the gas-to-heat conversion efficiencies of the CHP. H (d) is the total household heat demand at hour t. The maximum capacity of the CHP unit is shown as, $C_{\mathrm{CHP}}^{\mathrm{max}}$.

H_{CHP} (t) and E_{CHP} (t) are calculated based on the CHP's dispatch factor and conversion efficiency. However, the CHP capacity is restricted, as shown in equation (4.11). RES is assumed to be the solar panel system installed on the house's rooftop that meets most of the house's electric demand. Solar panel output cannot be dispatched like a conventional power source because environmental conditions affect this output. Therefore, battery storage should be installed as an ES to tackle the inherent intermittency of the PV system. An appropriate PV system and battery storage are configured according to the demand of the house, and details are explained in the following sections. The operational efficiencies of EHs are considered constant to avoid unnecessary complications. In the problem formulation, the extent of the dispatch factor and the amount of gas and electricity received at the hub input are determined by solving the optimization problem of the EH.

Electricity demand:

The typical above-average residential house is selected from the rural area of Quetta city, Pakistan, where 3–4 people live, while only one person remains in the house during the daytime, as was the case previously. ***Table 21*** comprises the list and number of appliances installed in the house and the energy consumption of each appliance per hour to calculate the daily energy demand of the whole house. (Gray backgrounded lines are added to compare with ***Table 16***)

Table 21. *Installation of power consumption appliances*

Appliance	Reference	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
Fluorescent light	LF1	0	0	0	1	1	1
Fluorescent light	LF2	0	1	1	0	0	0
Fluorescent light, porch	LFP	1	0	0	0	0	0
TV	TV	0	1	0	0	0	0
Table fan	TF	0	1	0	0	0	0
Water heater and cooler	WHC	0	0	0	1	0	0
Extractor 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
Dishwasher	DW	0	0	1	0	0	0
Washing machine	WM	0	0	1	0	0	0
Iron	IR	0	0	0	0	1	0

Table 22 shows the estimated appliance usage data based on each appliance's time, hour, and power consumption, taken from the manufacturer's official website. The ceiling fan in the main hall (living hall + dining hall) (CF1) and the ceiling fan (CF2) in rooms only operate during the summer season, while in winter, there is no need for fans, so CF1 and CF2 remain OFF. The 8 W fluorescent lights (LF1) are in small places like the room, bathroom, and toilet, and 25 W fluorescent lights are in large areas of the house like the hall, kitchen, and porch. LF2 and LF1 are ON at night from 7 p.m. until 12 a.m. and from 6 a.m. till 7 a.m. LF2 stays ON during the day if someone works in the kitchen or living room. The light on the porch (LFP) is ON only for three hours, from 8 p.m. until 11 p.m. Since one person stays at home, the television (TV) is turned ON during the day from 8 a.m. until midnight. A table fan (TF) is placed in room 2 and operates according to seasonal requirements. A washing machine (WM) is used for an hour per day. An exhaust fan (EF) is mounted in the kitchen, and it is ON while cooking breakfast (7 a.m.), lunch (12 a.m.), and dinner (7 p.m. until 8 p.m.). A dishwasher (DW) operates for one hour twice daily, in the morning and evening. A water pump (WP) is used during peak hours, operating in the morning (6 a.m. to 8 a.m.), afternoon (1 p.m.), and night (7 p.m. until 8 p.m.). The water heater and cooler (WHC) are turned ON for one hour in the evening. The refrigerator (RF) is on for 24 hours. The iron is used for around 30 minutes. Based on the above data, the energy demand is 6.4 kWh/day. However, it is quite possible that two or more appliances are turned on at the same time, so keep in mind that some miscellaneous loads and quite unusual usage times of 10 kWh/day are the estimated maximum demand for this house. Electrical demand for a winter day is assumed, as shown in ***Figure 26***.

Table 22. *Energy demand per day according to appliance usage*

Appliance	Power (W)	Quantity	Hours used	Energy (Wh/day)
Ceiling fan, hall	82.5	1	-	0
Ceiling fan, room	82.5	2	-	0
Fluorescent light 1	8	3	7	168
Fluorescent light 2	25	2	10	500
Fluorescent light, porch	25	1	3	75
TV	39	1	16	624
Table fan	42.5	1	-	0
Water heater and cooler	750	1	1	750
Extractor fan	18.3	1	3	54.9
Water pump	100	1	4	400
Refrigerator	93.3	1	24	2 239.2
Dishwasher	350	1	2	700
Washing machine	423	1	1	423
Iron	1000	1	0.5	500
Total Energy				6 434.1
By adding miscellaneous load				10 000

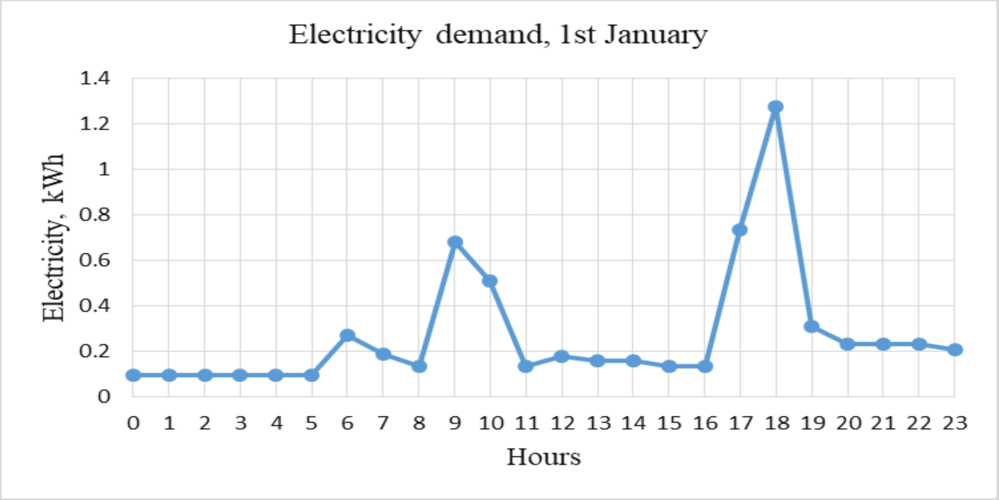


Figure 26. *Hourly electricity demand on the 1st of January*

Home load management:

Mathematical equations for residential load management for multi-carrier EHs are presented in [108]. The electrical appliances are divided into two categories: responsive $\mathrm{E}_{\mathrm{app}}^{\mathrm{R}}$ (t) and non-responsive $\mathrm{E}_{\mathrm{app}}^{\mathrm{NR}}$ (t), because the electricity prices are time-varying. The energy consumption at an hour t is Eapp (t), as shown in equation (4.12).

$$\mathrm{Eapp}\ (\mathrm{t}) = \mathrm{E}_{\mathrm{app}}^{\mathrm{R}}\ (\mathrm{t}) + \mathrm{E}_{\mathrm{app}}^{\mathrm{NR}}\ (\mathrm{t}) \qquad (4.12)$$

Responsive devices participate in the HLM program. Based on their operation time and energy consumption in response to time-varying prices, the responsive devices are further categorized as follows:

Group M includes a set of appliances whose energy consumption at each operating hour (t) is known, and the HLM program can set their operation time. The energy consumption of appliances m in group M at hour t on the next day is:

$$\mathrm{Em}\ (\mathrm{t}) = \mathrm{Em} \cdot \mathrm{Im}\ (\mathrm{t}) \qquad (4.13)$$

Where E_{m} is the energy consumption of the appliances as shown in ***Table 23***, and Im (t) is determined by solving the optimization problem by using the following equation:

$$\sum_{t=bm}^{Im} Im(t) = Um \qquad (4.14)$$

Im and bm represent the allowable time interval in which the responsive device can operate, and Um specifies a definite operation time, which should be within ([bm, Im]).

Group N includes those appliances whose total energy consumption in a time interval likely more than one hour is known, while the HLM program can set their energy consumption at each hour.

As mentioned earlier, the total energy consumption for appliances of group N is definite for the allowable operation time interval. However, the energy consumption of appliances at hour t should be determined by solving the HLM.

$$\sum_{\mathrm{t=bn}}^{\mathrm{In}} \mathrm{En(t)} = \mathrm{En} \tag{4.15}$$

Where *n* is the index of appliances in group *N* and *En* is the total energy consumed by appliances *n* in the time interval from *bn* to *In*. To provide several scheduling choices, the interval between start time *bn* and end time *In* should be more than one hour. The customer specifies the operational interval, so *En (t)* can be limited to a certain minimum and maximum value.

$$\mathrm{E_n^{min}}\ (\mathrm{t}) \leq \mathrm{En}\ (\mathrm{t}) \leq \mathrm{E_n^{max}}\ (\mathrm{t}) \tag{4.16}$$

The responsive appliances' energy consumption is the sum of the energy consumption of the appliances of group M and group N:

$$\mathrm{E_{app}^{R}} = \mathrm{Em}\ (\mathrm{t}) + \mathrm{En}\ (\mathrm{t}) \tag{4.17}$$

The operational interval and energy demand of the specific responsive appliances of group M and group N are shown in ***Table 23*** and

Table 24.

Table 23. *Data of responsive devices in group M*

Appliance	*Um* (h)	Em (kWh)	*bm*	*Im*	-
Dishwasher	2	0.35	3	13	$\sum_{\mathrm{t=3}}^{13} I = 2$
Washing machine	1	0.423	6	11	$\sum_{\mathrm{t=6}}^{11} I = 1$
Iron	0.5	1	5	13	$\sum_{\mathrm{t=5}}^{13} I = 0.5$

Table 24. *WHC data*

En (kWh/day)	bn	In	$\mathrm{E_n^{min}}$ (t)	$\mathrm{E_n^{max}}$ (t)	Um (h)	En/h (kWh)	$\sum_{20}^{6} E = 5$
0.75	20	6	0	0.15	5	0.15	

Heat demand:

The heating energy needed for a household has two parts: the energy for making domestic hot water (DHW) and the energy for maintaining inner comfort in the cold period. The amount of DHW depends on the number of family members and habits, but habits are not considered here. I assumed each family member's DHW needed to be 50 liters/day. A hot water storage tank is installed, and the boiler's heating can be electrical, or heat supplied from the CHP unit. The actual heating demand to maintain comfort in the cold season depends on the difference between the outer and the inner temperatures and on the heat transfer properties of the house envelope. The parts of the house envelope have different thermal characteristics, so the heat transfer is not uniform for the surfaces where the heat losses occur. Since precise heat loss analysis is not the subject of this research, I assume an average overall heat transfer rate (heat transfer coefficient multiplied by the heat loss area) for calculating the heat losses/heat demand for the investigated family house. In our case, a 7 x 9 m house is considered. According to Pakistan's building code (BCP-2011), the overall U value for the roof and wall should be 0.44 W/m^{2}K and 0.57 W/m^{2}K [109]. Since the regulation is over ten years old, 30% better values are considered (0.31 and 0.39). According to this, the result for the whole house envelope is 0.0535 kW/K. This value means that if the temperature difference is 1 K, the heat flow equals 0.0535 kW; this is applied since the outer temperature is available hourly. This way, the heating demand can be calculated hourly for the cold period. ***Figure 27*** depicts the hourly values of the heat flow and the heat summations on the 1st of January.

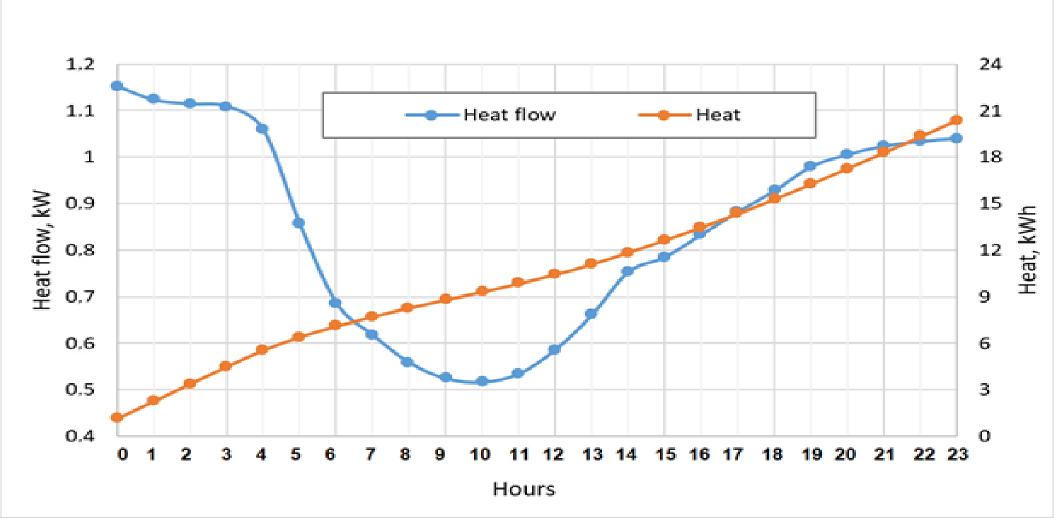


Figure 27. *Hourly heat flow values and the summations on the 1st of January*

PV modeling:

The total load for a typical residential home on a winter day (P_{load}) is 6.4 kWh. However, I assumed 10 kWh for this particular study, including some miscellaneous loads, because the number and type of appliances and their operating hours might differ. The average load demand is higher during the summer due to cooling needs. The kW power's PV size (P_{pv}) can be calculated using equation (4.2). According to the calculation, 2.8 kW power solar panels, Jinko Solar JKM 400 M–72H with a rating of 400 W, are assumed to be installed on the house's rooftop at a 28º slope [85]. Seven solar panels, each with 400 W peak power, are assumed to be installed to satisfy the 10 kWh/day household demand. A solar panel's output power is the function of incident radiation and the ambient temperature. The PV system's instantaneous power output (Epv) can be estimated using the PVGIS database tool. PVGIS estimates the hourly solar energy production from the 2.8 kW power solar panels installed at a 28º slope. According to these assumptions and data, the output power of the PV system is represented in ***Figure 28***.

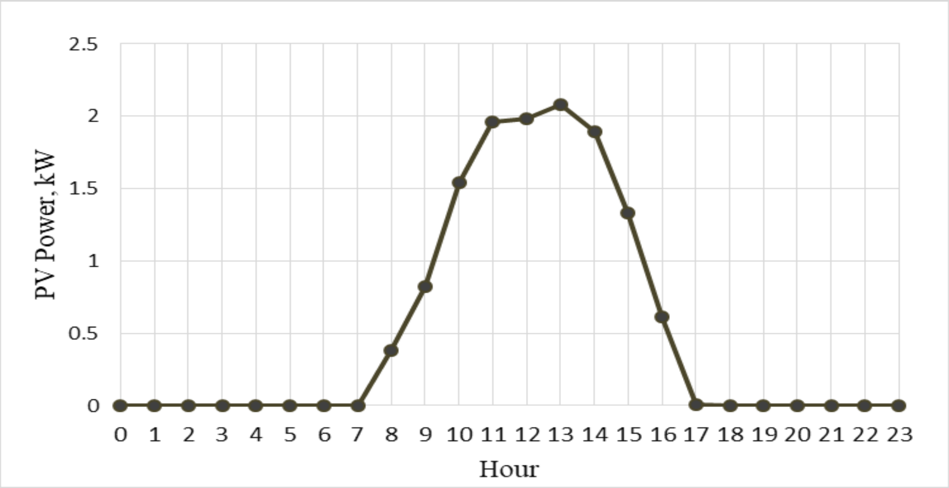


Figure 28. *PV power (kW), 1st of January*

Battery characteristics:

The battery is used as an ES system to improve load reliability. The Nissan Leaf AESC LiNM battery is assumed to be installed in the house again; for this case, a 500 Ah rating battery with 50% DOD, 83% efficiency, and 48 V rated voltage is selected. So, seven cells, each of 7.5 V, are connected in series, forming a module, and eight such modules are connected in parallel to obtain the optimum battery capacity as in the previous section.

If the energy produced by the solar panels exceeds the load demand at a specific time (t), the excess energy is stored in the battery. The energy stored in the battery at a given time (t) is represented by SOC_{batt} (t) and calculated as follows:

$$\text{SOCbatt}(t) = \text{SOCbatt}(t-1) + \left[\text{Ppv}(t) - \frac{Pload\ (t)}{\eta Inv}\right] \cdot \Delta t \tag{4.18}$$

P_{pv} represents the PV output power, and P_{load} is the load demand at a time (t). Δt shows the time step, which is one h. When the load demand exceeds the energy the RES produces, excess energy stored in the battery is used to maintain the demand. The state of battery energy at a time (t) is calculated as follows:

$$\mathrm{SOCbatt}(t) = \mathrm{SOCbatt}(t-1) - \left[\frac{\mathrm{Pload}(t)}{\eta\mathrm{Inv}} - \mathrm{Ppv}(t)\right] \cdot \Delta t \tag{4.19}$$

The ES system has some operational limitations that should be considered optimization constraints, where $E_{ch}^{batt}(t), E_{dch}^{batt}(t)$, are the charging amount and discharging amount at hour t, and similarly, ch_{max}^{batt}, dch_{max}^{batt} are the maximum allowable charging and discharging rates at each hour. SOC_{min} for the Nissan Leaf AESC LiNM battery is 20% [86].

$$E_{ch}^{batt}(t) \leq ch_{max}^{batt} \tag{4.20}$$

$$E_{dch}^{batt}(t) \leq dch_{max}^{batt} \tag{4.21}$$

Table 25. *Storage system characteristics*

Cap^{batt} (kWh)	ch_{max}^{batt} (kW/h)	dch_{max}^{batt} (kW/h)	η_{ch}^{batt}	η_{dch}^{batt}
25	3	3	0.83	0.83

Combined heat and power unit:

The micro-CHP unit is considered a fuel cell-based unit in this study. According to [110], a similar power level is feasible for residential buildings, and the optimal power level might be found in the 0.4 -0.7 kW range for Japanese households.

Table 26. *CHP characteristics*

ηg-e	ηg-h	C_{CHP}^{max} (kW)
0.3	0.4	0.75

4.4.2. Result and discussion:

This section proposes three cases, and formulations are implemented to investigate the optimal energy consumption patterns to achieve minimum cost options. The impact of the RES on the ESS's charge/discharge scheduling is adequately optimized. Input data and assumptions required to solve the optimization problem are extracted from valid reports and papers. The 1st of January is selected as a sample winter day for input data, and the proposed optimization results are presented for the same season. Winter days were chosen for two reasons: first, to evaluate the heat demand as a potential parameter of the EH and second, to optimize the EH on low PV output days. In Pakistan, the output power of solar panels is deficient during the winter season. After extensive evaluation, the most suitable type of PV array and the battery with the highest cost reduction potential is selected, as the cost of the hub components affects the overall best cost optimization. The optimization-based problem is designed to:

Case I. Determine the optimal operation of the residential EH;
Case II. Coordinate the solar panels' operation in the residential EH and scheduling of the ESS;
Case III. Manage the household load corresponding to responsive appliances.
The power flow equations (1–5) are the functions for solving optimization-based problems.

The gas supply is assumed to be 30% higher than the heat demand to ensure that the total heat demand and a part of the CHP unit are met. The hourly dispatch factor at the hub input and the received electricity and gas are obtained by solving the optimization problem with an Excel solver.

Scheduling responsive appliances in HLM with operational constraints, such as the working time for the appliances of set M and the energy consumption level at each hour for appliances of set N, is also optimized with the help of the Excel solver. Responsive appliance scheduling is planned from a customer point of view to minimize customer payment costs.

Case I

The optimal operation of a residential EH without RES is investigated in this case, as shown in ***Figure 25***. This is the base case for the numerical investigation. The daily energy demand (electricity and heat) for the sample winter day is summarized in sections 2.4 and 2.6. A CHP unit of 0.75 kW is also coordinated to support the balance of the overall system. The electrical grid and gas are energy sources that meet daily energy demands. The gas supply has increased by 30% more than the total heat demand of the energy system. It is ensured that the gas supply is sufficient to meet the heating demand and surplus supply used in the CHP unit. The hourly hub dispatch factor is shown in ***Table 27***, considering the same for all three cases with the primary purpose of using gas to meet the heat demand. By solving the proposed optimization problem, the power received at the input of the EH is presented in ***Figure 29***.

Table 27. *Dispatch factor*

t	0	1	2	3	4	5	6	7	8	9	10	11
V(t)	0.29	0.3	0.3	0.3	0.32	0.39	0.47	0.51	0.55	0.58	0.58	0.57
t	12	13	14	15	16	17	18	19	20	21	22	23
V(t)	0.53	0.48	0.43	0.42	0.4	0.38	0.36	0.34	0.33	0.33	0.32	0.32

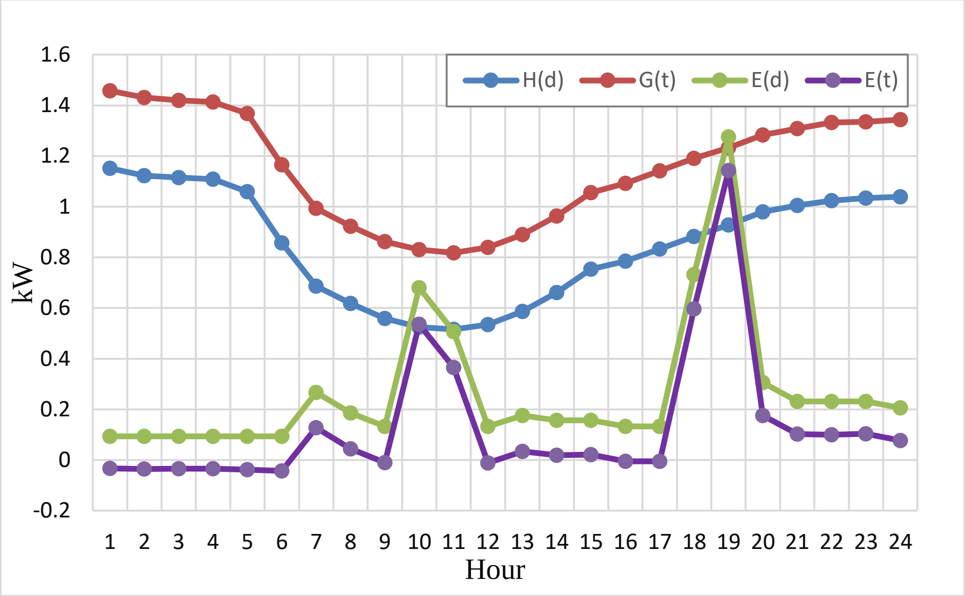


Figure 29. *Input and output power of the EH in Case I, showing the heat demand H(d), gas at the input of the EH G(t), electricity demand E(d), and electricity at the hub input E(t)*

Figure 29 shows enough gas supply to satisfy the house's heating demand and a portion of the electrical demand through the CHP unit. The grid provides the remaining electrical demand. According to the current scenario, most of the electrical demand of the EHs depends on the energy input provided by the grid. The hub output can rely more on gas by increasing the size of the CHP device, but that is not economically suitable. So, integration of RES is undoubtedly the best solution for such a scenario. However, adding a storage system with the RES is essential to enhance the system's stability. The impact of incorporating the RES with the ES is discussed below.

Case II

In this case, solar panels and storage systems are considered. It is assumed that 2.8 kW power solar panels are mounted on the rooftops of residential buildings. According to the design parameter of the PV panels described in section 2.7, the output power produced by the solar system is shown in ***Figure 28***. Along with this PV setup, a 25kWh battery (2014 Nissan Leaf AESC LiNM battery) is added as an ES to store energy during excess production hours. By solving the optimization problem, the power received at the input of the EH and the charge/discharge scheduling of the battery are presented in ***Figure 30***. Notably, the demand for gas follows the demand for heat, and the PV system supplies the demand for household electricity.

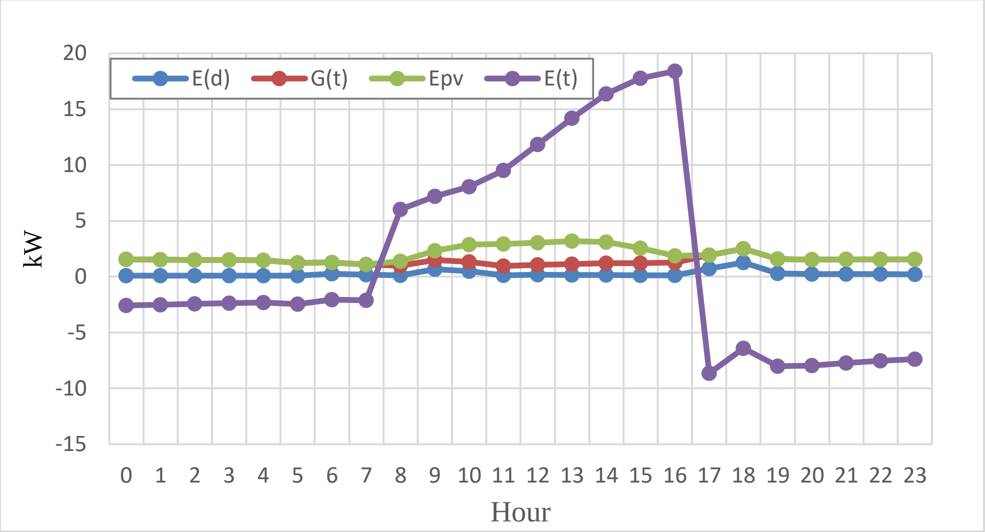


Figure 30. *Received input and charge/discharge schedule at the EH in Case II, showing the electricity demand E(d), gas at the input of EH G(t), solar panel production Epv, and electricity at the hub input E(t)*

Nissan Leaf AESC LiNM batteries are the best suited for residential use due to their low upfront cost. In this case, a 25kWh battery is assumed to be installed with the PV system. Still, according to 70% of the initial state of health, only a 17.5 kWh battery is incorporated with this system, sufficient for one day of autonomy. SOC_{min} for the Nissan Leaf AESC LiNM battery is 20%. Therefore, 5 kWh is considered as the initial state of charge of the battery. Output power excess and demand can be stored in the battery. ***Figure 30*** shows that the PV output at hours 8–17 exceeds the household demand, so the battery is charged during these hours while discharging from 18 to 7. This discharge is because the PV production cannot meet the household demand during these hours.

Case III

For this case, HLM is incorporated in Case II. According to the data and assumptions in section 2.5, the responsive load curve is shown below in ***Figure 31***. The hourly demand for responsive and non-responsive devices is listed in ***Table 28***. During winter days, the non-responsive load is considerably less than in summer. The proposed optimization problem for this case is solved with the same hub dispatch factor used in the previous two cases, along with the scheduling parameters for the responsive load. The results of the power received at the input of the EH and the discharge scheduling of the battery are presented below in ***Figure 32***.

Table 28. *Hourly demand for responsive and non-responsive devices*

t	E_{app}^{R} (t), kW	E_{app}^{NR} (t), kW	Eapp (t), kW
0	0.15	0.0933	0.2433
1	0.15	0.0933	0.2433
2	0.15	0.0933	0.2433
3	0.15	0.0933	0.2433
4	0	0.0933	0.0933
5	0.5	0.0933	0.5933
6	0.35	0.2673	0.6173
7	0	0.1856	0.1856
8	0	0.1323	0.1323
9	0	0.2573	0.2573
10	0	0.1573	0.1573
11	0.423	0.1323	0.5553
12	0	0.1756	0.1756
13	0.35	0.2573	0.6073
14	0	0.1573	0.1573
15	0	0.1323	0.1323
16	0	0.1323	0.1323
17	0	0.1323	0.1323
18	0	0.1756	0.1756
19	0	0.3063	0.3063
20	0	0.2313	0.2313
21	0	0.2313	0.2313
22	0	0.2313	0.2313
23	0.15	0.2063	0.3563
Total energy kWh/day	2.373	4.0611	6.4341

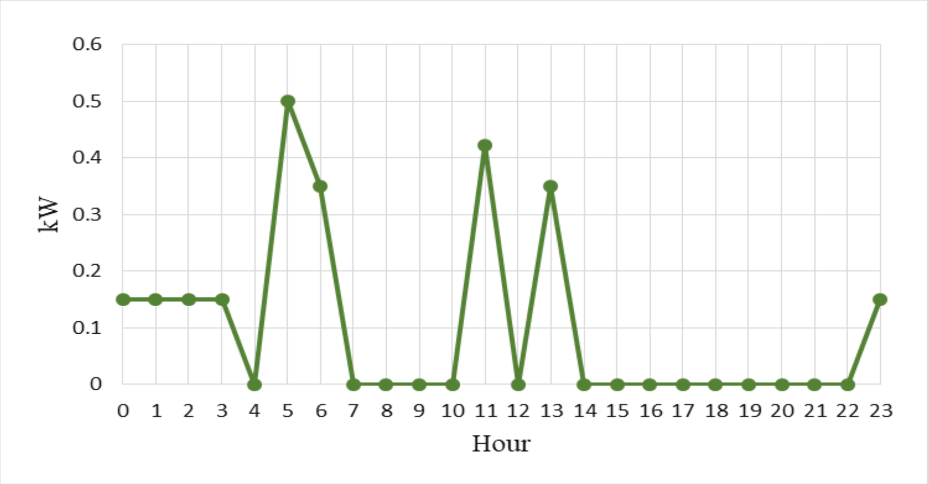


Figure 31. *The electricity demand for responsive appliances for the 1st of January*

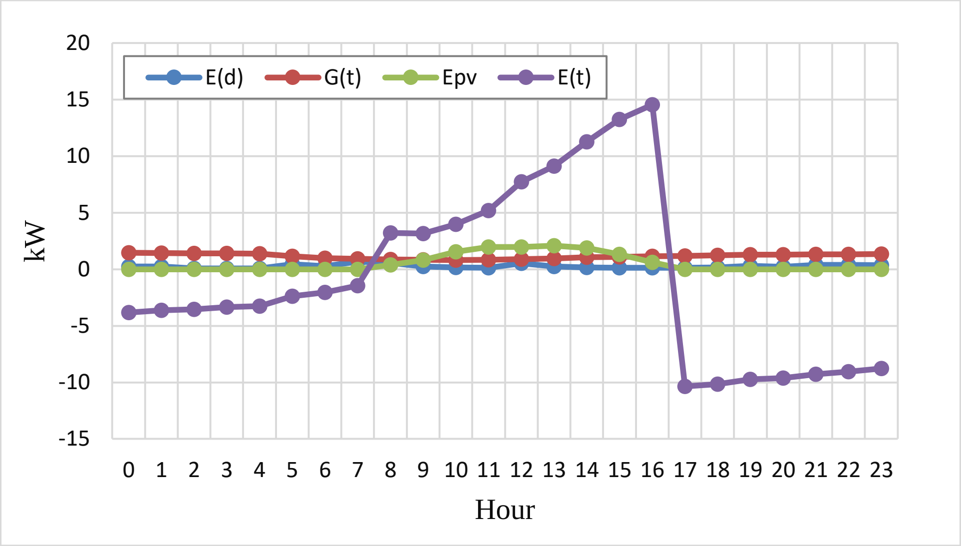


Figure 32. *Received input and charge/discharge schedule at the EH in Case III, showing the electricity demand E(d), gas at the input of EH G(t), Solar panel production Epv, and electricity at the hub input E(t)*

Figure 32 shows that the battery starts charging during the hours when the PV output exceeds the domestic demand and discharges otherwise. The battery is charged from hours 8 to 17 and discharged in the remaining hours. In this case, the charging and discharging behavior of the battery is smoother than in Case II. Due to the winter demand, the difference is small but present.

Cost estimation:

Set cost: An appropriate economic analysis is essential to understand the profitability of investment in the PV system. The upfront cost is important, and replacement and maintenance costs are usually ignored for small-scale projects. The upfront cost is the sum of the capital cost of all equipment. According to this PV panel's datasheet, a lifespan of 20 years is assumed. The investment cost, operation and maintenance cost, PV system and maximum power point tracker (MPPT), and battery replacement cost are listed in ***Table 29***.

__Table 29.__ Cost of the installed system

Parameters	Components	Value	Quantity
Capital cost	PV array ($/kW)	350	980
	PV array MPPT controller ($/kW)	100	280
	Battery ($/kWh)	90	2250
Replacement cost	Battery ($/kWh)	90	
Maintenance cost	PV array ($/kW/year)	9	25.2
	Battery ($/kWh/year)	18	450
	PV array MPPT controller ($/kW/year)	2	5.6
Annual interest rate (%)		2	
Annual inflation rate (%)		1.2	

Energy carrier prices: Electricity and gas prices are considered for energy carrier prices [111]. Gas prices are not time-dependent, while electricity prices are based on the time of use (TOU). TOU rates are high during peak demand for electricity and low during off-peak hours. In some cases, there are three periods: off-peak, mid-peak, and peak, but this varies from country to country. In Pakistan, there are two periods during the day [112], as shown in ***Table 30***: peak and off-peak. Tariffs must be according to user comfort, and customer satisfaction should not be endangered.

__Table 30.__ Time of use tariff

Time	Winter	Summer	Price $/kWh
Peak	5 p.m. – 9 p.m.	6:30 p.m. – 10:30 p.m.	0.1
Off-peak	Remaining hours	Remaining hours	0.067

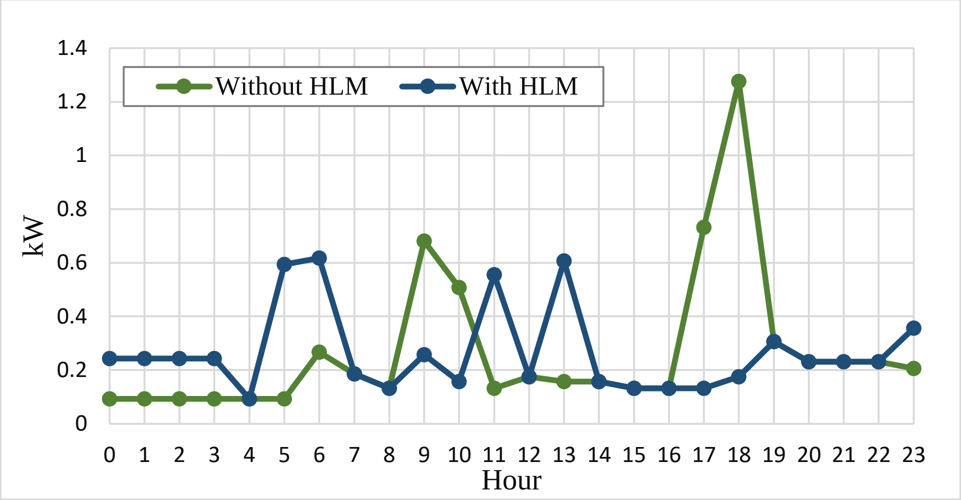


Figure 33. *Electricity demand on the 1st of January with and without HLM*

The HLM program is beneficial for time-varying tariff cases, as ***Figure 33*** shows that the peak value of electricity demand with the HLM case is much less than the possible peak demand in the case without HLM. According to the TOU tariff listed in ***Table 30***, the cost of daily electricity demand without HLM is 0.53 $/6.4 kWh, and with HLM is 0.46 $/6.4 kWh. These results show that HLM reduced users' daily payments by about 13.2 % compared to those without HLM.

Comparison of costs: This section provides an economic analysis of all cases to understand the comparative cost-effectiveness. In Case I, the total electricity demand is based on conventional grid supply, and per unit cost of electricity follows the government-approved website NEPRA [112]. According to the NEPRA report, the current cost of electricity is 0.054 $/kWh. For the second case, the PV system's levelized cost of electricity (LCOE) is calculated using equation (4.5). In general, estimates of the LCOE for solar PV tend to be higher than alternatives based on common assumptions [101].

Table 31. *Comparison of costs in different cases*

Type	Attribute	Value
Case I	Average electricity requirement per year	3650 kWh
	Total bills for the household for one year	200 $
Case II	PV installation cost	1260 $
	Yearly maintenance cost	30.8 $
	Life span	20 years
	Energy production per year	4380 kWh
	LCOE	0.021 $/kWh
Case III	Daily electricity demand without HLM	0.53 $/6.4kWh
	Daily electricity demand with HLM	0.46 $/6.4kWh

Energy flow and cash flow: Energy flow and cash flow analysis can provide insight into key elements of financial analysis. Cash inflows and outflows help to analyze costs and budgeted amounts of money throughout the project. ***Figure 29*** shows the monthly electricity demand of the typical house described in section 2.4 and the energy output from a 2.8 kW_p PV system installed on the roof to represent the energy flow. Most of the time, the PV output exceeds the demand of the house. Therefore, the cumulative demand and cumulative production for a year are highlighted to emphasize the PV installation.

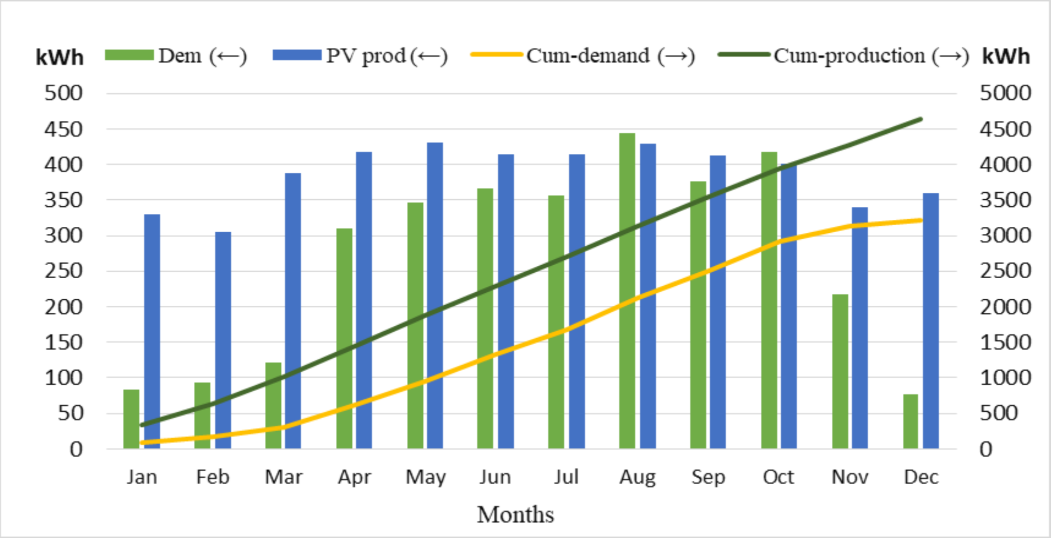


Figure 34. *Annual energy flow*

The annual cash flow graph represents all costs over time, the levelized cost of PV production, including fixed initial costs and recurring maintenance costs, and the value of PV production. ***Table 31*** presents 1260 $ as the initial investment and 30.8 $ as the annual fixed maintenance cost. PVGIS software estimates the monthly kWh PV production from the 2.8 kW power solar panels installed on a 28° slope in Quetta City, Pakistan. Based on the LCOE of 0.021 $/kWh for PV production, the monthly cost of PV production is calculated. The value of PV production is based on the NEPRA price per kWh, and the current electricity price is 0.054 $/kWh. The cash flow is calculated from the difference between the cumulative value of PV production and cumulative monthly costs. The cash flow shows the equivalent lump sum at the end of the period, as shown below in ***Figure 35***.

It should be noted that PV production covers the fixed monthly cost, and there is also a specific payback period that shows that all the initial investment will be recouped in the next few years. The length of the payback period depends on how surplus energy is used. General practice is that excess energy can be sold to the grid or neighbors, but the price varies in each case.

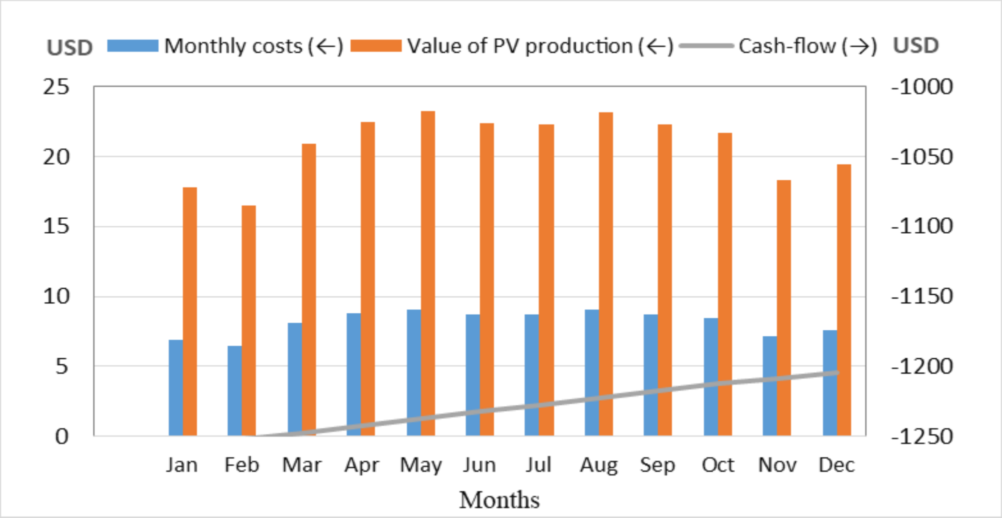


Figure 35. *Annual cash flow*

Emission mitigation potential: PV systems generate green energy and help to reduce greenhouse gas emissions. The fuel used most to generate electricity in rural Pakistan is diesel [113]. PV systems produce little or no emissions compared to conventional generators. Therefore, PV has substantial potential to mitigate CO_2 emissions compared to other alternatives. The reduction in CO_2 emissions can be calculated based on the amount of diesel fuel saved (Fs), as presented in equation (4.22).

$$\mathrm{Fs} = \mathrm{Epv} \cdot \mathrm{Fr} \tag{4.22}$$

Fr is the fuel required to generate 1 kWh of electricity using a diesel generator. A typical 20 kW diesel generator produces 4 kWh of electricity using 1 liter (L) of diesel [114]. On average, 12 kWh/day of energy is produced by the 2.8 kW power PV, so 3L diesel is saved daily by replacing a diesel generator with a PV system.

The amount of CO_2 abated using the PV system in kg (Es) can be measured by equation (4.23).

$$\mathrm{Es} = \mathrm{Epv}\,(\mathrm{Md} - \mathrm{Mpv}) \tag{4.23}$$

Md is the carbon equivalent in kg emitted for generating 1 kWh of electricity using a diesel generator. Mpv is the carbon equivalent in kg emitted for generating 1 kWh of electricity using PV. Md is 2.7 kg of CO_2 per liter of diesel fuel consumed, while Mpv is 0.083 kg CO_2-equivalent per kWh. So, based on equation (4.23), 7.104 kg CO_2 per day per household is mitigated, and about 2160 kg CO_2 per household can be mitigated every year.

Factors affecting HLM:

Smart energy consumption strategies enable understanding of how certain factors affect energy usage and help adopt more accurate, flexible, and efficient energy consumption and conservation practices. Therefore, HLM formulates vital techniques for making informed decisions to increase energy efficiency and potential use.

In the case mentioned earlier, almost 13.2% cost reduction is reported due to HLM, where only 36% of the load was flexible and only one peak power time was 5 p.m.-9 p.m. per day. This value is not general because many factors drive the HLM, such as the number of peak times during a day, TOU tariff rates, percentage of flexible load, and number of responsive appliances turned on at a time. To investigate the impact of these parameters, I extended HLM case 3 to examine the behavior of the number of peak times in a day with the same TOU rates. The same Excel solver method was adopted to investigate the three categories further. The results show that if there are two peak times throughout the day, the cost to the consumer after HLM is lower than when there is only one peak time of electricity consumption. It decreases from 13% to 14.5%, as shown in ***Table 32***. Because electricity rates are higher during peak hours, HLM shifts the load from peak to off-peak hours. The number of responsive appliances that can be turned on at a time is limited, so the overall cost is not affected.

An example of sample house load demand is used to demonstrate the influence of multiple factors. We cannot generalize the HLM cost reduction as many system limitations restrict it. We can only investigate the trend of influencing factors, which we did for two parameters: the number of peak hours per day and the number of responding devices at once.

Table 32. *Effect of TOU and responsive appliances on HLM*

Categories	Conditions			Cost Comparison		
	Status	Time	Price $/kWh	With HLM	Without HLM	Difference %
On peak/day and only one responsive appliance at a time	Peak	5 p.m.-9 p.m.	0.1	0.46	0.53	13.2%
	Off-peak	All remaining	0.067			
Two peaks/day and only one responsive appliance at a time	Peak	7 a.m.-10 a.m. 5 p.m.-9 p.m.	0.1	0.49	0.57	14.5%
	Off-peak	All remaining	0.067			
Two peaks/day and more than one responsive appliance at a time	Peak	7 a.m.-10 a.m. 5 p.m.-9 p.m.	0.1	0.49	0.57	14.5%
	Off-peak	All remaining	0.067			

4.4.3. HLM-based domestic energy trading using TRNSYS software

Section 4.4 shows that the PV system installed for domestic energy demand generates surplus energy due to the specific regional conditions. Most of the time, the battery remains charged, showing the possibility of selling excess energy to a neighboring consumer. Thus, I can say that this research provides a starting point for energy trading between residential buildings. I investigated the technical feasibility of energy trading capability at the household level with the help of TRNSYS software and presented a brief overview of HLM's contribution to energy sharing. However, a simple configuration of two blockchain-connected is considered for the TRNSYS-based simulation.

4.4.4. Methodology

A novel approach is analyzed using TRNSYS software to identify real-time execution of household-level energy production and local trading potential. Furthermore, the contribution of HLM to energy sharing is investigated from the prosumer-consumer perspective.

The proposed method consists of several steps that can be summarized as follows:

1. TRNSYS model pre-processing (modeling PV, battery, and backup source according to electrical demand);
2. Simulation analysis to determine prosumer capacity to use surplus production for trade;
3. Estimating the effect of incorporating HLM into the consumer-producer energy trade-off.

Residential electrical load demand and supply analysis is calculated for an entire year (8760 h) using Simulation Studio of TRNSYS software. Simulations were performed at a time step of 0.125 h, while hourly average results were considered for analysis. Major components of the model shown in ***Figure 36*** include electricity demand of 10kWh/day of the sample house on a typical working day, as explained in section 2.4. TRNSYS (Type9c) is used to simulate the load demand, and a 2.8 kW PV system (Jinko Solar JKM 400 M–72H with a rating of 400 W) is simulated with (Type103b). The weather data input file of the selected location is loaded to the (Type15-6) of the model. Power production of the PV system flows into the Inverter/Charge controller. The (Type48b) Inverter/Charge controller model is designed to interact with the (Type47a) battery. A 25-kWh 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 RE. 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 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 1kW 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 discharge. (Type 65d) is used to plot the simulation results, and simulation studio component "equations" can process expressions not included in the standard components. A limitation of the model is that only electricity demand is considered, and heat demand is not included to avoid further complexity of the model.

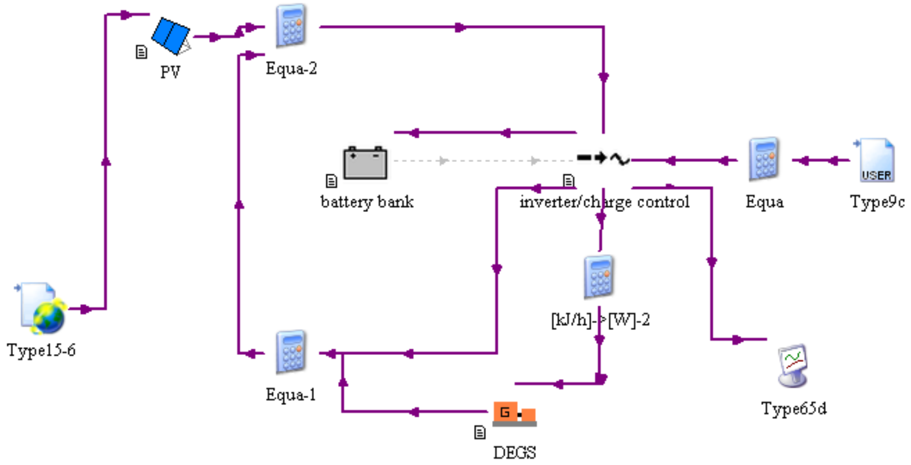


Figure 36. *The layout of the electricity model in TRNSYS-18*

4.4.5. Results and discussion

A simple configuration of two blockchain-connected houses, one consumer and one prosumer, is outlined in ***Figure 24*** earlier and is considered for investigation of the technical feasibility of energy trading capability at the household level with the help of TRNSYS software. The simulation results in the period of daily energy shares by all sources to meet the load demand, which is analyzed in three scenarios, as shown in ***Figure 37***.

In the first scenario, I chose a house with a load of 6.4 kWh/day without HLM and a sized amount of roof-mounted 2.8kW PV, with the 25kWh battery as an optimal ES option and DEGS as a backup source. In the second scenario, I modeled the same plan for two houses with identical demand patterns connected to the same local grid. Only one house is equipped with a PV and battery storage system and acts as a prosumer. In contrast, the other house depends on grid power and the surplus energy produced by the prosumer during enough production hours. The total energy demand is 12.8 kWh/day, and just 2.8 kW$_P$ panels are installed on the roof of the prosumer house. The third scenario is similar to the second one, but the HLM approach is applied to the power demand. The overall demand equals 12.8 kWh per day, but the peak is reduced this time, as shown in ***Figure 33***. For each specific scenario, I plotted the power output from all sources (PV, battery, DEGS) versus demand and the battery charge/discharge and fractional state of battery charge.

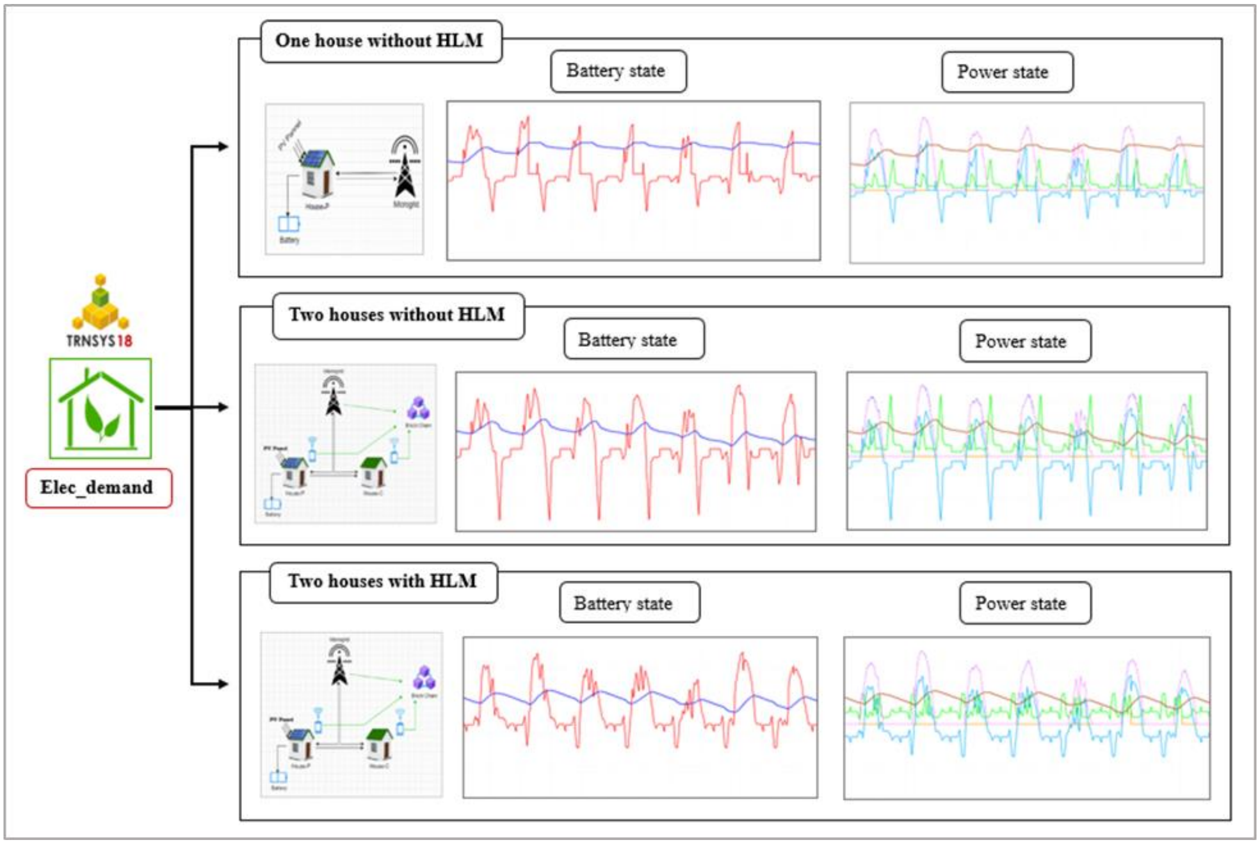


__Figure 37.__ Simulation results of battery state and power state Oct1-8

Simulation results for the first scenario show that the PV generation is sufficient during the day to meet the load demand and charge the battery. When PV is unavailable at night, the battery is discharged to meet the demand. Despite being discharged all night; the battery did not reach its lowest limit. DEGS does not supply electricity as PV and batteries cover the entire demand. Similarly, PV and battery try to meet the demand for the second scenario, but on day six and day seven, the DEGS has to step in to meet the demand due to limited PV production and battery capacity.

After incorporating the HLM strategy in the third scenario, the battery discharge is more stable than in the second scenario. A peak power demand occurs during the PV production period, hence the minimum load on the battery and the grid. The simulation results of energy shares from all sources to meet the load demand in Scenario 2 and Scenario 3 are shown in ***Figure 38*** and ***Figure 39*** below. The difference in battery discharge behavior proves the importance of the HLM approach.

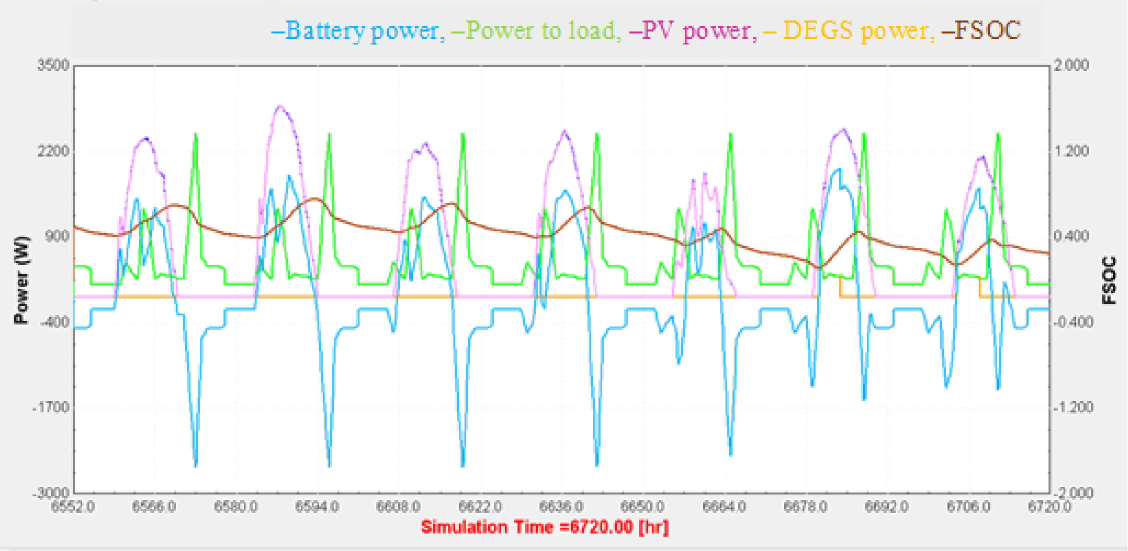


Figure 38. *Power state Oct1-8 (two houses without HLM)*

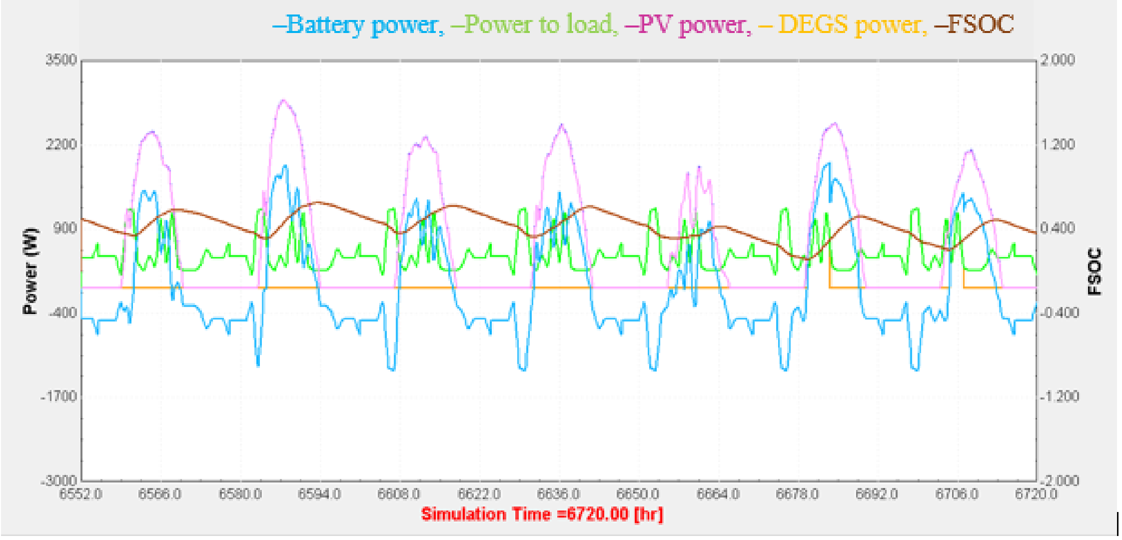


Figure 39. *Power state Oct1-8 (two houses with HLM)*

The scientific finding of the Chapter 4.4 summarized as follow:

Preface of Thesis 5 and Thesis 6: I investigated the optimal operation of a residential EH. The optimization problem in a renewable-based EH is solved by considering HML for responsive appliances in a 3–4-person house. The first case demonstrates that the household energy demand depends on gas and the inflated cost of electricity from the common grid. In the second case, I explained the operation strategy of the EH with proper coordination of the PV and ES system, which leads to lower dependence on the grid. The scheduling of responsive appliances is optimized according to time-varying tariffs, resulting in lower peak power demand and customer cost, making this model more consumer-friendly. The designed model exhibits that the PV system installed at home is usually sufficient to meet the real demand and the excess energy is stored in ES during hours of enough production.

Thesis 5:

I proved that the Demand Response Program (DRP) plays a leading role in HLM and prevents high power demand during peak hours. The results show that incorporating TOU in HLM benefits the consumers without neglecting the concerns of the network operator. Simultaneously, comparing the difference between the target cost in the base case (based on grid supply) and the cost of the alternative strategies, I proved that the HLM application alone reduces the daily payment of customers by about 13.2% compared to those without HLM. It should be noted that the average tariff is higher in summer than in winter. Consequently, the customer cost reduction could be more significant in summer than winter.

Thesis 6:

I proved by the TRNSYS simulation that the possibility of local energy trading is a cost-reduction option. The electrical load of the prosumer is simulated according to the size and optimized parameters of the PV, battery, and backup source. The Fractional Stage of Charge (FSOC) of a battery shows that sufficient RE generation is available to share the demand of neighbors. I investigated utilizing the surplus production consumer-prosumer strategy, including the HLM approach. The simulation results support the household-level energy trading strategy considering the HLM and show a high demand for electricity during the PV production period, so there is a minimum load on the battery and the grid. The proposed modeling approach to upgrade the energy consumption behavior of general household users is also suitable for more modern urban households. In practice, various home energy hubs can be designed for optimization based on the introduced strategies. In addition, a peer-to-peer strategy of domestic-level trading should be implemented along consumer and producer principles.

4.5. Local energy trade – whole village case assessment

The expansion of the industrial sector and the increase in population are the reasons for the ever-increasing demand for electricity, which directly burdens the central grid. Absence and remoteness from the central grid make off-grid power generation the most reliable source of electricity to meet the needs of peripheral areas. Electrification of remote areas through decentralized generation using RES has emerged as a low-cost and practically viable solution. Domestic-level energy trading makes the system more cost-effective.

I developed a hybrid energy model consisting of PV and diesel generators to electrify a remote village and address all these aspects. First, resource evaluation and total load demand are estimated at the selected site, then system sizing optimization and techno-economic feasibility are evaluated using HOMER-Pro software. Based on the optimized system, a new system is proposed and developed using HOMER-Pro software to investigate the energy trading potential. Economic rationality is checked using the economic parameters of net present cost (NPC), levelized cost of electricity (LCOE), initial capital, and operation and maintenance cost (O&M) of the system. A sensitivity analysis is performed further to evaluate the system's feasibility under different conditions. This approach fills the gap in the energy trading sector by providing a more efficient and cost-effective simulation-based study.

4.5.1. Methodology

A pre-HOMER analysis was conducted by estimating the load requirements for the community and thoroughly evaluating the available energy resources around the area. The load data was then fed into the software interface and analyzed for the hybrid system using the tools available in the software. Electric load, PV, diesel generator, batteries, and converters are the main components of a hybrid RES system. The properties of these components, which are modeled in HOMER-Pro, are described in the following subsections,

The HOMER-Pro simulation tool optimizes the RES-based system configuration and performs techno-economic analysis, operational feasibility assessment, and system robustness. The proposed method consists of several steps that can be summarized as follows:

1. A pre-HOMER analysis was performed for resource evaluation, and total load demand was estimated at the selected site.
2. System components (electric load, PV, diesel generators, batteries, and converters) are optimally sized, and the techno-economic feasibility of the overall system is evaluated using HOMER-Pro software.
3. Based on the optimized system, a new system is proposed and developed using HOMER-Pro software to investigate the energy trading potential.
4. A sensitivity analysis is performed further to evaluate the system's feasibility under different conditions.

Electrical Load Assessment:

The electricity demand of the rural residential community is calculated based on daily electricity consumption. The number of appliances and energy consumption by each appliance per hour must be known to calculate the daily energy demand. The primary demand for electricity in homes is usually for lights, fans, water pumps, and other basic utility devices, as shown in ***Table 34***. According to the Pakistan Bureau of Statistics [115], a village has an average of 250 houses, ranging from two-bedroom houses to 5 or more bedrooms. ***Table 33*** shows the average percentage of each type of house in the village.

Table 33. *Pakistan Bureau of Statistics data on housing units*

No.	Statistics of housing units		Our estimation	
	Bedrooms	%	Bedrooms	%
1	1 Bed	41.65	1 Bed	41
2	2 Bed	30.02	2 Bed	30
3	3 to 4 Bed	22.24	3 Bed	15
4	5 or more Bed	6.09	4 Bed	8
5			5 Bed	4
6			6 Bed	2
sum		100		100

Electric load demand is assessed carefully for each type of household, considering the load requirement throughout 24 hours of the day. Maximum load appears in the morning and night as most family members may not be home during the day. Summer is the peak season, as the fans turn on during summer. ***Table 34*** shows the appliance usage estimation data based on each appliance's time, hour, and power consumption, taken from the official brand's website. The ceiling fan at the main hall (living hall + dining hall) (CF1) and the ceiling fan (CF2) in rooms only operate during the summer season, while in winter, there is no need for fans. The 8 W fluorescent lights (LF1) are in small places like the room, bathroom, and toilet, and 25 W fluorescent lights are in large areas like the main hall, kitchen, and porch. The light fluorescent lamp on the porch (LFP) is 25W. Since few people stay at home, the television (TV) is ON during the day until midnight. A table fan (TF) is placed in room 2 and operates according to seasonal requirements. A washing machine (WM) is used per the house's demand. An exhaust fan (EF) is placed in the kitchen and ON while cooking breakfast, lunch, and dinner. A water pump (WP) is usually used during peak hours, operating in the morning, afternoon, and night. The refrigerator (RF) is on for 24 hours. Iron is used for a limited time.

Based on the data mentioned above, energy demand per day is calculated for each type of house. 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 an unusual usage time, the estimated maximum demand of this house is scaled a little bit above the calculated using HOMER-Pro software built-in function.

Table 34. *Installation of power consumption appliances*

Appliances	Reference	Power (W)	Location									
			Porch	Living/ Dining	Kitchen	Bathroom / Toilet	Room1	Room2	Room3	Room4	Room5	Room6
Ceiling fan, hall	CFH	82.5	0	1	0	0	0	0	0	0	0	0
Ceiling fan, room	CFR	82.5	0	0	0	0	1	1	1	1	1	1
Light small	LF1	8	0	0	0	1	1	1	1	1	1	1
Light big	LF2	25	0	1	1	0	0	0	0	0	0	0
Light Porch	LFP	25	1	0	0	0	0	0	0	0	0	0
TV	TV	39	0	1	0	0	0	0	0	0	0	0
Table Fan	TF	42.5	0	0	0	0	0	0	0	0	0	0
Washing Machine	WM	423	0	0	1	0	0	0	0	0	0	0
Exhaust Fan	EF	18.3	0	0	1	0	0	0	0	0	0	0
Water Pump	WP	100	0	0	0	1	0	0	0	0	0	0
Refrigerator	RF	93.3	0	0	1	0	0	0	0	0	0	0
Iron	IR	1000	0	0	0	0	1	0	0	0	0	0

Table 35. *Total usage time in hours and power consumption per day*

Appliance	Power (W)	Energy per day (Wh/day)					
		Type 1	Type 2	Type3	Type4	Type5	Type6
		1-bedroom	2-bedroom	3-bedroom	4-bedroom	5-bedroom	6-bedroom
CFH	82.5	1×17	1×17	1×17	1×17	1×17	1×17
CFR	82.5	1×12	2×12	3×12	4×12	5×12	6×12
LF1	8	2×7	3×7	4×7	5×7	6×7	7×7
LF2	25	2×7	2×7	2×7	2×7	2×7	2×7
LFP	25	1×3	1×3	1×3	1×3	1×3	1×3
TV	39	1×16	1v16	1×16	1×16	1×16	1×16
TF	42.5	-	-	-	-	-	-
WM	423	1×0.5	1×0.5	1×0.5	1×1	1×1	1×1
EF	18.3	1×3	1×3	1×3	1×3	1×3	1×3
WP	100	1×3	1×4	1×4	1×5	1×5.5	1×5.5
RF	93.3	1×24	1×24	1×24	1×24	1×24	1×24
IR	1000	1×0.5	1×0.5	1×0.5	1×1	1×1	1×1
Total energy consumption per day (Wh/day)		6 859.1	8 500.1	9 051.1	10 908.6	12 004.6	13 083.6

Table 36. *Appliance-based usage for every type of house*

References	Type1	Type2	Type3	Type4	Type5	Type6
CFH	1 402.5	1 402.5	1 402.5	1 402.5	1 402.5	1 402.5
CFR	990	1 980	2 970	3 960	4 950	5 940
LF1	112	168	224	280	336	392
LF2	350	350	350	350	350	350
LFP	75	75	75	75	75	75
TV	624	624	624	624	624	624
TF	0	0	0	0	0	0
WM	211.5	211.5	211.5	423	423	423
EF	54.9	54.9	54.9	54.9	54.9	54.9
WP	300	400	400	500	550	550
RF	2 239.2	2 239.2	2 239.2	2 239.2	2 239.2	2 239.2
IR	500	500	500	1000	1000	1000
Total Wh/day	6 859.1	8 005.1	9 051.1	10 908.6	12 004.6	13 083.6

Table 37. *Hourly energy demand for every type of house (kWh/day)*

Hours	Type1	Type2	Type3	Type4	Type5	Type6
0	175.8	258.3	340.8	423.3	505.8	588.3
1	175.8	258.3	340.8	423.3	505.8	588.3
2	175.8	258.3	340.8	423.3	505.8	588.3
3	175.8	258.3	340.8	423.3	505.8	588.3
4	175.8	258.3	340.8	423.3	505.8	588.3
5	175.8	258.3	340.8	423.3	505.8	588.3
6	341.8	432.3	522.8	613.3	703.8	794.3
7	760.1	868.1	876.1	1384.1	1392.1	1400.1
8	426.3	426.3	426.3	637.8	637.8	637.8
9	214.8	214.8	214.8	214.8	214.8	214.8
10	214.8	214.8	214.8	214.8	214.8	214.8
11	214.8	214.8	214.8	214.8	214.8	214.8
12	233.1	233.1	233.1	233.1	283.1	283.1
13	314.8	314.8	314.8	314.8	314.8	314.8
14	214.8	214.8	214.8	214.8	214.8	214.8
15	214.8	214.8	214.8	214.8	214.8	214.8
16	214.8	214.8	214.8	214.8	214.8	214.8
17	214.8	214.8	214.8	214.8	214.8	214.8
18	214.8	214.8	214.8	214.8	214.8	214.8
19	481.6	572.1	662.6	753.1	843.6	934.1
20	388.3	478.8	569.3	759.8	850.3	940.8
21	388.3	478.8	569.3	659.8	750.3	840.8
22	388.3	478.8	569.3	659.8	750.3	840.8
23	363.3	453.8	544.3	634.8	725.3	815.8
Exact total	6 859.1	8 005.1	9 051.1	10 908.6	12 004.6	13 050.6

Demand profile:

When load data is entered into the HOMER-Pro software, monthly load profiles of electricity demand are generated based on hourly demand patterns for the entire village. ***Figure 40*** shows the average monthly load profile, and ***Figure 41*** provides the hourly load profiles for winter, summer, and the average.

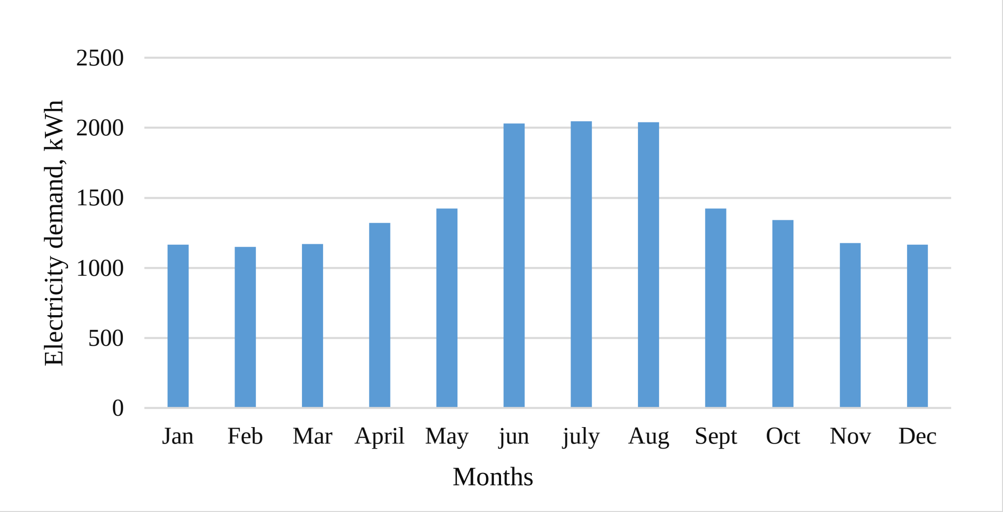


Figure 40. *Average monthly demand for the entire village*

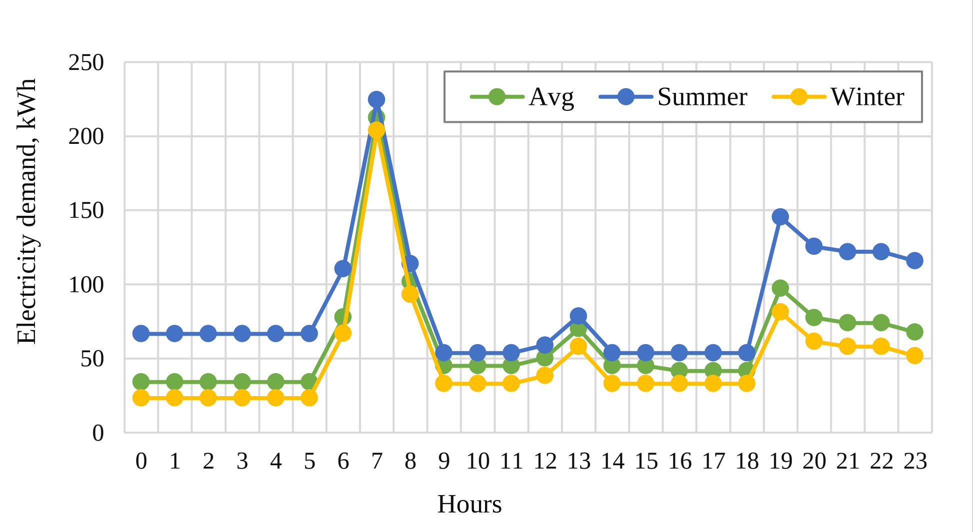


Figure 41. *Hourly energy demand for the entire village for winter, summer, and average*

Energy Resource Assessment:

The real-time solar irradiance (kWh/m^2/day) data for the targeted site is required to estimate the available solar energy potential for selected sites. Monthly average global solar radiation data can be generated for any location using the HOMER-Pro software [116]. This data is loaded from the National Aeronautics and Space Administration (NASA) website. For this research, a village was selected from the rural area of the Quetta district of Baluchistan province, Pakistan. The solar radiation data for the selected site is obtained from the solar energy resources available in NASA's surface meteorology and HOMER-Pro database, and the estimated average solar radiation is 5.97kW/m^2/day, as shown in ***Figure 42***. The data show that this location has good solar energy potential and can generate electricity efficiently using PV panels.

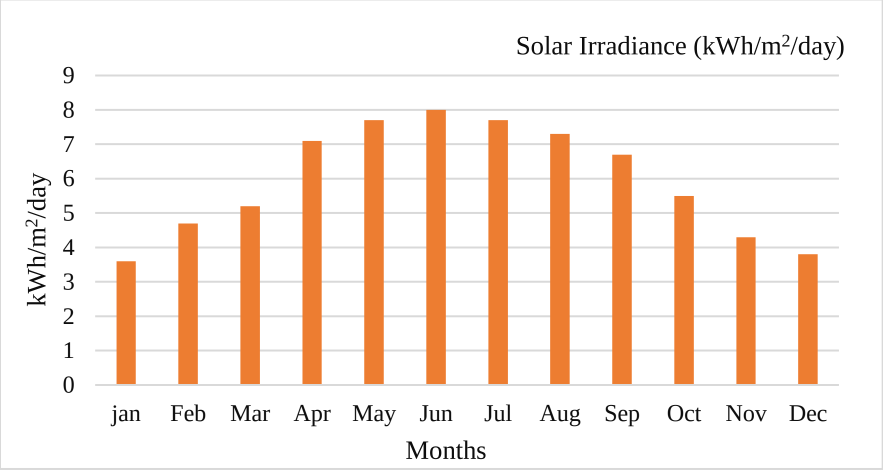


Figure 42. *Solar radiation data for the region located at 30.17⁰ N and 66.97⁰ E of Pakistan*

System design and simulation:

HOMER-Pro software is employed on a hybrid energy system to conduct techno-economic analysis for the electrification of a sample village. A system modeling design includes multiple components, as shown in ***Figure 43*** and ***Figure 44***. These components are the PV modules, battery bank, power converter, diesel generation, and advanced grid. HOMER-Pro space capacity is primarily used to optimize the capacity of used components. Technical parameters, cost, and detailed specifications are discussed in later sub-sections. HOMER-Pro software performs three main tasks for the selected system: simulation, optimization, and sensitivity analysis.

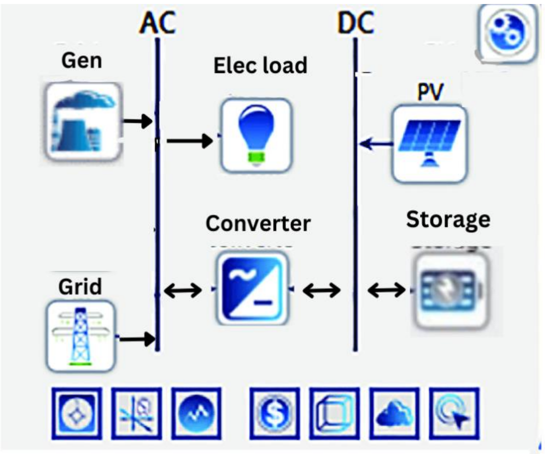


Figure 43. *Optimized system configuration*

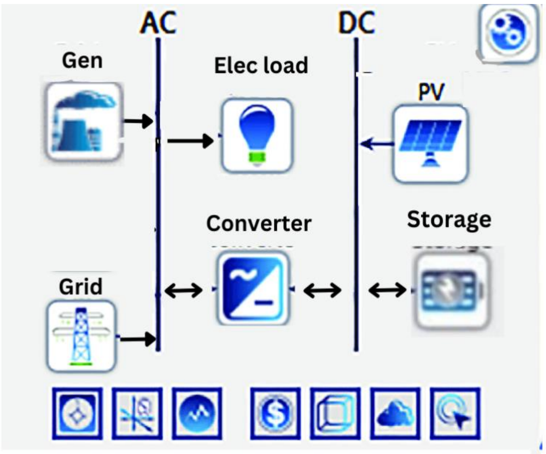


Figure 44. *Proposed system configuration*

Optimization setting:

HOMER-Pro simulates all possible system combinations to find the most suitable and practically feasible cost-effective configuration. The primary objective of deciding the best hybrid system is determining the RES contribution percentage, NPC, LCOE, and emission limit. The optimization settings of the system to run the simulation are listed in ***Table 38***.

Table 38. *Optimization settings*

System settings	Values	Source of information
Design precision	0.01	Generic data from HOMER-Pro [117]
Simulation time step	1 hour	Generic setting [116]
Inflation rate	6.17 %	Official website of State Bank of Pakistan [118]
System lifetime	25 years	Generic setting [116]
Annual capacity shortage	0.00 %	Generic setting [116]

PV module: The only PV system is assumed to be the RES for this case. Generic flat-plate PV modules, Jinko Solar JKM 400 M–72H, with a rating of 400 W [85], are assumed to be installed on the house's rooftop. In general, rooftop PV systems are widely accepted distributed generation technology that enhances household self-sufficiency and reduces the burden on traditional power plants. The capital cost taken from the manufacturer is 248 $/kW, and the O&M cost is 10 $/kW with a lifetime of 25 years and an 80% derating factor. The replacement cost for PV is 192 $/kW [119]

Converter: This case study uses a bidirectional converter to act as a rectifier and inverter at the same time, where power can flow in both directions. The capital cost of the used converter is considered 200 $/kW, and the replacement cost is considered 200 $/kW. In contrast, there is no O&M cost as the available converters are maintenance-free for a lifetime. Typically, a converter has an efficiency of 85% [117].

Battery: Installing the storage system supports system reliability, which is the most important aspect of the system's continuous operation. The proposed system mainly depends on intermittent solar energy. Since solar energy does not guarantee continuous supply, the village needs a storage system for regular supply. Batteries were selected as the storage system for this study, with an expected lifetime of 10 years. The capital cost for batteries is 300 $/kWh, and the replacement cost is 240 $/kWh [120].

Diesel Generator: Due to the uncertain nature of RES, the diesel generator is used as the hybrid system's primary backup source to increase the overall system's stability. Different capacities are simulated during the simulation to optimize the diesel generator capacity for the system. Capital cost, replacement cost, O&M, and fuel cost of diesel generator are taken as 250 $/kW, 250$/kW, 0.018$/op-hours, and 0.88 liters, respectively. Operating lifetime hours are considered to be 15000 hours [121].

Grid: An advanced grid is integrated with the system to improve the system's cost efficiency. For the current mode of operation in this study, the purchase rate from the grid is set to be 100,000 $/kWh, and the sale rate is 0.05 $/kWh [99]. This unrealistic purchase rate is intentionally set to avoid purchasing from the grid. This study uses the grid only to sell excess electricity during enough production hours to review prosumer capacity.

4.5.2. Results and discussion

HOMER-Pro software simulates multiple configurations to find the most optimal system for the specific load demand based on potential energy sources in the area. The proposed optimal system achieves the following properties.

- The system should be able to meet the complete load demand.
- The total NPC of the system should be low.
- The initial capital required to install the system should be minimal.

HOMER-Pro software supports two types of simulation analysis of the system:

- Optimization analysis
- Sensitivity analysis

4.5.2.1. Optimization analysis

The key objective of this research is to provide affordable electricity to remote villages with maximum use of RE. A HOMER-Pro simulation analysis based on NPC, LCOE, RF, EE, and CO_2 emissions is carried out for a village in Pakistan. Optimization analysis is done in two steps. In the first step, various system strategies are evaluated to meet the demand, and in the second step, different production units are further optimized, and a strategy is proposed based on the optimal solution and utilization of maximum output. Then, a comparison between the optimized and proposed cases is established.

Step1: Optimal System selection

The first step tests three base cases using HOMER-Pro software for optimal decision values. Techno-economic comparison is described below.

Case1: Existing Grid:

The study's main objective is access to electricity in remote areas that are not yet connected to the grid. Although access to electricity from the nearby existing grid is currently the most cost-effective solution if it is available, I considered eliminating this issue for this study because of the objective of the study.

Case 2: Grid extension:

Grid connection through on-site sources and components is unsuitable due to high extension costs [122], as shown in ***Table 39***. Due to economic constraints, the HOMER-Pro software did not recommend grid expansion as a viable option.

Table 39. *Grid extension parameters*

Parameter	Value
Capital cost	67746 $/km
Operation and maintenance cost	6889 $/km
Grid power tariff	0.28 Wh

Case 3: Hybrid renewable system

In this case, the system is based primarily on RE (solar energy, depending on site suitability) and is chosen with a small battery bank to enhance system stability. A diesel generator is added as a secondary power source to the system to act as a backup source in case the power provided by the PV and battery is insufficient for any reason. HOMER-Pro provided the most optimized and economical system, taking cost as an optimization variable. ***Table 40*** summarizes the detailed contribution of system components and installed capacity. This hybrid power generation system is the best of the total 394 options simulated by HOMER-Pro simulation. The results show that the PV system meets 75.4 % of the total demand while the diesel generator and battery bank meet the remaining. In this case, 627 447 kWh of excess electricity is generated annually. The system can be improved further with the utilization of excess power. The following study is proposed based on excess energy, and the next section provides further details.

Table 40. *Optimized (Case_3) and proposed (case_4) model configuration*

Case_3		Case_4	
System configuration		System configuration	
PV	636 kW	PV	636 kW
Gen	400 kW	Gen	400 kW
Battery	1 409 kWh	Battery	1 318 kWh
Converter	111 kW	Converter	92.2kW
Cost		Cost	
NPC	$ 2.68 M	NPC	$ 2.09 M
Initial capital	$702,177	Initial capital	$671,571
O&M	$ 121 667/year	O&M	$ 90 681/year
LCOE	$ 0.301/kWh	LCOE	$0.1/kWh
Emissions CO_2	102 911 kg/year	Emissions CO_2	101 375 kg/year
Excess Electricity	627 447 kWh/year	Excess Electricity	no
Renewable fraction	75.4%	Renewable fraction	75.4%

Step 2: Prosumer-consumer potential

The prosumers are new performers progressing towards a more sustainable future. The above simulation results show that much excess energy is generated with optimal solutions that require optimal utilization. Selling the excess electricity to nearby consumers makes the system more profitable overall. A thorough techno-economic investigation is needed to understand this prosumer-consumer potential better. Case 4 is proposed based on this idea and further investigated with HOMER-Pro software; the results of the economic analysis support this proposed strategy.

Case 4: Proposed case

> Optimized case 3 is the basis for estimating the prosumer potential in case 4. In this case, system optimization is done with PV size based on previous optimization (75% of the entire demand from PV). However, excess electricity is produced with the 75% integration of PV. A viable option for utilizing excess electricity is to sell it to neighboring consumers. This case is like Case 3, but an advanced grid is added into the system just as buyers of excess electricity. Power is not purchased from the grid by setting an unrealistic price for purchasing power from the grid. Considering 75% of the total electricity demand of the village depends on PV generation, LCOE, NPC, O&M cost, CO_2 emissions, and amount of electricity sold are estimated.

Table 41. *Charges for buying and selling electricity to the grid*

Electricity buys from the grid	100000$/kWh
Electricity sold to the grid	0.05$/kWh

Comparison of the optimized case and proposed case:

Case 3 is just a simple hybrid system optimized, and Case 4 is an extension of Case 3 with an advanced grid as a buyer only. Simulation results proved that case 4 is better in every way. ***Figure 45*** compares NPC, LCOE, O&M cost, and initial cost.

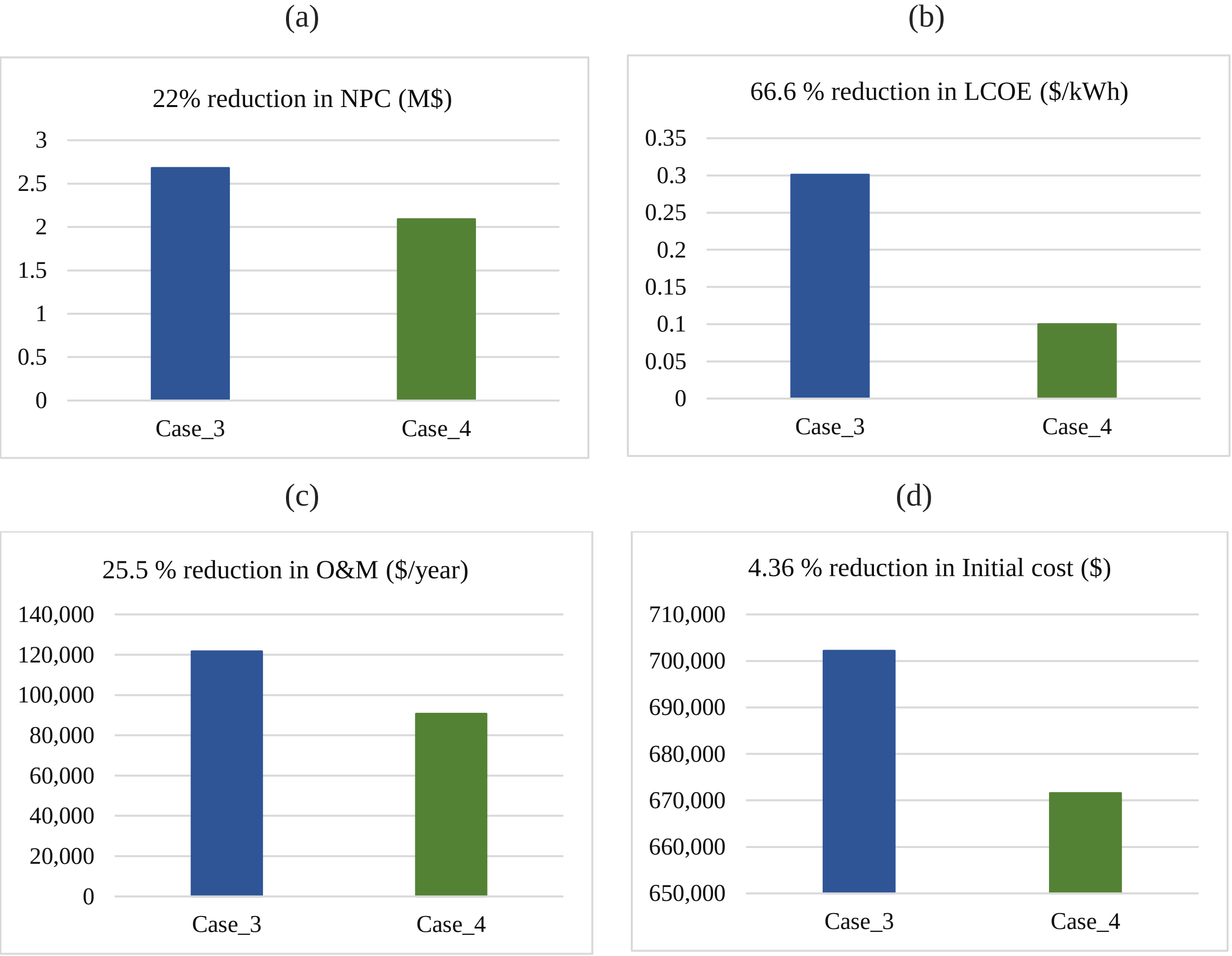


Figure 45. *(a) NPC, (b) LCOE, (c) O&M, and (d) Initial cost*

4.5.2.2. Sensitivity analysis:

A system should be defined by control variables or constraints that are effective on the system output. Testing the system under various conditions to help the designer select the most economical system for given conditions is called sensitivity analysis. I have designed both our optimized and proposed systems; considering some generic values, sensitivity analysis is performed on the proposed system to evaluate the system's performance under various constraints.

According to the official report of the State Bank of Pakistan, the present inflation rate is 6.17 %, but inflation is currently increasing, which drives additional fuel cost adjustments in electricity tariffs. Meanwhile, core inflation is rising; given the pace of inflation, the projection for the year 2023 is considered to be on the upside. However, state bureaucracy predicts this pace will not persist in the long run, and inflation could reach 3.5 percent in 2024. With these options in mind, 10%, 6.17%, and 3.5% inflation rates are considered suitable variables for sensitivity analysis of the system.

Since our modeled system is based on PV, the lifetime of the PV system is considered a major constraint. The generic PV system considered in the simulation has a lifetime of 20 years, so considering the rapid development of technology, values of 25 years and 30 years are also set as control variables. Similarly, I designed our optimized and proposed system with a 0% capacity shortage, but slight capacity shortages of 2.5% and 5% are considered for further economic analysis. ***Table 42*** lists the sensitivity variables.

Table 42. *Sensitivity variable*

Sensitivity inputs		
Expected inflation rate (%)	Capacity shortage (%)	PV lifetime (years)
3.5	0.00	20
6.17	2.5	25
10	5	30

Table 43 summarizes the simulation results and depicts that with increasing inflation rates, the NPC of the system increases, and with the expanding lifespan of the PV system, NPC decreases. Hence, if we compromise the system's capacity shortage, the system's net present cost will be enormously decreased. Results indicate that with a 0.0 % capacity shortage, the NPC of the system is 1 747 692 $, and with a 2.27% capacity shortage, the value of NPC reaches 1 555 612 $.

Table 43. *System cost and other parameters corresponding to the sensitivity variable*

Sensitivity			Cost			System parameters			
PV time (years)	Capacity Shortage (%)	Expected Inflation Rate (%)	NPC ($)	LCOE ($/kWh)	O&M ($/year)	CO_2 (kg/year)	Capacity Short (%)	Energy Purchased from Grid (kWh)	Energy Sold to Grid (kWh)
20	0	10	2860783	0.09705228	88778.63	104380.9	0	0	631568.9
20	0	3.5	1747692	0.1191352	89401.52	104296.8	0	0	630801.6
20	0	6.17	2113633	0.1104146	88518.84	101375.1	0	0	627546.3
20	2.5	10	2706640	0.09147049	83809.8	104701	1.119993	0	649518.8
20	2.5	3.5	1654776	0.1122953	83805.93	104701	1.119993	0	649518.8
20	2.5	6.17	1987438	0.1030709	84466.37	104701	1.119993	0	649518.8
20	5	10	2545576	0.08572885	78818.29	104694.7	2.274693	0	667880.1
20	5	3.5	1555612	0.1051996	78754.68	104694.7	2.274693	0	667880.1
20	5	6.17	1868126	0.096547	79369.3	104694.7	2.274693	0	667880.1
25	0	10	2830255	0.09601662	87557.5	104380.9	0	0	631568.9
25	0	3.5	1731551	0.1180349	88105.05	104296.8	0	0	630801.6
25	0	6.17	2091285	0.1092471	87147.05	101375.1	0	0	627546.3
25	2.5	10	2676112	0.09043881	82588.69	104701	1.119993	0	649518.8
25	2.5	3.5	1638635	0.1111999	82509.47	104701	1.119993	0	649518.8
25	2.5	6.17	1965090	0.1019119	83094.58	104701	1.119993	0	649518.8
25	5	10	2515048	0.08470073	77597.16	104694.7	2.274693	0	667880.1
25	5	3.5	1539471	0.104108	77458.22	104694.7	2.274693	0	667880.1
25	5	6.17	1845778	0.09539203	77997.52	104694.7	2.274693	0	667880.1
30	0	10	2809903	0.09532617	86743.42	104380.9	0	0	631568.9
30	0	3.5	1727112	0.1177323	87748.5	104296.8	0	0	630801.6
30	0	6.17	2082894	0.1088088	86631.96	101375.1	0	0	627546.3
30	2.5	10	2655760	0.08975101	81774.6	104701	1.119993	0	649518.8
30	2.5	3.5	1634196	0.1108987	82152.91	104701	1.119993	0	649518.8
30	2.5	6.17	1956699	0.1014767	82579.48	104701	1.119993	0	649518.8
30	5	10	2494696	0.08401532	76783.09	104694.7	2.274693	0	667880.1
30	5	3.5	1535032	0.1038078	77101.66	104694.7	2.274693	0	667880.1
30	5	6.17	1837387	0.09495836	77482.42	104694.7	2.274693	0	667880.1

Economic viability of the proposed system: ***Figure 46*** shows the overall cash flow of the system. PV systems, including batteries, share most of the initial capital cost, while diesel generators share less. However, diesel generators have a huge portion of fuel costs. The operational and maintenance cost of the system is low. Replacement of batteries accounts for a massive portion of replacement costs. At the end of the plant's life, the saving value of the system is about 200 000 $.

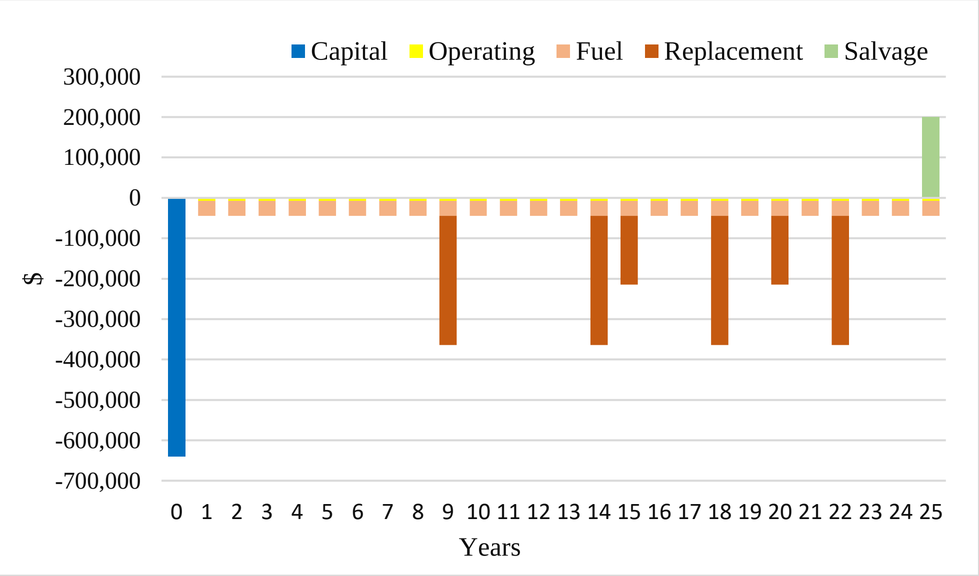


Figure 46. *Yearly cash flow of the system during the whole lifetime*

The scientific finding of the Chapter 4.5 summarized as follow:

Preface of Thesis 7 and Thesis 8:

Chapter 4.5 develops a comprehensive, integrated rural energy system model based on locally available RES with decentralized power generation. The proposed model is further developed to investigate adequate RES estimation. First, a village consisting of 250 households with six different types of houses from the Baluchistan province of Pakistan is selected, and the total load of the village is calculated using a simple engineering method. I assumed that this area was not connected to the main grid. Considering the socio-economic profile of the region, PV has been selected as the most suitable RES to meet the village's energy demand. Batteries are added to the system as energy storage during excess production hours to increase system stability, and a diesel generator is used as a backup source. Subsequently, proper sizing and optimization are carried out using the generic feature of HOMER-Pro software, and different strategies and configurations are analyzed after various simulations. The optimized system is considered for techno-economic feasibility analysis. Under these circumstances, I found that grid expansion is not financially viable, so I considered only decentralized hybrid power generation as a practically feasible option for this remote area. The optimal system consists of a 636 kW PV system, a 1409 kWh battery, and a 400-kW diesel generator, which is enough to meet the village's requirements. Simulation results show this optimal configuration generates 627 447 kWh/year of additional energy. Although using additional energy further increases the system's economic viability, I proposed a model to estimate accurately how much financial benefit we can achieve. I used the same optimized model and added an advanced grid as a buyer only. The price of power from the grid is set so high as to eliminate the option of buying power from the grid. Then, I simulated the proposed model again with HOMER-Pro software, and the results show that the model has become more efficient and cost-effective.

Thesis 7: The numerical results proved that the proposed system considering energy trading at the domestic level is a viable option in practice with significant benefits: reducing the load on the shared grid and reducing consumer costs. This idea of energy trade potential assessment with system optimization applying the optimum selling price is new and bridges the gap between RES integration and excess energy utilization. The resulting data can be solid input for the local energy trading models. The simulation results of the developed model verified that the local electricity trade results in 22% lower NPC, 66% lower LCOE, 25.5% lower O&M, and 4.36% lower initial cost with 200 000 $ as the salvage value of the system.

Thesis 8: The sensitivity analysis shows that the highest NPC appears when the PV lifetime is 20 years, the capacity shortage is 0.0 %, and the inflation rate is 10%; the lowest NPC appears when the PV lifetime is 30 years, the capacity shortage is 5.0 % and inflation rate is 3.5% while the highest LCOE appears when the PV lifetime is 20 years, capacity shortage is 0.0 % and inflation rate is 3.5% and the lowest LCOE appears when the PV lifetime is 30 years, capacity shortage is 5.0 % and inflation rate is 10%.

4.6. Summary

The EH approach simplifies the interconnection of diverse energy infrastructure; further, integrating RES and ES systems streamlines the EH framework. A mathematical formulation is presented to evaluate the operational mode of a residential EH model, and the optimization problem in a RES-based EH is solved by considering HLM for responsive appliances in a 3–4-person house. HLM strategy is proposed to manage the energy consumption of responsive appliances to minimize the peak demand. Thus, consumer costs can be reduced by considering the hourly effects of time-varying electric tariffs on the EH optimization results. Solar panels and battery operation are coordinated with the household demand response to minimize customer costs and maximize self-consumption. The presented results proved that the HLM application alone reduced the daily payment of customers by around 13.2% compared to those without HLM. The increased surplus energy may be a basis for local energy trading without grid involvement and is considered a viable option to reduce customer payments further. The proposed modeling approach can potentially upgrade the energy consumption behavior of typical household consumers and be one step closer to achieving society's sustainability goals.

Energy trade with blockchain technology is a suitable option, making a more economical microgrid system for abandoned areas. I developed the starting point of a real-time framework of energy trade between two rural houses connected with a common microgrid. Even though blockchain is not implemented pragmatically to analyze the behavior of prosumer and consumer, two identical building cases are 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. This approach 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.

The optimal hybrid system is decided based on the RES contribution percentage, NPC, LCOE, and emission limit using HOMER-Pro software. A comprehensive framework for rural electrification based on locally available energy sources is recommended. The HOMER-Pro simulation tool optimizes the RES-based system configuration and performs techno-economic analysis, operational feasibility assessment, and system robustness. A consumer-prosumer-based energy trading strategy is proposed to improve the system's commercial efficiency. A sensitivity analysis is done further to evaluate the system's feasibility under different conditions.

5. Conclusion & Future Work

5.1. Conclusion

In this thesis, the author focused on increasing the role of solar and wind energy in the electrification of developing countries.

- Providing a more realistic insight into the South Asian energy problem, I emphasized long-term energy system planning and proposed VRE as the most suitable energy alternative. The novelty lies in the techno-economic investigation of VRE integration potential limits through the EnergyPLAN model. A more intensive scenario for transforming the Pakistani electricity system was developed by considering the system integration costs associated with increasing the VRE share. I considered the areas connected to electricity, and alternative scenarios were formulated, such as increasing levels of renewable energies and their combination concerning the national plan as a BaU scenario to determine more appropriate targets. Although several studies have found that 100% renewable electricity generation is insanity for countries in the region, I believe that it is more appropriate to set more realistic but, at the same time, ambitious targets.
- Energy trading with blockchain technology is a viable option for electrification in peripheral areas, and it creates a more economical microgrid system for abandoned areas. I provided the starting point of a real-time framework of energy trade between two rural houses connected with a common microgrid using TRNSYS software. Simulation results for this scenario show that neighboring prosumers can contribute to meeting the demand for a second house. Selling electricity to nearby consumers is more profitable for both the prosumer and the grid.
- A modeling approach is proposed to upgrade the energy consumption behavior of typical household consumers. The optimal operation of a residential energy hub is investigated considering a family house of 3-4 persons. The HLM strategy is based on DRP and consumer-prosumer energy trading, which is investigated. The presented results proved that the HLM application alone reduced the daily payment of customers by about 13.2% compared to those without HLM. The simulation results based on TRNSYS software support the household-level energy trade-off considering the HLM and show that a higher electricity demand appears during the period of PV production. This new strategy outlines the potential importance of energy trading mechanisms and paves the way for sustainable community building.
- A comprehensive, integrated rural energy system model is investigated based on locally available RES with decentralized power generation. The total load of a village comprising 250 households with six different types of houses is calculated using a simple engineering method, assuming that the area is not connected to the central grid. According to the socio-economic profile of the region, PV has been selected as the most suitable RES to meet the village's energy demand. Batteries are added to the system as energy storage during peak production hours to increase system stability, and a diesel generator is used as a backup

source. Proper sizing and optimization are done using the generic feature of HOMER-Pro software. Based on the optimized system, a new system is proposed and developed using HOMER-Pro software to investigate the energy trading potential. Economic feasibility is evaluated using the economical parameters of the system: NPC, LCOE, initial capital and O&M. A further sensitivity analysis is performed to test the system's feasibility under different conditions. The results show that the proposed system has 22% lower NPC, 66% lower LCOE, 25.5% lower O&M, and 4.36% lower initial cost. This idea of energy trade potential assessment with system optimization is new and bridges the gap between RES integration and excess energy utilization. The resulting data can be solid input for the local energy trading models.

5.2. Future work

Through the research conducted in this dissertation, several related future research opportunities have been identified as the following:

- In my EnergyPLAN model, I focused on the generation side, considered the areas connected to electricity, and did not deal with those not connected to electricity. I see the electrification of these areas as feasible rather than expanding the electricity network with a technological leap of sorts, where small and medium-sized local networks are created in cooperation with new market methods like blockchain technology. I see the need to develop long-term planning further to include these new technologies in the design toolkits.
- The trade-off between the energy purchase price, greenhouse gas emissions, and energy efficiency is worth investigating to achieve society's sustainability goals. The work highlighted in this Ph.D. study can be extended to the practical implementation of energy trading for energy management between different buildings. Future work will focus on the price mechanism of energy trading, which requires the active participation of both the supply and demand sides.
- Further research may investigate whether the local grid operation can be realized in a non-profit way, for example, by sharing the local grid operation cost between the prosumers and consumers – since both have specific interests – resulting in a low local electricity price.
- Implementing local energy production and energy trading at the household level helps achieve dual benefits. Developers have an excellent opportunity to explore this research domain. Consideration of energy trading methodology and power consumption of multiple buildings, including heating and cooling demand using TRNSYS software, could be future studies.

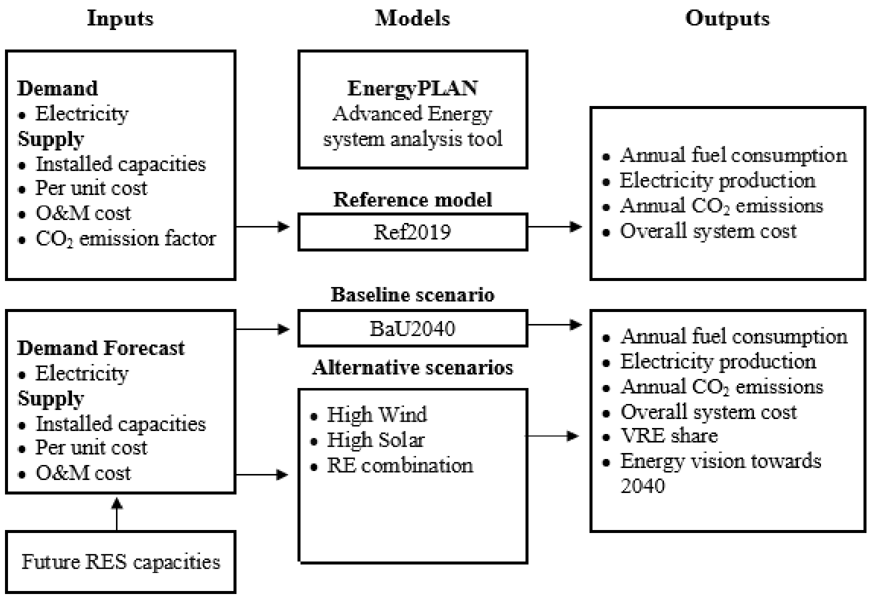
Scientific Contribution

Preface of Thesis 1 and Thesis 2: Developing a model of a country's entire electricity system is usually a complex task. The complexity depends on the content and scope of the model. During the PhD study, the depth of the developed model of the Pakistani electricity system is suitable for conducting medium- and long-term technical and economic studies.

Thesis 1: According to the requirements of the EnergyPLAN framework, a model of Pakistan's electricity system has been developed. The implementation of the model involves the development of the following main steps [P1, P3 and C3]:

1. Based on monthly aggregated energy demand, knowing the consumption curves of winter and summer seasonal working days and weekend days, the energy demand profile is generated for the entire year (8760 hours).
2. Thermal power plants are not considered individually but with a power plant characterized by average efficiency.
3. The hourly output curve of photovoltaic power plants (0..1) takes into account the location of power plants already installed in Pakistan and planned expansions so that the solar potential of each area is determined as the weighted proportion of the capacity in that area.
4. The hourly output curve of wind turbines (0..1) takes into account the location of wind farms already installed in Pakistan and the planned expansions so that the potential of each area favorable to wind energy is determined as the weighted proportion of capacities that can be considered in that area.
5. The hourly power curve of hydroelectric power plants (0..1) takes into account the geographical location of existing and planned hydroelectric power plants and the rainfall of the given area.
6. Validation is made by two steps: (1) is based on the present (2019) real power generation and consumption data, and (2) the projection calculated by another method (e.g., World Bank's projection) is re-modeled.

The following figure summarizes the content of the Thesis 1:



Thesis 2: The Grid Reinforcement Cost (GRC) for Asian countries can be calculated as $GRC = ap^2 + bp + c$, where for solar power generation: a=17.4, b=0.31, c=5.4, and for wind power generation: a=161, b=-16, c=2.5 and p means the penetration ratio, calculated as the yearly generated power by solar or wind relative to the whole yearly power production. [P1]

Thesis 3: Using the Pakistan electricity system model implemented in the EnergyPLAN framework, with the introduced formulae, the solar and wind capacities can be optimally utilized if 95 GW of solar capacity and 58 GW of wind power capacity are installed. [P1]

Preface for Thesis 4: 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 determines the appropriate PV and battery size. The results show that a 3–4-person family house has 10 kWh of electricity demand daily. A 3.5 kW PV system is required to meet this demand efficiently. A 30-kWh battery is installed as an energy storage unit for excess production.

Thesis 4: The TRNSYS simulation results validate that the system performance is satisfied according to design parameters, and 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. Considering the local energy trade, the simulation proved that the prosumer can cover more than half of the demand for the neighboring household. Selling electricity to nearby consumers is more profitable for the prosumer and the grid. [P4]

Preface of Thesis 5 and Thesis 6: I investigated the optimal operation of a residential energy hub. The optimization problem in a renewable-based Energy Hub (EH) is solved by considering Home Load Management (HML) for responsive appliances in a 3–4-person house. The first case demonstrates that the household energy demand depends on natural gas and the inflated cost of electricity from the common grid. In the second case, I explained the operation strategy of the EH with proper coordination of the PV system and Energy Storage System (ESS), which leads to lower dependence on the grid. The scheduling of responsive appliances is optimized according to time-varying tariffs, resulting in lower peak power demand and customer cost, to make this model more consumer-friendly. The designed model exhibits that the PV system installed at home is usually sufficient to meet the real demand. Excess energy is stored in ESS during hours of enough production.

Thesis 5: I proved that the Demand Response Program (DRP) plays a leading role in HLM and prevents high power demand during peak hours. The results show that incorporating TOU in HLM benefits the consumers without neglecting the concerns of the network operator. Simultaneously, comparing the difference between the target cost in the base case (based on grid supply) and the cost of the alternative strategies, I proved that the HLM application alone reduces the daily payment of customers by about 13.2% compared to those without HLM. It should be noted that the average tariff is higher in summer than in winter. Consequently, the customer cost reduction could be greater in summer than in winter. [P2]

Thesis 6: I proved by the TRNSYS simulation that the possibility of local energy trading is a cost-reduction option. The electrical load of the prosumer is simulated according to the size and optimized parameters of the PV, battery and backup source. The fractional Stage of Charge (FSOC) of the battery shows that sufficient RE generation is available to share the demand of neighbors. I investigated utilizing the surplus production consumer-prosumer strategy, including the HLM approach. The simulation results support the household-level energy trading strategy considering the HLM and show a high demand for electricity during the PV production period, so there is a minimum load on the battery and the grid. The proposed modeling approach to upgrade the energy consumption behavior of general household users is also suitable for more modern urban households. In practice, various home energy hubs can be designed for optimization based on the introduced strategies. In addition, a peer-to-peer strategy of domestic-level trading should be implemented along consumer and producer principles. [P2, C2]

Preface of Thesis 7 and Thesis 8:

Chapter 4.5 develops a comprehensive, integrated rural energy system model based on locally available RES with decentralized power generation. The proposed model is further developed to investigate adequate RES estimation. First, a village consisting of 250 households with six different types of houses from the Baluchistan province of Pakistan is selected, and the total load of the village is calculated using a simple engineering method. I assumed that this area was not connected to the main grid. Considering the socio-economic profile of the region, PV has been selected as the most suitable RES to meet the village's energy demand. Batteries are added to the system as energy storage during excess production hours to increase system stability, and a diesel generator is used as a backup source. Subsequently, proper sizing and optimization are carried out using the generic feature of HOMER-Pro software, and different strategies and configurations are analyzed after various simulations. The optimized system is considered for techno-economic feasibility analysis. Under these circumstances, I found that grid expansion is not financially viable, so I considered only decentralized hybrid power generation as a practically feasible option for this remote area. The optimal system consists of 636 kW PV panels, a 1409 kWh battery, and a 400-kW diesel generator, which is enough to meet the village's requirements. Simulation results show this optimal configuration generates 627 447 kWh/year of additional energy. Although using additional energy further increases the system's economic viability, I proposed a model to estimate accurately how much financial benefit we can achieve. I used the same optimized model and added an advanced grid as a buyer only. The price of power from the grid is set so high as to eliminate the option of buying power from the grid. Then, I simulated the proposed model again with HOMER-Pro software, and the results show that the model has become more efficient and cost-effective.

Thesis 7: The numerical results proved that the proposed system considering energy trading at the domestic level is a viable option in practice with significant benefits: reducing the load on the shared grid and reducing consumer costs. This idea of energy trade potential assessment with system optimization applying the optimum selling price is new and bridges the gap between RES integration and excess energy utilization. The resulting data can be solid input for the local energy trading models. The simulation results of the developed model verified that the local electricity trade results in 22% lower NPC, 66% lower LCOE, 25.5% lower O&M, and 4.36% lower initial cost with 200 000 $ as the salvage value of the system. [P5, P6]

Thesis 8: The sensitivity analysis shows that the highest NPC appears when the PV lifetime is 20 years, the capacity shortage is 0.0 %, and the inflation rate is 10%; the lowest NPC appears when the PV lifetime is 30 years, the capacity shortage is 5.0 % and inflation rate is 3.5% while the highest LCOE appears when the PV life time is 20 years, capacity shortage is 0.0 % and inflation rate is 3.5% and the lowest LCOE appears when the PV life time is 30 years, capacity shortage is 5.0 % and the inflation rate is 10%. [P5, P6]

List of Publications

- ❖ Journal Paper

P1. Aqsa Rana, Gróf Gyula: Assessment of the Electricity System Transition towards High Share of Renewable Energy Sources in South Asian Countries, Energies 2022, 15(3), 1139; https://doi.org/10.3390/en15031139, published

P2. Aqsa Rana, Gróf Gyula: Assessment of the Local Energy Trade in a Residential Energy Hub with Demand Management, Energy Reports, Volume 11, Jun 2024, Pages 1642-1658, https://doi.org/10.1016/j.egyr.2024.01.030, published

P3. Aqsa Rana, Gróf Gyula: Pakisztáni VER modellezése EnergyPLAN programmal, Energiagazdálkodás: 2021 év. 1-2 szám 38-42, published

P4. Aqsa Rana, Gróf Gyula: Assessment of Prosumer-based Energy System for rural area by using TRNSYS Software, Cleaner Energy system, Volume 8, August 2024, 100110, https://doi.org/10.1016/j.cles.2024.100110, published

P5. Aqsa Rana, Gróf Gyula: Prosumer Potential Assessment and Techno-Economic Feasibility Analysis of Rural Electrification, Energy Conversion and Management: X, Volume 22, April 2024, https://doi.org/10.1016/j.ecmx.2024.100542, published

P6. Aqsa Rana, Gróf Gyula: Fejlődő országok hálózattal nem ellátott területeinek villamosítása megújuló energia bázison, Energiagazdálkodás: 2023 év. 6. szám 11-19. oldal

- ❖ Conferences

C1. Aqsa Rana, Gyula Gróf, Environmental impact assessment of a coal-fired power plant to pave the way towards the eco-friendly country, LSEPP Social Inclusion Colloquium | Morocco 5th March 2021.

C2. Aqsa Rana, Gyula Gróf, Renewable Energy for Rural Electrification in Pakistan by Blockchain Technology, TÜBA World Conference on Energy Science and Technology Track Name: TUBAWCEST2021, Paper ID: 18

C3. Aqsa Rana, Gyula Gróf, Utilization of surplus power for Hydrogen production in case of the high share of renewable energy sources by EnergyPLAN model 13th International Exergy, Energy and Environment Symposium 14-17 March 2022

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Appendix

I. Solar generation profile hourly

I chose four cities (Baluchistan, Jhelum, Garo, and Turbat) with already installed solar plants. PVGIS software was used to get hourly global irradiance on the inclined plane (plane of the array) (W/m^2) for the PV system's nominal power. PVGIS monthly representative days of production and solar data are used to determine the actual month's hourly data, which can be merged for the whole year. ***Table A- 1*** shows the hourly power data of one city (Baluchistan), then I calculated the mean value between 0 and 1. Similarly, I generated the mean value for all four cities. ***Table A- 2*** shows the mean value of all four cities; I calculated the mean average to get one more precise value, as shown in **Figure A- 1**, for 100 hours and the entire year in ***Figure A- 2***.

Table A- 1 *Baluchistan city data extracted from PVGIS*

No.	Power (W)	0-1	Mean value
1	0	0	0
2	0	0	0
3	39927.5	0.399	0.399
4	69673.7	0.696	0.696
5	90355	0.903	0.903
6	101970	1.019	1
7	110140	1.101	1
8	101870	1.018	1
9	90715	0.907	0.907
10	68657.5	0.686	0.686
.	.	.	.
.	.	.	.
.	.	.	.
8760	0	0	0

Table A- 2 *Mean solar data for all four cities*

No.	Jhelum	Baluchistan	Turbat	Garo	Mean
1	0	0	0	0	0
2	0	0	0	0	0
3	0.0135	0	0	0.1149	0.0321
4	0.0175	0.3992	0.3942	0.4152	0.3065
5	0.0207	0.6967	0.6726	0.6531	0.5108
6	0.0365	0.9035	0.8491	0.8235	0.6532
7	0.0336	1	0.9655	0.8847	0.7211
8	0.0799	1	1	0.9038	0.7459
9	0.0298	1	0.9509	0.8264	0.7018
10	0.0799	0.9071	0.8331	0.7347	0.6387
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
8760	0	0	0	0	0

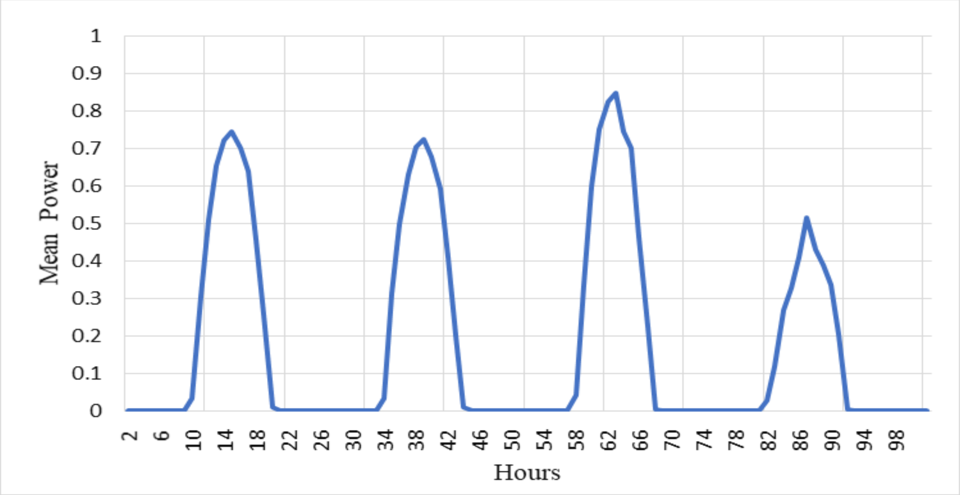

Figure A- 1 *Mean solar power value for 100 hours*

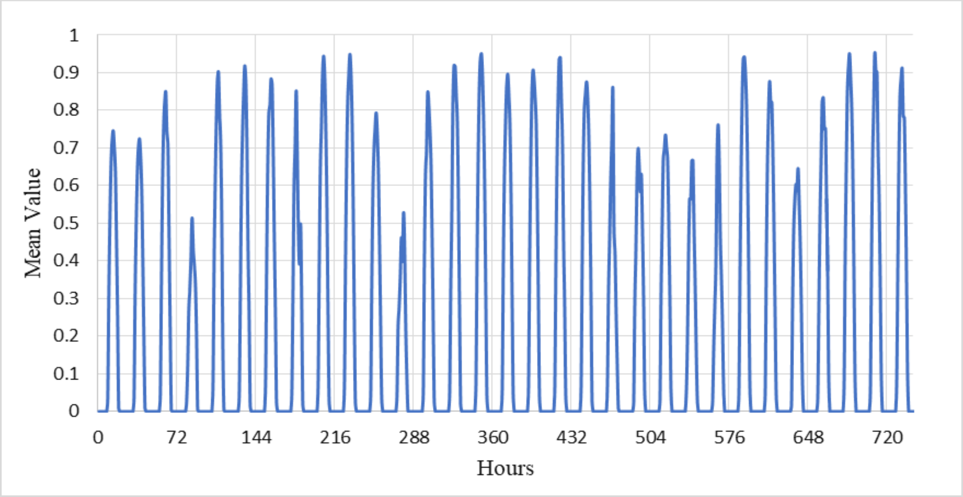

Figure A- 2 *Mean solar power value for 8760 hours*

II. Wind generation profile hourly

I selected four cities (West Baluchistan, Jhampir, Panjgoor, and Hyderabad) where different types of turbines are installed or planned soon, such as (Nordex, Siemens, and Vestas). PVGIS software was used to get hourly data for 10 m total wind speed (m/s). Then, from this 10 m data, wind speeds for 100 m and 220 m were calculated to meet each type of turbine requirement. Power for (Nordex, Siemens, and Vestas) was calculated using Equation (1A) [74] and parameters listed in ***Table A- 3***. Hence, ***Table A- 4*** shows Hyderabad data for three elevation points and three types of turbines. Similarly, all these steps were followed for all four cities, and the average value for all three types of turbines for all four cities was calculated. As

Table A- 5 shows the average value for three types of turbines, we calculated the mean value between 0 and 1 from the final three average values. ***Figure A- 3*** illustrates the results from 100 hours, and ***Figure A- 4*** shows the mean power for a year.

Table A- 3 *Parameters of different turbines*

Parameter	Vestas	Enercon	Siemens	Repower	Nordex	Siemens	Vestas164
P	2011.10	2065.20	2308.10	2062.90	2310.40	3620.00	7010.90
m	2.665	-0.959	0.398	2.665	1.714	0.027	-6.162
n	622.922	461.212	519.045	343.993	667.839	556.459	532.502
r	1.409	1.379	1.478	1.478	1.332	1.415	1.381

$$P(u) = P \cdot (1 + m \cdot exp(-\frac{u/_{r}}{1+n \cdot exp(-u/r)}) \qquad (1A)$$

Table A- 4 *Hyderabad city data for three elevation points and three types of turbines*

No.	W10	W100	Nordex	Siemens	W220	Vestas
1	4.12	6.5297	392.4508	556.048	7.6451	2207.008
2	4.31	6.8308	470.7233	663.7101	7.9976	2619.117
3	4.49	7.1161	555.2713	779.9956	8.3316	3033.475
4	4.67	7.4014	649.8161	910.3859	8.6656	3460.146
5	4.86	7.7025	759.7229	1062.873	9.0182	3910.421
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
8760	3.94	6.2444	328.3586	467.6602	7.3111	1849.238

Table A- 5 *Average power for all three turbines and mean value*

No.	Nordex	Siemens	Vestas	(Nordex + Siemens + Vestas) / (2300+3600+7000)
1	181.8511	259.0062	953.2417	0.1081
2	182.0624	258.3981	937.8234	0.1068
3	188.8363	266.7163	952.2396	0.1091
4	201.6711	283.4055	992.5177	0.1145
5	221.2025	309.5989	1057.403	0.1231
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
8760	191.0438	272.2579	1012.04	0.1143

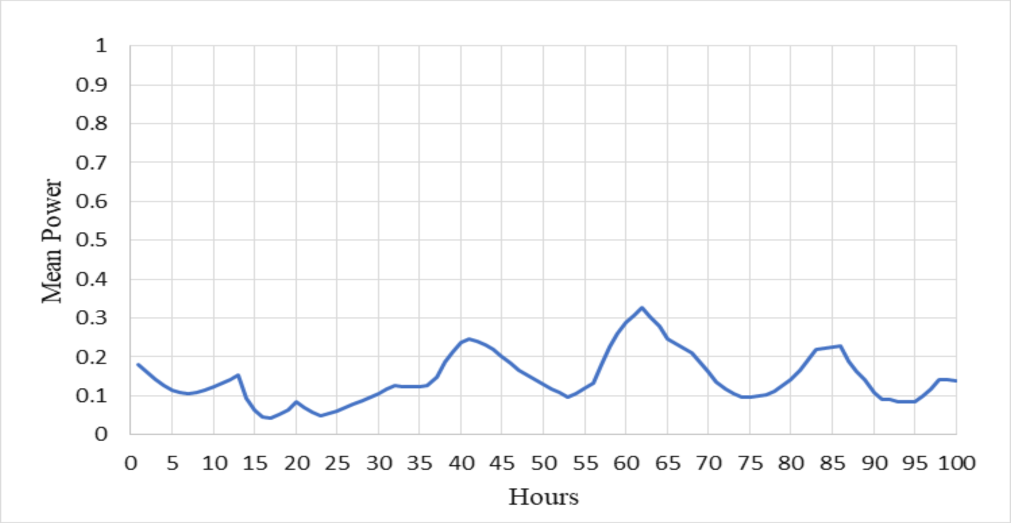

Figure A- 3 *Mean wind power value for 100 hours*

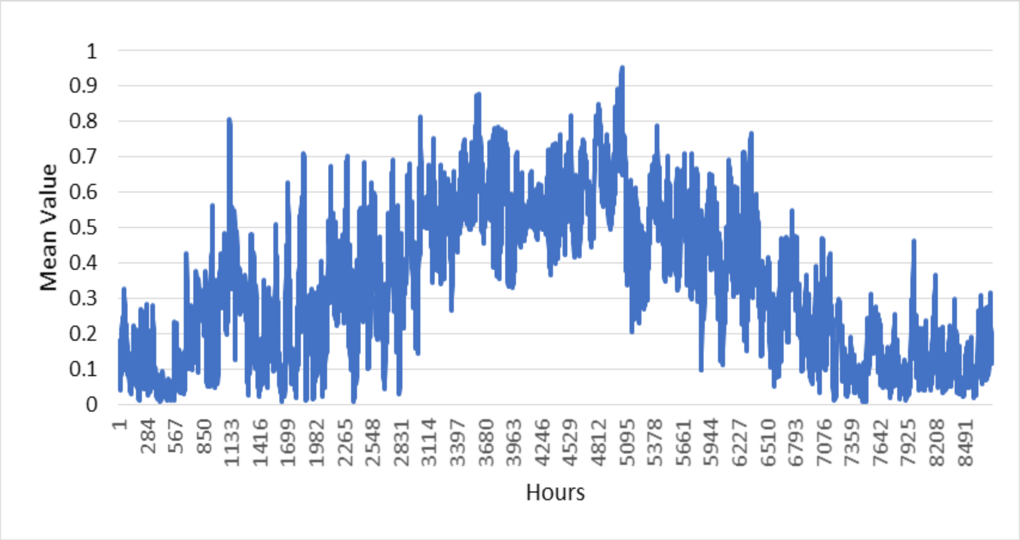

Figure A- 4 *Mean wind power value for 8760 hours*

III. Hydroelectric generation profile hourly

Based on monthly load demand [67], average monthly demand is calculated as shown in ***Table A-6***. The hourly load profile is generated from average monthly data, as shown in

Table A- 7 and ***Figure A- 5***.

***Table A- 6** Monthly demand data*

Hours	Month	Demand (MW)	Monthly demand/total
744	Jan	15,938	0.0669
1416	Feb	15,489	0.0651
2160	Mar	14,746	0.0619
2880	Apr	18,516	0.0777
3624	May	21,191	0.0889
4344	Jun	24,349	0.1022
5088	Jul	24,927	0.1046
5832	Aug	25,198	0.1058
6552	Sep	25,753	0.1081
7296	Oct	19,328	0.0812
8016	Nov	16,704	0.0701
8760	Dec	15,973	0.0671
Total demand (MW)		238,112	

***Table A- 7** Hourly demand data*

Hours	Monthly demand/total	= (Monthly demand/total) ·5.434734 · 0.9954 ·0.9
1	0.0669	0.3259
2	0.0669	0.3259
3	0.0669	0.3259
.	.	.
.	.	.
.	.	.
744	0.0669	0.3259
745	0.0651	0.3167
746	0.0651	0.3167
.	.	.
.	.	.
.	.	.
1416	0.0651	0.3167
1417	0.0619	0.3015
1418	0.0619	0.3015
.	.	.
.	.	.
.	.	.
8760	0.0671	0.3266

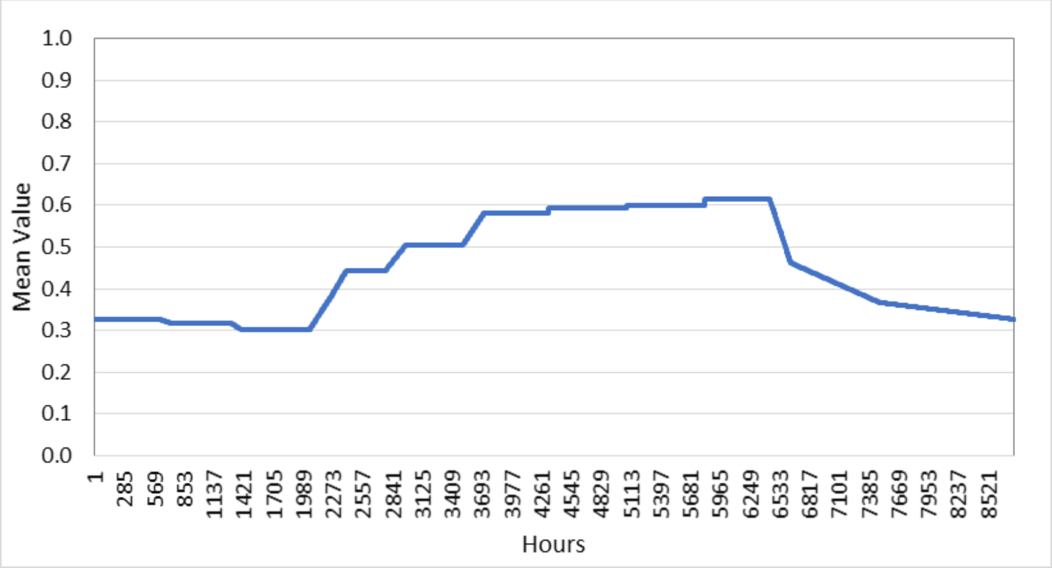

Figure A- 5 *Mean hydroelectric power value for 8760 hours*