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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

By

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1. Introduction

The principal subject of my 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. Continuous development cannot be imagined without higher electricity use. Still, 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: 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). This does not mean that people living there do not use electricity. They use natural resources (direct burning) and small generators that run on different fuels, producing 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. 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 sources. Adopting renewable energy sources (RES) in distributed networks prevents the expansion of transmission lines and lowers the pressure of establishing fossil fuel power plants.

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

2. Research context, scope, and objectives

Most of the power plants in the conventional energy system are based on fossil fuels. They are currently the main source of balancing the supply/demand dynamics of the global energy system. But, 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. Therefore, with the threat of phasing out fossil fuels in the future, the transition from conventional to renewable energy supply has become necessary. On the other hand, continuous industrialization and rapid technological advancement are increasing electricity demand. The latest energy trends show that the world is not on track to meet Sustainable Development Goals (SDG). So, SDG-7 custodian agencies emphasize the need for more substantial and concrete commitments to clean energy access.

Generally, RE integration is increasing rapidly, contributing to 90 % of the total power capacity growth in 2020 [1]. 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 [2], developing sustainable energy technologies with RE sources [3], and emphasizing RE integration in urban areas [4], as well as rural areas with microgrid installation [5] and maximizing utilization of existing grids [6]. Technical, economic, social, environmental, and infrastructural factors affect the choice of suitable and affordable technologies for particular circumstances [7]. Solar energy is one of the attractive options among all the RE sources due to its abundance and sustainable availability across the globe [8]. Solar power experienced significant growth with a 21-fold increase during 2010-2021, resulting in substantial cost reduction, technological advancement, and supportive financing models [9].

The main scope of my research 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. The increasing use of RES has encouraged producers to sell excess electricity to nearby consumers to promote collective self-consumption [10]. Adequate rules and specialized trading technologies, such as peer-to-peer blockchain, are substantial [11]. Energy trading problems like privacy breaches, miscommunication, and network speed are more challenging to overcome in conventional centralized systems [12].

Global energy consumption practices are undergoing essential reforms to cope with growing energy demands and severe climate challenges. 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. My 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. My 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 (Energy PLAN 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.

3. Method, Data, and Analysis Tool

Developing sustainable communities requires strong planning and policies to implement RES [13]. Energy system models can provide essential analytical benefits and have a long history of supporting decision-making at national and international levels [14]. 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 [15]. EnergyPLAN software tool developed at Alborg University in Denmark is used to simulate national long-term energy planning scenarios [16]. 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 [17]. Assessing building energy performance through modeling and simulation is a more promising approach to solving complex problems. Several household simulation tools, such as TRNSYS, EnergyPlus, ESP-r, and Design-Builder, are used to estimate the energy performance of the households. 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 [18]. TRNSYS was developed at the

Solar Energy Laboratory at the University of Wisconsin-Madison [19]. Community-scale energy planning with considerations such as local supply sources, storage facilities, climate conditions, and user involvement is receiving increasing attention. 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 with minimum net present value (NPC) as an objective function [20]

The entire research in this dissertation was developed and analyzed using various software and specific modeling tools. Microsoft Excel, EnergyPLAN, TRNSYS, and Homer Pro are the tools and software used. The results are generated by data processing and simulation.

4. Overview of the research

4.1. Long-term energy system planning

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 business as usual (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 to include these new technologies in the design toolkits.

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 the Photovoltaic Geographical Information System (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;

Thesis 1, thesis 2, and thesis 3 are concluded from long-term energy system planning.

4.2. Renewable energy-based rural electrification

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.

4.2.1. Prosumer-based rural electrification using TRNSYS software

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 households 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. Model and evaluate PV and ES systems for the residential load of a typical two-bedroom house.
3. Estimated and calculated results are tested using transient simulation software TRNSYS-18.
4. The system's technical, economic, and environmental performance is evaluated.

Thesis 4 is concluded related to prosumer-based rural electrification.

4.2.2. Residential EH concept for assessment of local energy trade potential

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 home load management (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.

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 can be managed by managing the energy consumption of responsive appliances.
2. Scheduling of responsive appliances is 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, considering the energy trade as a viable option.

Thesis 5 is concluded related to energy consumption management.

4.2.3. HLM-based domestic energy trading using TRNSYS software

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 households 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.

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.

Thesis 6 is concluded related to energy sharing between buildings.

4.2.4. Local energy trade – whole village case assessment

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 [21]. RES-based electrification of remote areas through decentralized generation has emerged as a low-cost and practically viable solution, as grid expansion is expensive [22]. 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.

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.

Thesis 7 and thesis 8 are related to the dynamic framework of energy trade between prosumer and consumer using HOMER Pro software.

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 (mico-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.

5. Conclusion & Future Work

5.1. Conclusion

In my Ph.D. study, I 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 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.

6. Summary of new scientific results-Theses

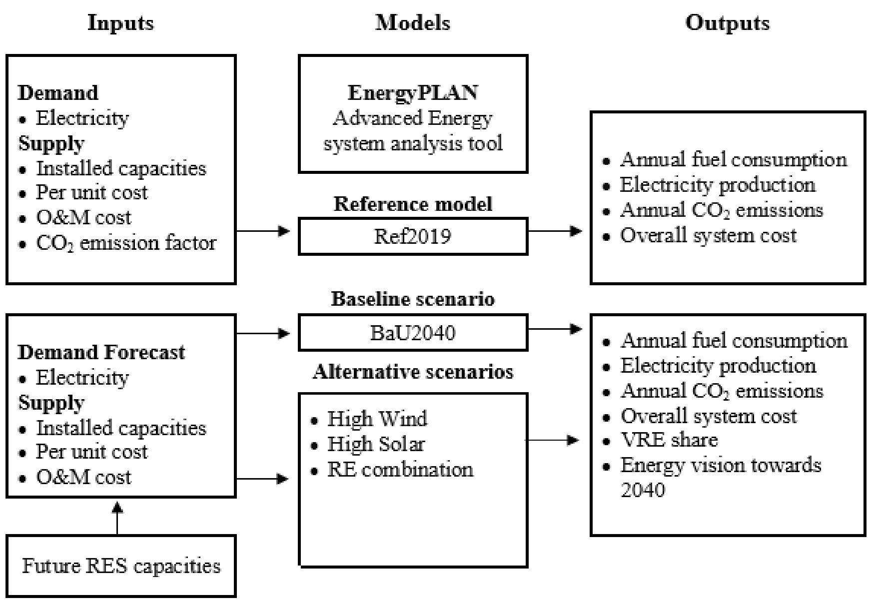
Preface of Thesis 1, Thesis 2, and Thesis 3: Developing a model of a country's entire electricity system is usually a complex task. The complexity depends on the content and scope of the model. During the PhD study, the depth of the developed model of the Pakistani electricity system is suitable for conducting medium- and long-term technical and economic studies.

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, 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. Two-step validation is done: (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.

Thesis 1 can be summarized in the following figure:



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 reduced 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. 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 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: These numerical results proved that the proposed system considering energy trading at the domestic level is a viable option 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 the inflation rate is 3.5% while the highest LCOE appears when the PV lifetime is 20 years, the capacity shortage is 0.0 %, and the inflation rate is 3.5%. The lowest LCOE appears when the PV lifetime is 30 years, the capacity shortage is 5.0 %, and the inflation rate is 10%. [P5, P6]

7. 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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