National University of Science and Technology

POLITEHNICA Bucharest

Doctoral School of Energy Engineering

Faculty of Power Engineering

DOCTORAL SUMMERY

SOLUTIONS FOR LOCAL CONSUMERS ENERGY SUPPLY FROM RENEWABLE SOURCES

Author: Ph.D. Candidate Eng. Mohammed Gmal Osman Abdelfadeel

Supervisor: Professor Gheorghe LAZAROIU, Ph.D.

Romania, Bucharest

2024

National University of Science and Technology
POLITEHNICA Bucharest
Doctoral School of Energy Engineering
Faculty of Power Engineering

Decision no. …… / 2024

DOCTORAL THESIS

Solutions for Local Consumers Energy Supply from Renewable Sources

Author: *Ph.D. Candidate Eng. Mohammed Gmal Osman Abdelfadeel*
Supervisor: *Professor Gheorghe LAZAROIU, Ph.D.*

Doctoral Commission

Chair	Professor Radu PORUMB, Ph.D.	From National University of Science and Technology POLITEHNICA Bucharest, Romania
Supervisor	Professor Gheorghe LAZAROIU, Ph.D.	From National University of Science and Technology POLITEHNICA Bucharest, Romania.
Referee	Professor Vali Violeta CIUCUR, Ph.D.	From Maritime University of Constanta, Romania.
Referee	Professor Ion V. ION, Ph.D.	From Dunarea de Jos University of Galati, Romania.
Referee	Conf. Eng, Dorel STOICA, Ph.D.	From National University of Science and Technology POLITEHNICA Bucharest, Romania

Bucharest
2024

Contents

Abstract

The thesis titled ***"Solutions for Local Consumers' Energy Supply from Renewable Sources"*** embarks on a thorough exploration of the feasibility of a robust solar energy system tailored to the unique conditions of Sudan. Photovoltaic technology emerges as the most suitable solution for the generation of electrical energy across all Sudanese cities, largely owing to Sudan's strategically advantageous geographical location. This implementation becomes a compelling necessity not only for remote regions distanced from the national grid but also for densely populated urban centers, including the national capital, which grapples with recurrent power disruptions. The integration of rooftop solar panels further augments the feasibility of this approach, making it accessible to every household.

The analysis conducted in this study is multifaceted and encompasses four critical dimensions. Firstly, the research scrutinizes the Sudan Energy Profile and its characterization, including aspects such as the percentage of the population with access to electricity and per capita energy consumption trends over a span of 20 years. Secondly, it delves into the rapid advancements in photovoltaic cell technology and innovative connection architectures, which have significantly reshaped the solar energy landscape, providing insights into the latest technological developments. The third dimension of the analysis revolves around the assessment of solar energy potential in various regions of Sudan, with a focus on identifying optimal locations for solar energy utilization. The study examines Sudan's solar radiation, total renewable energy resources, and delineates the most suitable regions for solar energy deployment. Lastly, the thesis explores the design and comparison between solar energy and conventional power for supplying energy to a remote village in Sudan. Multiple mathematical models are defined and simulated using MATLAB and Homer environments, and these models are subsequently validated in the context of a remote village.

In summation, this thesis encompasses a holistic investigation into the utilization of solar energy in Sudan, offering a promising solution for enhancing energy access and resilience and contributing to the nation's sustainable energy future.

Keywords: *renewable energy; solar cells; solar irradiation; energy conversion; hybrid energy systems.*

Express of gratitude

The three years of dedicated research for my Ph.D. were a journey filled with challenges, persistent efforts to expand my knowledge, and contributions to enriching scientific literature with the outcomes of my investigations. This accomplishment was realized within the esteemed academic setting of the National University of Science and Technology POLITEHNICA Bucharest.

I express my sincere gratitude to Professor Gheorghe LAZAROIU, my supervisor, for nurturing my development, opening doors to groundbreaking research, and fostering valuable collaborations. I am also indebted to him for being an academic mentor, offering valuable guidance, and consistently motivating me throughout these three years.

A special appreciation goes to Professor Lucian MIHAESCU for his constructive insights, invaluable observations, and instrumental assistance in refining the final version of my thesis.

I express my sincere gratitude for the thoughtful review of my thesis by the esteemed members of the doctoral committee: Chair Professor Radu PORUMB, and Referees Professor, Professor Violeta Vali CIUCUR, Professor Ion V. ION, and Conf. Eng, Dorel STOICA, Ph.D.

I extend my gratitude to Professor Gabriel Paul NEGREANU and Professor Ionel PISA for their invaluable discussions and advice during progress report meetings.

To my colleague Ph.D. Student Cristian STREJOIU, who stood with me, I extend my heartfelt gratitude for support.

I dedicated this endeavor to my late father, whose unwavering presence continues to inspire and guide me despite his physical absence, my enduring mother Fathia Abdelmalik, whose sacrifices and resolute support have been the bedrock upon which I've constructed my academic aspirations, my esteemed brothers Fakhreldin, Alaaldin, Mohieldin, and Osman, whose steadfast camaraderie and unwavering faith in my potential have been instrumental in shaping my academic journey, and my beloved grandmother Fatima Alzaki, whose profound wisdom and guidance have served as a compass leading me towards the paths of knowledge and virtue, This dedication stands as a testament to the collective love, encouragement, and inspiration I've received from these extraordinary individuals, shaping not only my academic journey but also the very essence of my being. To the woman of my dreams, Shadia ABD ELDAIM, a beacon of light in my life's journey, with all my love and devotion.

I extend my sincere gratitude to the Romanian government for granting me a scholarship, a gesture that not only supported my academic endeavors but also demonstrated its dedication to fostering education and empowering individuals to fulfill their aspirations.

My heartfelt appreciation also extends to the Ministry of Electricity, embodied in the Sudanese Electricity Transmission Company, for their generous support throughout my journey.

To everyone who has contributed to my path, your kindness and encouragement have been invaluable. May your goodness be rewarded abundantly.

With deep gratitude: Mohammed Gmal Osman Abdelfadeel

Foreword

The solutions for supplying local consumers from renewable sources aim to:

- Meet the energy needs in areas not connected to a centralized grid.
- Fulfill energy requirements solely from renewable sources for specific periods in a particular geographic area using a microgrid system.

In the relentless pursuit of sustainable energy solutions, this doctoral thesis, titled "**Solutions for Local Consumers Energy Supply from Renewable Sources**," embarks on a significant journey into the intricate realm of alternative energy generation systems. As we stand on the precipice of a global energy transition, the need for environmentally friendly and economically viable energy sources has never been more urgent. This doctoral thesis navigates the complex terrain of sustainable solutions for local consumer energy supply. The journey begins with a comprehensive present world situation energy landscape and a thorough examination of literature related to renewable energy solutions.

The Foreword serves as a prelude to the chapters that follow, providing a glimpse into the motivations, challenges, and aspirations that underpin the research. Embarking on a quest for sustainable energy beckons individuals to explore inventive alternatives, inviting them to uncover eco-friendly options that have the potential to reshape the energy landscape. Let's join forces in the pursuit of a greener tomorrow.

Considering the present global energy environment, where climate change and environmental degradation loom large, the Foreword sets the stage for a comprehensive investigation into renewable energy solutions. It signals the necessity to not only understand the theoretical aspects but to also delve into practical applications and considerations that might pave the road for a more environmentally friendly and sustainable future.

This thesis unfolds as a narrative, with each chapter contributing a distinct layer to the overarching story of harnessing energy from renewable sources. As the exploration begins, we delve into the energy landscape of Sudan, a country with a rich tapestry of energy resources. From biomass and hydropower to oil, natural gas, and the promising avenues of wind, geothermal, and solar power, **Chapter 1** lays the groundwork for the subsequent chapters.

The exploration then focuses on the cutting-edge developments in solar energy technologies. **Chapter 2** unravels the advancements in photovoltaic cell technology and connection architectures, highlighting the dynamic evolution of solar power as a key player in the renewable energy spectrum.

Moving forward, **Chapter 3** takes us on a journey to assess the solar energy potential across different regions of Sudan. This involves a meticulous examination of solar radiation, photovoltaic utilization, and global horizontal irradiance, ultimately leading to the determination of optimal photovoltaic configurations tailored to specific geographical nuances.

Chapter 4 shifts the focus to the realm of solar thermal energy, exploring its viability as an efficient and sustainable heating solution. This involves a comprehensive overview of solar water heating systems, technology considerations, and economic analyses, offering insights into the multifaceted applications of solar thermal energy.

In **Chapter 5**, the exploration takes a pragmatic turn, focusing on real-world applications. A thorough examination of the planning and comparison between solar energy and traditional power sources for supplying a rural community in Sudan unfolds. This chapter serves as a bridge between theoretical insights and real-world implications, addressing issues of geographical considerations, load demands, and cost-effectiveness.

As the narrative approaches its culmination in **Chapter 6**, the Conclusions and Further Research Perspectives chapter, it draws together the threads of knowledge woven throughout the thesis. It synthesizes overarching conclusions, emphasizes the original contributions made, and paves the way for future research endeavors in the dynamic field of sustainable energy.

In essence, this Foreword sets the tone for a comprehensive exploration, inviting readers to embark on a journey of discovery into the world of renewable energy solutions. May the insights gleaned from this thesis contribute meaningfully to the ongoing global discourse on sustainable energy transitions, guiding us toward a future powered by clean, efficient, and eco-friendly energy sources.

Ph.D. Thesis Contents

Sudan, a country blessed with abundant solar resources, stands at the precipice of a renewable energy revolution. With vast expanses of sun-drenched terrain and a growing need for sustainable energy solutions, the exploration and utilization of solar energy have emerged as imperative pursuits. This thesis embarks on a comprehensive journey through Sudan's solar energy landscape, aiming to unlock its full potential and chart a course towards a greener, more sustainable future [1].

The research objectives *were as follows:*

- Conducting a comprehensive study of solar energy resources and technologies, serving as a model for the adoption and implementation of solar energy systems in diverse geographical contexts, including Romania, Sudan, and worldwide.
- Providing an overview of Sudan's abundant solar resources and their broader implications for addressing global energy challenges, highlighting the universal relevance of solar energy as a clean and renewable energy source.
- Identifying optimal locations for solar power plants across Sudan, using site selection methodologies that can be replicated and adapted for similar efforts in other regions, contributing to the expansion of solar energy infrastructure globally.
- Analyzing the evolution of solar panel technology and advancements in solar energy systems, providing insights into technological innovations that can be leveraged to maximize energy generation efficiency and scalability in diverse geographical contexts.
- Evaluating the effectiveness of solar energy in heating applications and assessing hybrid energy solutions, offering a comprehensive understanding of the versatility and scalability of solar energy technologies for meeting various energy needs globally.
- Developing a practical code in MATLAB for analyzing energy scenarios in hypothetical villages, facilitating scientifically informed decision-making and strategic planning in the implementation of solar energy systems in different regions and communities.
- Contributions to the knowledge of solar energy through empirical analyses, theoretical frameworks, and practical tools, promoting collaboration, innovation, and shared commitment towards a brighter and more sustainable future for all.
- Promoting knowledge exchange and capacity development in the field of solar energy through the dissemination of research findings, best practices, and practical tools, facilitating technology transfer and collaboration among stakeholders from different regions and sectors.

The thesis unfolds logically, with each chapter making distinct contributions to the overall effort of harnessing energy from renewable sources.

The **Chapter 1** of this study offers a panoramic view of Sudan's rich and diverse solar resources. By casting a spotlight on the untapped reservoirs of solar energy, we aim to capture the reader's attention and underscore the urgency of harnessing this abundant source of power. From the sunbaked deserts of the north to the fertile plains of the south, Sudan boasts an array of solar assets waiting to be harnessed for the benefit of its populace [2]. When delving into Sudan's energy production, there's a notable surge from 2000 to 2019, as reported by the International Energy Agency. However, a critical aspect arises: a significant portion of this output relies on traditional biomass fuels, emphasizing the urgent need for Sudan to transition to greener and more sustainable energy sources.

Sudan's electricity production mix in 2019 was dominated by thermal power plants, contributing 89% to the total. Despite the significant potential of hydroelectric and solar power, their contributions remain relatively modest. To address this, Sudan aims to produce 20% of its electricity from renewable sources by 2030, with a focus on solar and wind power.

This shift is crucial not only for sustainability but also for improving access to electricity. While significant progress has been made since 1992, when only 32.6% of Sudan's population had access to electricity, there's still work to be done. With 53.6% having access in 2019, initiatives to increase renewable energy production will likely contribute to further improvements in access.

In **Chapter 2**, we embark on a journey through the evolution of solar panel technology. From its humble beginnings to the cutting-edge innovations of today, solar panel technology has undergone a remarkable transformation. By tracing this trajectory of progress, we seek to highlight the tremendous potential for further advancements in the field, paving the way for more efficient and cost-effective solar energy solutions [4]. PV technology converts solar energy into electricity, with two main techniques: photovoltaic (PV) and concentrated solar power (CSP) systems.

Crystalline silicon dominates the photovoltaic sector, representing over 90% of the market share due to its reliability and efficiency. The evolution of PV technology has led to the development of more efficient and economically viable solar panels.

First-generation PV technologies primarily use crystalline silicon, with efficiency typically ranging from 13% to 18%. These technologies benefit from mature manufacturing processes but face challenges related to manufacturing costs.

Second-generation PV technologies, such as thin-film solar cells, offer potential cost advantages over crystalline silicon. However, they generally exhibit lower efficiency, ranging from 5% to 21.2%, depending on the specific material used.

Third-generation PV technologies encompass emerging concepts and materials aimed at further improving efficiency and reducing costs. These include concentrating PV (CPV), dye-sensitized solar cells (DSSC), organic solar cells, and novel materials like quantum dots and perovskites. While these technologies hold promise for higher efficiency, they face challenges related to limited commercialization and technical complexities.

The investigation into PV array and connection architectures underscores a range of methodologies aimed at alleviating power loss concerns arising from shading or malfunctions.

These include the deployment of bypass diodes, the utilization of maximum power point tracking (MPPT) techniques, and the adoption of innovative array configurations like series-parallel, total cross-tied, bridge-linked, and honeycomb arrays. Each approach offers distinct advantages and trade-offs, highlighting the complexity of optimizing solar power systems for efficiency and resilience in varying environmental conditions.

Building upon this foundation, **chapter 3** delves deeper into the practicalities of solar energy utilization. Through the meticulous examination of 11 sites across Sudan, each selected based on stringent criteria, we endeavor to identify the optimal locations for the establishment of solar power plants. By pinpointing these strategic hubs, we aim to lay the groundwork for the widespread adoption of solar energy generation, thereby bolstering Sudan's energy independence and resilience [3]. The study conducted using HOMER software aimed to identify the optimal solar photovoltaic (PV) system to meet the energy needs of a Sudanese city. Among the various PV systems analyzed, the Studer VarioTrack VT-60 emerged as the most suitable option, with a Cost of Energy (COE) of USD 0.08748/kWh and requiring only 30 PV panels to meet demand. Subsequent simulations in 11 different locations across Sudan revealed that Dongola and Khartoum are the most favorable locations for solar energy utilization, with COEs of USD 0.08255/kWh and USD 0.08299/kWh, respectively.

Chapter 4 of this study shines a spotlight on the versatility of solar energy in heating applications. By assessing its efficacy as a sustainable heating solution, we aim to showcase the myriad benefits of solar energy beyond electricity generation. From residential heating to industrial processes, solar energy holds the promise of reducing reliance on fossil fuels and mitigating harmful carbon emissions. The study explores the thermal efficiency and economic viability of solar energy systems in Khartoum, Sudan. It utilizes the Polysun software for dynamic annual simulations and economic assessments. The software provides accurate simulations without requiring correlation terms, incorporating ecological balance and economic viability assessments. Sudan's solar potential is highlighted, with nine hours of sunlight per day and an average daily solar insolation of 6.2 kWh/m^2.

Efficiency calculations for solar collectors, daily water heating energy load, system size, cost, and economic viability are presented. Results show significant annual energy savings and cost-effectiveness compared to conventional energy sources. Monthly solar contribution analysis demonstrates the system's ability to meet summer and winter demands efficiently. MATLAB simulations and results showcase the efficiency and versatility of hybrid solar panels, known as PVT panels, in generating both electricity and heat.

In **Chapter 5**, the author conducts a series of original applications of the concrete and real situation in Sudan. They undertake a thorough examination of the planning and comparison between solar energy and traditional energy sources for powering a rural community in Sudan. This chapter serves as a bridge between theoretical knowledge and real-world implications. He focuses on a village in Sudan's Shariq al-Nil unit, which, despite lacking access to the national electricity grid and relying on diesel generators, is suitable for photovoltaic projects due to its geographical location and small, agricultural community.

Basic loads in this remote area are mainly for water pumps, lighting, cooling, and heating, the total load is represented in the Table 5.1

Table 5.1 The total load of the village

Load	No	(W)	Total Installation Load (W)
House	30	3000	90000
Street	1	600	600
Medical	1	1300	1300
Supermarket	1	200	200
Pump Water	2	11000	22000
Total Load			114100

The study conducted a thorough examination of these loads across three stages to identify the optimal combination of efficiency and economic viability. Initially, the loads were intended to be powered by solar panels. Subsequently, in the second scenario, distinct panels were allocated for hot water generation and electricity production. Finally, hybrid panels were employed to simultaneously generate electricity and provide hot water.

Table 5.2 Summary of the System Components

Component	Model	Component Rating			Size (inch)	Unit Price USD	Total price	Warranty
		W/Ah	A	V				
Panels	Longi LNGLR4-72HPH-455M	455 /339W	10.92/8.75	41.7/38.8	209.4 x 103.8 x 3.5 cm	100	26000	25
Batteries	Lithium Battery	100 Ah	~	12	3.3x1.7x2.2	75	5000	2
Inverter	VG1012	800W	~	24/220	4.7x3.35x2.1	100	3300	5
Wires	#02 AWG				Diameter= 6.54 mm, Area= 32.0 mm^2	50	100	
	#10 AWG				Diameter= 2.59 mm, Area= 5.27 mm^2	50	100	
Diesel	Stager	5000	18	230	9.50 x 5.50 x 7.65	2000	4000	2
Diesel	Stager	20000	86.9	230	18.9x9.1x11.6	10000	30000	2

In this configuration, solar panels generate daytime electricity for the village and charge batteries. At night, batteries power lights and appliances. With a COE of $0.673 per kWh and an NPC of $1.58 million, the system prioritizes sustainability by emitting no carbon. While the COE is relatively high, the NPC suggests a significant upfront investment, potentially leading to long-term cost-effectiveness. Striking a balance between financial viability and environmental impact is essential for a reliable and cost-effective power solution.

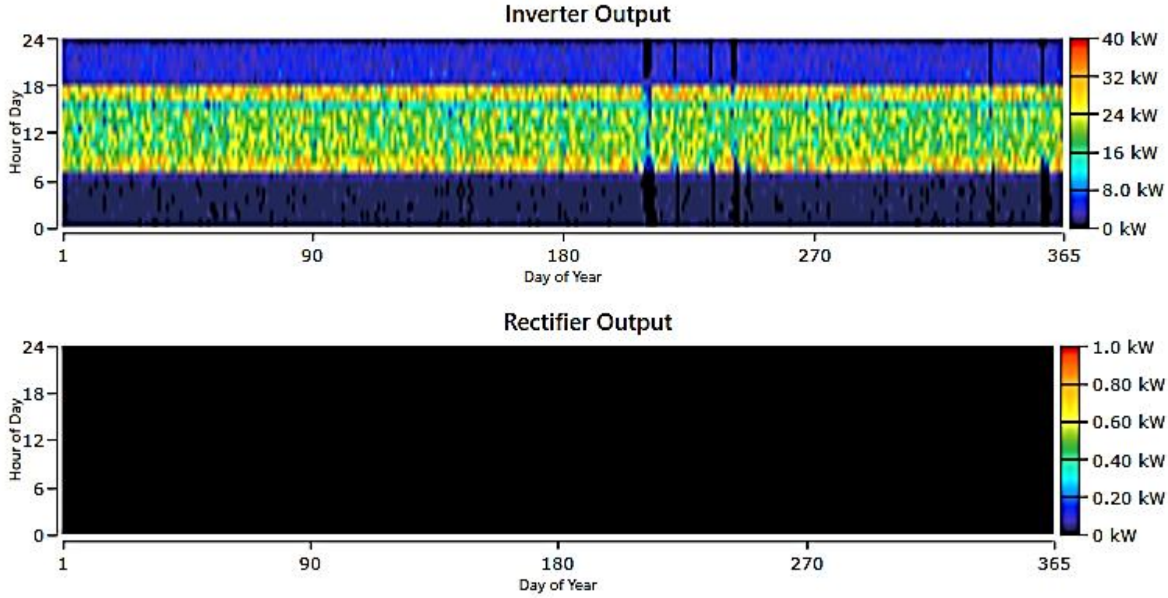

Figure 5.1 simulation results of Converter.

The system operates for 8629 hours per year, with both the inverter and rectifier capable of handling a maximum power of 35 kW.

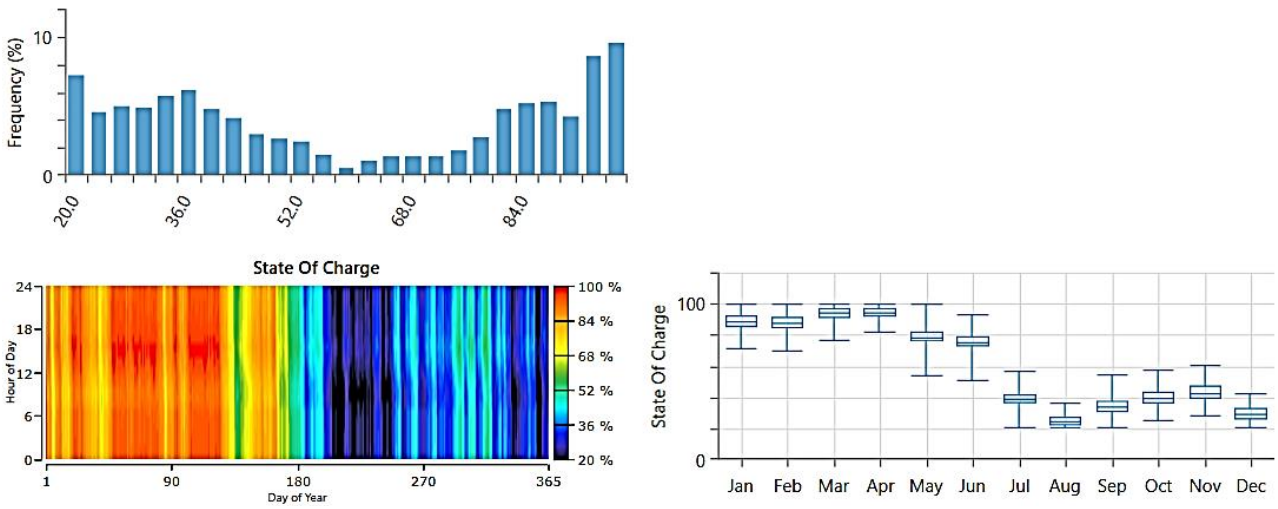

Figure 5.2 Status of Batteries charging.

The bus voltage is noted at 48 V, with a nominal capacity of 1613 kW/h for the energy storage batteries, an energy input of 37363 kWh/year, an energy output of 36706 kWh/year, and a total operational duration of 8473 hours.

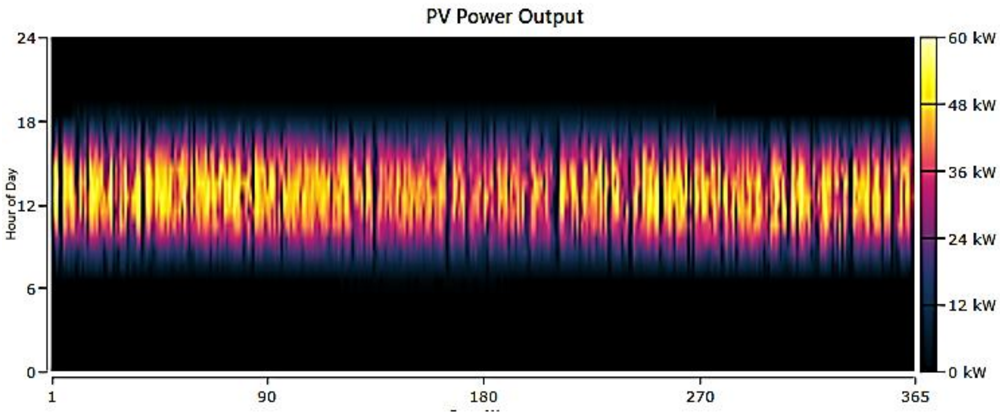

Figure 5.1 PV panel output over the year.

The equipment used in the system costs a total of 34300 USD PV and 34000 USD diesel. Additional costs must be added for design, labor, wiring, metering, monitoring, disconnect devices, and shipment, this additional expense is estimated to cost 4000USD on diesel.

A study of the production of hot water separates

The system, with a rated capacity of 58.8 kW and a maximum output of 57.3 kW, has operated for 4361 hours in a year, achieving a total production of 112.017 kWh per year and a mean daily output of 307 kWh, indicating robust performance in solar photovoltaic energy generation.

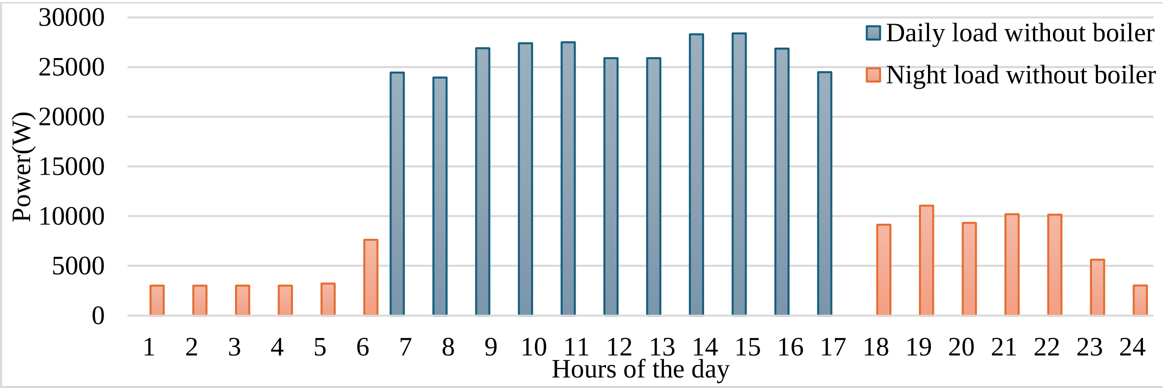

Figure 5.4 Daily and Night Load Without Boiler

The MATLAB code sets up system parameters and simulates a solar panel system's performance across 24 hours. It computes the hourly distribution of boiler load and total consumption without the boiler, then generates curves for hot water production, energy production, and total hourly consumption. These results are displayed, showing the hour, hot water production, and electricity production for each hour, along with the total hot water and electricity production for the entire period.

The script initially generates random energy production data, adjusting it based on solar radiation levels. It models battery charging and discharging according to energy production and consumption patterns, ensuring the battery charge remains within defined limits. Additionally, it simulates temperature variations for hot water and inlet water, constraining them within reasonable ranges. Finally, various aspects of the simulation results, such as energy production, battery charge, temperature, solar radiation, and battery voltage, are visualized.

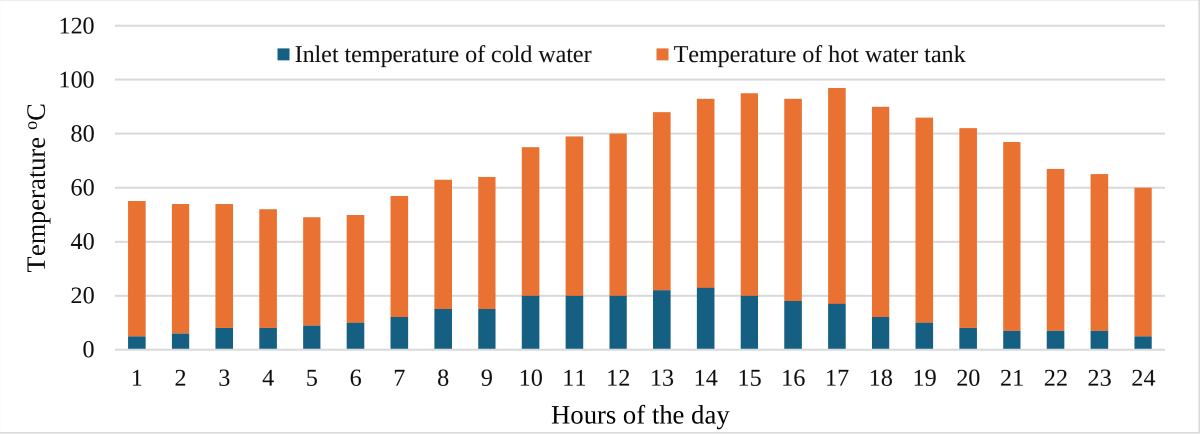

Figure 5.5 Inlet and outlet temperature of water.

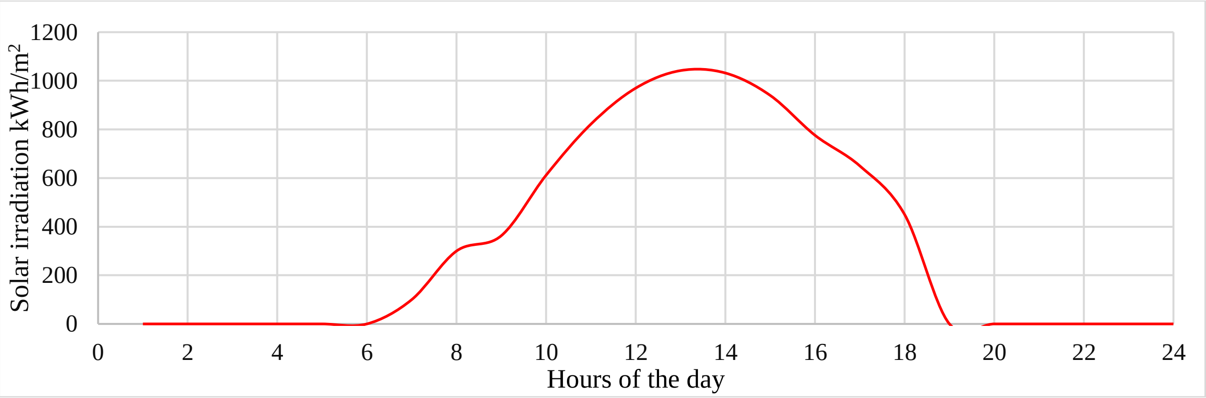

Figure 5.6 Solar radiation kWh/m^2.

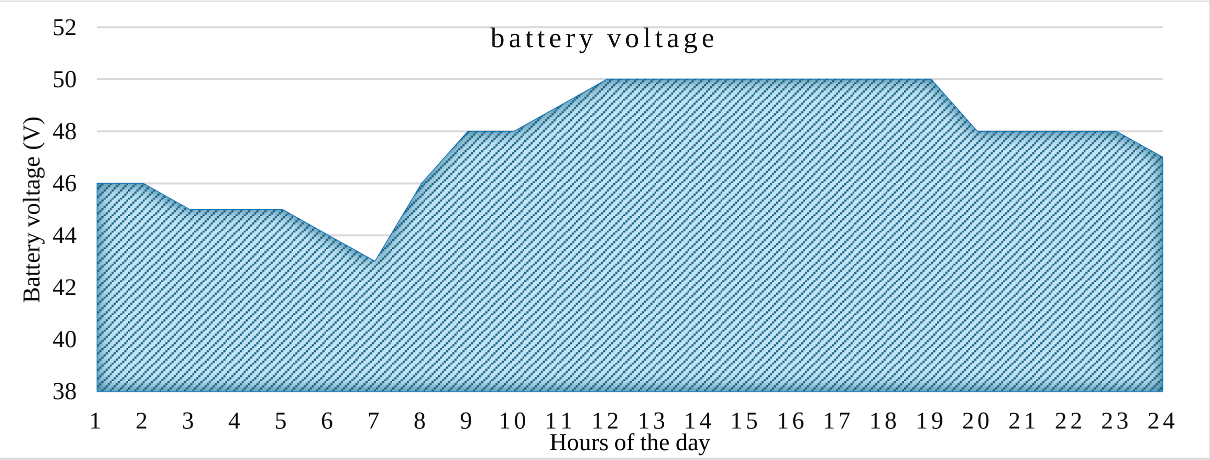

Figure 5.7 State of battery charge.

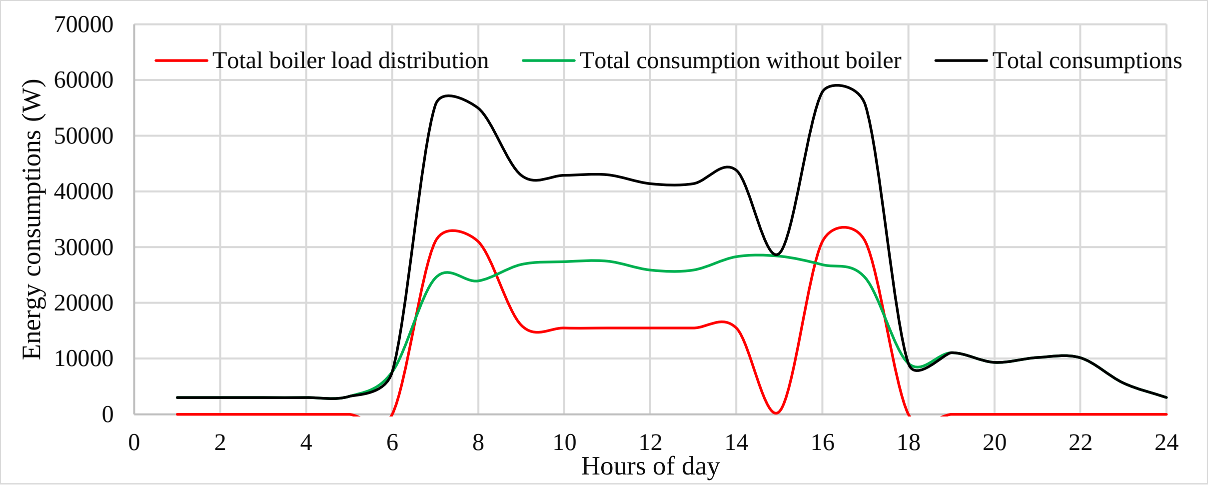

Figure 5.8Comparisons analysis between energy consumption.

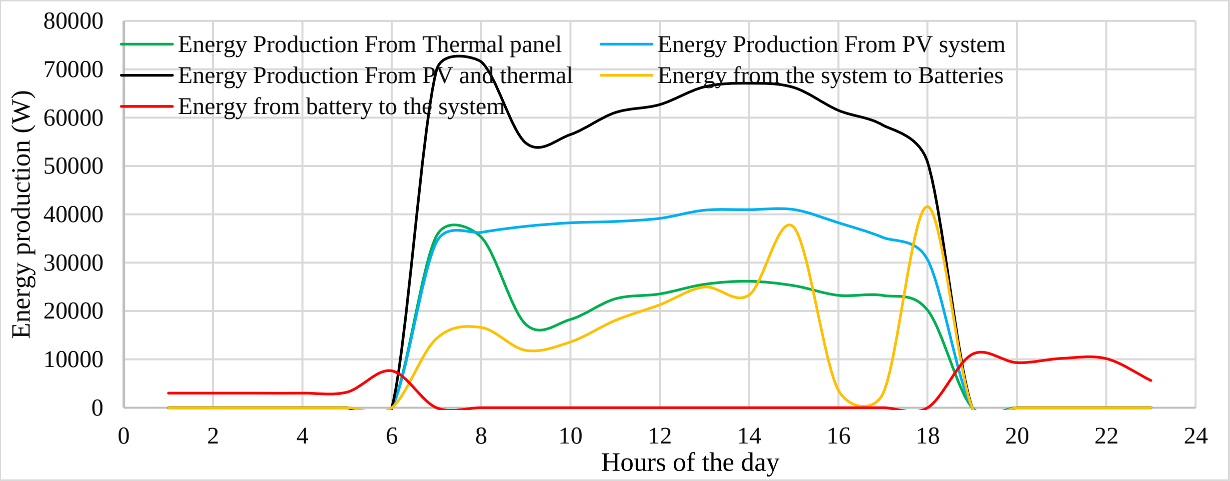

Figure 5.9 Comparisons analysis between energy generation

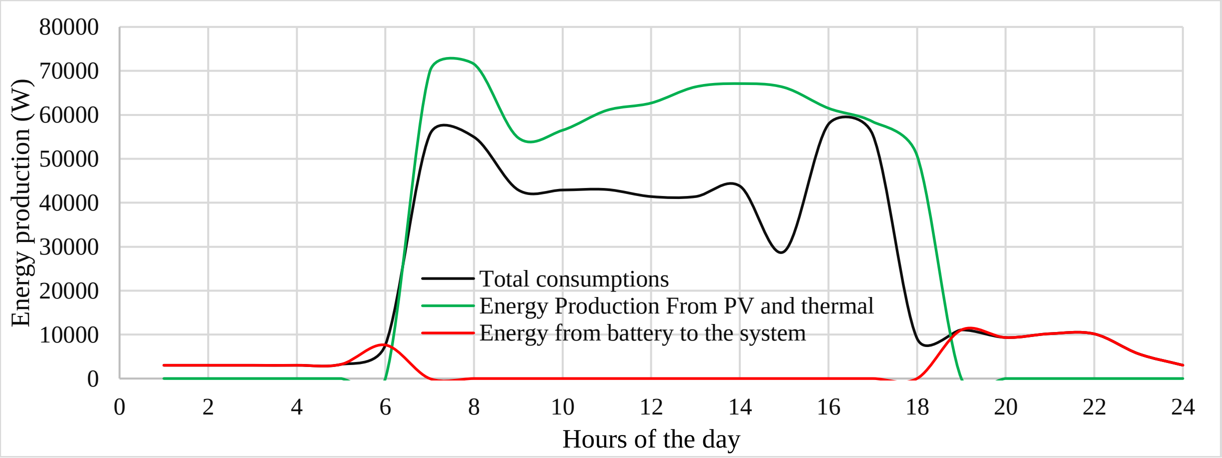

Figure 5.10 Comparisons analysis between energy consumption and generation,

In this case, the number of panels in every building is 4, and the total number of panels required is (4x33) = 132 panels. the price of a single panel is 100 USD at total cost of panels is 13000 USD, and the cost Reduction with 13000 USD.

Study of Photovoltaic panel and Thermal (PV/T) panel

The hybrid solar panel functions dually by generating electricity and heating water tanks, achieved through integrating a photovoltaic module for electricity generation with a solar thermal collector for water heating, offering increased efficiency, cost savings, and versatility in sustainable energy production.

The MATLAB code conducts a simulation of a PV/T panel system's performance over 24 hours, initializing by setting system parameters such as tank capacity, family size, the required energy for hot water and electricity, and the number of houses in the village. Subsequently, it utilizes supplied data on solar radiation, boiler load distribution, and total energy consumption to generate random energy production data, adjusted according to solar radiation levels. The simulation integrates battery charging and discharging based on energy production and consumption profiles, ensuring the battery charge remains within predefined limits throughout the day. Additionally, temperature profiles for hot water and inlet water are simulated while being constrained within realistic boundaries. Finally, the code generates plots illustrating various aspects of the simulation results, encompassing energy production, battery charge, temperature, solar radiation, and battery voltage.

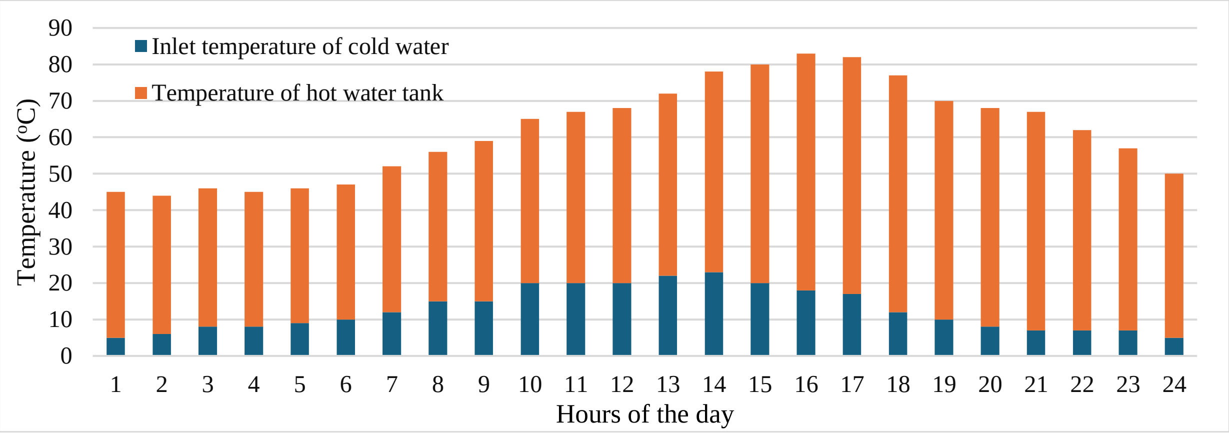

Figure 5.11 Inlet and outlet temperature of water.

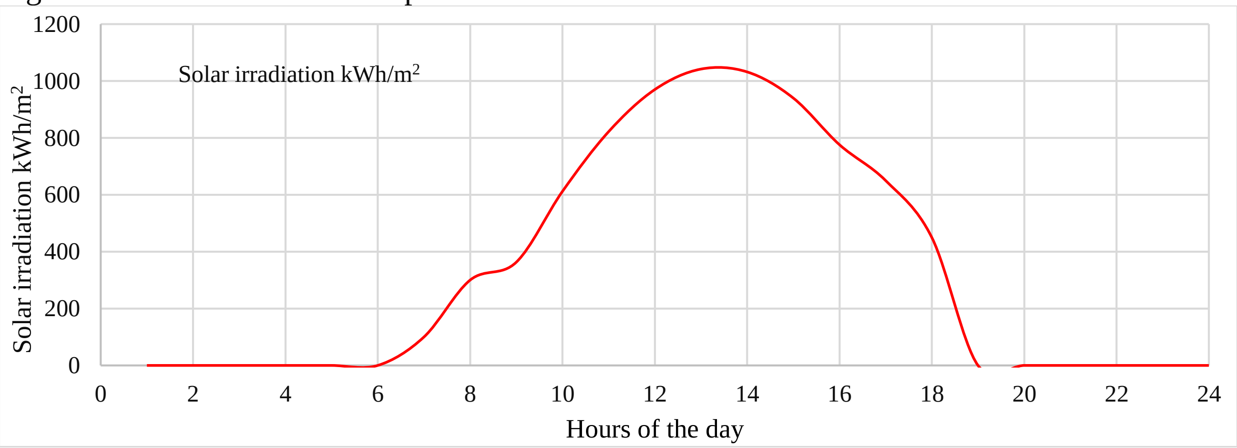

Figure 5.12 Solar radiation per kWh/m^2.

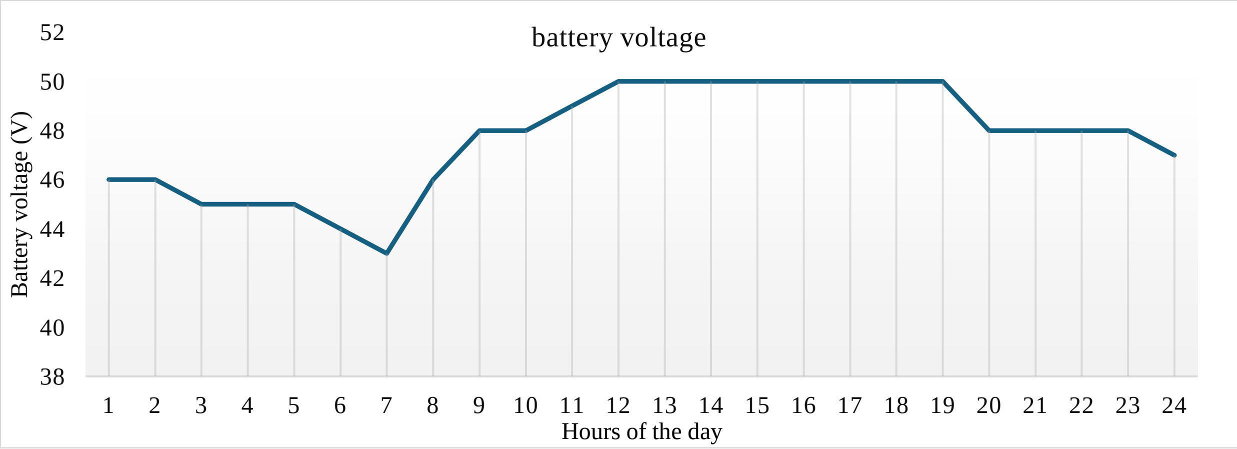

Figure 5.13 State of battery charge.

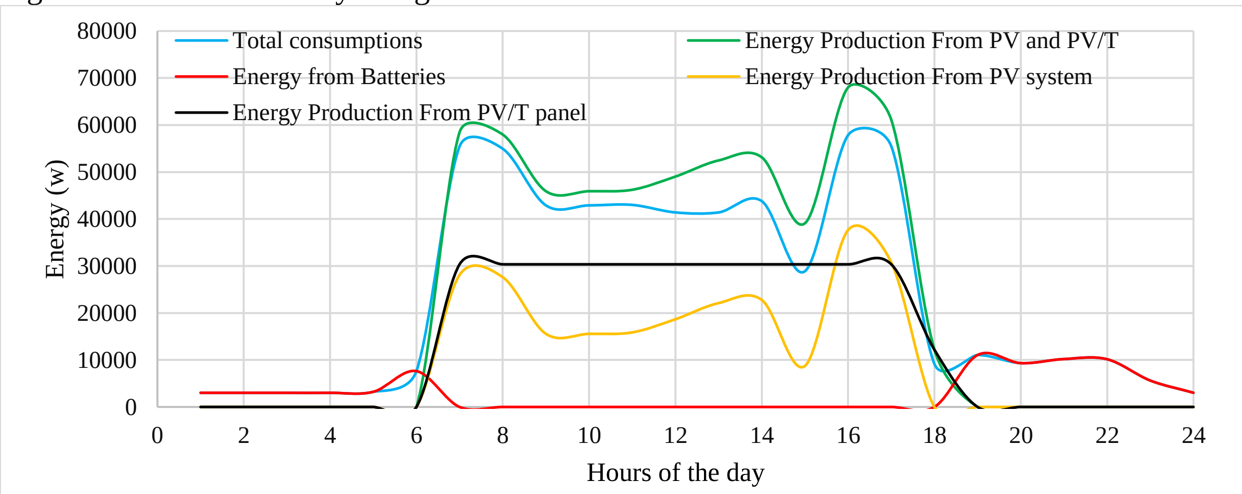

Figure 5.14 Total energy production and consumption.

The total cost of the PVT system is 15500USD, this system can provide the village with hot water and power 7.750kW we should add 22.5kW with PV normal which can cost 23000USD.

In summary, our evaluation encompassed an examination of five distinct options for village power generation through the utilization of Homer software. Among these options, the foremost choice involved the deployment of a PV system with battery backup, recognized as the most financially viable and environmentally sustainable solution. However, the fourth alternative, integrating PV panels with battery backup alongside diesel support, emerged as a practical contingency plan, particularly during emergency scenarios. In contrast, the remaining options were characterized by either exorbitant operational costs, excessive carbon emissions, or both, rendering them less desirable. Transitioning to our developed MATLAB code, designated as annex 2, we delineated several crucial parameters to ascertain requisite values such as yearly energy demand, essential PV panel area, necessary battery capacity, the requisite number of batteries, total expenditure, and the cost per kilowatt-hour (kWh) of energy generated. The code operated on predetermined assumptions concerning solar radiation and daily energy consumption to derive these parameters. Furthermore, it meticulously accounted for the costs associated with the components constituting the system, including PV panels, batteries, and inverters, thereby facilitating the computation of both the overall system cost and the cost per kWh of energy generated.

It's imperative to acknowledge that while the code's assumptions may hold true in certain scenarios, they may necessitate adjustments based on the unique circumstances of each project. The results yielded by the MATLAB calculations were enlightening, revealing a daily energy demand of 589.50 kWh and a yearly energy demand totaling 215167.50 kWh. The computed requisite PV panel area stood at 34.6 m2, with a corresponding battery capacity requirement of 6900.00 kWh. Notably, the analysis stipulated the procurement of 72 batteries to adequately support the system's operations. The estimated total system cost amounted to 113500.00 USD, accompanied by a cost of 0.671 USD/kWh. Furthermore, the system was forecasted to generate an annual energy output of 12113294.13 MWh.

Considering the provided information, it becomes evident that the most cost-effective approach is the integration of a PV system for electricity generation alongside solar thermal panels for hot water provision. This dual-system configuration not only optimizes cost efficiency but also minimizes maintenance requirements. The initial investment for such a combined PVT system is estimated at 15500 USD, capable of supplying the entire village with hot water and a power output of 7.750 kW. Moreover, augmenting this setup with an additional 22.5 kW from conventional PV panels, at an approximate cost of 23000 USD, further enhances the overall energy production capacity.

This underscores the superiority of utilizing PV systems for electricity generation and solar thermal panels for hot water production, particularly due to their favorable cost dynamics and lower maintenance demands. In comparison, hybrid systems entail higher initial costs and necessitate more intensive maintenance, making them less attractive options in terms of cost-effectiveness and practicality. Furthermore, the declining trend in the initial costs of PV systems, juxtaposed with the escalating costs associated with diesel procurement, transportation, and their adverse environmental impacts, accentuates the compelling advantages of solar energy. Solar energy stands out as a clean, sustainable, and economically advantageous alternative, offering not only substantial cost savings but also mitigating environmental concerns without any detrimental side effects. These results serve as a resounding affirmation of the feasibility of solar energy systems as both sustainable and economically advantageous alternatives to conventional energy sources.

Validation results

In a concerted effort to validate the findings, the study meticulously employed a multi-pronged approach, utilizing sophisticated software tools like MATLAB and HOMER for a thorough examination of renewable energy solutions. This comprehensive analysis was characterized by stringent scrutiny and careful evaluation, ensuring the accuracy and reliability of the results. By meticulously comparing the outcomes obtained from these diverse platforms, the study's credibility was significantly enhanced. This rigorous methodology not only bolstered the robustness of the findings but also paved the way for widespread dissemination through a plethora of publications and active engagement in numerous conferences.

Chapter 6 presents the Conclusions and Future Research Perspectives resulting from the thesis research. General conclusions are synthesized, emphasizing original contributions, and paving the way for future research efforts in the dynamic field of sustainable energy.

General Conclusions, Original contributions, and further research perspectives

1. General conclusions

The doctoral thesis entitled "***Solutions for Local Consumers Energy Supply from Renewable Sources***" conducts an exhaustive investigation into the utilization of solar energy in Sudan, offering a promising solution to improve access to energy and resilience, and contributing to the nation's sustainable energy future.

In validating the results, the study was meticulously conducted using multiple programs, including MATLAB and HOMER, to analyze renewable energy solutions comprehensively. After this analysis, the findings were rigorously compared across these programs to ensure consistency and reliability, thereby enhancing the robustness and credibility of the study's outcomes.

The main conclusions and general contributions resulting from the research conducted for the thesis are:

- ✓ *Literature Review:* An extensive review of literature covering solar energy resources, technologies, and applications was conducted. Scientific articles, technical reports, governmental publications, and industry sources were examined to establish a theoretical foundation for the study, identify research gaps, and make original contributions.
- ✓ *Data Collection:* Relevant primary and secondary data pertaining to the study objectives, including solar resources, geographical information, technological specifications, and socio-economic factors, were researched through field surveys, remote sensing techniques, and data acquisition from reliable sources such as governmental agencies and research institutions.
- ✓ *Site Selection Criteria:* Criteria were developed for selecting optimal locations for solar power plant installations, which included solar irradiance levels, land availability, proximity to infrastructure, environmental considerations, and socio-economic impact. Geographic Information Systems (GIS) tools and spatial analysis techniques were utilized to evaluate potential sites based on these criteria.

- ✓ *Solar Panel Technology Analysis:* The evolution of solar panel technology and advancements in solar energy systems were analyzed using key performance metrics, including efficiency, durability, and cost-effectiveness. Various technologies, including photovoltaic panels (PV), concentrated solar power (CSP) systems, and emerging technologies, were compared to identify trends and innovation opportunities.
- ✓ *Economic Feasibility Assessment:* A comprehensive analysis of the economic feasibility of solar energy solutions was conducted using cost-benefit analysis, financial modeling, and sensitivity analyses to evaluate capital costs, operational expenses, revenue streams, and return on investment (ROI). This assessed the economic viability and attractiveness of solar energy investments.
- ✓ *Environmental Impact Assessment:* The environmental impact of solar energy utilization was evaluated through life cycle assessments (LCA) of greenhouse gas emissions, water consumption, land use, and other environmental indicators, comparing the ecological footprint of solar energy systems with conventional energy sources to assess their contribution to climate change mitigation and environmental sustainability.
- ✓ *Case Studies and Simulation Modeling:* Case studies and simulation models were developed to analyze energy scenarios in hypothetical villages or communities under different conditions. Original MATLAB programs were developed to simulate the implementation of solar energy systems in various configurations, evaluate their performance, and assess socio-economic and environmental implications.
- ✓ *Stakeholder Engagement:* Relevant stakeholders, including governmental agencies, industry representatives, community leaders, and non-governmental organizations (NGOs), were involved in developing proposed solutions, receiving feedback on the relevance and applicability of study results.
- ✓ *Policy Analysis and Recommendations:* Existing policy frameworks and regulatory mechanisms governing solar energy implementation were analyzed, barriers to adoption were identified, and policy recommendations were proposed to promote solar energy integration into national energy strategies, stimulate investments, and facilitate market penetration of solar technologies.
- ✓ *Interdisciplinary Approach:* The thesis adopted an interdisciplinary approach, integrating knowledge from various fields such as engineering, environmental science, economics, sociology, and policy analysis to develop holistic solutions to energy challenges.
- ✓ *Holistic Characterization:* A comprehensive and detailed characterization of diverse energy resources in Sudan, including biomass, hydroelectricity, oil, natural gas, wind, geothermal, and solar sources, was provided. This holistic understanding formed the basis for assessing the country's energy potential and identifying sustainable solutions.

- ✓ *Emphasis on Hybrid Configurations and Diversified Approaches:* The research placed strong emphasis on hybrid configurations and exploring multiple energy resources. This emphasis underscores the need for integrated and diversified approaches to efficiently meet Sudan's evolving energy requirements. The thesis advocates for a holistic energy strategy that considers synergies between various renewable sources.
- ✓ *Insights into Economic Viability and Feasibility*: Through numerical findings and economic analyses, the thesis confirms the economic viability, versatility, and feasibility of solar energy systems in Sudan. This data-driven approach provides essential quantifiable insights for policymakers, researchers, and industry leaders involved in shaping the energy landscape.
- ✓ *Contribution to the Global Discourse on Sustainable Energy Transitions:* The thesis positions itself within the broader global discourse on sustainable energy transitions. By highlighting the importance of context-specific strategies and the transformative potential of solar energy, the research contributes to the ongoing dialogue on shaping a sustainable and environmentally conscious energy future.

2. Original Contributions of the Ph.D. thesis

The original contributions of this thesis, addressing urgent challenges in the field of global energy, are remarkable and are highlighted by their publication in high-impact journals and numerous indexed international conferences. The innovation and significance of the research are explained in detail in each chapter, with references to the doctoral candidate's publications, confirming their significant contributions to the scientific community. The thesis, entitled "***Solutions for Local Consumers Energy Supply from Renewable Sources***" introduces new elements and original perspectives that advance our understanding of sustainable energy solutions.

The main ***contributions with a high degree of originality*** can be outlined as follows:

- ➢ Comprehensive Overview of Sudan, focusing on its natural resources and untapped potential, with the challenges faced in fully utilizing these resources for economic development and sustainability. Chapter 1 addressed the availability of renewable energy sources in Sudan, including solar, wind, and hydroelectric energy, emphasizing their importance in meeting the country's energy needs and promoting environmental sustainability.
- ➢ Comprehensive Presentation of Solar Panel Technology Evolution, in Chapter 2, elucidating its journey from inception to contemporary progress to analyze the best and most efficient and economical solar energy solutions.
- ➢ Analysis of 11 Sites in Sudan, using specific criteria to determine the most suitable locations for establishing solar power stations [1].
- ➢ Exploration of Various Solar Panel Connection Techniques and the Impact of Cloud Cover on Solar Energy Generation [2].

- Evaluation of its effectiveness as a sustainable heating solution, from residential heating to industrial processes [3].
- Simulation of the implementation of solar energy systems in different configurations, certifying solar energy's ability to meet the energy needs of communities, including in remote or off-grid locations [4].
- Exploration of Connection Architectures and Solar Thermal Systems [chapter 3].
- Optimal Photovoltaic Configurations for Sudanese Regions based on solar radiation analysis, providing practical guidance for the efficient utilization of solar energy in diverse geographical contexts [5][6].
- Analysis of Solar Thermal Energy Viability in Sudan, including the development of solar water heating systems, rigorous thermal and economic analyses, and selection of optimal collectors [Chapter 4].
- Practical Application in an Isolated Village in Sudan through the evaluation of design and comparison between solar and conventional energy for powering an isolated village in Sudan, providing a pragmatic dimension to the research, highlighting the potential of renewable energy solutions in addressing localized energy demands [chapter 5].
- This suggests that the most effective strategy involves implementing a photovoltaic (PV) system for electricity generation and solar thermal panels for hot water production, capitalizing on their cost-effectiveness and low maintenance requirements. Hybrid systems, while feasible, present pricier alternatives with higher maintenance demands compared to standalone PV systems. The initial cost of PV decreases annually, in contrast to the rising expenses associated with diesel fuel and transportation, emphasizing significant environmental consequences. In contrast, solar energy presents a clean, sustainable, and economically advantageous solution devoid of such adverse effects [7].
- These conclusions stem from MATLAB analysis, which elucidated various parameters crucial to a solar energy setup. The daily energy demand stood at 589.50 kWh, with an annual requirement totaling 215167.50 kWh. The calculated area needed for PV panels was 34.6 m^2, paired with a necessary battery capacity of 6900.00 kWh, requiring 72 batteries for system support. The total projected system cost was 113500.00 USD, with a cost of 0.671 USD per kWh. Furthermore, the system's annual energy generation was estimated at 12113294.13 MWh. These results underscore the feasibility of solar energy as a sustainable, cost-effective alternative to traditional energy sources [chapter 5].
- In essence, the original contributions of the Ph.D. thesis lie in its holistic exploration, practical applications, and nuanced insights into renewable energy solutions, specifically tailored to the unique energy dynamics of Sudan. The research provides a valuable foundation for future endeavors in the pursuit of sustainable and locally relevant energy solutions. The primary contributions of this doctoral thesis revolve around its innovative analysis approach

titled "*Solutions for Local Consumers Energy Supply from Renewable Sources*." Extensive simulations were carried out within the MATLAB environment to validate the findings. The quality and significance of the research outcomes are underscored by the three publications in esteemed Q2 journals and two papers in UPB Sci. Bull along with seven ISI and Scopus publications, as outlined in the publication list.

3. Further Research Perspectives

The doctoral thesis entitled "Solutions for Local Consumers Energy Supply from Renewable Sources," initiates a vital exploration into alternative energy generation systems, with a specific focus on meeting the energy needs of local communities.

Based on the research conducted during the thesis development, we suggest that for the future, it would be useful to focus research efforts on:

- *Implementation of Localized Policies:* Investigating the implementation of localized policies to explore and streamline the adoption of renewable energy solutions by assessing the effectiveness of tailored legislative frameworks for promoting sustainable practices at both community and national levels, including in Sudan.
- *Socio-Economic Impact Assessment*: Conducting a comprehensive assessment of the socio-economic impact of integrating renewable energy by analyzing how the implementation of renewable energy systems influences employment, income generation, and overall community development.
- *Community-Centered Renewable Energy Projects:* Exploring the feasibility and impact of community-centered renewable energy projects and evaluating how community involvement in planning, implementation, and management of energy initiatives contributes to sustainability and fosters a sense of ownership.
- *Integration of Traditional Practices:* Investigating the integration of traditional practices and knowledge into modern renewable energy projects and leveraging indigenous knowledge to improve the efficiency and acceptance of renewable energy technologies in communities, including in Sudanese communities.
- *Techno-Economic Analysis of Solar Thermal Systems:* Conducting a detailed techno-economic analysis of solar thermal systems, focusing on long-term viability and economic feasibility, with an evaluation of the profitability and return on investment in solar water and space heating solutions.
- *Energy Storage Solutions for Isolated Villages:* Exploring innovative energy storage solutions tailored to the unique needs of isolated villages and investigating the feasibility and economic viability of energy storage technologies to ensure a consistent and reliable energy supply.

- *Optimization of Hybrid Energy Systems:* Further optimizing hybrid energy systems through advanced modeling and simulation techniques, exploring how advances in simulation tools and technologies can improve the performance and efficiency of integrated renewable energy solutions.
- *Climate Change Impact on Renewable Resources:* Assessing the potential impact of climate change on the availability and efficiency of renewable resources in Sudan. Investigating adaptation strategies for renewable energy systems to changing climatic conditions and ensuring resilience against environmental challenges.
- *Intersectoral Collaboration for Sustainable Development:* Promoting intersectoral collaboration for sustainable development through renewable energy, exploring partnerships between energy stakeholders, agricultural practices, and local industries to create synergies that contribute to both energy sustainability and economic growth.
- *Awareness and Public Education Programs:* Developing and implementing awareness and public education programs focused on renewable energy and investigating the effectiveness of educational initiatives in promoting a deeper understanding of renewable technologies and fostering a culture of sustainability.

Dissemination of results - Author's contributions to the development of the thesis research domain

The dissemination of results highlights the author's extensive contributions to advancing the thesis research field, reflected through significant publications in prestigious journals and conferences:

- Two articles published in the UPB Sci. Bull. journal.
- Three articles published in Q2-ranked journals.
- Presentation of seven papers at ISI and Scopus-indexed conferences.

These contributions cover a wide range of topics, including optimal loading strategies for off-grid solar photovoltaic systems, performance assessment of renewable energy systems, increasing participation in renewable energy, solar radiation analysis, microgrid modeling, smart city development involvement, sustainable transportation modeling, renewable energy integration, climate analysis, efficiency optimization, independent power generation solutions, optimal design of energy systems for off-grid residences, and optimization of solar photovoltaic systems and off-grid energy systems.

1 **Osman MG**, Ciupageanu D, Stan A. *Analysis of Solar Radiation in Sudan, and Optimal Location of Photovoltaic Panels*. UPB Sci. Bull., Series C. 2022;84(4).

2 Strejoiu CV, **Osman MG**, Lazaroiu G '*Towards Sustainable Transportation: Modeling and Simulation of PV Panel Implementation on National Highways for Charging Electric Vehicles Which leads to Mitigate Carbon Emission'* UPB Sci. Bull., Series C. 2023;85(4).

3 Dorel S, **Gmal Osman M,** Strejoiu CV, Lazaroiu G. *Exploring Optimal Charging Strategies for Off-Grid Solar Photovoltaic Systems: A Comparative Study on Battery Storage Techniques. Batteries.* 2023 Sep 18;9(9):470. Q2

4 Lazaroiu G, **Gmal Osman M,** Strejoiu CV. *Performance Evaluation of Renewable Energy Systems: Photovoltaic, Wind Turbine, Battery Bank, and Hydrogen Storage. Batteries*. 2023 Sep 18;9(9):468. Q2

5 Lazaroiu AC, **Gmal Osman M,** Strejoiu CV, Lazaroiu G. A *Comprehensive Overview of Photovoltaic Technologies and Their Efficiency for Climate Neutrality. Sustainability*. 2023 Nov 24;15(23):16297. Q2

6 **Osman, M.G.,** Ciupagenau, D.A., Lazaroiu, G. and Pisa, I., 2022, September. *Increasing Renewable Energy Participation in Sudan.* In 2022 11th International Conference on Renewable Energy Research and Application (ICRERA) (pp. 169-173). IEEE.

7 Strejoiu CV, **Osman MG,** Lazaroiu G. *Analyzing Energy Consumption and Hot Water Usage in the Titan Neighborhood of Bucharest: Implications for Smart City Development*. In2023 IEEE International Smart Cities Conference (ISC2) 2023 Sep 24 (pp. 1-6). IEEE.

8 **Gmal Osman M.,** Strejoiu CV., Panait C., Lazaroiu G., Lazaroiu *AC. Renewable energy integration, climate analysis, and efficiency optimization for greener transportation - case study in Dobrogea.* International Multidisciplinary Scientific GeoConference-SGEM; 2023; (pp. 675-687), DOI: 10.5593/sgem2023V/6.2/s27.83

9 **Osman MG.,** Strejoiu CV., Panait C., Lazaroiu G., Lazaroiu *AC. Optimal Power System Design for Off-Grid Residences in Dobrogea, Romania: Integrating Renewable Energy and Generator Technology.* 2024 IEEE ATOMS Conference. Accepted.

10 Strejoiu CV., **Osman MG.,** Panait C., Lazaroiu G., Dorel S. '*Optimizing Solar Photovoltaic Systems: A Geometric Approach to Enhance Energy Production and Economic Viability'* 2024 IEEE ATOMS Conference. Accepted.

11 **Osman MG.,** Strejoiu CV., Panait C., Lazaroiu G., Lazaroiu *AC 'Microgrid Model for Evaluating the Operational Dynamics of Solar-Powered Hydrogen Production'. IEEE***,** EE& AE 2024. Accepted.

12 Strejoiu CV., **Osman MG.,** Panait C., Lazaroiu G., Dorel S. *'Efficiency evaluation and performance analysis of a photovoltaic park connected to a 20 kV distribution network in Galati County, Romania 'IEEE, EE*& AE 2024. Accepted.

13 **Osman MG**, EZ. Abdalla, *Modeling of Automatic Generation Control and Automatic Voltage Regulator Under Generation Rate Constraint* UNIVERSITY of KHARTOUM ENGINEERING JOURNAL (UofKEJ) 6 (2), 43-51

References

[1] "POWER | Data Access Viewer." Accessed: Sep. 04, 2023. [Online]. Available: https://power.larc.nasa.gov/data-access-viewer/ access 10/10/2022

[2] "Sudan | Africa Energy Portal." Accessed: Jun. 19, 2022. [Online]. Available: https://africa-energy-portal.org/country/sudan

[3] "Sudan - Electric power consumption." Accessed: May 29, 2022. [Online]. Available: https://www.indexmundi.com/facts/sudan/electric-power-consumption

[4] A. M. Omer, "Sudan energy background; an overview," *Renew Energy*, vol. 14, no. 1–4, pp. 467–472, 1998.

[5] "Sudan - Access to electricity (% of population)." Accessed: May 29, 2022. [Online]. Available: https://www.indexmundi.com/facts/sudan/indicator/EG.ELC.ACCS.ZS

[6] "Sudan energy handbook (1987 edition) | Open Library." Accessed: Mar. 19, 2022. [Online].Available:https://openlibrary.org/works/OL23029117W/Sudan_energy_handbook

[7] A. M. Omer, "Renewable energy resources for electricity generation in Sudan," vol. 11, pp. 1481–1497, 2007,

[8] "Energy Profile: Sudan | UNEP - UN Environment Programmed." Accessed: Jun. 13, 2022. [Online]. Available: https://www.unep.org/resources/report/energy-profile-sudan

[9] "Developing the enabling environment for renewable energy in Sudan – Clean Energy 4 Africa." Accessed: Jun. 19, 2022. [Online]. Available: https://cleanenergy4africa.org/developing-the-enabling-environment-for-renewable energy-in-sudan/

[10] "IRENA – International Renewable Energy Agency." Accessed: Jun. 19, 2022. [Online]. Available: https://www.irena.org/

[11] "Best Research-Cell Efficiency Chart | Photovoltaic Research | NREL." Accessed: Feb. 13, 2022. [Online]. Available: https://www.nrel.gov/pv/cell-efficiency.html

[12] "Best Solar Panels in 2022: Top Products Compared | EnergySage." Accessed: Feb. 12, 2022. [Online]. Available: https://news.energysage.com/best-solar-panels-complete-ranking/

[13] "JRC Photovoltaic Geographical Information System (PVGIS) - European Commission." Accessed: Feb. 14, 2023.[Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/en/

[14] "Sudan: Energy Country Profile - Our World in Data." Accessed: Mar. 19, 2022. [Online]. Available: https://ourworldindata.org/energy/country/sudan#energy-intensity-how-much-energy-does-it-use-per-unit-of-gdp

[15] "Integral Collector Storage or ICS for Solar Hot Water." Accessed: May 15, 2022. [Online]. Available: https://www.alternative-energy-tutorials.com/solar-hot-water/integral-collector-storage.html

[16] T. Mubark Saeed, B. M. Tayeb, and G. Osman, "Sustainable energy potential in Sudan," 2019.

[17] L. J. Arone, "Sudan–A Country Study, edited by Helen Chapin Metz.(Area Handbook Series) 336 pages, maps, charts, tables, illustrations, bibliography, glossary, index. Washington, DC: Library of Congress, 1992.(Cloth) ISBN 0-8444-0750-X," *Review of Middle East Studies*, vol. 27, no. 2, pp. 240–241, 1993.

[18] W. Chen et al., "A manganese–hydrogen battery with potential for grid-scale energy storage," Nat Energy, vol. 3, no. 5, pp. 428–435, 2018.

[19] F. Yu et al., "Performance Evaluation of a Scaled-Up Membraneless Organic-Based Hybrid Flow Battery," Batteries, vol. 9, no. 7, p. 336, 2023.

[20] T. Ajadi et al., "Global trends in renewable energy investment 2020," 2020.

[21] W. Bank, The World Bank Annual Report 2013.The World Bank, 2013.

K. B. Hueso, M. Armand, and T. Rojo, "High temperature sodium batteries: Status, challenges and future trends," Energy Environ Sci, vol. 6, no. 3, pp. 734–749, 2013,

[22] M. Debbache, M. Hazmoune, S. Derfouf, D.-A. Ciupageanu, and G. Lazaroiu, "Wind Blade Twist Correction for Enhanced Annual Energy Production of Wind Turbines," Sustainability, vol. 13, no. 12, p. 6931, 2021,

[23] S. M. Mousavi G, F. Faraji, A. Majazi, and K. Al-Haddad, "A comprehensive review of Flywheel Energy Storage System technology," Renewable and Sustainable Energy Reviews, vol. 67, pp. 477–490, 2017.