REPUBLIC OF TURKEY
ISTANBUL GELISIM UNIVERSITY
INSTITUTE OF GRADUATE STUDIES

Department of Electrical and Electronics Engineering

# GRID INTEGRATION STRATEGIES WITH THE USE OF RENEWABLE ENERGY DEPLOYMENT AND GRID RESILIENCE

Master Thesis

**IHSAN ABDUL KAREEM ALSHRAEEDAH**

Supervisor
Asst. Prof. Dr. Ercan AYKUT

**Istanbul – 2024**

**THESIS INTRODUCTION FORM**

| | |
|---|---|
| **Name and Surname** | : Ihsan Abdul Kareem Alshraeedah |
| **Language of the Thesis** | : English |
| **Name of the Thesis** | : Grid Integration Strategies With The Use Of Renewable Energy Deployment and Grid Resilience |
| **Institute** | : Istanbul Gelisim University Institute of Graduate Studies |
| **Department** | : Electrical and Electronics Engineering |
| **Thesis Type** | : Master |
| **Date of the Thesis** | : 03/07/2024 |
| **Page Number** | : 88 |
| **Thesis Supervisors** | : Asst. Prof. Dr. Ercan AYKUT |
| **Index Terms** | : Renewable Energy Integration, Grid Resilience, Energy Forecasting, Optimization Strategies, Sustainable Energy Infrastructure. |
| **Turkish Anstract** | : Yürütülen araştırma, dört yıl boyunca elektrik tüketimi, üretim, fiyatlandırma ve hava durumu ile ilgili verileri topladı ve bunları uygun entegrasyon modellerini anlamak için analiz etmiştir. |
| **Distribution List** | : 1. To the Institute of Graduate Studies of Istanbul Gelisim University<br>2. To the National Thesis Center of YÖK (Higher Education Council) |

*Signature*

*Ihsan Abdul Kareem Alshraeedah*

**REPUBLIC OF TURKEY**
**ISTANBUL GELISIM UNIVERSITY**
**INSTITUTE OF GRADUATE STUDIES**

Department of Electrical and Electronics Engineering

# GRID INTEGRATION STRATEGIES WITH THE USE OF RENEWABLE ENERGY DEPLOYMENT AND GRID RESILIENCE

Master Thesis

**IHSAN ABDUL KAREEM ALSHRAEEDAH**

Supervisor

Asst. Prof. Dr. Ercan Aykut

**Istanbul – 2024**

**DECLARATION**

I hereby declare that in the preparation of this thesis, scientific ethical rules have been followed, the works of other persons have been referenced in accordance with the scientific norms if used, there is no falsification in the used data, any part of the thesis has not been submitted to this university or any other university as another thesis.

Ihsan Abdul Kareem Alshraeedah

03/07/2024

**TO ISTANBUL GELISIM UNIVERSITY**
**THE DIRECTORATE OF ENGINERRING INSTITUTE**

The thesis study of grid Integration titled "Grid Integration Strategies With The Use Of Renewable Energy Deployment and Grid Resilience" has been accepted as MASTER THESIS in the department of Electrical and Computer Engineering by out jury.

Director

*Signature*

*Asst. Prof. Dr. Ulvi Baspinar*

Member

*Signature*

*Asst. Prof. Dr. Ercan Aykut*

(Supervisor)

Member

*Signature*

*Asst. Prof. Dr. Halit Yahya*

APPROVAL

I approve that the signatures above signatures belong to the aforementioned faculty members.

…./…./ 2024

*Signature*

*Prof. Dr. Izzet Gumus*

Director of the Institute

# SUMMARY

This study investigates the strategies of integrating renewable energy sources into the electrical grid. In particular, this study concentrates on solar and wind energy and examines suitable measures of their integration into the grid of Spain. The conducted research collected data on electrical consumption, generation, pricing, and weather for four years and analyzed them to understand the patterns of suitable integration . The study used several statistical methods and models such as regression analysis, correlation analysis, and forecasting methods, and optimization techniques to forecast the generation of wind and solar power and to define the best possible energy generation mix, taking into account its cost, demand, and sustainability. The results indicate that weather also plays a significant role in the output of renewable energy sources and demonstrate the extent to which a renewable energy-focused grid can be more efficient and resilient. The study concludes with recommendations to enhance the quality of future forecasting, grid development and modernisation, policy development, public engagement, and continuation of research.



**Key Words:** Renewable Energy Integration, Grid Resilience, Energy Forecasting, Optimization Strategies, Sustainable Energy Infrastructure.

# ÖZET

Bu çalışmada yenilenebilir enerji kaynaklarının elektrik şebekesine entegre edilmesi stratejileri araştırılmaktadır. Bu çalışma özellikle güneş ve rüzgar enerjisi üzerine yoğunlaşmakta ve bunların İspanya şebekesine entegrasyonuna yönelik uygun önlemleri incelemektedir. Yürütülen araştırma, dört yıl boyunca elektrik tüketimi, üretim, fiyatlandırma ve hava durumu ile ilgili verileri topladı ve bunları uygun entegrasyon modellerini anlamak için analiz etti. Çalışmada, rüzgar ve güneş enerjisi üretimini tahmin etmek ve maliyet, talep, maliyet dikkate alınarak mümkün olan en iyi enerji üretim karışımını tanımlamak için regresyon analizi, korelasyon analizi ve tahmin yöntemleri ile optimizasyon teknikleri gibi çeşitli istatistiksel yöntemler ve modeller kullanılmıştır. ve sürdürülebilirlik. Sonuçlar, hava durumunun yenilenebilir enerji kaynaklarının çıktısında da önemli bir rol oynadığını gösteriyor ve yenilenebilir enerji odaklı bir şebekenin ne ölçüde daha verimli ve dayanıklı olabileceğini gösteriyor. Çalışma, geleceğe yönelik tahminlerin, şebeke geliştirme ve modernizasyonun, politika geliştirmenin, halkın katılımının ve araştırmanın sürekliliğinin kalitesinin artırılmasına yönelik önerilerle sona ermektedir.



**Anahtar kelimeler:** Yenilenebilir Enerji Entegrasyonu, Şebeke Dayanıklılığı, Enerji Tahmini, Optimizasyon Stratejileri, Sürdürülebilir Enerji Altyapısı.

# TABLE OF CONTENTS



## CHAPTER ONE
## BACKGROUND



## CHAPTER TWO
## LITERATURE REVIEW

## CHAPTER THREE
## METHODOLOGY



## CHAPTER FOUR
## DATA COLLECTION AND ANALYSIS



## CHAPTER FIVE
## DISCUSSION

# ABBREDIVATIONS

| | | |
|---|---|---|
| **TSO** | **:** | Transmission Service Operator |
| **ENTSOE** | **:** | European Network of Transmission System Operators for Electricity |
| **MAE** | **:** | Mean Absolute Error |
| **R2** | **:** | Coefficient of Determination |
| **MWh** | **:** | Megawatt-hour |
| **CO2** | **:** | Carbon Dioxide |
| **MW** | **:** | Megawatt |
| **API** | **:** | Application Programming Interface |
| **REE** | **:** | Red Eléctrica de España |
| **PV** | **:** | Photovoltaic |

# LIST OF TABLES

# LIST OF FIGURES

# PREFACE

This thesis explores the intricacies of improving the deployment of renewable energy to enhance the resilience of the grid, aiming to better the integration of renewable energy into our existing system design. This endeavour was driven by the increasing global demand for energy and the urgent need to address the planet's environmental sustainability challenges. The objective was clear: to contribute to the development of a more sustainable and dependable energy infrastructure.

This work was motivated by the complex challenge of integrating renewable energy sources such as solar, wind, hydro, biomass, and geothermal into the power system. This integration is complex and involves several factors, including technological, economic, environmental, and regulatory issues. Therefore, a comprehensive approach is required to resolve it. The motivation behind my study was a strong sense of obligation to mitigate the adverse environmental impacts of conventional energy sources, while also enhancing the economic and operational efficiency of the power system.

Throughout my journey, I have been fortunate to have mentors and classmates who have provided unwavering support, alongside an academic community that highly esteems and acknowledges innovative research. The expertise, guidance, and unwavering support of my supervisor played a pivotal role during the whole duration of this project, and I am immensely appreciative of his contributions. Their insightful opinions have significantly contributed to both my intellectual and personal growth, shaping my research.

The thesis presented here is a prime example of the collaborative nature that characterises research in the field of renewable energy. Innumerable scholars and experts in the field have established the foundation for innovative solutions to our energy concerns. I am indebted to Istanbul Gelisim University and the ECE department for providing me with the necessary resources and conducive environment to do my research, and I express my gratitude to them as I present my thesis.

Developing this thesis has been a challenging yet ultimately fulfilling endeavour. Participating in this opportunity has provided valuable insights on optimisation strategies, the integration of renewable energy, and enhancing the resilience of the grid. Each stage of the research process, from subject definition to technique creation to data analysis, has presented both difficulties and gratification. The programme has equipped me with the necessary resources to further contribute to the advancement of sustainable energy and has strengthened my determination to actively participate in this endeavour.

I would want to express my gratitude to all those who have contributed to this journey as I conclude this preface. To my cherished family members, who have consistently provided unwavering support, to my close companions, who have consistently offered emotional support, and to my colleagues and scholars, who have consistently supplied vital input and profound insights. This thesis aims to facilitate the integration of renewable energy sources into our energy infrastructure, moving beyond their current role as mere supplements. I am optimistic that this study will contribute to the realisation of the world I see, and I am enthusiastic about being involved in its development.

# INTRODUCTION

Nowadays, the energy sector all around the globe is at an important crossroads. One of the many reasons this seems to be the case is the rising amount of environmental concerns and the pressing need for sustainable development (Leck, Conway, Bradshaw, & Rees, 2015). Historically, traditional ways of economic progress were heavily reliant on fossil fuels. In turn, over the years, such an approach served as a major factor in increased greenhouse gas emissions, and consequently, it has only accelerated the process of climate change (Sas, 2010). Regardless, there is a reason to be optimistic. Namely, the installation of renewable energy sources is becoming more and more viable. For these purposes, grid integration systems have never been more important (O'g'li, 2023). For this reason, the paper at hand aims to explore the relevance of grid integration solutions in terms of optimizing renewable energy source implementation overall and underscore the importance of overall grid-strengthening.

To start, in the path towards a power system that is sustainable, there are numerous legal, financial, and technological obstacles to be surmounted. According to Hassan et al., (Hassan et al., 2024) , the most relevant of them is the coupling of the full range of renewable energy sources to the grid already in place. For instance, electricity is generated by both wind and solar power on an intermittent and random basis which is largely undependable in nature, especially when it comes to the stability and reliability of the grid (Basit, Dilshad, Badar, & Sami ur Rehman, 2020). This research, therefore, seeks to proffer the solutions to the problems such as achieving a balance between the fluctuating supply of renewable energy sources, modern power systems, and the fluctuating patterns of demand of such. It also seeks to offer the path of least resistance regarding the shift to a more robust—and coupled up with renewable energy sources—grid through advanced optimization and grid integration strategies.

A crucial aspect of the thesis is the belief that cities have the potential to significantly reduce their carbon output and limit environmental damage. However, to achieve such a positive outcome, it is not enough to focus on technological advancements. Instead, researchers and policymakers need to gain an in-depth understanding of the financial and environmental effects of the implementation of renewable energy sources. For this reason, the final project investigates the financial benefits if all fossil fuels were eradicated, the environmental benefits if carbon emissions were reduced, and the social justification for adopting a cleaning up the energy perspective.

The methodology of the current research paper includes a multidisciplinary approach and is influenced by its concepts and theories. Overall, the final research aims to identify the most effective approach to disperse renewable energy sources in the grid. To achieve this aim, the current project will develop optimisation techniques and test the results with the help of mathematical techniques and computer simulations. Overall, the following study involves a multitude of grid integration solutions to identify the approach that would improve the grid's reliability and resilience the most. Together, the current options are evaluated throughout the technical, economic, and environmental dimensions.

The outcomes of the research have a ripple effect on various domains of public life. First, the final project is intended to contribute to the public debate on the adoption of renewable energy sources . Second, the current research seeks to affect the practices of the field. Finally, the project holds implications for policy-making. Overall, the primary goal is to increase the adoption of sustainable power systems by outlining the challenges that the relevant technology faces and providing response strategies. Such an intervention can accelerate the shift towards sustainable energy, and, given the global threat of climate change, this timely initiative is expected to meet support. Overall, the thesis presents a vision of the future in which renewable energy is integral for meeting the power needs of the Earth. In the end, the current project is an extensive study of the strategies and methods necessary for increasing the readiness of the grid to absorb renewable energy. The efforts are justified by the overwhelming benefits to the environment, the economy, and society at large. Given the current global climate change crisis and the scarcity of resources, such findings can play no small part in the aspiration to develop a sustainable, low-carbon energy future whether for a developed country or a developing nation.

As a result, the study can conclude that developing optimisation techniques is a crucial step in enhancing the capacity of an electrical grid to receive renewable energy.

# CHAPTER ONE

# BACKGROUND

Chapter 1 is dedicated to the discussion of the problem of the shift towards renewable energy integration into the electrical grid and its various consequences in terms of grid stability, economic efficiency, and environmental safety in preparation for the in-depth analysis. This chapter describes the historical context of the development of the electrical grid, highlighting the necessity of enhancing grid resilience in light of the increasing environmental perils and technological difficulties influenced by renewable energy sources. The provided article examines several advantages of renewable energy, such as the decrease of greenhouse gas emissions, economic growth, and energy independence. Besides, it includes a review of the conceptual and theoretical frameworks that will be utilised in the subsequent study, providing perspectives on the understanding of the difficulties associated with the compliance of renewable energy with this system . This inquiry is designated to be the part of the attempts undertaken in Chapter 1 to provide the context of the problem of renewable energy integration, acknowledging both the technological obstacle and the prerequisite for the environmental and economic security of future energy systems that this problem represents.

## 1.1. Introduction to Renewable Energy and Grid Integration

Renewable energy sources have experienced a considerable surge in popularity recently, with them being one of the main front runners of the change (Gladwin, Kennelly, & Krause, 1995). For decades, humans have relied on fossil fuels and other types of limited or non-sustainable fuel to power our society. However, they are becoming more and more detrimental to the environment and our planet, with the accretion of carbonic gas in the atmosphere, diminishing resources, accelerated climate change, among other pressing issues (Heinberg & Fridley, 2016). Moreover, fossil fuels pose a severe problem due to their non-renewable nature. That said, renewable energy sources can reduce the environmental impact they produce since they produce energy through varied natural processes (Ajewole et al., 2023).

Steps have been taken that may change the way our world is; there is no way back. Ranging from crude fossils to new and clean energy sources, such as wind and solar power, technologies developed so much within the past half century that they entirely changed the perception of what energy acquisition, distribution, and application might look like (Stephens, 2019). Businesses are taking advantage of these developments by engaging in the creation of solar panels and wind turbines, while some individuals are trying to build energy-efficient homes in order to feel independent and somewhat superior in relation to others (Brauch et al., 2009). A new era of infinite possibilities, excesses, and redundancy has begun, and these possibilities, as is argued, are limitless (Bordoff & L., 2022).

There are several challenges which are unique to renewable energy and that need to be overcome for the renewable energy to be implemented in the current electricity infrastructure (Ahmed, Al-Ismail, Shafiullah, Al-Sulaiman, & El-Amin, 2020). Specifically, because renewable energy sources are at their core variable and intermittent, both current grid architecture and management need to be revised in order to ensure stability and reliability. More specifically, in order for renewable energy to be integrated in the system it is necessary to develop strategies for monitoring energy storage, maintaining stability of the grid despite the intermittent nature of inputs, and balance between supply and demand (Shafiul Alam, Al-Ismail, Salem, & Abido, 2020).

The incorporation of renewable energy grids is a crucial aspect of the changing to sustainable energy arrangement. It offers flawless use of renewable resources to satisfy the global requirements of energy and is of vital strategic significance (Tovar-Facio, Martín, & Ponce-Ortega, 2021). It is an integration that is not exclusively essential for the long-term survivance of the energy sector, but also aids in maintaining prices undeviating and boosting energy security. The grid becomes mollifying and more resistant when renewable energy resources are integrated . This as well makes it simpler to provide power to end-users that is cheap, clean, and reliable.

Nonetheless, renewable energy should present a r obtain an efficient integration into the system, various legal and technological obstacles remain that should be considered and overcome. Speaking of the latter, there are a number of technological impediments that should be overtaken, including grid updating and energy storage contribution, better control systems' development, etc (Aguero, Takayesu, Novosel, & Masiello, 2017). At the same time, legislation and emerging regulatory issues usually belated the spread of technology, which can hinder the progress of renewable energy sources integration and application. In order to overcome these issues, it is critical that communities, corporations, and emerging governments will cooperate and create the conditions necessary for fostering innovations and certain benefits implementation.

Comprehensive and coordinated grid integration planning is a prerequisite for anticipating the future in which renewable resources are extensively used. Sustainable energy that will characterize the future as the one to come will not be limited to environmentally friendly, but also efficient energy systems (Gui & MacGill, 2018). Thus, in addition to technological excellence, ample policy reformation and community involvement will be required to achieve the goal. Moreover, since the rate of renewable energy revolution is imminent, the corresponding generation facilities need to be connected to the grid to ensure a sustainable and cost-effective good energy future .

## 1.2. Historical Context and Evolution of the Electrical Grid

The transformation to the existing grid began around four decades ago. Instead of only being produced, the first aspect was linked to industrial-driven economies and energy suppliers who had the capacity to develop decentralized resources (Geels, 2002). This development was not the technology itself but the tapping of renewable energy sources. Developments in information technology in the 1980s and 1990s enabled grids to be made more power-efficient, allowing them to transfer electricity in both directions and decentralize production and use. However, there are important strides remaining to be made (Masters, 2004). Embracing other technologies that have been rendered cost-effective by the above-mentioned advances and calling for new, politically and socially contentious measures that will help us bridge financial and political obstacles that have long since begun must accomplish them.

Over the course of the century, it has become increasingly evident that the conventional grid system supposed a tangible degree of constraints. The environmental problems emanating from the overreliance on fossil fuel resources have been accentuated in the wake of the growing realization of the reality of climate change and the potential setbacks it could pose to the natural world's ecosystem as well as humanity's civilization (Wood & Roelich, 2019). Even though the system was effective in many ways, it was all too vulnerable to interruptions by virtue of its centralized nature. Such interruptions could be driven by natural disasters, technical glitches, or even attacks planned in advance. Given this set of risks, a new kind of grid system is required – both stronger and more flexible.

The changes in the energy sector of the present century have been largely influenced by several factors, such as the rising acceptance of the necessity to address the problem of climate change and the development of renewables (Papaefthymiou & Dragoon, 2016). Solar and wind energy are among the relatively new sources of renewable energy, which is why their increasing use is so pleasant because they already can serve as serious alternatives to the fossil fuels. When these increasingly decentralised and far from steady sources were incorporated into the traditional system, a lot of challenges of various operational and technical nature were experienced. The grid, developed initially to supply centralised energy, had to be transformed and made suitable for a much more diverse range of sources, thus losing some of its former predictability (Fang, Misra, Xue, & Yang, 2012) .

The advancement in power engineering brings about the creation of a smart grid, which refers to an electrical grid that is far more reliable, efficient, and greener than the traditional ones and relies heavily on the use of digital technology. The smart grid represents a radical break from the way grids have traditionally operated, with its ability to use real-time data control, enhanced control methods, and increased connectivity to manage the moves of electricity from numerous distributed generating sources (Papaefthymiou & Dragoon, 2016). Another advantage is its application, as it now enables consumers and utilities to communicate, which adjusts the supply and demand state and facilitates the operation of demands response systems.

Transition to a smart grid presumes not only the launch of new technologies to the energy industry but also rethinking the legal and economic principles of energy market regulation. Revamping of energy markets, development of the rules and standards, which could ensure the reliability, equity, and safety, investment into infrastructure are the required actions to do therefore (Wood & Roelich, 2019). Owing to advanced technologies, which have decentralized the energy system, consumers participate more actively in production and administration of energy. Such technologies as electric cars and rooftop solar panels are applied as explicit evidence of this tendency. Moreover, this movement is the reflection of the broader societial trend of maintaining sustainability.

The almost continually evolving electrical grid is the greatest testament to humanity's ability to innovate and adapt. Renewable energy sources are becoming more prevalent, technologies to develop smart grids are being used, and a decentralised and more participatory energy system is taking hold. In this light, the contemporary challenges of the grid are likely to be seen as part of this broader historical context. The latter serves as a call to action for individuals who want to keep searching for answers to be able to make a difference to the grid in the next few decades and beyond.

As is seen from Figure 1 , which also displays the past, planned and actual future growth of the electrical grid is a continued line, depicting the process of change (Prinsloo, n.d.). A graphic description of the development of our energy system across a century from an obsolete grid to a modern, innovative one is provided by the given graphic. The implications for the evolution of The Electrical Grid are evident.

Electricity was generated throughout power plants and other energy-generating facilities and then delivered to customers by a method known as centralised electricity utilizing a network of substations in the past. In grid management, the system operator was of great importance, meanwhile, the contribution of the customers was almost non existing. Thus, at that time, home and business customers were well-equipped with this solution; nonetheless, it was highly inflexible and would result in catastrophic ramifications if even one component failed.

It should be noted that the grid was significantly changed and revised. Both transmission and distribution control centres set up with state-of-the-art communication tools enabled fully controlled electricity flows. The modern grid is interrelated and complex, which increases control capacity and reliability. The innovation made it possible to enhance the performance of distributed producing sources and provide more energy independence such as renewables, at the same while making sure that all consumers, including commercial and residential ones, will be supplied with it . It is agreed upon by the majority of stakeholders that the grid will develop in a direction of being intelligent and highly linked in the future. Some of the future estimates were used in the figure. First, the development of high-temperature superconductors for energy storage and electric cars as customers and reservoirs are included in the model. Moreover, it is possible to perform dynamic energy management due to improved interactivity between clients and their providers. This approach promotes the change of an energy consumer into a prosumer an entity that can both produce and consume energy . The whole range of distributed producing sources can have this meaning: from microgenerators of large organisations to small solar-energy power plants on participants' homes. It is also worth noting that the utilisation of renewable energy sources is an example of the demand for a decentralised and sustainable type of the energy system. Moreover, energy storage is likely to be one of the main solutions to the current problems of unreliability and unpredictability of such sources and their inconstancy. The development of commutation may give alive to real-time data flow, which will enable the modernised grid to be more flexible and survive various contingencies.

In the future model, all the users in residential, commercial, and industrial organisations are likely to have an opportunity to be active in power management. The main idea of the whole grid is to create a model that is more consumer-oriented. The installation of both home energy management systems and smart meters will provide clients with support in their electricity consumption decisions, and give them more independence, particularly via their ability to use distributed generation and storage and, as a result, stabilise the system. The figure illustrating the rendering of energy systems from highly centralised and inflexible to dispersed adaptive and smart was designed. Such a future grid is to be characterised by the high level of isolation and interrelationships, intelligence, and humanity. It should also be noted that in the first place, technical innovations and system integration are important for the sustainable and resilient electrical grid, which will help it to manage increasing levels of renewable energy use and changing needs of society.

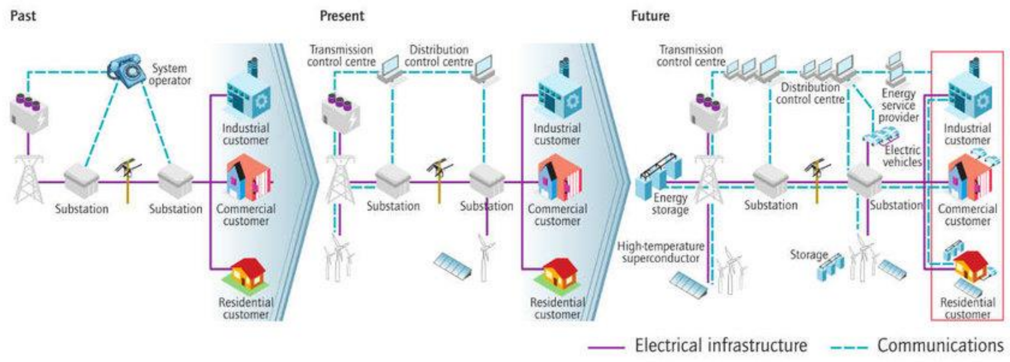


**Figure 1.** Evolution of the Electrical Grid: A Visual Representation from Past Centralization to Future Decentralization and Integration of Renewable Energy Sources (Prinsloo, n.d.)

### 1.3. The Importance of Grid Resilience

The importance of grid flexibility today is also difficult to underestimate. First of all, it should be noted that the terms resilience and flexibility are very similar, but the first concept is broader than the second. If the resilience describes the ability of a grid to prevent and combat disruptions, the flexibility refers to the adaptiveness of grids to use alternative energy sources (Mar, Pereira, & Martins, 2019). In this perspective, hoarding energy is important to be reduced.

The traditional electrical grid infrastructure is increasingly at risk as frequency and severity of extreme weather events rise with climate change. Hurricanes, floods, and ice storms have historically led to power outages that sometimes last for months and affect millions of people. In order to avoid the social and economic impacts of energy disruptions, it is paramount for the power grid to be able to sustain such a disruption and simultaneously decrease the downtime period and quicken the recovery process. Various natural disasters are experienced severally coupled with numerous technological and human-made hazards. The need to undermine the power supply and throw populations into chaos also calls for a high level of cybersecurity. Unfortunately, electric utilities are growing more vulnerable as specialized, streamlined and connected grid technologies keep advancing, despite the improvements in efficiency due to automated processes and application of renewable energy. It is evident that grid resilience would require a solid cybersecurity policy and practices.

A strong grid is essential for national security as it feeds hospitals, emergency response systems and military activities that require an uninterrupted power supply. The provision of these vital services must be ensured through grid resilience before, during and after a disaster. This can only be achieved with infrastructure improvements that virtually eliminate power failures or provide such low-frequency failures that their effect is contained. Furthermore, this attribute of power systems in turn affects the ability of the economy to experience and recover from shocks. Industries dependent on constant power use such as manufacturing or retail suffer serious financial consequences in the shape of lower output, reduced sales and degraded product quality. The loss of customer trust and volatility in supply chain relations have serious implications for the likes of investors and other stakeholders in the economy. These networks are strengthened through various means that include enhancing their physical infrastructure, incorporating advanced technological solutions such as smart grids and microgrids, and expanding their spectrum of energy sources, including the organized use of renewable power. Microgrids enable the local generation and delivery of electric power and can function independently in emergencies. Smart grid technologies provide better capabilities for forecasting and responding to power shortages, while renewable power sources reduce the reliance of the grid upon centralized power plants and fuel supply networks, both of which may be subject to vulnerabilities. Here, the main point is that grid resilience is a critical attribute that allows modern societies to function reliably and securely and refers to its capacity to anticipate, incorporate and recover from a variety of disruptions. The electrical grid must be improved in order to ensure its resilience to present and foreseeable future threats, which are expected to become more frequent and more severe.

### 1.4. Challenges in Integrating Renewable Energy into the Grid

There are several intricate challenges that need to be resolved when integrating renewable energy sources with the power system to fully use the potential of these sustainable resources. Solar and wind power sources are subjected to substantial disadvantages, being both intermittent and unpredictable. Since the patterns of sunlight and wind are prone to be intermittent, power generation cannot be always expected, and no guarantee can be fulfilled as to how steady the equilibrium between supply and demand is to be (Phuangpornpitak & Tia, 2013).

An added technology related obstacle is the current rigidness of the infrastructure. Instead of the distributed renewable sources, the traditional power grid was initially constructed to receive firm power flows from unvarying centralised power plants. In addition, the transmission and delivery networks must be renewed substantially to include sources of renewable energy because of the two-way and uncertain power fluctuations.

One of the major issues related to the transition is energy storage. In this case, batteries, as well as the combination of pumped hydro storage and compressed air energy storage, are likely alternatives to assist in dealing with the volatility of renewable power generation . In addition, due to this innovative development, it is possible to save energy for later use, in case the demand to the supply is higher, the process may run smoothly and simply switch to another condition. Nevertheless, batteries may not always be a perfect option due to their limited scale.-scale, and problems with technology, particularly, high prices (Phuangpornpitak & Tia, 2013).

In addition, the existing regulatory policies and market structures might not promote the adoption of renewable energy sources since they have already existed before the widespread use of these sources. The disadvantages of renewable energy also include the absence of environmental benefits and barriers to distributed generation, which might become a potential obstacle to the investment in renewable energy projects. Policy reform is necessary to ensure the emergence of all prerequisites for the adoption of renewable energy sources.

Since renewable energy sources are uncontrollable, there is an issue that arises for grid operators regarding their chance to manage the energy most effectively and forecast the demand in the future most accurately. The forecasting models and indexes along with the use of sophisticated weather predictions guarantee that the operators optimize the functioning of the grid about the expected level of renewable energy. Moreover, the way utility firms work and earn their money will change for the purpose of accommodating distributed renewable generation and encouraging their consumers to become producers of energy as well. The development of acute energy facilities and the updates to system bring a heavy price, and that is why the large-scale production of renewable energy is expensive. Moreover, a potential obstacle is that financial models that can identify the current expenditures of renewable energy need to emerge in countries.

On the whole, identifying and developing new renewable energy facilities raise notable social and environmental issues. Locally, any resistance or the well-known NIMBYism may halt or reduce the pace of building renewable energy infrastructure, such as wind turbines or solar panels (Phuangpornpitak & Tia, 2013). On the one hand, such projects can contribute to preventing harm to local species and their natural habitations. On the other hand, building environmentally friendly projects needs to assess and minimize their potential ecological impact . Thus, when discussing the integration of renewable energy into the grid, it is necessary to consider the technological, economic, legal, and social aspects thereof in a more holistic manner. A sustainable future is possible, but it will not come easily.

### 1.5. Opportunities Presented by Renewable Energy Integration

The implementation of renewable energy sources in the power system can serve as an impetus for a paradigm change in energy generation and utilization patterns, implying an extensive range of alternatives. The most substantial potential is related to the nature of the environment. The grid can substantially reduce its dependence on fossil fuels, cut greenhouse gas emissions, and minimize the negative effect of global warming. Thus, the power grid can benefit the environment by utilizing renewable energy sources, such as solar, wind, and hydropower . This transition is also favourable to air purity and health condition (Phuangpornpitak & Tia, 2013).

Moving to renewable energy may create new opportunities for the economy and job creation. If the production and application of new technologies will be less costly than those used currently, this may result in new jobs in the renewable energy sector, producing renewable technologies, and their maintenance, etc. As the use of renewable energy sources is expected to become less costly in the future due to the development and extension of the aforementioned types of energy, their cost-effectiveness is expected to produce positive effect for the economy in terms of stimulation of business expansion and equal opportunity to access to energy on the part of those who will be able to have access to cheaper energy sources.

Renewable integration pushes the growth of new methods of storage and grid operation. The need to balance between the swinging demand and intermittent renewable supply is driving the growth of clever grid applications, demand response and new and better battery technology (Phuangpornpitak & Tia, 2013). These technologies make the grid more reliable and flexible while improving the system's efficiency and responsiveness, making it appropriate for use in any kind of energy environment.

Renewable integration enhances energy security. In order to reduce the geopolitical and market risks linked with oil and natural gas supply, the government needs to explore other energy sources and cut down on its dependency on imported fuels in general. The production of energy from local renewable sources, such as rooftop solar panels and community wind farms, may lead to a more robust power system that is less vulnerable to largescale power outages.

The fact of the transition to renewable energy sources allows the energy market to prioritize individual users. People can become "prosumers," connecting to the grid with the help of renewable energy equipment and participating in the energy market through feed-in tariffs or net metering. They can both produce and consume energy, and this concept of activity promotes individuals to become a part of ensuring the future of the energy industry . It also gives them more rights to control their personal energy consumption and expenses.

The use of renewable energy sources has made governments in many countries all over the world reconsider their energy strategies in terms of policy. In this way, in recent years, different laws have been adopted to promote clean energy, provide financial mechanisms to invest in renewable energy development in terms of research and production, and offer incentives for investments . The promotion of implementing these laws in action can accelerate the transition towards a more sustainable energy sector. At the same time, it contributes to the formation of the regulatory framework that aims to facilitate innovation and sustainability (Phuangpornpitak & Tia, 2013).

At the same time, on a larger scale, the incorporation of renewable energy sources will reflect the goals established on the global level in wast sphere. Sustainable cities, climate action, economic growth are the objectives about which the world community is concerned. Thus, the extensive benefits of the incorporation of renewable energy will affect numerous socioeconomic concerns and the enhancement of a sustainable and resistant future for everyone, not only in the realm of energy.

### 1.6. Theoretical and Conceptual Frameworks

The integration of renewable energy sources is supported by a multidisciplinary framework that includes a set of concepts and ideas from environmental science, optimisation theory, systems engineering, and energy economics. These frameworks offer a systematic way to consider the integration of renewable energy into the power grid and help design an accurate model and set of regulations.

Optimisation theory could be a ground for a variety of caballing strategies using to enhance a grid's complementary distribution of renewable energy. A mathematical approach should be used throughout the grid to balance resources due to an eligible unstable and varying nature and prospects for renewable energy sources. Among the appropriate techniques, one can name such approaches as Stochastic Optimisation , Mixed-integer Programming , and Linear Programming. In its turn, managing grid operations with the help of these strategies firms up a powerful and conceptual connection between the balance of reliability of the grid, its affordability, as well as environmental friendliness and grade. The systems engineering approach is used to watch over the renewable energy sources' integration process, which must keep up with the inherent architecture of the grid and allow it to be painstakingly developed, analysed, and implemented as a complex tool adaptable to the renewable energy sources' permanent change.

To maintain and enhance the distribution of residential and utility-scale battery installations, the following concepts must be used: system reliability, redundancy, and flexibility . The developed models are aimed at estimating the economic viability of renewable power generation and may take into consideration such factors as initial investment, structure of the sold product market and firm demand, customs and innings, as well as the advancing labor markets persistently tying the renewable towards the overall increase. Ordered economic models could easily be used to approximate new markets and job homes which could rise as a result of archived observations concerning the operations costs the preservation of operations of and the power with the inauguration of solar plants. At the same time, concepts of environmental science, including a life cycle evaluation and carbon account, illustrate the environmental benefits of renewable power generation and the prospects of a reduced amount of greenhouse gases and the russet energy depletion of fossil fuels.

The combination of models presents a wide view of the problem of the renewable energy integration and possible solutions to be taken by both academics and specialists. They can be used to develop affordable and pragmatic solutions that could be used with minimal disadvantage to the environment. Being developed along with a grid, frameworks enhance the integration of different renewable energy sources and streamline the transitionw towards 100% solutions including new knowledge and technology brought as it is developing.

## 1.7. Research Objectives

The research objectives can be listed as follows:

- The investigation of the technical challenges conceiving optimization strategies for the practical integration of renewable energy sources into the already existing electrical grid, with a focus on the preservation and resolution of the national grid stability and resilience.
- The investigation of the economic implications of the renewable energy integration, including such aspects as costs and possible savings, the pricing of energy, and the long-term feasibility of renewable energy adoption from a financial standpoint and towards the use of traditional resources.
- The investigation of the environmental implications of the increased adoption of renewable energy sources for the grid, primarily the reduction of greenhouse gas emissions and the potential contribution of renewable sources to global climate change .
- The development of policy recommendations and possible regulatory changes increasing the opportunities for renewable energy to be adopted on a wider scale.

## 1.8. Thesis Out line

The thesis opens with an Introduction chapter that provides an overview of the pervading trend towards renewable energy sources and the significance of this development for grid design. It continues in a logical sequence. The weight of these factors in the present day necessitates a comparison and reporting of historical development typically characterised by the reduced need for grid resilience. In order to build a basis for the theoretical and methodological structures that would guide the subsequent study, the chapter outlines initially many barriers to the inclusion of renewable energy sources, and then discusses benefits of the same into the power grid.

Chapter 2, Literature Review, is an overview of existing research on the topic of renewable energy integration. The bulk of the research on wind and solar power is also supported by optimisation methods employing models that must be occasionally modified under constraints that are discussed here. This chapter reviews the models, and constraints, and the difficulties in meeting them before the chapter covers a review of various models and challenges.

The third chapter, the Methodology, outlines the research plan and the types of research and data to be collected. This chapter also outlines assumptions, limitations, and hypotheses on the basis of the theoretical framework to guide the approach to data analysis and modelling in support of the thesis.

The fourth chapter will address optimal dispatch of renewable energy. The model provides a description of the constraints and objective function, which are also crucial for generation optimisation in the aim of renewable energy integration. This resource will offer an array of optimisation with computational tools to assist in generating dispatch strategies. The theoretical foundations have been supplemented with case studies to enhance a greater understanding of the application of these algorithms.

The Results and Discussion offer a summary of the empirical findings of this thesis. This study calculates the extent of the inclusion of renewable energy, the advantages in terms of less emissions, and the cost advantages. It assesses the entire process of inclusion and its impacts.

Policy implications offer an in-depth analysis of the strategic policy changes needed to foster further inclusion of renewable energy sources into the grid. The analysis goes further to discuss possible changes to current regulations as they aim to deal with the dynamic in renewable energy sources.

The final chapter, the Conclusion, offers a succinct summary of the main issues covered and goes into their broader implications. This chapter reviews major findings, indicates the importance of integration solutions for a greener energy. This thesis closes with a final section that overviews the impact of the research on the field and offers possible future directions.

# CHAPTER TWO

# LITERATURE REVIEW

Chapter 2 represents a detailed Literature Review that analizes carefully all the previous studies in scenario of renewable energy integrating into the power system, emphasizing its focus on Solar Energy and Wind Energy as two remarkable domains of renewable energy. It confers the effective and weak points of each in terms of integration, allocating the following section to System Integration Challenges. These are alluded to as a substantial pack of technological, financial, and legal obstacles that impair the coherent utilization of renewable energy sources in the domain . Besides, there is also Optimisation Models in Energy that confer a variety of sophisticated mathematical and computational backgrounds that are aimed at enhancing the reliability and efficiency of renewable energy dispatch. The latter enables synthesizing the existing knowledge and pointing at the existing gaps and compartments that have not yet become a subject of scientific inquiry . At the same time, it serves as a background that is needed to understand the results of the research.

## 2.1. Renewable Energy Integration

In a period like this, when the full energy statistics of the entire world threaten the future of a sustainable energy feature, the detailed analysis of the various methods along with the challenges of harvesting electricity from the sun and wind and harrowing it up into the power grid (Oyekale, Petrollese, Tola, & Cau, 2020). The sources are barely predictable, and the fact makes it even more difficult to execute the integration of renewable sources with the necessity of technical breakthroughs and the need for relevant grid management innovations. The latter is roundly difficult to pursue as the sources are from the beginning unpredictable, and they have unpredictable structure (Bajaj & Singh, 2020). This section of the literature review examines the analytic methods in the integration process with due privileges to solar and wind power, a landmark of the integration estimations in the current state of the energy field.

Solar energy is very appealing as a source of electricity because it is not only clean but also abundant. However, it is necessary to come up with innovative methods of grid integration because this source of energy is unpredictable (Hasan et al., 2023).

Research into the ways of solar energy deployment includes work on innovations in the photovoltaic technology (Rana et al., 2023). Moreover, the scientists study smart grids since they can reduce the effects of electricity being generated in a discontinuous way . It is possible to conclude that if people want to enhance the efficiency and the reliability of solar energy, they should use such devices as grid upgrades or storage technology.

Wind power, as well as solar and hydropower, has its own unique set of integration challenges, the most important of which is the need to come up with a way to deal with the volatility of wind energy and its impact on the system's stability (Sinsel, Riemke, & Hoffmann, 2020). Wind projects need to be geographically distributed, the methods of wind forecasting need to be developed further, and other forms of energy need to be included in a synergistic fashion; these are some of the ideas that are being explored in the field as potential solutions to these problems. However, other similar ideas are also being taken into consideration. Offshore wind energy projects also need to be given further consideration, as not just their establishment and the process of connecting them to the grid is challenging, but they also have the potential to become a major addition to portfolios of renewable energy sources.

Apart from a technological perspective, the issue of integrating renewable energy sources is also investigated in terms of the law and the economy. The themes under consideration in the discussion include the need for policy innovation for the alignment of energy systems with sustainability objectives; the economic feasibility of switching to renewables on a large scale; and policy and regulatory configurations, working to either promote or hinder the transition. The literature review enlightens the reader on how complex the issue of integrating renewable energy sources is, and highlights the role of created regulatory frameworks, economic feasibility, and the state of technology in determining how energy systems will develop in the future.

Solar and wind power are two exemplars of integrating renewable energy sources into the electrical grid. It is a complex endeavor, fraught with multiple challenges and opportunities at the same time. This part offers an extensive summary of how the situation with the integration of renewable energy sources stands right now.

It will be beneficial for the present study, which is supposed to be devoted to improving grid operations and regulations for a greater incorporation of renewable energy sources. An enhanced, more efficient, and greener power system is the aim of the present literature review, aiming to shed light on numerous strategies that could be utilized for achieving a specific objective.

### 2.1.1. Solar Energy

The development of solar energy technology has been significantly increased as a result of innovation. The emergence of quantum dots, solar trees, and solar panels that can float on water greatly promote these processes. First, quantum dots based solar cells, which can be applied to the collection of sun energy, became a significant breakthrough due to their customizable bandgap feature. Furthermore, they can absorb more of the sun spectrum, which is a novel concept to this issue . Besides, solar cells are projected to make a significant improvement in their efficiency and cost due to the broad variety of materials in which quantum dots can be applied. Finally, recent advances in this area showed that quantum dots have a great impact on energy collection methods, which may lead to a significant change in the sun technology systems over time (Khare, Chaturvedi, & Mishra, 2023).

Figure 2, Quantum Dots Production Chain is displayed in the document. One of the very important scientific breakthroughs occurred was made in the process of producing quantum dots to increase the efficiency of solar cells. The supplied figure provides the description of each part of production, beginning with the solid quantum dots and up to dicing the wafers.

Solar trees are another innovation and breakthrough in the sphere of solar energy gathering at present time. It can enhance the cityscape by their tree-like appearance and take the most practical approach towards the use of the space for solar electricity. It is common for urban locations to have a scarcity of horizontal ground space, but solar trees is a solution that is both achieve and beautiful. For instance, the design of these trees provides the possibility of best possible capture of solar energy, the efficiency of which is achieved with the modification of panel orientation to suit the model of efficiency that nature has to offer (Khare et al., 2023). Such design is the incorporation of modern technology with the inspiration provided by the nature itself.

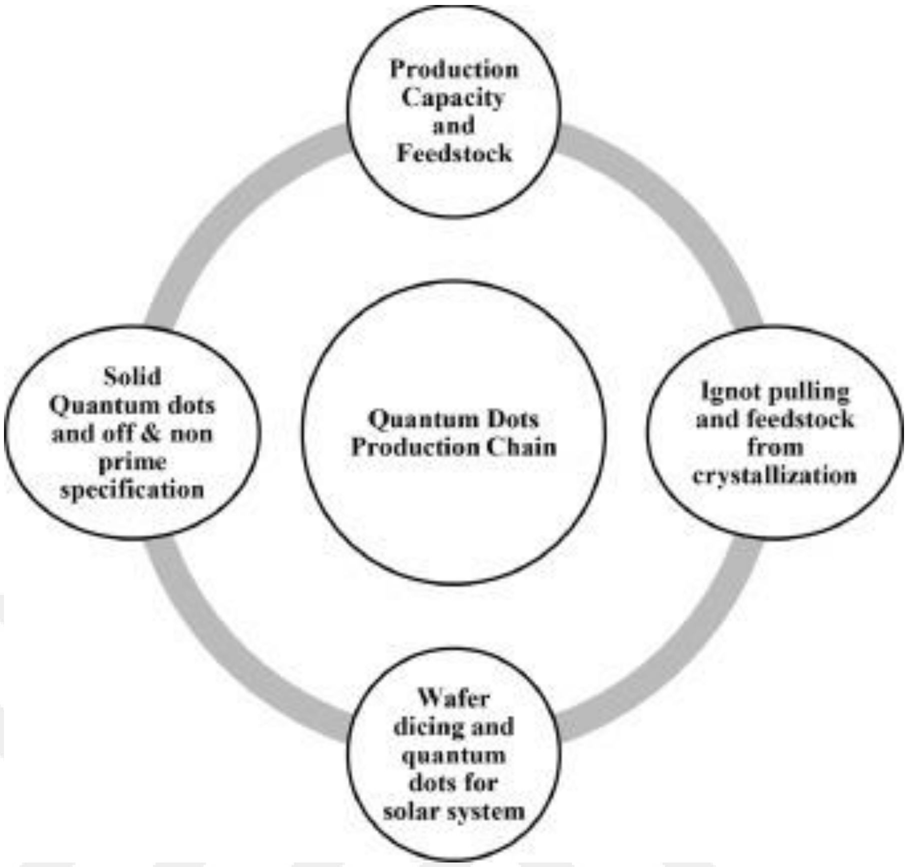


**Figure 2.** Quantum dots production chain for solar system (Khare et al., 2023)

In Figure 3, which represents the Four-Layer Architecture of a Solar Tree, the brilliant utilization of solar panels is demonstrated. This Picture best reflects the use of the specially designed technique, solar panels, since it provides a full view of the whole design of the solar tree and shows that it utilizes the beauty of solar panel usage in such a piece of art, design that looks like a creation of nature. This method looks like a piece of innovation, where solar panels are used in the air to gather the sun energy, not wasting land space. This design is usually applied on top of water reservoirs, lakes, and similar water bodies, so utilizing the sun energy and the water that would be left unattended. Besides solving the issue of land waste, these floating solar panels assist not to evaporate a lot of water. Thus, solar panels in the air look like an innovative approach, as a great example, when an advance in technology helps implement environment-friendly solutions for long-lasting effect renewable energy sources.

Based on all the reasons above, research about smart solar trees, floating solar panels, and quantum dot solar cells show that the solar energy sector has moved towards solutions which is more innovative, efficient, and sustained in the long run. It could be seen from the fact that solar power is becoming more and more attractive and essential in the future of renewable energy. The findings from above research were possible due to the development of these technologies, showing the transition of solar power over time in this aspect and others.

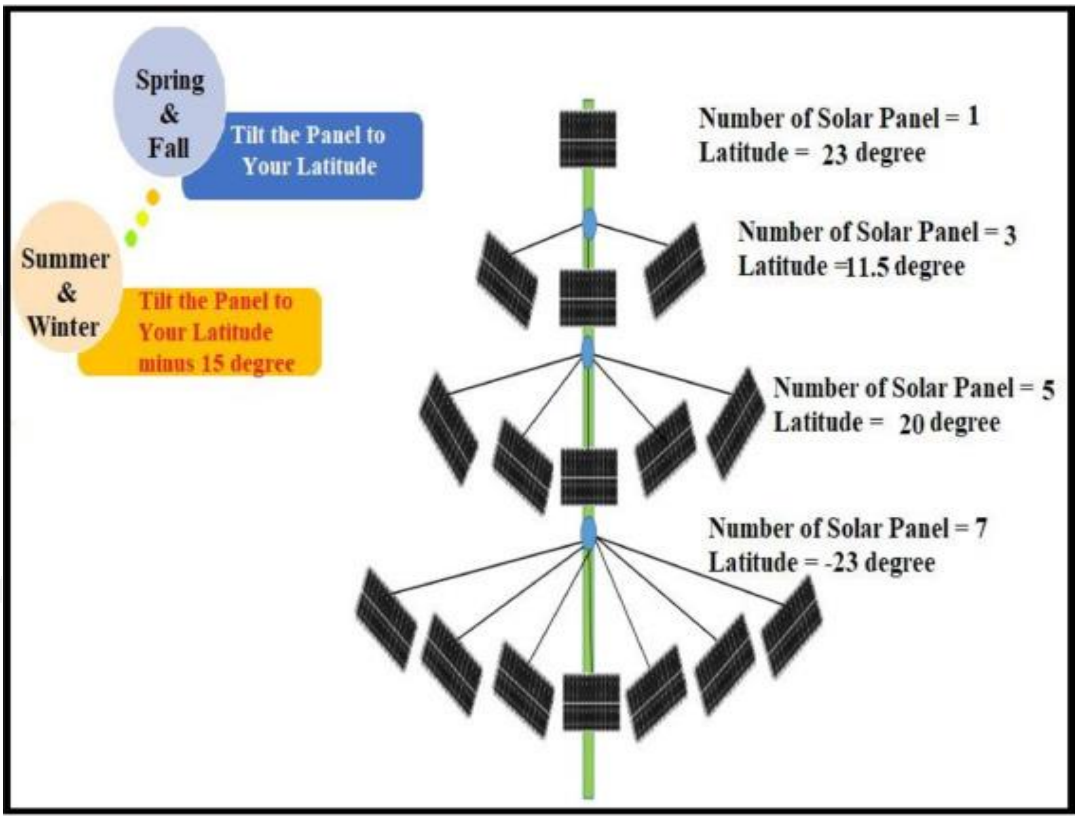


**Figure 3.** Four layer architecture of solar tree (Khare et al., 2023)

### 2.1.2. Wind Energy

Wind power is one of the renewable energy sources supplying electricity using the kinetic energy of air masses. Wind power became one of the main resources in transforming to other sources nowadays. Since windmills turning into wind turbines, this industry demonstrates its intention to convert one of the most generous gifts from nature. Nowadays, wind turbines are huge, complicated machines featuring the most recent achievements in materials science and aerodynamics. Thanks to these achievements, people can utilize wind power in an ecologically friendly way, and at the same time, it allows to harness energy in a smart, high-tech manner (Hassan, Algburi, Sameen, Salman, & Jaszczur, 2023).

The wind turbines' popularity has increased due to a number of key advancements. The modern turbines are of enormous size which affects the landscape. They are created to use winds of a better quality and to optimize the amount of energy which is obtained. Thanks to the advancement in blade materials modern turbine designs lighter and more resilient which results in more efficient and longer operation . Furthermore, the technology advance spreads to the area other than the size which is also helpful. The introduction of smart technology makes the turbine more efficient being possible to adapt to the exact circumstances and to monitor in real time and make sure no performance issues occur and that the turbine is not wasting possibilities.

The numerous applications of wind power have allowed people to harness natural forces and generate electricity in a simple and effective way. The use of such sites as offshore wind farms is a step forward for wind energy. One would be right to point to the arguments of wind farms that are located offshore, as according to the wind farm itself, they can produce more electricity "simply by being in the maritime regions, where the winds are more regular and stronger" (Hassan et al., 2023). However, there are a number of issues that arise in the marine setting, such as the need for more, stronger turbines and the increased cost associated with producing and maintaining them. Currently, these issues are becoming solvable thanks to advances in floating turbine technology, and these turbines will soon become widespread.

The inclusion of wind energy into the electrical grid serves as a reminder of the truism that due to its volatile nature, wind is both dangerous and beneficial. As such, it should further prompt gains in grid management and energy storage that will guarantee that our electrical supply remains stable in spite of the vagaries of wind speed. Moreover, to explicate wind power distribution and systematize its control in a more efficient way, the mentioned initiative seems to be highly dependent on predictive analytics and improved weather forecasting patterns.

Wind power is able to offer a series of advantages that are either practical or financial. First, it can be noted that the energy source is a clean one as it is capable of reducing the emissions of greenhouse gases significantly . In addition, the economic environment seems to be changing along with the sharp decrease of the production expenses related to wind power, making it among the most viable energy sources. Finally, the sector of wind energy is known to be one of the main employers when it comes to manufacturing and installation as well as maintenance, which can also be viewed as a substantial contribution to the development of regional and international economies (Hassan et al., 2023).

In conclusion, wind power is presently becoming a prominent portion of the world's present energy mix, and it is constantly developing due to the development of new technologies as well as the overcoming of obstructions against its implementation. It must be combined with other renewable sources such as solar energy to power the whole globe in a reliable and sustainable manner. As a result, wind power is reshaping the future and serves as a strong instance demonstrating how people are constantly attempting to improve their relationship with nature by going to new lengths. Wind power is a breath-taking example of how green-friendly humans are.

### 2.2. Grid Integration Challenges

Due to the difficulties related to the use of renewable energy sources in the power grid, it is important to reconsider the existing approach to the grid configuration and develop creative measures to make the system reliable and efficient. While discussing renewable energy sources, wind and solar power should be mentioned as sources of extremely high volatility and intermittence. To some extent, their extremely variable nature is dependent on the weather, as opposed to the permanent characteristics of the large power plants generating the power in the more "traditional" manner. As a result, as a contrasting element of the grid development, immediate measures should be made to improve the operational conditions of this power system. This can be achieved by enhancing the flexibility of the grid management, advancing the quality of demand and supply forecasting, and growing the investment in energy storage facilities (Khalid, 2024).

The integration of distributed renewable energy systems is likely to be a challenging task due to the failure of existing infrastructure to cope with the generation of power from centralised and dependable sources. The transmission and distribution networks need to be massively modernised and expanded to counter the problem of the renewable resources covering the planetary surface rather than being localised and concentrated in one specific area (Khalid, 2024). This will be not only a costly matter but also will face numerous problems related to social, environmental, and regulatory issues. The flexibility of the system is required to be enhanced through demand response activities and the application of smart grid technologies to deal with the fluctuating input of solar and wind.

The problem of energy storage is the most significant hindrance to grid integration. In order to store the extra energy when the sources of renewable energy are being used at full capacity, it is necessary to create a capacity for countering the intermittent trends in this energy. Technologies such as batteries, compressed air energy storage, and pumped hydro storage, which are some of the many technologies relevant in this context, are suitable as they serve as a buffering measure against the volatile nature of renewable power generation at times of heightened output.

Moreover, energy sources are also faced with a number of technological and structural hurdles that can impede their assimilation. They extract the sun's energy and converting it into useful energy causes both CSP and PV cells to rely on sunlight . The latter requirement is important for photovoltaic cell operation, which must be continuous to provide a stable and ongoing supply of energy to the system (Khalid, 2024). Simply put, there is no way to solve this problem because there is no way to make the sun shine at night to provide power in the dark.

On the more granular level, there are several technological challenges, the most essential of which are connected with grid operation and management . In other words, technology of the system has to expand in order to accommodate the renewable energy sources. It means that more sophisticated management software has to be developed, better tools for forecasting, and methods, which could make the system more responsive to the fluctuations of supply. In order to overcome these challenges, a diverse poly of players should collaborate, government regulators, utility companies, and technology providers. Working together and adopting innovative policies, market systems, and technology could make the grid better prepared to accommodate an energy future primarily created by renewable sources. However, environmental sustainability, economic development, and the smooth transition of the sphere to a low-carbon future depend heavily on our ability to overcome these challenges.

The uncertainty for renewable energy sources is virtually inherent. Even though wind and solar power are the most commonly preferred sources for renewable domains, they possess a series of erratic features, limited dispatchability, and generally intermittent nature. Thus, for the system to be feasible and adequately satisfy the operation requirements, the system requires several specialized auxiliary services, such as spinning reserves, and other regulatory operations . Figure 4 provides an overview of the auxiliary services required for the feasible operation of power systems in any planning horizon. These services are needed in the majority of the locations to preserve the quality of power supply. Another factor is the fact that the produced output power may swiftly fluctuate . Therefore, as a result of this, the existing uncertainty of demand causes the overall system to become more unpredictable and volatile. Therefore, both fundamental systems are in need of improvement and upgrade.

It seems that the existing power grid is decentralised, with the only requirement being the generation, transmission, and distribution of increasing amounts of energy, in view of the rapidly changing requirements of renewable energy distribution. Even at the level of distribution, energy management is not a problem. Ensuring that the electricity being distributed is at the correct level is the main priority. A synchronised system upgrade is required to scale renewable energy at both the generation and distribution levels in order to effectively observe, control, and manage the entire combined renewable energy system Manditereza and Bansal, 2016 (Manditereza & Bansal, 2016) . At the distribution level, the technology requires additional supervision and management in order for the implementation to be reliable, secure, and optimal. This will support the implementation of many different small-scale renewable energy systems. The overall goal is to reduce the level of complexity of randomness while maximising the effectiveness of power supply and management.


**Figure 4.** Supplemental services to ensure the operation of energy systems that generate electricity (Khalid, 2024)

The conventional synchronous generators offer stability, controllability, and additional support to minimise the adverse impact of the fluctuations in demand. However, when the renewable energy sources are installed, then the level of the power grid's support is substantially reduced . As a result, the time variability of the renewable energy sources demands and their swift changes drive the systematic reinforcement of the power grid in order to substitute or modify the capacity of synchronous generators. The wind speed here and now determines the electricity generation amount by the wind turbine. The standard output of a wind turbine is 100 percent. It used to be 8% at the very beginning . However, the output increases considerably when the wind speed jumps from 5 ms-1 to 13 ms-1. This operating range for wind turbines is seen quite often; moreover, wind turbines with such ranges often have highly variable outputs. The output remains at 100% from 13 ms-1 to about 25 ms-1; then the output decreases to 0 after 25 ms-1 (Sinden, 2007). The wind speeds are volatile, and the output of wind turbines is not set in stone; such, it is difficult to determine the quantity of electricity generated.

Overgeneration during the peak load hours could also result from the widespread use of wind power. Accurate estimates of wind and solar outputs are vital for the possibility of implementing new services and ensuring the hourly ramping constraint that is necessary for unit commitment in the future. To solve this problem, an advanced equipment and algorithms should be applied. In the context of the need for satisfaction of the energy market demands, it is crucial to improve the regional scheduling of the intermittent resources and the energy as a whole (Lee, Ban, & Kim, 2022). The most significant challenge in this context is the lack of a reliable model of renewable resources and a relevant accurate forecast of the generation. In addition, it should be noted that the wind and solar power require higher precision in planning and forecasting than the traditional sources of energy due to their unpredictability, variability, and the wide range of patterns that could be applied (Cheng et al., 2020).

One aspect that is particularly relevant to the topic of renewable energy production and capacity is that measuring weather forecasts and future periods of generation for this source is essential, both in the short and long term (Khalid, 2018; Naz et al., 2019; Sarshar, Moosapour, & Joorabian, 2017). Unlike standard generators, renewable sources cannot be relied upon to generate electricity constantly. For instance, solar panels cannot deliver maximum electricity on demand at night, and windy environments may produce such instability and even disconnect from the grid, with ramifications contributing even more strain to the network. This suggests that very detailed energy management including factors like power supply-demand, energy unit price, storage price, and generating possibilities must be coordinated when part of a network involves renewable sources. Likewise, the grid has the option of declaring up to 5% to 10% of renewable energy output to be ‘noise’ if it is less than the standard demand (Sgouridis et al., 2016). One associated challenge is that the varied provisions of this source make everyday network planning more difficult to predict and operate.

To begin with, it is important to state that many levels exist throughout the day that renewable energy may change. Thus, in order to ensure proper functioning of the system, operators should have an opportunity to adjust operations at the system immediately, at an hourly level, and a day-ahead. As a result, the system of conventional power generation requires continuous changes to ensure proper load fulfilled. A similar process also occurs for minutes. It is a vicious circle as almost every minute, an RE formation will change, while demand will do so approximately constantly as well. As a result, it is not efficient for generators, because they are put on so much stress. Thus, when this process is intersected with load profile change, the problem is exacerbated. It also means that for a period of time, the grid is following a real-time load , and power off due to wind or sunlight might severely harm this procedure. The types of real-time load following are hourly and second. Thus, it is clear that a substantial challenge occurs when it comes to minimizing the cost of control (Alhammad, Khan, Alismail, & Khalid, 2021).

Correctly implemented, scaled, and administered wind turbines can progressively replace synchronous generation with wind power in the electric power systems. However, their unpredicted power fluctuation and the effect on the power flow and system's operating conditions in the grid also need to be considered. The identification of need, optimisation, and design and implementation of electrical power systems is an interdisciplinary approach that combines engineering and energy sciences. The challenges in the area fall within several sectors of electrical power systems(Qays et al., 2022; Reddy, Kumar, Mallick, Sharon, & Lokeswaran, 2014). The four fundamental principles of power system functioning are the following: grid stability, optimal power flow, power quality and power balance. If we talk about power balance, it will be necessary to deal with the long-term and short-term operation of system generation and demand. Balance of the whole system requires the proper management of the capacity of the grid to change variations of power produced and minimum production that may be maintained at all times. It is significant to note that this problem is challenging due to the uncertainty and randomness inherent in renewable energy sources. The greatest performance is expected from the end user and power quality is of paramount importance. If problems with power quality arise, the need of the hour is to check whether the power is supplied continuously, whether the voltage and current are consistent and the system contains appropriate security. There are two main issues that account for power quality ones. They are the non-synchronous nature of REPs and their modular structure. The optimal power flow literature is devoted to specific problems related to the transmission and distribution of electricity in a way that is as efficient as possible. Unlike other types of issues, due to the transient and modular capabilities of the sources, the problems with the optimal power flow of all kinds renewable energy sources with it modular nature and lack of any form are dependent on the power topology. If we consider stability, the vast majority of issues have to do with the attempt to restore the electric system after a scheme collapse, and to adjust the system frequency and voltage. The main features accounting for the instability of these systems are the non-synchrony of renewable energy producers and the modular architecture of these systems. The areas identified in Table 1 give a more comprehensive understanding of the challenges and problems caused by the integration of RE. Finally, Figure 5 shows the overall flowchart that is relevant to the work relating to the integration of renewable energy systems. The last example illustrates how when incorporating renewable energy sources, utility-grade bulk renewable installations consider power quality, contingencies, RE allocation, and financial issues.

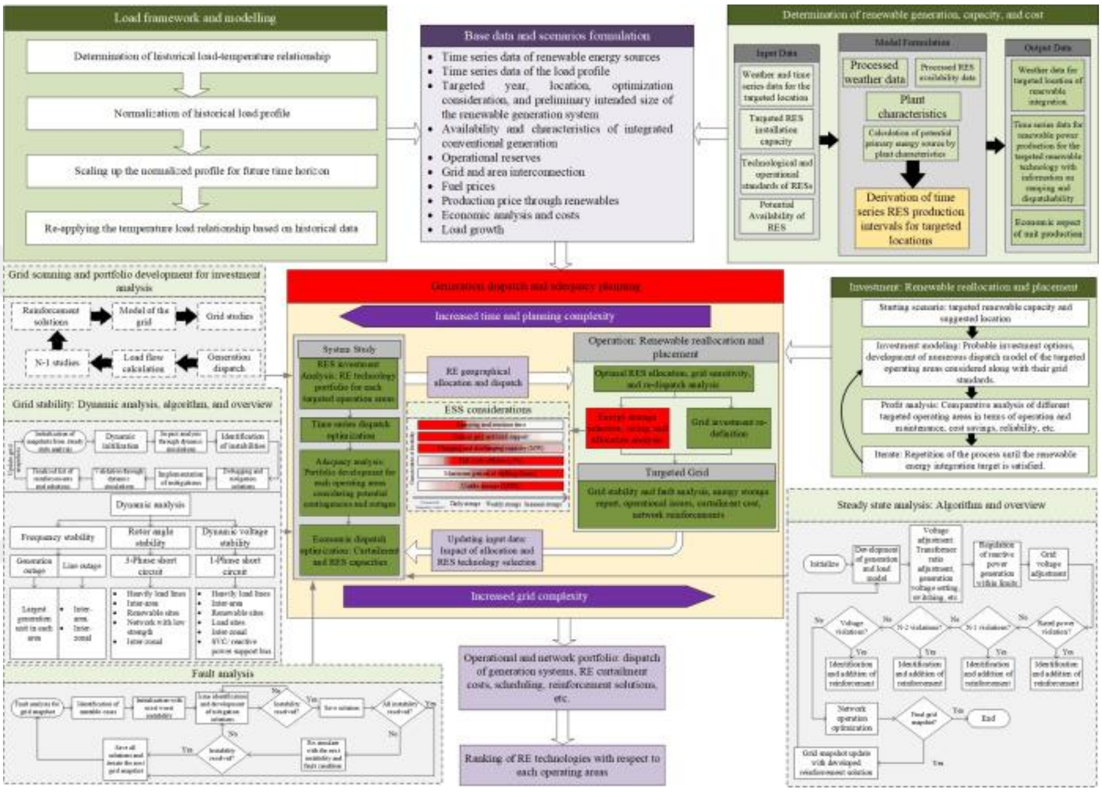


**Figure 5.** Common elements of renewable integration planning include power quality, backup plans, and investments (Khalid, 2024).

**Table 1.** RE integration concerns and obstacles.

| Issue | Challenge | Description | Flexibility | Reliability | Resilience | References |
|---|---|---|---|---|---|---|
| **Grid Stability** | Increased controllability and observability for inverter-dominated grid | RE generating that supports grid decentralisation will need inverters to connect to the grid. Unobserved power oscillations will arise from the changed grid. Thus, the grid may experience more inexplicable tripping, requiring a specific control method to regulate such cases. | | X | X | (Song, Jiang, Schlegel, & Westermann, 2020) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Increased reserve for frequency control | RE generation cannot supply grid operating reserves. Short-term, unpredictable RE generating output power needs specialised and extra reserves to equip the system for frequency deviation stability difficulties. In case of unforeseen RE integration and operation, operators may have to reduce RE generation, load, or make decisions to maintain grid stability during critical situations. | X | | | (Rapizza & Canevese, 2020) |
| | Decrement in the grid inertia | Many RE generation methods are electronic and have less inertia. Unlike synchronous grids, a quick frequency excursion can make the grid unstable. Due to demand-generation equality restrictions, generation curtailment or load shedding may be needed to ensure system stability. | X | X | | (Du & Matevosyan, 2018) |
| | Reduced capability towards fault detection | RE generation systems have lower short-circuit power, making fault detection and voltage instability unnoticed. This can hinder grid stability and RE microgrid isolation. | | X | X | (Aftab, Hussain, Ali, & Ustun, 2020) |
| | Decrease in reactive power support | Most RE generating systems introduce little reactive power. Transmission lines need reactive power to maintain voltage standards per grid dynamics. Due to voltage violations, RE growth and penetration will be restricted. Without reactive power assistance, power quality and stability would suffer, causing RE generators to be curtailed or isolated. | X | X | | (Khalid, 2022) |
| **Power Quality** | Voltage congestion at distribution level | Integration of RE Low grid voltage increases voltage violations. Overvoltage with high RE production or low load demand | X | X | | (Panda & Nayak, 2022) |
| | Low reliability during blackout | Unconnected RE generators are subject to stability and power balancing difficulties, posing safety and operational risks. | X | X | X | (Barakat, Emam, & Samy, 2022) |
| | Harmonics | Inverter-integrated RE increases harmonic distortions. End customers have shorter equipment lifespans, trips, or damage. | | | X | (Sakar, Balci, Abdel Aleem, & Zobaa, 2018) |
| | Voltage Flickering | Due to the features of most RE power generating technologies, RE generators cannot stabilise grid frequency. Unexpected outages will result from the demand-generation mismatch. | | | X | (Ghaffari, Askarzadeh, & Fadaeinedjad, 2022) |
| **Optimal Power Flow** | Increased transmission line distances | Location reliability goes with REs' unpredictability and uncontrollability. Thus, longer transmission lines may increase transmission line losses. | X | | | (Yu, Zhou, & Qin, 2022) |
| | Limited transmission capacity of the grid | RE integration into the grid may need extra transmission lines. Otherwise, RE power curtailment, lower transmission capacity statement during planning, and reduced regional power dispatch will occur. | X | X | | (Conlon, Waite, & Modi, 2019) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Low degree of observability of the REs | The grid's lower voltage levels lack measuring instruments to match RE generation system fluctuation. Thus, an undetected power flow at these voltage levels can cause unplanned grid operation that is technically and economically detrimental. | | X | X | (Su, Wang, Li, Liu, & Wu, 2019) |
| | Low degree of controllability over the REs | Increasing RE integration with unanticipated small unit capacity will affect power flow and system dynamics. It reduces forecasting and planning reliability, which can cause grid instability. | X | X | X | (Månsson, 2015) |
| | Grid Protection | Lower voltage grid levels usually lack protective preparedness due to stochasticity dynamics from RE integration. In addition to load unpredictability, inadequate protection planning at lower voltage grids may increase overloading, unscheduled trips, and equipment lifespan. | | X | X | (Panigrahi, Bhuyan, Shukla, Ray, & Pati, 2021; Yang, Blaabjerg, & Wang, 2014) |
| | Grid capacity limitation | Current grid networks may not be able to integrate RE generation capacity. RE integration will reduce power if planned. Unplanned integration makes systems vulnerable to malfunctions and equipment damage. | X | | X | (Yang et al., 2014) |
| **Power Balance** | Limited dispatchability of RE sources | Due to the features of most RE power generating technologies, RE generators cannot stabilise grid frequency. Unexpected outages will result from the demand-generation mismatch. | X | X | | (W. Wang, Huang, Zhang, Liu, & Chen, 2021) |

## 2.3. Optimization Models in Energy

### 2.3.1. Linear Programming Models for Energy Optimization

The purpose of the optimisation can be formulated in mathematical terms. This formulation is called the objective function. Thus, the objective function is a mathematical expression of the aim of optimisation. It can be represented by the following examples. For instance, one of the aim functions is minimising overall operating cost. Another example is optimising the output from renewable sources through optimisation. Moreover, they serve as a foundation for the existing LP models in energy optimisation.

LP capabilities allow operators to form decisions by dispatching grid power, allocating resources, and scheduling generation. This is possible because of LP models’ capability to define objective functions and constraints through the linear relationships between various elements of an energy system. As a result, an optimal operation strategy can be determined. With the help of LP, the costs can be either minimised, effectiveness maximised, or an equilibrium of energy sources can be achieved (Bagherian et al., 2021). Alternatively, limitations are the restraints that existing on the energy system by the requirements to which it is beholden. Some examples of these factors might include the whereabouts and availability of fuel, fuel demand, environmental imposition and generation capacity constraints . LP models solve for the optimal dispatch of routes that need to sit between the objective function and those limits.

Indeed, grid managers have discovered that LP is very useful in terms of scheduling the generation of various sources that they have to offer in an effort to meet demands while minimising the cost, operations and environmental constraints that apply (Y. Wang et al., 2018). The optimal generating mix should be defined at each particular point of time by taking a variety of factors into account, such as the cost of fuel, generation efficiency, and availability of renewable sources. LP models facilitate the maintenance of a stable and balanced energy supply by providing a basis for grid managers to follow.

The principal advantages of an LP model are the computational efficiency and heuristic simplicity, according to M. Alsaç, G. Bright, J. Prais, and A. Stott (Alsaç, Bright, Prais, & Stott, 1990). Although LP models deal with multifaceted optimization problems involving numerous variables and constraints, the solutions generated by them are both pragmatic and easy to implement. Conversely, with regard to the integration of variable renewable generation sources, the employment of linear relationships could result in the failure of an LP model to reflect the nonlinearities of the genuine energy systems . Moreover, LP models are “highly dependent on getting the right information on the nature of the system and its constraints” . If this information is incorrect, the results of optimization will not be credible.

#### *2.3.1.1. Flexible linear program (ORES)*

The aim of a decision-support tool that is formulated as a linear programme is to realize solutions for optimizing investment and operational decisions for home energy systems (Lauinger, Caliandro, Van herle, & Kuhn, 2016) . It shows how energy storage devices or a which are storage units can be combined with conversion units that comprise a heat pump or , and a boiler, photovoltaic or , and solar thermal collectors to achieve cost savings and $CO_2$ emissions reductions with annual energy economics while satisfying the requirements for space heating, hot water, and the use of electricity . In case the available estimates of production and demand are accurate, the household may save 5-60% of the energy costs attributable to the ability of the dwelling to exchange electricity with the grid. Moreover, such decision-making can result in emissions reductions by 45-90% compared to a base case scenario.

The energy flow diagram is depicted in Figure 6, which shows the means of realizing a typical energy system for a home . The energy sources are integrated starting from the sources through the conversion units, or the storage units, and the energy should be used in the order provided. The goal of the optimisation problem is to find what the cheapest path is starting from the left, i.e. the source, to the right, i.e. the use that is coming to the right, or from the source to the right.

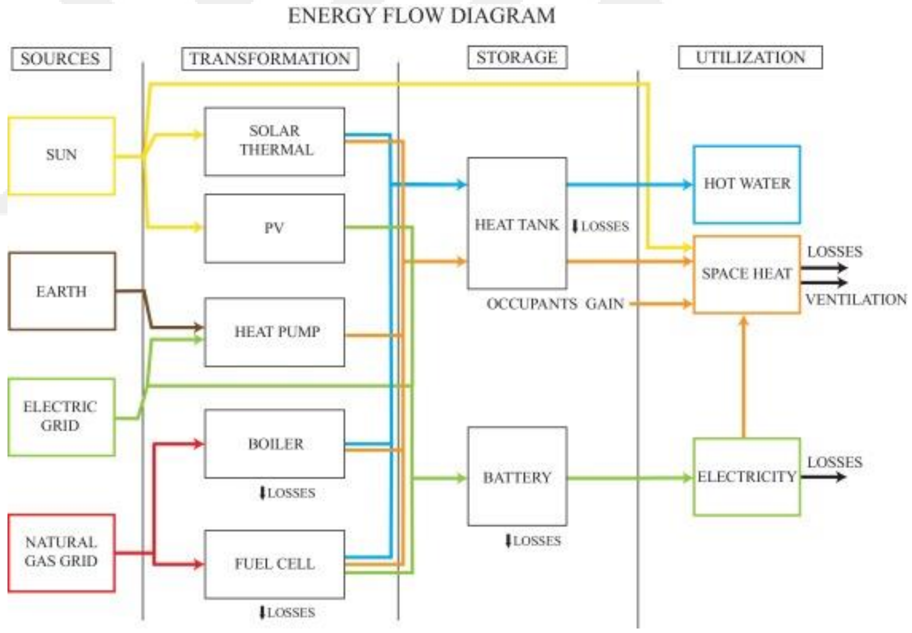


**Figure 6.** Energy flow diagram (Lauinger et al., 2016)

Therefore, the use of the stochastic program allowed the reduction of the susceptibility of the meteorological parameters due to the uncertainty in their availability. Due to the lack of a concept, the price increased by not more than 1.2%. If there are any unanticipated changes in the electric load, these changes can be addressed by the decision rules. The installation of a battery system for a household that is off-the-grid, which is assumed can have peak demands at any time during the planning horizon of a week, can increase the cost of the energy produced by 9% when the battery is designed to be larger.

*2.3.1.2. General Algebraic Modeling System*

The utilization of off-grid energy using the hybrid model introduced in the research provided is possible for both economically and ecologically advantageous purposes (Huneke, Henkel, González, & Erdmann, 2012). This model can be refined to better reflect the optimal operation of an off-grid energy system. In the present study, an energy system suitable for off-grid, remote areas is proposed, as shown in Figure 7 . It was found that using a three-phase alternating current bus-type configuration has four specific advantages over other grid designs . Linear programming with the GAMS environment can be employed to determine the optimal configuration of the electrical power supply system. This will account for both the characteristic restrictions and the exchange of hourly data between the weather and demand. By doing so, the most efficient mix of renewable energy sources like solar and wind power, or energy storage for the DG set, can be determined.

In developing a tested and functional concept, several communities in India and Titumate, Colombia, have successfully implemented operational off-grid energy systems. To balance the load, a diesel generator was used. The hybrid energy system was a product of the two optimization processes. The systems were powered using a combination of PV, lead-acid batteries and electric batteries . In addition to this, the integration of renewable energy sources and electric storage devices slashed the cost of energy for small off-grid systems. The decrease in cost is relative to that for diesel generator sets alone. When choosing efficient solutions, the shape of the load demand curve is crucial. Further, it is suggested that one may link solar photovoltaics and wind turbines to the energy storage as they both need it to work. This also implies that the cost of the battery can be attributed to both technologies. In conclusion, renewable energy sources are gradually taking the place of diesel generators in overall power generation. Technology use is the backbone of the shift, and solutions that reduce the use of fuel are constantly being advanced. The most efficient capacity for the diesel engine is essentially the same for its use.

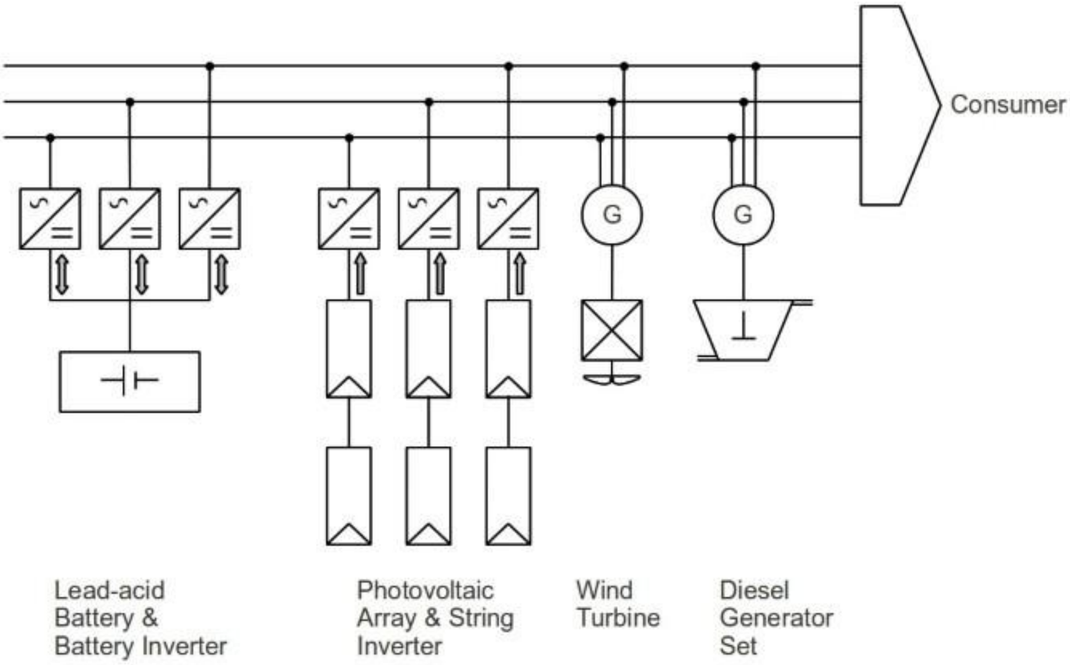


**Figure 7**. Remote area energy system designed (Huneke et al., 2012)

*2.3.1.3. Mathematical Model of Optimization Distributed Energy*

Poland's energy industry is currently facing problems related to the country's adherence to coal, which results in power supplies disruptions and an outdated transmission system (Rabe, Bilan, Widera, & Vasa, 2022). One of the prospective solutions is distributed energy, which can help the country's rural and less urbanised regions satisfy their energy needs and contribute to the areas' long-term viability. However, one of the most important issues to be investigated is whether a centralised approach can be transferred into a localised one. It is especially important in the context of the need to guarantee the state's energy security (Rabe et al., 2022).

The study subjects of were useful for determining the pros and cons of the distributed energy that was practiced. It can be concluded that the advent of local energy is beneficial due to several reasons, such as guaranteeing energy security and the continuous provision. There is also the need to do it in compliance with the criteria defined in regulations adopted by the European Union. They underline the critical role of following the energy efficiency norms and the use of methodologies aimed at providing the necessary energy with the help of renewables.

The model has determined that energy storage tanks are tasked with five different services . This is through response on demand servicing, taming the anxious power of the receiver, the reactive power and deformation compensation, where the voltage control is done using the active and reactive power, and the stabilisation of renewable energy source capacity. It is important for the local level to be returned, to for local government and local government business policy to be harmonised, for the law to be moulded, for monitoring to be stepped up, to solve the financial issue, and to do business there . To this day, neither central energy sector nor regional and local authorities in Poland have shown any interest in distributed energy. This is mainly due to the unpredictability of the EU regulations and national decisions, which poses a threat to the expansion of prosumers and renewable energy. The current state energy policy cannot lead to establishing regional energy generation on a decentralised basis. Thanks to this, it would be municipalities, not energy businesses, that would primarily determine the extent and composition of generated electricity. It is important to restructure the infrastructure, to extend and change the power transmission networks so as to meet the needs of the solicitor, to follow the local power consumption trend . With the transition to low-carbon energy, the use of tomogeographic electricity storage as a power supply provider becomes inevitable. The technological achievements we have attained regarding batteries and supercapacitors made it possible . It was a result of the creation of new market lods of the electric market on the one hand, associated with the development of electromobility and renewable sources.

The distributed energy optimisation model developed within the framework of the municipality's energy and climate policy, which has been designed for regional energy planning , also assists the municipality in meeting its targets with respect to energy efficiency, renewable energy, and greenhouse gas emissions reductions.

### 2.3.2. Stochastic Models for Managing Uncertainty

Stochastic models provide an opportunity to optimize energy systems. For the case when renewable power sources like wind or sun cannot be predicted due to their stochastic nature, these models are considered crucially important since they integrate randomness and uncertainty right into the design and operation of energy systems. As opposed to deterministic models, with stochastic models, users do not need to have sufficient knowledge nor power to know all input parameters. Stochastic models are an excellent way to design and run energy systems.(Zakaria, Ismail, Lipu, & Hannan, 2020).

#### *2.3.2.1. Incorporating Uncertainty in Energy Optimization*

Rather than treating uncertainties in energy systems as deterministic quantities, it should be noted that stochastic modelling approach treats them as probability distributions. According to Marwali et al. , the uncertainty of renewable energy source production, electricity demand displacement, and the fuel cost can all be considered as uncertainties. The intention in this domain is to consider all the possible outcomes and the likelihood of them happening. This, in turn, empowers energy planners and operators to come up with solutions that would be efficient under the conditions. In the context of a wind energy system, it is possible to note that wind speed is not identifiable and how it affects the amount of energy produced (Zakaria et al., 2020).

#### *2.3.2.2. Applications and Benefits*

Many different parts of energy system optimisation use stochastic models. This would include scheduling of generation and planning of capacity development, as well as the analysis of investments and the management of risks . Stochastic models are used to define which methods minimise the expenses or maximise performance, taking into consideration the risk of unknowns that can occur. Decision-makers can explicitly manage the trade-off between economic efficiency and dependability . This is a crucial consideration when dealing with renewable energy sources as they are volatile in a manner that is enormous across time and geography. Stochastic models can do this because they explicitly consider uncertainty (Zakaria et al., 2020).

#### *2.3.2.3. Challenges and Considerations*

Employing stochastic models for purposes of uncertainty management have a number of advantages, however, it is also associated with a number of disadvantages, such as the amount of data and computational complexity required. In particular, the existence of large scale systems with several sources of uncertainty could be computationally very expensive to deal with. Stochastic optimisation problems are a subtype of optimisation problems . Additionally, the availability of probabilistic data that is reliable and the quality of this data has a significant effect on the accuracy of this type of model. Utilising large quantities of historical data and advanced statistical analysis, such as survival analysis, can create accurate probability distributions for multiple inputs (Zakaria et al., 2020).

Stochastic models, in other words, are a crucial means for the optimisation of energy systems under uncertainty. They facilitate the better planning and operational decisions that are informed and resilient. Through the incorporation of renewable energy sources, they enhance the overall reliability and sustainability of the system by embedding it into the grid more effectively. This is done despite the intrinsic unpredictability and intermittency of the renewable energy sources. Hence, the energy landscapes of the future can only be successfully navigated through the continual updating and leveraging of the stochastic models, noting the difficulties posed by the complexity of the models and the amount of data it requires.

### 2.3.3. Machine Learning Approaches to Energy System Optimization

Machine Learning techniques are getting more and more important for the optimization of energy systems. These approaches offer precise tools that can help to deal with the range of the grid management or the integration of renewable energies. By using machine learning algorithms, which are capable of perceiving patterns and making predictions based on extensive data, energy systems can be provided with the power to become more efficient, reliable, and sustainable.

#### *2.3.3.1. Enhancing Predictive Capabilities*

Machine learning is particularly beneficial when it comes to developing energy systems. This fact can be explained by a need to produce more accurate forecasts concerning energy demand and the availability of renewable energy to power further generations of green extras. Also, grid operators need accurate projections to negotiate energy demand ahead of time. More importantly, it is essential to develop precise estimates of the amount of generated renewable energy such as wind or solar irradiance to ensure they are successfully incorporated into a grid. This way, there is a positive relationship between higher efficiency of machine learning algorithms performing traditional forecasting approaches leading and grid operators to become more efficient and reliable. This efficiency can be attributed to the fact that machine learning algorithms (Mosavi et al., 2019).

#### *2.3.3.2. Optimizing Grid Operations*

In addition to anticipating, another use of machine learning techniques is the optimisation of grid operations in real time (Rangel-Martinez, Nigam, & Ricardez-Sandoval, 2021). Reinforcement learning refers to a class of machine learning approaches in which computers learn optimal behaviors through trial and error. Such learning has a substantial capacity for use in constructing control algorithms that can effectively manage the dispatch of energy resources, balance supply and demand, and optimize the use of energy storage . Furthermore, grids that encompass a large number of renewable sources and operate in environments where conditions are prone to changing rapidly can also greatly benefit from such flexible opportunities.

#### *2.3.3.3. Predictive Maintenance and Anomaly Detection*

One of the areas where machine learning is indispensable is predictive maintenance for energy infrastructure. By evaluating sensor data and monitoring devices, machine learning can predict when a particular piece of equipment is likely to fail. This approach means that maintenance can be performed that is more preventative or proactive and less driven by the amount of unplanned downtime which had previously occurred. In the same context, anomaly detection algorithms can monitor the running of the system in real time and identify when minor problems are developing which could lead to major problems and disruptions to the reliability of the energy supply (Hallaji, Fang, & Winfrey, 2022).

#### *2.3.3.4. Challenges and Future Directions*

Machine learning provides an opportunity for solving a wide range of issues associated with better energy systems. Nevertheless, there are a few challenges that will have to be addressed even if this process is already started and can be distinguished. In particular, it is vital to remember the fact that an enormous volume of high-quality data should be provided to train excellent machine learning models . However, it can be rather difficult to obtain datasets of this kind. Furthermore, one should not forget about the fact that the ‘black box’ aspect of some machine learning algorithms can make it rather tough to understand how the particular decision is made . People are afraid that it can threaten the reliability and openness of the systems that are vital to society. All the problems are associated with the reality that this kind of algorithms is already created. Based on the partnerships, it is possible to add that there are quite a few ways to improve every area. In particular, they are creating the techniques that are more effective for data collection and processing, making machine learning models that are easier to understand, and presenting more effective ways to embed them in the operational and planning of the energy system.

In conclusion, one should say that machine learning approaches are already revolutionising the way energy systems can be optimized. These tools provide power for grid control, prediction, and, perhaps, maintenance of infrastructure. It can be necessary to mention that the whole world is going to switch to alternative energy sources and machine learning can pave the way for a more efficient, reliable, and greener future.

### 2.4. Conclusion

The research of energy optimisation models that include machine learning approaches, stochastic models, and linear programming teaches us how difficult it is to integrate renewable energy sources into the power system. As such, it is essential to mention that they all have their unique benefits and weaknesses. For instance, linear programming approaches bring our attention to the importance of cost reduction and system efficiency and are implemented to improve the energy production and distribution systems because of their simplicity and accuracy. However, due to the fact that renewable energy sources are not deterministic and linear, and are rather nonlinear and uncertain, they require a more sophisticated approach. Therefore, massive machine-learning techniques that require a significant amount of data will dominate the energy system optimisation. Thus, to address the concern about inefficiency, weakness, and uncertainty of energy systems, stochastic models incorporate uncertainty from the beginning of the optimisation process, which improves their ability to consider unpredictability of renewable energy sources. As a result, the approach enhances the complexity of calculations and data requirements, but it also increases the reliability and robustness of the energy systems. Machine learning models, which significantly depend on algorithms and big data, will lead the way in energy optimisation, and can be used for anything from predicting equipment needs and optimising grid operations to forecasting changes in demand and supply. Their ability to adapt and handle the complexity of renewable energy sources and their ability to learn through applications that are thousands and tens of thousands scenarios make them the best candidates. Nevertheless, something that remains to be done is to fix problems with model adaptability, data quality, and system implementation, what is necessary for optimisation models to achieve the desired output.

In conclusion, it is possible to note that in the long run, creating a whole range of optimisation models is crucial in order to move towards a sustainable energy system that is primarily dependent on renewable electricity and can help overcome all challenges from grid and equipment management to uncertainty and unpredictability. And, over time, these optimisation models and methodologies will respond to trends in the energy landscape changes, developing alongside advancements in data analytics and system design and technology. We will need to intelligently apply and refine these optimisation models to integrate renewable energy into the grid effectively, given the complexity of emerging energy dynamics.

# CHAPTER THREE

# METHODOLOGY

## 3.1. Theoretical Framework

The thesis is based on a strategy using a multi-disciplinary approach which integrates optimisation theory, energy economics, and sustainable environment to develop a conceptual framework that defines strategies for increasing grid integration and efficiency. This multidisciplinary strategy aims to provides a measure that maximizes energy dispatch, integrates energy, incorporates the renewable sources of energy to the existing electrical system and provides grid resilience. This is a response to the growing demand for new and sustainable energy sources.

### 3.1.1. Optimization Theory

The subject of this research is the application of the optimization theory, namely the investigation focused on finding the most suitable way of Renewable Energy Sources distribution across the grid. The mathematical models and methods, such as dynamic programming, mixed-integer programming, and linear programming are used in order to form and solve the optimization problems including the energy production and supply equilibriums. The underlying models are supposed to determine the optimal mixture of the “renewable energy sources and non-renewable energy sources” in order to make costs reduction and dispatching processes optimization.

### 3.1.2. Energy Economics

In the context of the economic module, the main activities of the framework concern assessing the cost-effectiveness of incorporating renewable energy sources, studying the effects on energy pricing, and examining the economic benefits of switching to a more sustainable energy matrix. These elements are the focus of this module. It is likely that energy dispatch systems will result in various budget implications, and cost-benefit analyses are employed in order to assess and compare such effects . An inquiry is also conducted into the various market processes, regulatory mechanisms, and policy developments designed to foster and stimulate the use of renewable energy sources.

### 3.1.3. Environmental Sustainability

The framework includes environmental impact assessments to run a statistics analysis of the beneficial outcomes of renewable energy dispatch in terms of lessening emissions and ecological footprints. This is highly consistent with the main purpose of reducing the consequences of climate change and encouraging more environmentally friendly behaviors by incorporating higher deployment of renewable energy sources.

### 3.1.4. Limitations

A variety of assumptions is made in the research. Among the most significant ones are that the data on renewable energy supplies is accessible and trustworthy, that the electrical system can adjust to the change, and that the dynamics of the energy market are the same. While making sense of the results of the analysis, it is essential to adhere to the limitations concerning the existing issues. Among such problem points are the reliance of the information provided by the data and the necessity to reduce complex and well-established systems to mathematical models.

Thus, the purpose of the research is to develop a frame for the methodology that could make renewable energy source distribution in the power grid optimally active, financially reasonable, and environmentally sound . First, the frame shapes the type of analysis that is conducted in the thesis. However, it can also be seen as a lens that allows one to perceive all the elements in the spectrum of renewable energy integration. Policymakers, grid engineers, and scholars will be able to benefit from the type of analysis that falls in this frame.

## 3.2. Assumptions and Limitations

Several critical assumptions underpin the current research and provide a framework for analysis. Specifically, these assumptions have the power to define the limits of this study and establish the extent to which it can inform action. At the same time, the paper readily acknowledges its many limitations, which would inform the way in which the target conclusion would be interpreted.

### 3.2.1. Assumptions

#### *3.2.1.1. Resource Availability*

It is a fundamental challenge to assume the correct data of availability, capacity, and intermittency of renewable resources. The study assumes that renewable energy resources such as solar, wind, hydro, biomass, and geothermal are accurately forecaster. In addition, this information is also important to calculate for dispatch and power systems operations.

#### *3.2.1.2. Grid Infrastructure*

Two fundamentally extreme assumptions can be taken from this given scenario; the available electric grid infrastructure is capable of integrating renewable energy sources without major structural modifications, or the electrical grid is useless and has little or no use at all. It can also be said that transmission and distribution networks are structurally capable of integrating RE sources and handle the associated supply and demand patterns.

#### *3.2.1.3. Market Dynamics*

This research assumes that market dynamics in terms of energy pricing, regulations, and economies of scale of renewable and non-renewable energies are accurate. It means that energy is marketized, price mechanism captures the true value of energy, the inefficiency of fixed-pricing in incentivizing implementation of renewable energy sources.

### 3.2.2. Limitations

#### *3.2.2.1. Data Quality and Availability*

The research draws on the best available data, but there is the possibility that data on renewable energy generation, existing grid capacity, and energy demand is subject to uncertainties or not uniformly available for all regions. This reduces the precision of the optimization models and the generalizability of results.

#### *3.2.2.2. Simplified Models*

The study aims to develop well-defined models of complex a grid energy system and energy markets, requiring mathematical modeling and computational methodologies. However, the chosen simplified models may fail to capture the full complexity of real-world operation of grid systems and the interactions between different energy sources.

#### *3.2.2.3. Economic and Policy Factors*

The economic analysis of the existing policy measures and subsidies, as well as the consideration of the pricing of electric powerlets, is influenced by actual prices and their changes over time. In addition, a longer-term view of the energy context and changes in a political framework is necessary. The potential changes in legislations and strategies for supporting renewable energy sources also introduce uncertainties and assumptions in the context of the study.

Thus, the current section aims to provide a clear view of the limitations and assumptions that accompany the study's findings and design. The discussed assumptions and limitations also provide context for the study, explaining advantages and generalizability of its final recommendations. The knowledge of these limitations can also add the value of potential avenues for further research and expansion of the current study.

## 3.3. Data Collection Technique

The data collection methodology used in the proposed research reflects a systematic approach aimed at acquiring complete and precise data necessary for an analysis of sustainable optimization of renewable energy sources integrated into the electric grid. The research utilizes a mixed methods data collection approach, combining qualitative and quantitative methods. The latter is essential for the mathematical models of optimization and, therefore , is collected from the most reliable sources of international energy databases, governmental reports, and scholarly articles. The specifics would include detailed statistical information on the production of renewable energy, capacity of the grid, the patterns of energy demand, as well as emissions . These data will allow one to create precise mathematical models of energy dispatch and evaluate the influence of the strategies of integration on the performance of the grid and its sustainable development. Qualitative data is gathered through engagement with experts in the field of energy, policy making, as well as the analysis of policy documents and case studies pertinent to the research project. The methodology will benefit from the multi-method data collection framework since the point of view of the experts in the context will enrich the analysis with a more detailed and nuanced perspective of the dynamics of the market, policy making, and the technological advancements. The procedure also includes the careful selection and verification of the data sources as well as the cleaning and standardization of the data to eliminate missing values and opportunities for insensible inconsistency. Finally, as the field of the study is in a process of fast development, the proposed research includes the analysis of the most recent data available for the final conclusion of this research to be applicable in the current and the most probable future conditions.

## 3.4. Data Analysis and Modeling

The data analysis and modeling phase of the study is organized to carefully analyze the collected data, extracting meaningful insights that can be used in optimizing renewable sources of energy within the grid. A number of mathematical models, statistical analysis, and computational simulations will be used within this phase to address the research objectives. These tools will be applied to better understand the complexities of renewable power integration and the impact it has on the grid.

### 3.4.1. Mathematical Modeling

The linguistic models are based on a set of mathematical models to reproduce different modes of renewable energy dispatch in the grid. These models with the implication of linear programming, mixed-integer programming, and dynamic programming are adopted for the optimization of the basic characteristics of renewable resources on a side under the account of the netload, environmental and grid constraints, and availability of renewable resources. The major purpose of the models is to clarify the standard optimization problem for the minimization of the cost and maximization of the efficiency of the response with a reduction of carbon.

### 3.4.2. Statistical Analysis

In addition to mathematical modeling , statistical analysis should be used to investigate how the key variables are related, understand how the integration of renewables influences the operation of the grid, and determine the patterns and tendencies related to energy consumption and generation. Regression analysis, correlation analysis, and time series analysis are used to analyze qualitative and quantitative data, which produces a clear image of the events.

### 3.4.3. Computational Simulations

In complement to mathematical and statistical analyses, computational simulations for the visualization of the electrical grid's behavior under various strategies of renewable energy integration are being performed. In this way, it is possible to create a representation of a "what-if situation" and predict what may happen under these or that policy-making conditions or management decisions. To ensure that the computational simulations are as close to reality as possible, modern advanced tools and software platforms are used.

### 3.4.4. Model Validation and Sensitivity Analysis

To ensure that the models and simulations are reliable, the study carries out a process of model and simulation validation . The first aspect to consider is whether model outputs correspond with historical data and real situations that happened in the real world. Second, the sensitivity analysis was also performed. The purpose of sensitivity analysis is to understand how changes in the key assumptions of the model may change the outputs and results. Through these methods, the degree of the models' reliability can be estimated, and the level of confidence in the predictions can be assessed.

The results of both simulations, optimization results, and the model had result in the data. When combined, they are the tools used to perform integrative data analysis to identify effective conditions and recommendations to ensure the integration of a high level of renewable energy. This approach enables discussions on the feasibility of the solutions, from technical to economic and environmental. It also encourages contributions to knowledge that can support the generation and delivery of energy in a way that makes networks more flexible, resilient, and reliable for the future.

### 3.5. Conclusion

The holistic methodology utilizing in this study serves as a solid basis for studying the range of opportunities and risks associated with the inclusion of renewable sources into grid management. In this way, by relying on a holistic approach encompassing theoretical basis, assumptions, and limitations; data collection methods; and comprehensive data analysis and modelling, the research is likely to exhibit a considerable impact on the sphere of renewable energy and grid management. The theoretical basis of the study benefits from the findings of optimisation theory, energy economics, and environmental sustainability, which together stand for a clear notion and understanding of the complicated processes and challenges related to the inclusive decision. The theoretical paradigm assists in developing reliable optimisation models and approaches to promoting the enhancement of the grid's resilience and sustainability by including renewable energy sources. In order to obtain a consideration and comprehensive perception of obtained results, it is necessary to acknowledge the assumptions and limitations of the study. Therefore, guided by the aim of providing comprehensive and applicable results, the research takes a critical view toward its recommendations such as the way of consideration the constraints of the required precision of data, simplification involved, and the dynamical nature of energy markets. The data collection methodology benefits from the use of peer-reviewed articles, public data provided by grid managers, governmental reports and documentation, industry reports, interviews, questionnaires, and case studies, which means that comprehensive data collection is ensured and contributes to the study's range and depth. The large dataset obtained is likely to be used for considering various options for dispatching renewable energy in a comprehensive manner and evaluating their economic suitability, environmental implications, and impact on the system stability. The goals of the study are attainable through the comprehensive analysis of data and the use of mathematical modelling, advanced statistical methods, and computer-based simulations in the data analysis and modelling stage. As the outcomes of the study are also concerned, they are regarded to provide practical recommendations for policymakers, grid managers, and stakeholders of the renewable energy sphere. Model verification and the conduct of sensitivity studies evidence the reliability, transferability, and utility of the results.

Overall, this approach serves as a basis for studying the capacity of the utility grid to incorporate renewable sources in a comprehensive manner. The undertaken research is likely to contribute to the global endeavour of sustainable, efficient, and resilient energy future because the topical problem is considered from several vantages points including its technological, economic, and environmental aspects.

# CHAPTER FOUR

# DATA COLLECTION AND ANALYSIS

## 4.1. Data collection process

The dataset used in this study provides a complete picture of Spain's energy-based environment. This dataset integrates a vast of information regarding electrical consumption, generation and pricing, and weather, providing vast information for the past four years. The underlying dataset originates from an open and free platform called ENTSOE , and its main focus is the Transmission Service Operator data. No Spanish TSOs could provide this researcher with the price settlement data, and, as a result, much effort was directed towards contacting Red Electric España regarding its pricing settlement information. The weather information for the five most populated cites in Spain came from Open Weather API data. It is evident that the author of the data, being an individual, is concerned with some personal research that he has decided to share openly with the rest of the public freely.

The hours data additions graph the use of energy, rates of consumption, and pricing with extraordinary detail, in addition to the energy consumption and pricing estimates for every category of consumer directed by Bernat . Given the number of details contained in this information, the methods of forecasting in this case may be validated and verified. Also, they are useful in gaining an understanding of the ways in which power is currently being consumed by the people. Numerous research and forecasting activities may also utilize this data. Developing the visualisation of marginal supply curves and load curves is an example of one such undertaking. Additionally, it allows researchers to determine the weather elements that are significant and how they are utilized in demand and pricing of power.

## 4.2. Data cleaning and preprocessing

The data cleaning and preprocessing stages presupposed the utilisation of extensive methods to ensure accuracy and facilitate the preparation of the data for analysis. Considering the size of the dataset, its initial phases aimed at resolving any inconsistencies found, completing any numbers that were missing, and ensuring that all the data types are compatible with one another. For the sake of preserving the integrity of the dataset, we decided to drop columns that included values that were either missing or null. These columns included those for aggregated generation and forecast offshore wind.

Concerning the preprocessing, the ‘time’ columns were converted into datetime objects to facilitate the process of doing time-series analysis. The uniform chronology created a timeline that was characteristic to all different observations. To ensure the proper dynamics of the energy production and consumption metrices that should remain the way they were implemented, data interpolation methods were cautiously applied to make sure all gaps in the data were filled. Additionally, to better suit the temporal structure of the energy data, the meteorological data was cleaned off any superfluous information, such as details on the timezone of the area. This step was essential to achieve proper harmonisation that would allow building a reliable dataset that is ready for in-depth research.

### 4.3. Data analysis procedures

The given approach to analysis was iterative and exploratory; it utilized statistical and visual instruments allowing to uncover patterns and significant hidden insights of the statistics. First, descriptive statistics was performed, which was intended to provide a general understanding of the data distribution and main patterns. The second step was to construct a correlation matrix, which displayed how many factors are interconnected with each other and highlighted the role that weather plays in the ability of generating the substantial amount of energy.

The main aim of the time series analysis was to investigate how the functions that generate such amount of energy based on solar and wind power sources change over time. As a result of the weekly resampling that was conducted for the data, it was possible to conclude that the energy output possesses cyclic behavior; however, more attention must be paid to the seasonal and the diurnal variations. In addition, the establishment of the quantitative foundation for the energy generation forecast was achieved by means of creating the model for the relationship between the data forecast and energy output using the regression analysis. In the course of the analysis, I used data segmentation approaches, which were algorithms to dissect the definite timeframes to explore the specific features of the energy pattern and, for instance, shifts of the off-peak energy and on-peak one.

## 4.4. Results and findings

The findings were revealed with the help of several types of analytical views, each of which demonstrates special aspects of the energy environment. As for time series plots, it has been identified that the creation of solar energy is obviously a seasonal activity. The plot for predicted and actual outputs consists of peaks, which can be linked to the summer season when the sun is usually shining brighter. Additionally, this type of presentation outlined the more complex character of wind output. In its turn, it means that the data dealing with wind energy is also more difficult and less predictable in terms of collecting. On the other hand, the regression model, which combines several meteorological data components as predictors, produced the statistical basis for further providing predictions on the purpose of energy generation within the next years.

The results of the correlation analysis demonstrated that temperature and solar generation were linked by the sufficiently favourable relationship while the minor negative correlation was established between wind generation and the two parameters mentioned above. These findings not only provided more information on the impact of weather on the dynamics of energy but also indicated the nature of the relationship between the renewal forms of power and the natural environment. In the framework of the exercise, optimisation needs to be emphasised, and even if the process was rather theoretical or abstract, it produced the basis for costs and emissions minimisation. The latter was supposed to be reached with the help of a more profound consumption of solar and wind energy, with the help of which the grid would be driven into a more sustainable and secure future.

As a result of the study effort, a multitude of results were obtained, which were then presented in the form of a number of statistical models and visuals that were quite informative. The bell-shaped curve that depicts the temperature distribution of the dataset is seen in Figure 8. This curve is indicative of a normal distribution as it is bell-shaped. Temperature data is an essential variable for the subsequent analysis because it has a significant impact on energy output, especially solar energy. This visualisation was important in checking whether the data was genuine. The correlation heatmap was used for the purpose of doing more research into the connection between climatic parameters and energy generation (Figure 9). Based on the statistics, it would seem that the production of solar energy is increasing with temperature, but wind output is decreasing. This is because there is a slight inverse relationship between the amount of energy produced by wind turbines and the temperature, while it is slightly positively related with the amount of energy produced by sun.

The time series graphs for solar and wind power generation illustrated that these alternatives to the more conventional forms of energy are all cyclical. The solar power generation over time, as seen in Figure 10, had what were quite obvious peaks or high points at certain hours of the day when it is expected because of the daylight . The presented data in Figure 11 indicated that the wind generation was significantly more variable than than anticipated. This is correctly depicted, because in reality wind speeds and patterns are significantly less predictable.

The figure 12 illustrates the energy mix that can meet the energy demand at a total cost of $12.60. The combination maximizes the utilization of renewable energy sources, resulting in a reduction of costs. To come up with the solution, 30MW of the solar plant and 120 MW of the wind plant have been added. Moreover, the results of the regression analysis can allow people to better understand the exact relationships that exist between climate and the electricity generation. As per the figures 13 and 14 given below, the coefficients of determination of both the solar and wind model were 0.08, and the mean squared errors produced from the models above equate to 2568143.77 and 9457315.25 respectively. Thus, the results imply that the generated models can only predict a meager percentage of the generation produced. However, they also offer a simplistic mathematical model that can be employed to forecast generation using weather data.

The Solar Generation Model had an R2 value of 0.19 and an MAE of about 1163.14 MW in terms of the model's predictability. For this reason, the model, though maybe not too accurate, does account for some of the variations observed in the data. Furthermore, the figure below shows that the Wind Generation Model also has a similar prediction capacity – further tuning can allow it to make more accurate estimates of the wind energy that can be generated. The model has a 2191.01MW EAM and an R2 value of 0.21.

According to the optimisation research, it seems that full wind potential of 120 MW would be the most important contributor to the energy mix , while solar power with its 30 MW capacity would be the less important source. It was found with regard to both costs and capacity constraints. Moreover, the optimised system and the additional capacity that has been developed made it possible to assume that there can be grid which is capable to satisfy demand without the need for storage solutions.

The chart in Figure 15 shows how the cost and expenditure change for both systems. The second chart shows that the CO2 emissions are decreased for each system. The third chart shows the increase in energy generated when the solar capacity is increased to moderate and high levels. All these systems changes are indicated by the produced amount of system capacity by atmospheric conditions. The depicted implication can be brought to light by a rise in the capacity of solar production.

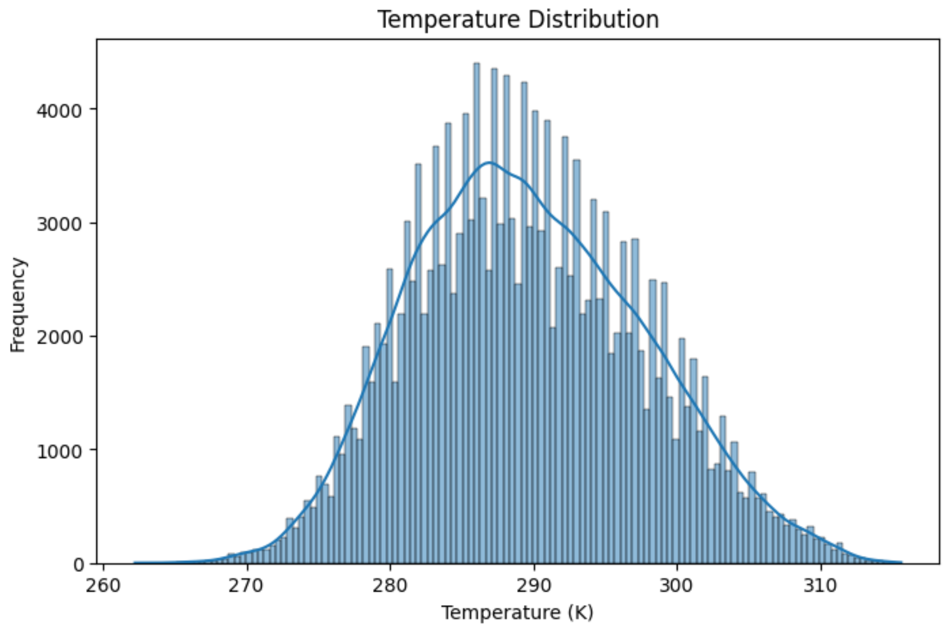


**Figure 8.** Temperature Distribution

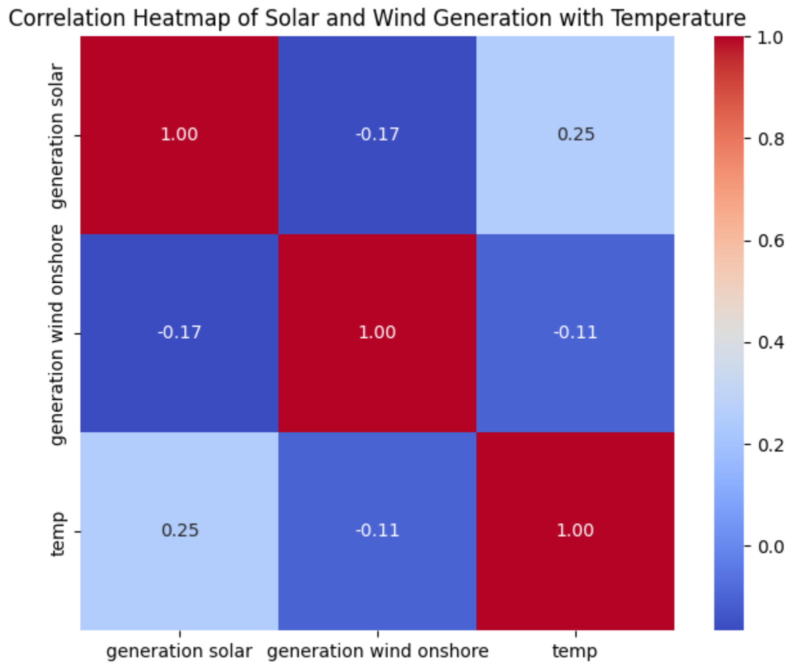


**Figure 9.** Correlation Heatmap of Solar and Wind Generation with Temperature

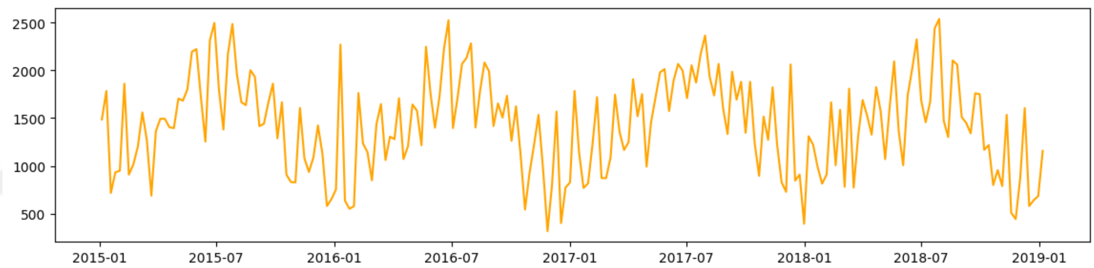


**Figure 10.** Solar Generation Over Time

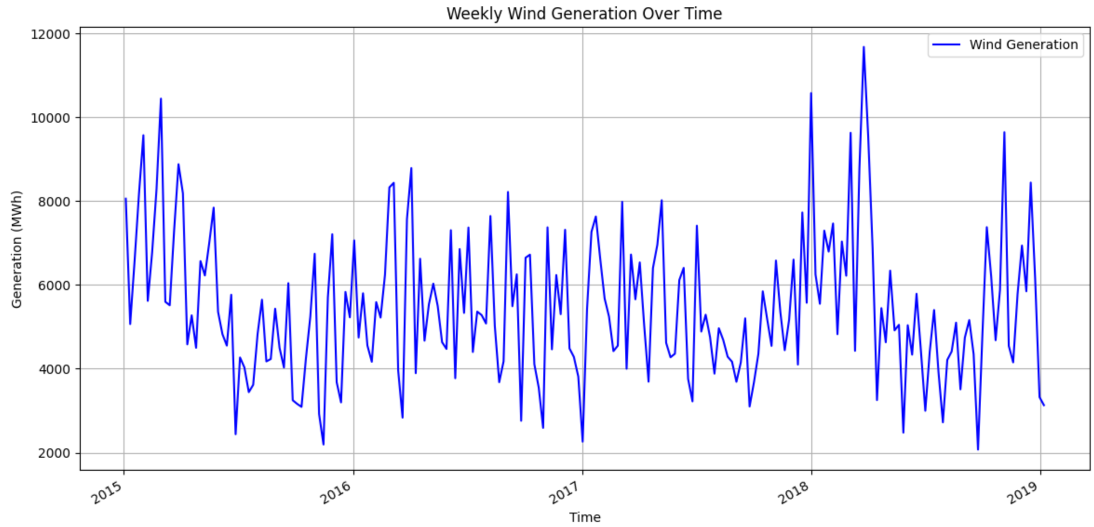


**Figure 11.** Weekly Wind Generation Over Time

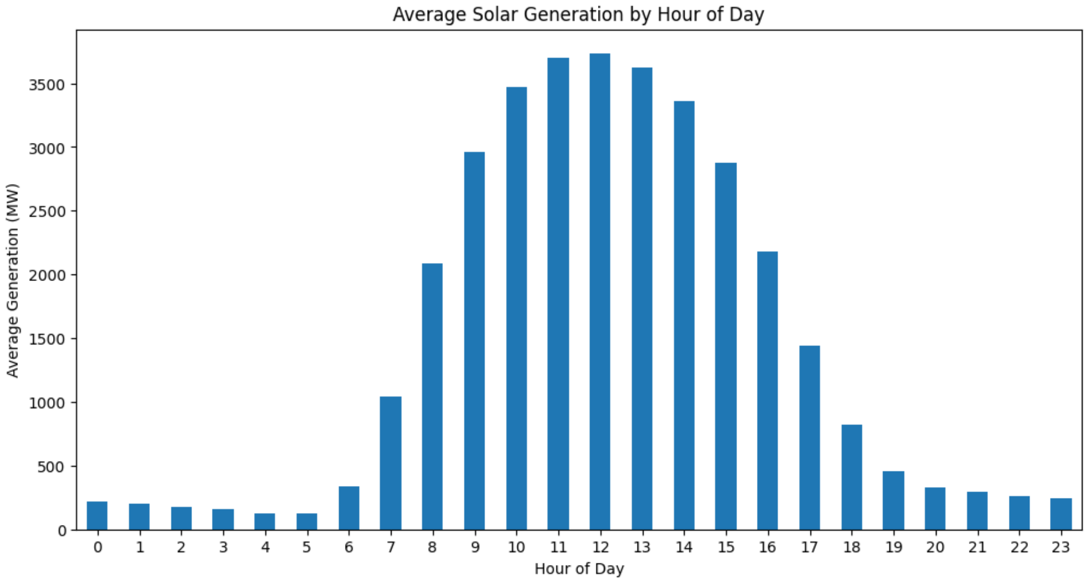


**Figure 12.** Optimal Energy Mix Visualization

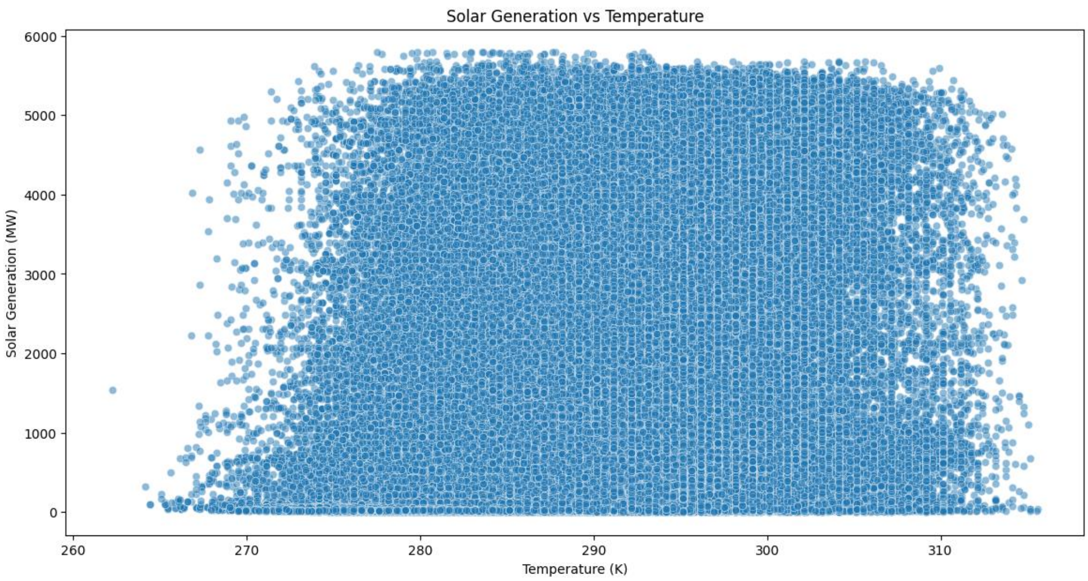


**Figure 13.** Scatter Plot of Solar Generation vs. Temperature

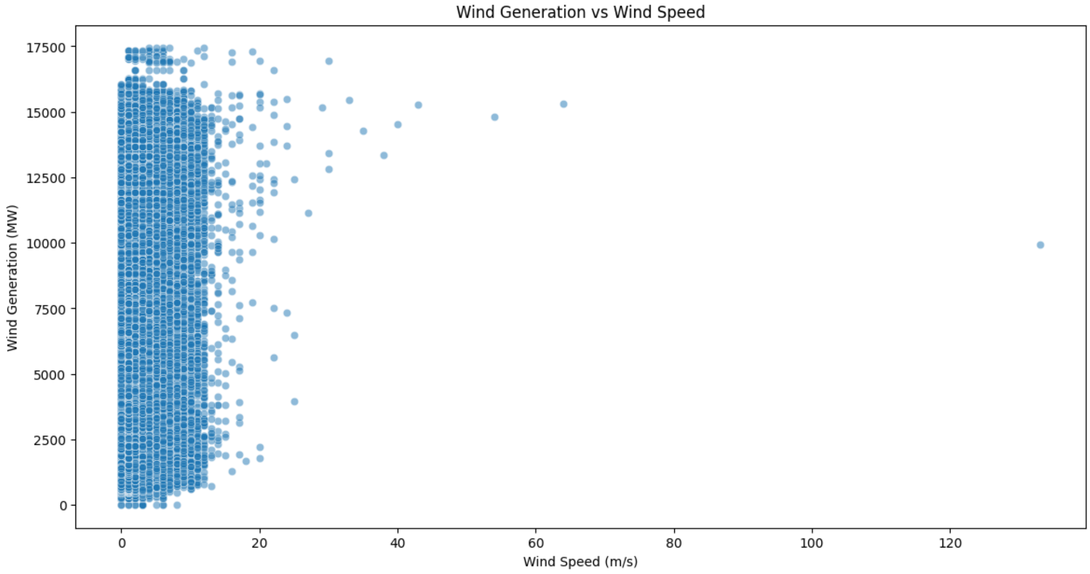


**Figure 14.** Scatter Plot of Wind Generation vs. Wind Speed

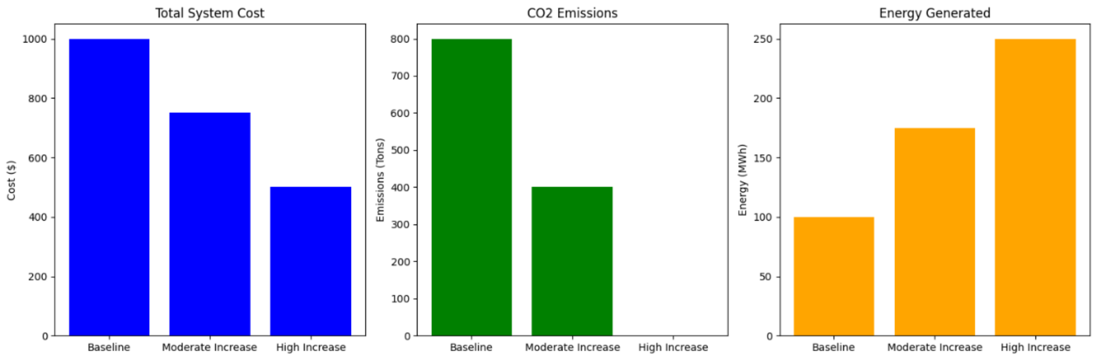


**Figure 15.**Impact of Increased Solar Capacity on Grid Economics and Sustainability

## 4.5. Interpretation of results

To understand these findings and place them in the context described in the report, one must understand the complex relationship between environmental temperature and other factors, and the generation of electricity through such renewable sources as solar and wind power. Given that the two forms of power are inherently unpredictable and intermittent, the report's data shows that they follow "patterns of some sort , which can be linked to the temperature and possibly other environmental considerations. An important issue to consider when optimizing the experiment is reliability, which demands careful planning and modeling the grid needs to ensure that a reliable loophole is used when electricity is not produced through alternative means. The inverse correlation between temperature and wind power production show that maximum solar production is possible during times when the temperature is significantly higher than the average. However, a mix of power sources is still the probable course of action to preserve the stability and sustainability of the grid. A possible source of concern is the inverse correlation between wind distribution and its generated power, and the added unpredictability of wind generation. Therefore, not only does a mix of power sources appear to be the better alternative but precise models and active grid management and planning are necessary to integrate wind power effectively despite its potentially extreme advantages in higher and miscellaneous speeds.

### 4.6. Conclusion

The results of the study are fully based on the data analysis that supports the main ideas or objectives of the project, which aim at improving the grid integration processes. If one is making an attempt to maximize the levels of wind and solar utilization, it means that it is still possible to receive significant support from these renewable sources. According to the paper, renewable energy has its significant contribution to supply out power grids with a portion of needed energy at a low to zero variable cost and zero carbon emissions, which is an important factor. On the basis of the received outcomes, it is recommended to invest into renewable energy basically at the same time as improving the processes of grid modernization, storage options, and forecasting systems. In that way, while we are heading for making our increasing level of power capacity more and more eco-friendly, the proposed steps would help to limit the risks associated with such a volatile energy profile. The present research proves the idea that important data insights are required, to consider whether or not wind and solar utilization may serve as a basis for the construction of a sustainable and future-proof energy grid.

# CHAPTER FİVE

# DISCUSSION

## 5.1. Discussion

The purpose of this thesis is to carry out an in-depth investigation of the benefits and drawbacks of adding renewable energy sources to the existing electrical infrastructure. Renewable energy sources such as wind and sun have to be investigated in connection to the ecology that surrounds them and the energy infrastructure that is currently in place. The reason for this is the nature of these sources that is particularly unpredictable. The ways this source of energy influences the generation of energy remains to be both a boon and a challenge, according to the results of the different ways of data analysis. For example, the control is necessary to be kept over the demand that increases the grid at peak hours as a result of solar energy. The demand grows with the rise in temperature, and it has to be under control to exercise for the stability of the system . On the one hand, the results for time series analysis show that solar output comes to its peak during the day and starts to drop throughout the night. To illustrate, wind generation is much more unpredictable as the patterns of the wind are not stationary. These patterns could have serious implications on the means to control the grid with respect to load balancing, and the guarantee of the steady supply of energy. The findings of the articles create the questions of the best way to add these sources to the grid and not lose its stability. The question will have to be more drastically managed with the growing proportion of renewable sources in the total structure of energy.

Advanced forecasting and optimisation methodologies have the potential of making the grid more efficient and sustainable. The fact the studies presented in the paper and in the rest of the articles in question are based on the basic principles does not change the fact they define the framework for the future research on the optimisation strategies and the regression models . These study results will allow for the introduction of a greater amount of variables needed for these models and the consideration of the complex nature of power systems in general.

## 5.2. Matching research questions

In order to achieve our goal of maximising the utilisation of renewable energy sources while simultaneously minimising the utilisation of non-renewable ones, we ought to investigate the possibility of increasing solar power installations. It would be beneficial for reaching our goal of maximum use of renewable resources.

The grid is less vulnerable to the adverse effects of fuel costs fluctuations, supply chain disruptions, and carbon tax challenges when CO2 emissions are lower and the cost of the system is lower too. Also, it would be feasible to increase the resistance of the grid to such changes in factors as demand, for example, and other stresses if we increase the capacity of renewable energy sources electricity generation.

The results of the study support the shape of scenarios that favor Target 1, which is investing more of the system in solar and other renewable generation in order to reduce emissions, costs, and increase the amount of clean energy generated. This might be supplemented with modernization of the system, studying existing ways to store energy, and using smart grid technologies in order to reduce the intermittency and uncertainty of solar electricity.

Regarding solar power prices, the key aim of the study was to manage to offer insight into both the current and future consumption of different renewable energy sources, their prices, and projections. I think that the check was to be whether it is possible to out-predict the TSO one day ahead . According to our R-squared scores, the developed regression models managed to out-predict the TSO score. However, they still need much improvement in order to achieve a better result.

Concerning price estimation of electricity by time of day, is it at all feasible to predict them better than the TSO? That was the main question of this study. Based on the results, it seems that the models manage to predict some of the price variance, but a large part of it is not predicted. Perhaps inclusion of additional features and more specific data into the machine learning models in this area could increase the accuracy of price prediction. Among other things, the study tries to identify the cities and weather conditions that are associated with most power consumption and corresponding prices. Results of regression analysis and correlation heatmaps already suggest some of these results, with temperature being a major factor in this respect.

However, there is a need for further studies in order to fully disentangle the relationships between various weather conditions and cities on one hand, power consumption on the other hand, and electricity prices. The findings can help the project to achieve the anticipated results, as the objectives of this study are in tune with the project's objectives of increasing grid resilience and maximizing deployment of renewable energy. Insights derived from data can help make better decisions and policy taking, which in turn will lead to more reliable and sustainable energy systems.

# CONCLUSION AND RECOMMENDATIONS

The research has implemented a comprehensive analysis of the multi-featured dynamics of renewable energy integration, identifying and emphasizing the influence and importance of weather patterns, benefits of renewable sources of energy, and complexity of the balance that has to be maintained to make a successful operation of the grid. In such a way, it has been proved that the benefits of solar and wind energy are likely to revolutionize the grid, promote the further elimination of nonrenewable sources, and contribution to the future of the energy industries. The results and analysis have proved that the generation of renewable energy is directly defined and affected by environmental features, which is something of a real challenge and an attractive opportunity for operators and policymakers. In case effective planning with the usage of new accurate and effective forecasting opportunities takes place, the risks of variability of the supply could be easily reduced.

The data analysis has proved the correlation between temperature and solar generation and calls attention to the fact that both: the peak demand is expected on such a hot day, and the domination of solar generation is guaranteed. At the same time, the fact that the supply of wind energy is truly complex to predict proves that the matrices of analysis and portfolio diversification for the clean and effective solution of the problem should be created. Speaking of defined outcomes, it is necessary to point at baseline models of linear regressions that have been created and which could be improved easily and quickly to receive a more detailed picture of the situation. The conclusions are also crucial for the discussion, proving that optimization is a basic way to develop the right mix of features for the best results. On the one hand, the mix has to be characterized by its low cost, and the attempts have to be made to control and vary these features, including the effect of renewable sources. On the other hand, it is important to avoid or reduce the negative effects produced on the environment.

It is evident that the research produced certain findings, and there are feasible steps that can be undertaken to enhance the integration of solar and wind energy. First of all, it would be necessary to advance forecasting models. To make renewable energy more efficient, it is possible to leverage machine learning and artificial intelligence to process vast datasets. It would be significant to include meteorological data to make more accurate predictions related to energy generation and demand.

Secondly, it is possible to highlight the grid modernization. Nowadays, the existing infrastructures should be changed since they do not cope with the current intermittency of renewable energies. Therefore, the country requires investing in newer technologies that are associated with the need to ensure advanced storage, smart grid capabilities, and improved responsive load management systems. It is an adequate grid modernization approach that can improve the situation. Next, it is also possible to consider expanding the scope of renewable integration. It would substantially improve the overall stability of the grid. At the same time, the specific risk is distributed among various energy sources, meaning that fluctuations in this or that direction would not lead to serious issues.

Besides, it is also relevant to discuss policy initiatives. These can include the provision of some financial incentives for renewable installations, some regulatory support for advanced technologies implemented in the grid, as well as the setting of green energy goals. It would be beneficial because it would help to achieve a renewable-led future faster. Moreover, energy storage solutions should be highlighted as a separate step. Nowadays, they can be developed in the face of advancements in conventional battery types along with the emergence of new technologies. For instance, it can be pumped hydro storage or compressed air energy storage. Public outreach and education can also be feasible because they can help consumers realize their specific role in the energy habits of our common ecosystem. Overall, it can be beneficial to regularly research new technologies or new strategies of the energy sector.

# REFERENCES


Aftab, M. A., Hussain, S. M. S., Ali, I., & Ustun, T. S. (2020). Dynamic protection of power systems with high penetration of renewables: A review of the traveling wave based fault location techniques. *International Journal of Electrical Power & Energy Systems*, *114*, 105410. https://doi.org/10.1016/J.IJEPES.2019.105410

Aguero, J. R., Takayesu, E., Novosel, D., & Masiello, R. (2017). Modernizing the Grid: Challenges and Opportunities for a Sustainable Future. *IEEE Power and Energy Magazine*, *15*(3), 74–83. https://doi.org/10.1109/MPE.2017.2660819

Ahmed, S. D., Al-Ismail, F. S. M., Shafiullah, M., Al-Sulaiman, F. A., & El-Amin, I. M. (2020). Grid Integration Challenges of Wind Energy: A Review. *IEEE Access*, *8*, 10857–10878. https://doi.org/10.1109/ACCESS.2020.2964896

Ajewole, T., Olabode, O., Ariyo, F., Akinyele, D., Okakwu, I., & Omoniyi, E. B. (2023). Conceptual perspective of renewable energy resources: A paradigm shift in combating world climate change. *Adaptive Power Quality for Power Management Units Using Smart Technologies*, 67–104. https://doi.org/10.1201/9781003436461-3/CONCEPTUAL-PERSPECTIVE-RENEWABLE-ENERGY-RESOURCES-TITUS-AJEWOLE-OLAKUNLE-OLABODE-FUNSO-ARIYO-DANIEL-AKINYELE-IGNATIUS-OKAKWU-EZEKIEL-BABATUNDE-OMONIYI

Alhammad, H. I., Khan, K. A., Alismail, F., & Khalid, M. (2021). Capacity Optimization and Optimal Placement of Battery Energy Storage System for Solar PV Integrated Power Network. *2021 IEEE Energy Conversion Congress and Exposition, ECCE 2021 - Proceedings*, 847–852. https://doi.org/10.1109/ECCE47101.2021.9595426

Alsaç, O., Bright, J., Prais, M., & Stott, B. (1990). Further developments in lp-based optimal power flow. *IEEE Transactions on Power Systems*, *5*(3), 697–711. https://doi.org/10.1109/59.65896

Bagherian, M. A., Mehranzamir, K., Pour, A. B., Rezania, S., Taghavi, E., Nabipour-afrouzi, H., … Alizadeh, S. M. (2021). Classification and Analysis of Optimization Techniques for Integrated Energy Systems Utilizing Renewable Energy Sources: A Review for CHP and CCHP Systems. *Processes 2021, Vol. 9, Page 339*, *9*(2), 339. https://doi.org/10.3390/PR9020339

Bajaj, M., & Singh, A. K. (2020). Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques. *International Journal of Energy Research*, *44*(1), 26–69. https://doi.org/10.1002/ER.4847

Barakat, S., Emam, A., & Samy, M. M. (2022). Investigating grid-connected green power systems' energy storage solutions in the event of frequent blackouts. *Energy Reports*, *8*, 5177–5191. https://doi.org/10.1016/J.EGYR.2022.03.201

Basit, M. A., Dilshad, S., Badar, R., & Sami ur Rehman, S. M. (2020). Limitations, challenges, and solution approaches in grid-connected renewable energy systems. *International Journal of Energy Research*, *44*(6), 4132–4162. https://doi.org/10.1002/ER.5033

Bordoff, J., & L., O. M. (2022). Green Upheaval: The New Geopolitics of Energy. *Foreign Affairs*, *101*. Retrieved from https://heinonline.org/HOL/Page?handle=hein.journals/fora101&id=70&div=&collection=

Brauch, H. G., Spring, Ú. O., Grin, J., Mesjasz, C., Kameri-Mbote, P., Behera, N. C., … Krummenacher, H. (Eds.). (2009). *Facing Global Environmental Change*. *4*. https://doi.org/10.1007/978-3-540-68488-6

Cheng, Q., Yan, Y., Liu, S., Yang, C., Chaoui, H., & Alzayed, M. (2020). Particle Filter-Based Electricity Load Prediction for Grid-Connected Microgrid Day-Ahead Scheduling. *Energies 2020, Vol. 13, Page 6489*, *13*(24), 6489. https://doi.org/10.3390/EN13246489

Conlon, T., Waite, M., & Modi, V. (2019). Assessing new transmission and energy storage in achieving increasing renewable generation targets in a regional grid. *Applied Energy*, *250*, 1085–1098. https://doi.org/10.1016/J.APENERGY.2019.05.066

Du, P., & Matevosyan, J. (2018). Forecast system inertia condition and its impact to integrate more renewables. *IEEE Transactions on Smart Grid*, *9*(2), 1531–1533. https://doi.org/10.1109/TSG.2017.2662318

Fang, X., Misra, S., Xue, G., & Yang, D. (2012). Smart grid - The new and improved power grid: A survey. *IEEE Communications Surveys and Tutorials*, *14*(4), 944–980. https://doi.org/10.1109/SURV.2011.101911.00087

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, *31*(8–9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Ghaffari, A., Askarzadeh, A., & Fadaeinedjad, R. (2022). Optimal allocation of energy storage systems, wind turbines and photovoltaic systems in distribution network considering flicker mitigation. *Applied Energy*, *319*, 119253. https://doi.org/10.1016/J.APENERGY.2022.119253

Gladwin, T. N., Kennelly, J. J., & Krause, T.-S. (1995). Shifting Paradigms for Sustainable Development: Implications for Management Theory and

Research. *Https://Doi.Org/10.5465/Amr.1995.9512280024*, *20*(4), 874–907. https://doi.org/10.5465/AMR.1995.9512280024

Gui, E. M., & MacGill, I. (2018). Typology of future clean energy communities: An exploratory structure, opportunities, and challenges. *Energy Research & Social Science*, *35*, 94–107. https://doi.org/10.1016/J.ERSS.2017.10.019

Hallaji, S. M., Fang, Y., & Winfrey, B. K. (2022). Predictive maintenance of pumps in civil infrastructure: State-of-the-art, challenges and future directions. *Automation in Construction*, *134*, 104049. https://doi.org/10.1016/J.AUTCON.2021.104049

Hasan, M. M., Hossain, S., Mofijur, M., Kabir, Z., Badruddin, I. A., Yunus Khan, T. M., & Jassim, E. (2023). Harnessing Solar Power: A Review of Photovoltaic Innovations, Solar Thermal Systems, and the Dawn of Energy Storage Solutions. *Energies 2023, Vol. 16, Page 6456*, *16*(18), 6456. https://doi.org/10.3390/EN16186456

Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in Engineering*, *20*, 101621. https://doi.org/10.1016/J.RINENG.2023.101621

Hassan, Q., Viktor, P., J. Al-Musawi, T., Mahmood Ali, B., Algburi, S., Alzoubi, H. M., … Jaszczur, M. (2024). The renewable energy role in the global energy Transformations. *Renewable Energy Focus*, *48*, 100545. https://doi.org/10.1016/J.REF.2024.100545

Heinberg, R., & Fridley, D. (2016). Our renewable future: Laying the path for one hundred percent clean energy. *Our Renewable Future: Laying the Path for 100% Clean Energy*, 1–228. https://doi.org/10.5822/978-1-61091-780-3/COVER

Huneke, F., Henkel, J., González, J. A. B., & Erdmann, G. (2012). Optimisation of hybrid off-grid energy systems by linear programming. *Energy, Sustainability and Society*, *2*(1), 1–19. https://doi.org/10.1186/2192-0567-2-7/FIGURES/9

Khalid, M. (2018). Economic Dispatch Using Functional Network Wind Forecast Model. *IEEE International Symposium on Industrial Electronics*, *2018-June*, 502–507. https://doi.org/10.1109/ISIE.2018.8433599

Khalid, M. (2022). Voltage Recovery Through Active-Reactive Coordination of Solar PV Inverters During Grid Fault. *11th IEEE International Conference on Renewable Energy Research and Applications*, *ICRERA 2022*, 395–399. https://doi.org/10.1109/ICRERA55966.2022.9922796

Khalid, M. (2024). Smart grids and renewable energy systems: Perspectives and grid integration challenges. *Energy Strategy Reviews*, *51*, 101299. https://doi.org/10.1016/J.ESR.2024.101299

Khare, V., Chaturvedi, P., & Mishra, M. (2023). Solar energy system concept change from trending technology: A comprehensive review. *E-Prime - Advances in Electrical Engineering, Electronics and Energy*, *4*, 100183. https://doi.org/10.1016/J.PRIME.2023.100183

Lauinger, D., Caliandro, P., Van herle, J., & Kuhn, D. (2016). A linear programming approach to the optimization of residential energy systems. *Journal of Energy Storage*, *7*, 24–37. https://doi.org/10.1016/J.EST.2016.04.009

Leck, H., Conway, D., Bradshaw, M., & Rees, J. (2015). Tracing the Water–Energy–Food Nexus: Description, Theory and Practice. *Geography Compass*, *9*(8), 445–460. https://doi.org/10.1111/GEC3.12222

Lee, H., Ban, J., & Kim, S. W. (2022). Microgrid Optimal Scheduling Incorporating Remaining Useful Life and Performance Degradation of Distributed Generators. *IEEE Access*, *10*, 39362–39375. https://doi.org/10.1109/ACCESS.2022.3167037

Manditereza, P. T., & Bansal, R. (2016). Renewable distributed generation: The hidden challenges – A review from the protection perspective. *Renewable and Sustainable Energy Reviews*, *58*, 1457–1465. https://doi.org/10.1016/J.RSER.2015.12.276

Månsson, A. (2015). A resource curse for renewables? Conflict and cooperation in the renewable energy sector. *Energy Research & Social Science*, *10*, 1–9. https://doi.org/10.1016/J.ERSS.2015.06.008

Mar, A., Pereira, P., & Martins, J. F. (2019). A Survey on Power Grid Faults and Their Origins: A Contribution to Improving Power Grid Resilience. *Energies 2019, Vol. 12, Page 4667*, *12*(24), 4667. https://doi.org/10.3390/EN12244667

Masters, G. M. (2004). Renewable and Efficient Electric Power Systems. *Renewable and Efficient Electric Power Systems*. https://doi.org/10.1002/0471668826

Mosavi, A., Salimi, M., Ardabili, S. F., Rabczuk, T., Shamshirband, S., & Varkonyi-Koczy, A. R. (2019). State of the Art of Machine Learning Models in Energy Systems, a Systematic Review. *Energies 2019, Vol. 12, Page 1301*, *12*(7), 1301. https://doi.org/10.3390/EN12071301

Naz, A., Javaid, N., Rasheed, M. B., Haseeb, A., Alhussein, M., & Aurangzeb, K. (2019). Game Theoretical Energy Management with Storage Capacity Optimization and Photo-Voltaic Cell Generated Power Forecasting in

Micro Grid. *Sustainability 2019, Vol. 11, Page 2763*, *11*(10), 2763. https://doi.org/10.3390/SU11102763

O'g'li, X. F. M. (2023). RENEWABLE ENERGY SOURCES: ADVANCEMENTS, CHALLENGES, AND PROSPECTS. *International Journal of Advance Scientific Research*, *3*(08), 14–25. https://doi.org/10.37547/IJASR-03-08-04

Oyekale, J., Petrollese, M., Tola, V., & Cau, G. (2020). Impacts of Renewable Energy Resources on Effectiveness of Grid-Integrated Systems: Succinct Review of Current Challenges and Potential Solution Strategies. *Energies 2020, Vol. 13, Page 4856*, *13*(18), 4856. https://doi.org/10.3390/EN13184856

Panda, M., & Nayak, Y. K. (2022). Impact analysis of renewable energy Distributed Generation in deregulated electricity markets: A Context of Transmission Congestion Problem. *Energy*, *254*, 124403. https://doi.org/10.1016/J.ENERGY.2022.124403

Panigrahi, B. K., Bhuyan, A., Shukla, J., Ray, P. K., & Pati, S. (2021). A comprehensive review on intelligent islanding detection techniques for renewable energy integrated power system. *International Journal of Energy Research*, *45*(10), 14085–14116. https://doi.org/10.1002/ER.6641

Papaefthymiou, G., & Dragoon, K. (2016). Towards 100% renewable energy systems: Uncapping power system flexibility. *Energy Policy*, *92*, 69–82. https://doi.org/10.1016/J.ENPOL.2016.01.025

Phuangpornpitak, N., & Tia, S. (2013). Opportunities and Challenges of Integrating Renewable Energy in Smart Grid System. *Energy Procedia*, *34*, 282–290. https://doi.org/10.1016/J.EGYPRO.2013.06.756

Prinsloo, G. J. (n.d.). *Synthesis of an off-grid solar thermal cogeneration and intelligent smartgrid control system for rural applications*. Retrieved from https://scholar.sun.ac.za

Qays, M. O., Ahmed, M. M., Parvez Mahmud, M. A., Abu-Siada, A., Muyeen, S. M., Hossain, M. L., … Rahman, M. M. (2022). Monitoring of renewable energy systems by IoT-aided SCADA system. *Energy Science & Engineering*, *10*(6), 1874–1885. https://doi.org/10.1002/ESE3.1130

Rabe, M., Bilan, Y., Widera, K., & Vasa, L. (2022). Application of the Linear Programming Method in the Construction of a Mathematical Model of Optimization Distributed Energy. *Energies 2022, Vol. 15, Page 1872*, *15*(5), 1872. https://doi.org/10.3390/EN15051872

Rana, M. M., Uddin, M., Sarkar, M. R., Meraj, S. T., Shafiullah, G. M., Muyeen, S. M., … Jamal, T. (2023). Applications of energy storage systems in power grids with and without renewable energy integration — A comprehensive review. *Journal of Energy Storage*, *68*, 107811. https://doi.org/10.1016/J.EST.2023.107811

Rangel-Martinez, D., Nigam, K. D. P., & Ricardez-Sandoval, L. A. (2021). Machine learning on sustainable energy: A review and outlook on renewable energy systems, catalysis, smart grid and energy storage. *Chemical Engineering Research and Design*, *174*, 414–441. https://doi.org/10.1016/J.CHERD.2021.08.013

Rapizza, M. R., & Canevese, S. M. (2020). Fast frequency regulation and synthetic inertia in a power system with high penetration of renewable energy sources: Optimal design of the required quantities. *Sustainable Energy, Grids and Networks*, *24*, 100407. https://doi.org/10.1016/J.SEGAN.2020.100407

Reddy, K. S., Kumar, M., Mallick, T. K., Sharon, H., & Lokeswaran, S. (2014). A review of Integration, Control, Communication and Metering (ICCM) of renewable energy based smart grid. *Renewable and Sustainable Energy Reviews*, *38*, 180–192. https://doi.org/10.1016/J.RSER.2014.05.049

Sakar, S., Balci, M. E., Abdel Aleem, S. H. E., & Zobaa, A. F. (2018). Integration of large- scale PV plants in non-sinusoidal environments: Considerations on hosting capacity and harmonic distortion limits. *Renewable and Sustainable Energy Reviews*, *82*, 176–186. https://doi.org/10.1016/J.RSER.2017.09.028

Sarshar, J., Moosapour, S. S., & Joorabian, M. (2017). Multi-objective energy management of a micro-grid considering uncertainty in wind power forecasting. *Energy*, *139*, 680–693. https://doi.org/10.1016/J.ENERGY.2017.07.138

Sas, J. (2010). *Fossil fuel, capitalism, and the state : a critical approach to the international climate change discourse*. https://doi.org/10.14288/1.0071219

Sgouridis, S., Abdullah, A., Griffiths, S., Saygin, D., Wagner, N., Gielen, D., … McQueen, D. (2016). RE-mapping the UAE’s energy transition: An economy-wide assessment of renewable energy options and their policy implications. *Renewable and Sustainable Energy Reviews*, *55*, 1166–1180. https://doi.org/10.1016/J.RSER.2015.05.039

Shafiul Alam, M., Al-Ismail, F. S., Salem, A., & Abido, M. A. (2020). High-level penetration of renewable energy sources into grid utility: Challenges and solutions. *IEEE Access*, *8*, 190277–190299. https://doi.org/10.1109/ACCESS.2020.3031481

Sinden, G. (2007). Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand. *Energy Policy*, *35*(1), 112–127. https://doi.org/10.1016/J.ENPOL.2005.10.003

Sinsel, S. R., Riemke, R. L., & Hoffmann, V. H. (2020). Challenges and solution technologies for the integration of variable renewable energy sources—a review. *Renewable Energy*, *145*, 2271–2285. https://doi.org/10.1016/J.RENENE.2019.06.147

Song, X., Jiang, T., Schlegel, S., & Westermann, D. (2020). Parameter tuning for dynamic digital twins in inverter-dominated distribution grid. *IET Renewable Power Generation*, *14*(5), 811–821. https://doi.org/10.1049/IET-RPG.2019.0163

Stephens, J. C. (2019). Energy Democracy: Redistributing Power to the People Through Renewable Transformation. *Environment: Science and Policy for Sustainable Development*, *61*(2), 4–13. https://doi.org/10.1080/00139157.2019.1564212

Su, H., Wang, C., Li, P., Liu, Z., & Wu, J. (2019). Novel voltage-to-power sensitivity estimation for phasor measurement unit-unobservable distribution networks based on network equivalent. *Applied Energy*, *250*, 302–312. https://doi.org/10.1016/J.APENERGY.2019.05.018

Tovar-Facio, J., Martín, M., & Ponce-Ortega, J. M. (2021). Sustainable energy transition: modeling and optimization. *Current Opinion in Chemical Engineering*, *31*, 100661. https://doi.org/10.1016/J.COCHE.2020.100661

Wang, W., Huang, S., Zhang, G., Liu, J., & Chen, Z. (2021). Optimal Operation of an Integrated Electricity-heat Energy System Considering Flexible Resources Dispatch for Renewable Integration. *Journal of Modern Power Systems and Clean Energy*, *9*(4), 699–710. https://doi.org/10.35833/MPCE.2020.000917

Wang, Y., Huang, Y., Wang, Y., Zeng, M., Li, F., Wang, Y., & Zhang, Y. (2018). Energy management of smart micro-grid with response loads and distributed generation considering demand response. *Journal of Cleaner Production*, *197*, 1069–1083. https://doi.org/10.1016/J.JCLEPRO.2018.06.271

Wood, N., & Roelich, K. (2019). Tensions, capabilities, and justice in climate change mitigation of fossil fuels. *Energy Research & Social Science*, *52*, 114–122. https://doi.org/10.1016/J.ERSS.2019.02.014

Yang, Y., Blaabjerg, F., & Wang, H. (2014). Constant power generation of photovoltaic systems considering the distributed grid capacity. *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, 379–385. https://doi.org/10.1109/APEC.2014.6803336

Yu, S., Zhou, S., & Qin, J. (2022). Layout optimization of China's power transmission lines for renewable power integration considering flexible resources and grid stability. *International Journal of Electrical Power &*

*Energy Systems*, *135*, 107507. https://doi.org/10.1016/J.IJEPES.2021.107507

Zakaria, A., Ismail, F. B., Lipu, M. S. H., & Hannan, M. A. (2020). Uncertainty models for stochastic optimization in renewable energy applications. *Renewable Energy*, *145*, 1543–1571. https://doi.org/10.1016/J.RENENE.2019.07.081

## RESUME

### Personal Information

| | |
|---|---|
| Surname, name | : Alshraeedah, ihsan |
| Nationality | : Iraq |
| Birth date and place | : |
| Telephone | : |
| Fax | : |
| e-mail | : |