# An Optimal Controller Based Energy Balancing System in a Renewable Energy Integrated Smart Grid

*By*

ABC

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# An Optimal Controller Based Energy Balancing System in a Renewable Energy Integrated Smart Grid

A Thesis Presented to

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# An Optimal Controller Based Energy Balancing System in a Renewable Energy Integrated Smart Grid

A Post Graduate Thesis submitted to the Department of Electrical Engineering as partial fulfillment of the requirement for the award of Degree of MSc in "An Optimal Controller Based Energy Balancing System in a Renewable Energy Integrated Smart Grid".

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# DEDICATION

I dedicate my thesis to my parents for their endless love, encouragement and support throughout my education. I hope this helps me fulfill my dreams in the future.

# ACKNOWLEDGEMENTS

I would like to acknowledge and give my sincere thanks to my supervisor Dr. Imran khan who made this work possible. His guidance and advice made me pushed harder and made this possible to finish my thesis.

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**ABC & 12345**

# ABSTRACT

## Title: “An Optimal Controller Based Energy Balancing System in a Renewable Energy Integrated Smart Grid”

The dynamic evolution of modern energy markets calls for innovative approaches to ensure efficient energy utilization and balance. This study explores the application of Proportional-Integral-Derivative (PID) control in shaping energy pricing dynamics and maintaining equilibrium in multi-source energy markets. Through comprehensive simulations and analyses, this research investigates the effectiveness, robustness, and potential of PID-controlled energy price regulation. The simulation results provide a nuanced understanding of PID-controlled energy price regulation's performance across various scenarios. One simulation delves into reducing reliance on traditional power resources by integrating renewable energy sources. The PID controller adapts energy prices in real-time to encourage efficient energy consumption while balancing renewable and conventional generation sources. The results demonstrate the potential for PID control to drive renewable energy utilization and promote sustainable energy practices. Another simulation focuses on optimizing controller performance to ensure energy balance. The PID controller efficiently adjusts energy prices based on demand-supply dynamics, maintaining stability even during peak demand fluctuations. The findings underscore the role of PID control in mitigating imbalances and enhancing overall grid resilience. The study further examines the robustness of PID-controlled energy pricing by simulating peak and dip alterations in consumer demand. The PID controller responds adeptly, increasing prices during demand peaks and reducing them during dips, ensuring energy balance and uninterrupted supply. These results highlight the adaptability and reliability of PID-controlled energy price regulation. The research concludes with recommendations for real-world implementation, technological innovation, policy support, consumer engagement, collaborative research, and environmental considerations. It emphasizes the transformative potential of PID-controlled energy price regulation in creating a responsive, sustainable, and balanced energy ecosystem.

**Keywords:** PID control, energy balance, renewable energy integration, demand response, smart grid, SolidWorks, MATLAB

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| PID | Proportional-Integral-Derivative |
| RES | Renewable energy sources |
| DE | Decentralized energy |
| CHP | Combined Heat and Power |
| LLP | Linear programming |
| GWO | Grey Wolf Optimization |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the study

One of the chief types of energy traded in modern life is electricity. The benefits of electricity as an energy source include its speed (it moves at almost the pace of light), ease of transportation over great distances, silence, and relatively simple conversion to other energy sources. Green energy methods enable energy production without direct atmospheric or greenhouse gas pollution. Although most of us take electricity for granted, its fundamental production processes are incredibly complex. Electricity must be created at the same time that it is consumed because it cannot be easily stored in its current condition. This delicate balancing act between total generation and consumption calls for a significant investment in coordination, labor, costs, and technology [1].

The global energy landscape is undergoing a profound transformation, driven by escalating concerns about climate change, depleting fossil fuel reserves, and the need for sustainable development. In response to these challenges, the addition of renewable energy sources into the power grid has added significant momentum. Renewable energy skills, such as solar photovoltaic, wind turbines, and hydropower, offer clean and abundant sources of electricity. However, the inherent intermittency and unpredictability of these sources pose a considerable challenge to grid stability and energy management [2].

To address this challenge, the concept of a smart grid has emerged as a comprehensive solution. A smart grid leverages advanced technologies, communication systems, and control strategies to enhance the reliability, efficiency, and sustainability of power generation, distribution, and consumption. One crucial aspect of a smart grid is the development of effective energy balancing systems that can seamlessly integrate renewable energy sources while maintaining grid stability. In this context, the Proportional-Integral-Derivative (PID) controller has proven to be a powerful tool for achieving optimal energy management in a renewable energy integrated smart grid [3].

The PID controller is a widely used control algorithm that has found applications in various industries, including manufacturing, robotics, and process control. Its fundamental principle lies in modulating the control output based on three distinct terms: integral, proportional, and derivative. The proportional term responds to the current error among the wanted setpoint and the actual process variable [4]. The essential term accounts for the accumulation of past errors and helps remove steady-state errors. Finally, the unoriginal term anticipates future errors by analyzing the rate of change of the process variable. The PID controller's versatility, simplicity, and effectiveness make it a suitable candidate for managing the dynamic and stochastic nature of renewable energy resources in a smart grid [5].

In a renewable energy integrated smart grid, several key objectives must be met to ensure optimal energy balancing and efficient operation. Firstly, the variability and intermittence of renewable energy causes must be seamlessly accommodated to maintain a stable power supply. Secondly, the grid should be capable of adapting to sudden changes in energy demand and supply, thereby preventing frequency deviations and voltage fluctuations. Thirdly, the energy balancing system should minimize reliance on non-renewable energy sources, promoting sustainability and reducing greenhouse gas emissions. To achieve these goals, an intelligent and adaptive control mechanism is essential [6].

The utilization of a PID controller in the context of energy balancing offers several advantages that align with the requirements of a renewable energy integrated smart grid. The proportional term enables real-time adjustments of power generation based on the instantaneous mismatch between supply and demand [7]. This means that as renewable energy generation increases or decreases, the PID controller can modulate the output to maintain equilibrium, preventing overloading or underutilization of the grid. The integral term ensures the tracking and correction of long-term imbalances, such as those arising from daily or seasonal variations in renewable energy generation [8].

Furthermore, the derivative term of the PID controller enhances the grid's predictive capabilities. By analyzing the rate of change of energy supply and demand, the controller can anticipate potential disturbances and proactively respond to mitigate their effects. For instance, if a sudden drop in solar irradiance is detected, the PID controller can quickly adjust the output of other renewable sources or activate energy storage systems to compensate for the reduction in solar power generation. This dynamic and anticipatory nature of the PID controller aligns well with the fluctuating and uncertain behavior of renewable energy sources [9].

The integration of the PID controller into an energy management system in a smart grid setting involves the utilization of real-time data acquisition, communication networks, and advanced algorithms. Sensors and meters deployed throughout the grid collect information on energy production, consumption, voltage levels, and frequency. This data is continuously transmitted to a central control center where the PID controller operates. The controller processes the data, calculates the appropriate control actions, and sends commands to various grid components, such as renewable energy generators, energy storage systems, and load controllers [10].

The integration of renewable energy sources into the power grid necessitates the development of efficient and adaptable energy balancing systems. The Proportional-Integral-Derivative (PID) controller, with its ability to respond to current errors, track long-term imbalances, and anticipate future disturbances, presents a compelling solution for achieving optimal energy management in a renewable energy integrated smart grid [11]. The dynamic and versatile nature of the PID controller aligns well with the intermittent and unpredictable behavior of renewable energy sources. By leveraging advanced technologies and control strategies, a PID-based energy balancing system can contribute significantly to the stability, reliability, and sustainability of future power grids. This study delves into the design, implementation, and performance evaluation of such a system, shedding light on its potential to revolutionize the way we manage energy in the context of a rapidly evolving energy landscape [12].

Since the development of the steam turbine, the way electricity is produced worldwide has not altered significantly. Still, recent technological advancements and pollution-related worries have compelled society to turn to green renewable energy sources. Renewable energy is predicted to dominate the energy market in the future and has positive effects on the environment, economy, and health. It is essential to achieving more general energy and temperature objectives, such as lowering greenhouse gas releases, enhancing energy security and supply, and diversifying vigor sources. Green energy pioneering nations have shown that significant reliance on sustainable energy is feasible [13].

Conversely, producing renewable energy, particularly wind power, has several drawbacks. Green energy typically brings power variations because of its uncertain recurrent nature and dependence on natural incomes like the wind (although some energy bases, like tidal energy, are recurrent yet remarkably consistent). When actual generation or consumption differs from planned levels, energy management and power distribution issues develop [14]. There is continuously a discrepancy among the anticipated scenario and the existing power generation because it is difficult to precisely predict solar and breeze energy. Accidental disruptions are yet another reason for errors. Expensive backup power is needed to address the emerging imbalance caused by such forecast inaccuracies. As an alternative, cutting-edge, more precise forecasting techniques utilizing big data may help to solve this issue [15].

More effectual electricity generation is desired and preferably based on renewable incomes due to rising energy prices and the greenhouse effect [16]. Distributed renewable energy sources reduce consumers' need for grid power. Local power grids will soon be equipped with a variety of circulated generators, ranging in size from megawatt-scale to national kilowatt-scale generators, including thermal power florae, hydroelectric places, hybrid renewable bases (wind-solar), microturbines, and mutual heat and power (C.H.P.) plants [17]. Future smart grids' energy supply will be extra erratic due to swings and qualms in the energy generating and trading procedures caused by this diversity in market participants. For instance, weather conditions directly impact the ability of wind and solar power plants to generate electricity, and market participants and energy suppliers' decision-making processes can increase market volatility and uncertainty. Because of these factors, future intelligent grids will need to be highly flexible, and their management systems will need to react fast to changes and delays in energy output and request in real time. One strategy to balance energy demand and vigor generation is through dynamic, demand-responsive organization of the energy market [18]. Consumer demand and supplier generation are both directly impacted by energy prices.

Energy pricing, in particular, can serve as a helpful control signal for the community of dispersed and independent energy suppliers to prepare for impending responses to sudden changes in energy demand. Numerous approaches are presented in the literature [19] for achieving dynamic, real-time energy assessing for safe and effective intelligent grids. They advocated independent, demand-side organization based on game-theoretic energy feasting scheduling and generally addressed the interactions between utility firms (retailers) and their customers [20]. To develop a real-time pricing scheme, a recent study examined two game preparations for environments where power sellers are cooperative and highly competitive. A distributed utility maximization approach for real-time pricing was proposed in another paper. To achieve a dynamic, competitive equilibrium in power markets, Wang et al. devised a general economic symmetry model [21].

At the end of 2021, energy consumption may increase by 3% due to populace growth and economic growth [1]. 64.5% of the world's energy is produced by conventional power grids (PG.s), which are fuel-powered. These PG.s emit more carbon than the generating and transportation sectors, which almost each release 40% and 24% of carbon [22]. The Energy Information Administration (E.I.A.) predicts that the average household power bill in the US will rise by 2.3% in the upcoming year [23].

For all nations, especially those that heavily rely on coal, oil, and gas, renewable energy sources (R.E.S.), including solar, hydroelectric, wind, and geothermal power, are essential for ensuring future growth that is both sustainable and equitable [24]. The biggest economies in Asia, counting China and India, are gradually shifting to this clean vigor, where wind and solar are thought to be the most efficient and cost-effective R.E.S. Malaysia does not want to fall overdue in this cutting-edge technology as one of the Asian nations. Malaysia's primary energy bases were crude oil, natural gas, coal, and hydropower. But the nation also benefits from a wealth of R.E.S. potential, including biomass, biogas, wind, solar, and hydro [25].

Implementing renewable energy (RE) is one of the goals of sustainable development, which aims to lessen our reliance on fossil fuels and lessen the impact of climate change. Due to its advantageous location close to the equator, Malaysia is recognized as a nation with significant solar energy production latent. According to estimates, Malaysia's monthly sun irradiation ranges from 400 to 600 MJ/m2, providing up to 6500 MW of electricity [26]. On the other hand, the average wind speed in Malaysia is below three m/s, which is inadequate for continuous wind energy production. Most wind turbines on the market have cut-in speeds higher than three m/s, which is faster than Malaysia's usual yearly wind speed. The most excellent wind speed, which fluctuates depending on location and monsoon season, is reported between 6 and 12 m/s, suggesting a possibility for wind generation [27].

One method for balancing the benefits and drawbacks of R.E.S. is to integrate or combine them into a single system, or "microgrid." The new fundamental technology that makes it easier to integrate R.E.S. with current power generation is a microgrid [28]. The integration intends to improve energy efficiency, increase power supply reliability, and lessen environmental impact. An energy storing system (E.S.S.) may also be a way to assurance the security and stability of the power source due to the intermittent nature of RE [29]. According to reference [29], a microgrid mixes several energy bases, including solar P.V., wind turbines, E.S.S., diesel producer sets, and small hydropower facilities. Some describe a microgrid as an interconnection of dispersed generators, either a collection of dispatchable generators (such as gas turbines and fuel cells) or non-dispatchable producers (such as wind turbines and solar P.V.), integrated with electric and thermal energy storing devices, and with the capability of operating both grid-connected and islanded from the grid, upholding a high level of service and dependability [29].

## 1.2 The Problem Statement

In the view of sustainable and reliable operation, the smart grid is coping with various challenges, including energy balancing. The smart grid uses real-time communication through the use of Information Technology. It uses control management schemes to ensure the continuous supply of power to the user in fluctuating conditions of generation. However, due to the integration of renewable energy resources while balancing local power demand and supply side, the intelligent grid operators face energy balance challenges. Hence the adoption of an enhanced control scheme that simultaneously improves grid reliability and reduces operational costs by efficiently utilizing the integrated renewable energy resources.

## 1.3 Aims & Objectives

1. To reduce reliance on traditional power-producing resources by developing a mechanism to use renewable energy to fulfil consumer demand efficiently.
2. To reduce the instant demand and generation overshoot.
3. We are creating an optimal real-time energy price broadcasting mechanism for the energy market to maintain and achieve energy balance.
4. To optimize the controller for efficiently utilizing the available energy and gaining energy balance.

## 1.4 Scope / Significance of The Study

Because of economic progress, expanding population, and technological advancements, global demand for energy consumption is increasing exponentially. Dynamic pricing is one of the most hotly debated in the retail power market. An approach that can reduce peak load by charging varying prices at different times based on demand. Consumers' homes are equipped with IoT devices and dynamic pricing servers installed at both generation and consumer end in a closed loop; monitoring of market and age in real-time is observed. Based on the fluctuations in the demand-supply, the time-varying tariff is generated and signaled to the consumers. As a result, it analyses and implements energy-saving methods such as peak load shifting and non-critical load shedding to minimize energy costs.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Electrical grid background

The fundamental principles of both conventional and modern energy grids, including their methods for generation, consumption, and balancing, will be discussed in this part. As part of this thesis modeling and simulations of demand side management, it will also provide an overview of some forecasting methods and machine learning algorithms.

### 2.1.1 Electrical grid

The Alternating Current power system developed from Nikola Tesla's plane available in 1888 through the War of Currents. There were intense discussions at the time about whether AC and DC were better suited for important electrical systems. George Westinghouse's Westinghouse Electric Corporation teamed up with Tesla and bought his patents to build a complete AC system. Thomas Edison and his Edison Electric Light Corporation stood on the opposite side, representing the DC electrical system. The two primary contenders in the conflict of currents are generally acknowledged to be Thomas Edison and Nikola Tesla. The majority of the globe has adopted the AC system for broadcast and distribution due to its demonstrable advantages over the DC system. However, DC is still used in high-voltage DC subsea broadcast, current electronics, the railroad industry, etc. Electricity generation came first, shadowed by information, delivery, and users at the other end of the chain under the original, centralized, unidirectional design of the electric power system. A demand-driven control and the absolute minimum of monitoring were used. The system's design has seen little modification since its creation.

The three components of the conventional electrical grid are generating, transmission, and distribution. Large control florae that transform diverse forms of energy into electronic energy make up most of the generation component. It is then transferred onto high-voltage spread lines that can travel great reserves through a local substation. High-voltage communication lines are used to send electricity in large quantities to substations. A transmission grid is created when transmission lines are connected. Varying nations experience varying voltage levels. Redundant lines are currently used to enable electricity transmission in emergency scenarios. There is another channel for the current to flow when a transmission line fails. Unfortunately, most power tracking and rerouting are done manually, which results in power outages. Additional intermediate substations are needed since the transmission system typically has a range of voltage levels.

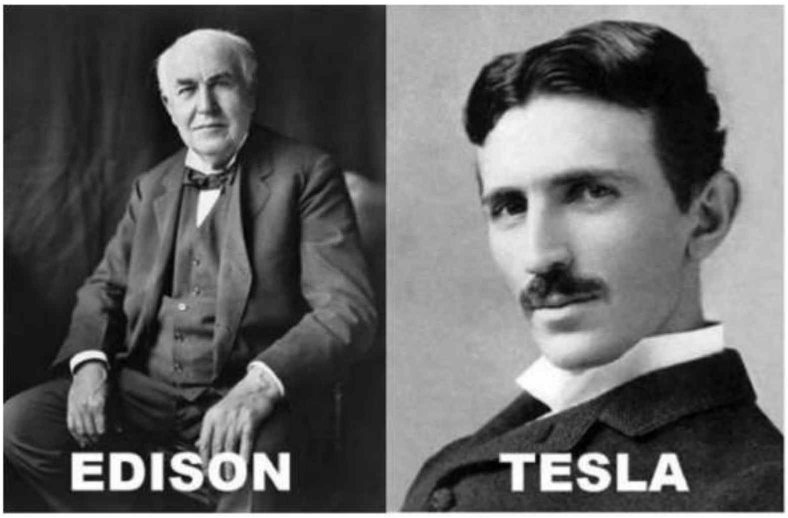

Figure 2.1: Thomas Edison - proponent of the DC (left), and Nikola Tesla - prominent sponsor to the development of the AC system (right).

Electricity is transferred to the so-called distribution network once it has reached the demand centers. The distribution system is the distribution system is the final step in supplying elec. It extends from the transformer at the substation to the end user's meter socket. Typically, it com several step-down transformers and medium to low-voltage lines. Sub-transmission clienteles (26 kV-69 kV), principal clienteles (13 kV-4 kV), and secondary customers (120 V-240 V) are a few different end-user kinds that can exist. Electricity in the classic grid design is distributed radially from many large-scale, centrally-located consumers [30].

Additionally, there may only be two distinct tariffs on the meters: daytime and nighttime. Real-time electricity pricing and the ability to buy and sell power would make adopting the smart grid possible. People may "trade" electricity in this new market that would be created. The general layout of the energy networks is shown in Figure 2.2 [31].

### 2.1.2 Electric energy generation

The many forms of decentralized energy production and centralized electricity generation are introduced in this section. Power grids started as local in the 20th century, developed through time, and eventually integrated for economic and reliability reasons. With multiple substantial centralized power plants and many interconnections, the grid had reached a relatively advanced stage by the 1960s. Most of the time, power plant locations were carefully picked. They were typically built close to supplies of cooling (lakes, seas, rivers, or other water reservoirs) and fuel (oil, natural gas, etc.).

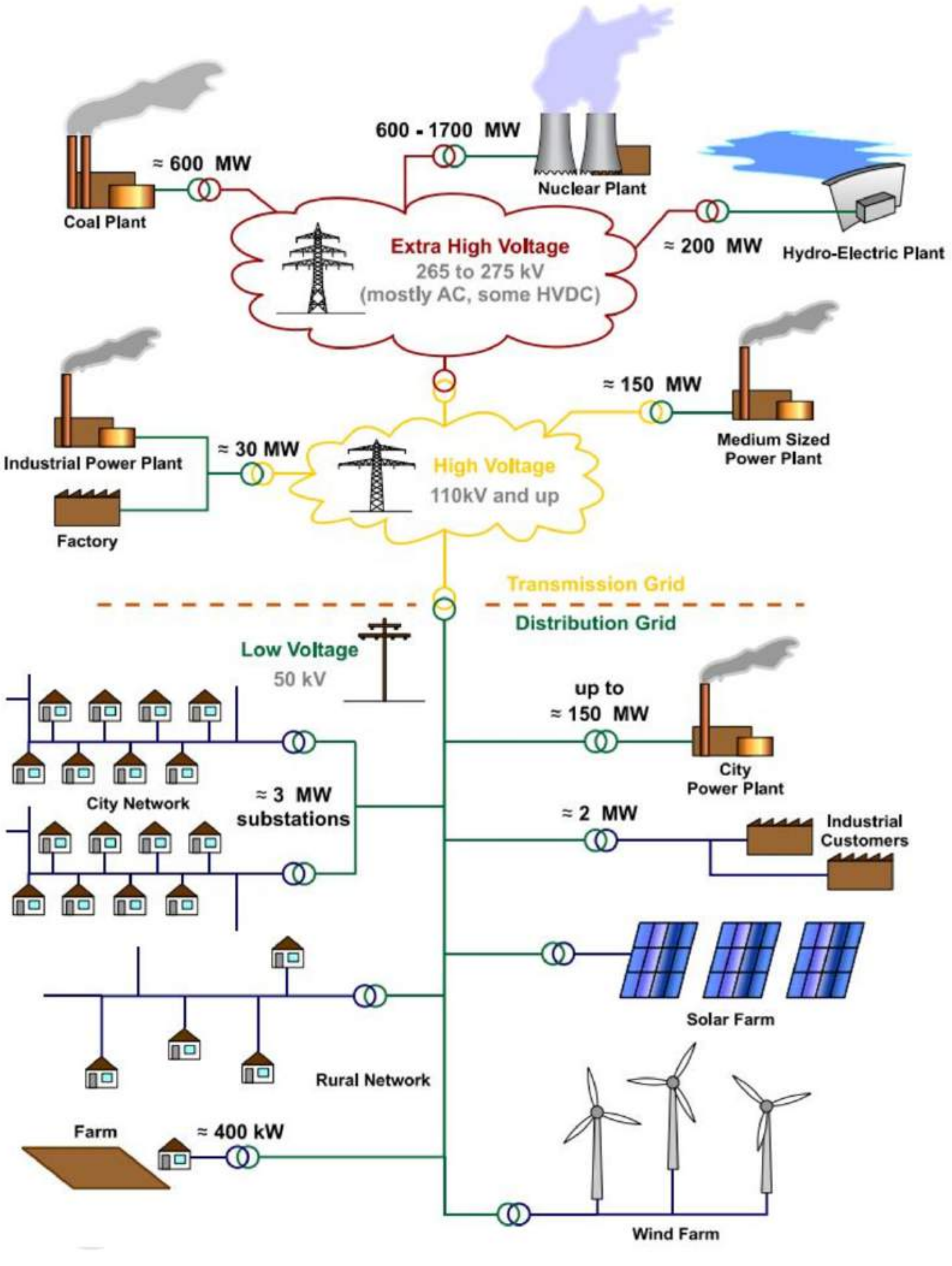

Figure 2.2: Electric energy generation System flow Diagram

A proper per-user metering system was required to track power ingesting as it varied for each customer as the grid became more linked. Electricity should be produced when needed because it cannot be easily stored without energy change. The cost of electricity is significantly increased during peak hours because expensive boost turbines must be fired. Double tariff metering was implemented to inspire people to use power during off-peak hours. This was a step toward Smart Grid metering, but real-time pricing was impossible due to technology restrictions. It is anticipated that Smart Grid technology will be used to fulfill this idea completely. Power stations produce electricity. These are commercial settings where different forms of energy are converted into electricity [32]. A generator, which transforms mechanical energy into electrical energy by causing motion among a magnetic field and a cathode, is at the center of almost all power plants. Power plants come in a variety of varieties. By fuel type, one may categorize the conventional ones.

Classification by Fuel:

- Hydro power stations.
- Nuclear power stations.
- Fossil-fuel power stations.
- Wind power stations.
- Photovoltaic power stations.
- Solar thermal power stations.
- Biomass-fuelled power stations.
- Waste heat from industrial processes.
- Geothermal power stations.
- Exhaust gas.

Despite a recent rise in renewable energy production, most electronic power is still generated using fossil oils (see Figure 2.3). Other options are now being researched because this centralized power generation style is outdated and negatively influences the environment. Decentralizing power cohort and incorporating renewable vigor into the network's distribution system will benefit greatly from innovative grid technology.

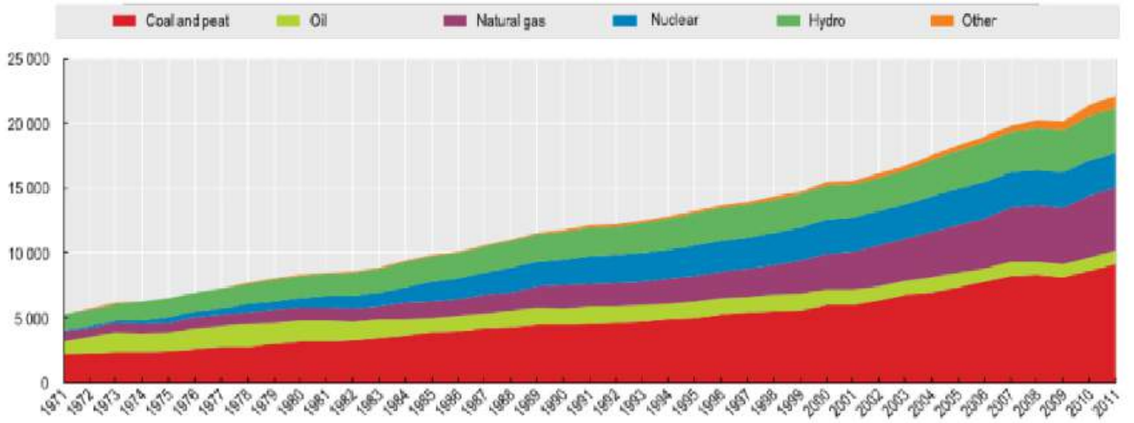

Figure 2.3: World electricity generation by source of energy (TWh)

Typically, renewable energy is defined as umph that derives from bases that can fully recuperate within the lifespan of a human. The primary sources of renewable electrical energy are wind, sun, hydro, geothermal, bio, and heat pumps. People have recently been more interested in renewable energy sources since they can lessen their dependence on fossil fuels. Governments and policymakers encourage renewable energy production, which has led to a surge in large-scale and small-scale domestic renewable energy investments [33]. The power distribution on the grid shifts from centralized to distributed when more and more small-scale power florae are put in place.

Over the past ten years, wind energy has grown significantly. Wind turbines are used to gather this form of significance locally, and in places with enough wind resources, it can be highly cost-effective. Differential sun irradiation causes air movement, and it has been calculated that the Earth contains around 10 T.T.W. of continually available wind power [34]. It is around four aeras the 2.5 TW global control consumption. Wind turbines come in numerous shapes and sizes, with vertical and horizontal axis projects. The maximum power output of commercial turbines can reach 8 M.M.W., and their efficiency ranges from 75% to 80% of Betz's limit.

The market for solar energy is likewise being pushed. An plentiful source of renewable energy is the sun. Photovoltaic (PV) panels, solar power attentiveness, and thermal heating are the three primary types of power capture techniques used by this technology to harness solar energy. Utilizing semiconductor materials, photovoltaic plans produce electricity directly from sunshine. The electricity can be fed into the grid with the aid of inverters. Harnessing reflecting surfaces is a popular method of harnessing the sun to create electricity.

These solar power plants focus sun energy using mirrors so that they may power traditional steam turbines and produce electricity [35].

The energy produced at or close to the place of use is decentralized energy (DE). According to innovative grid technologies, energy production should be distributed. Private rooftop photovoltaic solar boards and wind turbines are becoming increasingly common. Additionally, geothermal, tidal, wave, and small-scale hydroelectric power has grown in popularity. Micro Combined Heat and Power (C.H.P.) may also help generate electricity at residential buildings. And to control all of this electricity, a system that could track, sense, and route electricity intelligently and effectively is required [36].

Decentralized generation is strongly motivated by economic considerations. Contingent on the market, the network price constituent ranges between 50 and 60 cents per kWh. By implementing decentralized micro power plants, the group is brought closer to the consumer, lowering the costs associated with transmission and delivery. However, DE also has additional issues like power management and energy balancing that are related to it.

### 2.1.3 Electric energy balance using storage

Inappropriately, the most fragile resource on Earth is power. It must therefore be used right away when it is formed because it cannot be conveniently kept in its current state. Batteries are the most popular way to store electrical energy; however, since they involve converting electrical power into chemical energy, they shouldn't be regarded as a direct way to keep it. There are many different electrochemical battery types. However, flow series are typically recognized for grid utilization due to numerous beneficial characteristics.

District heating plants can also use electricity to create heat. This is accomplished by utilizing electric boilers and heat pumps, large involvement heaters in vast hot water cisterns. In this manner, excess power can be converted into warm water that can be utilized to heat our homes when necessary. Similarly, every home has a mechanism to stock energy in its hot water tanks when there is an excess of power or low cost. This fact is significant since a significant portion of this theory examines the potential for such energy storing technology to be modified to facilitate the addition of renewable energy sources and electrical energy balancing. Pump-storage For load balancing, hydroelectric facilities also offer electricity storage. They can be used economically by storing energy when prices are low and selling it when they are high. By impelling the water to a higher elevation, gravitational vigor is stored, and vice versa. [37] The standard cycle efficacy ranges from 70% to 85%.

Electric vehicles will be emotional and used as electricity storing as the number of electric cars rises. One automobile doesn't matter, but the storage capacity is apparent when thousands or even millions of them are joined. Therefore, while an electric automobile is not in use, it can act as storage to correct the imbalance between electricity generation and ingesting. Soon, supercapacitors or superconducting magnetic energy storing technologies might also be employed to store excess electrical energy. There are alternative technologies, such as compressed gas storage, flywheels, hot rocks, and others; nevertheless, this thesis mainly focuses on flow series and hot water storage [38]. With all these available storing options, every home will be a power generator and consumer. Every home will transform into an energy "prosumer."

### 2.1.4 Smart grid technologies

Modernizing the outdated electricity web is necessary. We can now monitor the grid and connected units in actual thanks to the revolution in communication skill (mainly the internet). To effectively offer sustainable, affordable, and secure power supplies, the European Technology Platform defines an intelligent grid as an electricity network that can logically integrate all users' activities, including generators, consumers, and those who do both. A Smart Grid's implementation holds out a lot of promise. It is the only practical method for decarbonizing our power industry at a fair price [39].

There are numerous further justifications for implementing Smart Grid right away. The introduction of the Smart Grid will revolutionize daily life and how we use energy, much as the internet revolutionized how we communicate. It will enhance generation and consumption forecasting, enable more effective energy use, and offer safety, robustness, and resilience. The current transmission and distribution networks need replacement in many world areas since they have outlived their intended lifespan. Instead of upgrading the outdated system, now is a fantastic time to use Smart system technologies. It is essential to track power flows and screen the transmission system's bulk as the number of distributed power-producing facilities (small and medium-sized wind, solar, and hydropower florae) increases. Smart Grid deployment is made simple by recent developments in the communications sector. Installing smart gadgets merely requires establishing internet connectivity, which is present in most homes in industrialized nations. In reality, the U.U.K. has planned to switch to smart meters for all electrical meters by 2020 [40].

A new technology is the smart grid. Along with numerous other components, it incorporates communication and power electronics layers. It usually refers to a group of technologies that improve how well the conventional electricity grid is used. It introduces some functions, including computer-based automation, monitoring, remote control, and sensing, that were not feasible before the twenty-first century. Millions of dollars are spent on this technology's research and development by numerous nations worldwide. To test and validate the idea, several of them have already begun to apply it in practical settings.

Regarding enhancing the energy supply's reliability, the smart grid will advance power quality and reduce control outages and blackouts. The goal is to foresee damage to electricity lines before it occurs. The Smart Grid could self-heal in the event of broken transmission cables by rerouting the power flow through an alternate or redundant path. The management, control, and balance of intermittent renewable energy generation will be the main focus of this thesis. To do this, intelligent devices will be connected to the network, and methods like demand side management, demand response, real-time pricing, energy storage, and forecasting will be used.

## 2.2 Integrating Renewable Energy in Smart Grid System

R.E.S. must be combined into the power system to limit the GHG emissions from conservative power plants and deliver a wide range of socioeconomic and ecological benefits. Two primary justifications were provided by Babatunde et al. [41] for the transition toward combining renewable energy sources with fossil oils used in power plants. These are reasons: power losses and environmental concerns. However, the intermittent and stochastic nature of P.P.V. power generation places great strain on the grid and causes the electricity supply to be unstable [42]. More specifically, intermittent energy sources cannot assurance the stability and continuity of the power stock. In addition to the difficulties above with P.P.V. integration, back-feeding creates enormous operational problems in power systems. Reverse power flows happen when local P.P.V. generation exceeds the local load demand. Distribution networks experience a voltage increase due to the reverse power [43].

Radaelli et al.'s [44] analysis of the implications of high PV diffusion as the primary energy source for the Spanish electric system was also conducted. The authors emphasized the impact of high P.P.V. penetration, which can cause local consumption to decline or even turn negative. The findings suggested that the electric grid should be talented to adapt to this new shape by changing the way it generates energy, regulating how much is consumed, or employing storage systems [44]. Similarly, Worighi et al.'s [45] simulation of a Sacramento feeder use case demonstrated negative values for load request and the enormous reverse power flow. The frequency of the reverse power flow and decreases in top loading was more influenced by feeder location (i.e., climate) than feeder type [45].

Stagner [46] have emphasized the effects of PV. power-producing units, including the potential for opposite power flow, high voltage levels, and increased tap actions. Decentralized P.P.V. power generation units have been suggested as an substitute to central generation units to address the reverse power flow. Furthermore, the dispatch ability and controllability of these possessions as well as the operation of the electricity system, may face difficulties due to the integration of renewable power group units as new distributed generations surrounding large scale at the show level, medium scale at the delivery level, and small scale on commercial or inhabited buildings [47].

The traditional grid must be modified to handle PV.'s rising penetration and inherent intermittency. In this context, energy storage devices can be crucial in addressing or reducing the difficulties above and adjusting to fluctuations in PV. power output. Energy storage technology is viewed from a technical perspective as one of the disruptive skills that could alter how the energy source is provided to end operators [48]. For instance, system constancy can be increased by inserting a storing battery as an energy bumper. This way, the P.V. electricity produced can be stored or fed into the microgrid. Therefore, scaling energy storage devices plays a significant part in the microgrid to accommodate the uncertainty of future understandings of demand and generation. This can lessen the P.V. power-producing units' intermittent and fluctuating output. Additionally, integrating energy storage devices can help shift electric demand from on-peak to off-peak during periods of high load [48].

To facilitate this integration, it is increasingly important to combine the analysis and enterprise of power electronics and power schemes. To encourage and execute Smart Grid topologies with R.E.S.s, the addition of new technologies into the traditional grid necessitates both inventive and reliable modelling of numerous mechanisms. Existing Smart Grid constructions that could facilitate R.E.S.s addition and accept higher levels of mutable E.S.S.s must be used to modernize the current electricity grid. Many academics have offered broad definitions of the smart grid in this setting. A modernized electrical network that relies on two-way communiqué infrastructure and power exchange among providers and customers is known as a "smart grid" [49]. Intelligent communication monitoring and management technologies have been thoroughly integrated into the network.

Power flow, information and communiqué technology (I.C.T.), and fiscal activities coexist. In this approach, the I.C.T. in the smart network may increase the efficiency of the current infrastructure, including generation, distribution, transmission, and consumers, and still be able to ensure that locally dispersed renewable group units and the power system are successfully coordinated [50]. The combination of new skills, intelligent plans, cutting-edge infrastructures, and controls forms the foundation of the smart grid, which is an development of the electrical grid. In this regard, numerous researchers have suggested an architecture for the Smart Grid to facilitate the integration of R.E.S.s. A general hierarchical architecture has been proposed in Ref. [50] as an outline for diverse energy management systems to address the issues provided by the increased penetration of dispersed renewable energy sources. The National Institute of Standards and Technology was also instructed by the U.S. Energy Independence and Security Act to submit a NIST perfect describing the Smart Grid as the existence of seven domains in 2007.

Although the NIST theoretical model offers a comprehensive view of how the essential shrewd network components connect and interconnect and appears to be a promising reference architecture for interface calibration, it still has some limitations due to the absence of a definition of Micro-grid systems with landlords of energy sources. The Smart Grid Architecture Model (SGAM) was created as a result of the Smart Grid Coordination Group, which was led by the European Committee for Standardization, European Committee for Electrotechnical Standardization, and European Telecommunications Standardization Institute. The SGAM offers a physical method for model intelligent grid use cases as a three-dimensional outline comprising zones, domains, and layers [51].

In this way, the European Community has expanded the NIST model by incorporating a domain for "Distributed Energy Resources" (D.E.R.s). The new model considers the D.E.R.'s growing significance, which includes unconventional sources like customer-owned solar and wind power installations. The power system creators can join "Micro-grids" into the current grid topologies thanks to these D.E.R.s' enhanced functions.

Because they can offer financial advantages by eliminating long-distance transmission, microgrids will become a viable alternative to the current centralized energy producing systems during the next ten years [52]. Additionally, they can improve how small and medium D.E.R. units are integrated into the electrical grid [52]. Additionally, the microgrids make it possible for the primary grid to separate various parts of it when control is lost successfully. As a result, the power scheme can be more reliable and adaptive against potential fluctuations or faults. In this regard, a Micro-grid perfect is necessary for event analysis after the detail. It can simplify the scheme and give integration studies for R.E.S. greater understanding.

An investigation of control techniques created for a Micro-grid control construction when it is integrated with renewable energy bases was reported by Cyubahiro et al. [53]. The authors used MATLAB/Simulink simulation to analyze and build a control method for load management. The goal was to increase the stability of Microgrid operation when the input voltage fluctuates. Similarly, PSCAD software was used in Ref. [53] to model distribution generators (D.D.G.) and renewables with seasonal change at various sites. The objective was to keep the system's power quality stable even while the load fluctuated. The authors [53] proposed a sweeping approach to design, control the capacity, and meet the power quality indexes for the microgrids.

## 2.3 Energy Storage Systems

The process of altering electrical energy from influence systems into a form that can be stowed for later conversion back to electric energy is referred to as energy storing. Energy storage devices have been broadly used for utility grid and transportation requests due to the emergence of renewable energy technology [54]. Energy storing is crucial for utility grid applications because it enables the integration of renewable vigor sources into power systems and ancillary facilities like peak load reduction, frequency control, and voltage rule. Grid-connected energy storage will proliferate, reaching 6GW in 2017 and exceeding 40GW in 2020, predicts an account by market research firm HIS [55]. To reduce CO2 emissions and the use of fossil fuels, however, hybrid and battery electronic vehicles have been advanced for decades and are currently in use. Plug-in electric vehicles with V2G capabilities can provision the integration of intermittent renewable energy foundations, such as solar and wind energy, into power grids. Reactive power compensation, active power regulation, load leveling through peak load shaving, and harmonic current filtering are further options that V2G technology can provide grid operators [55].

### 2.3.1 Comparison of Energy Storing Technologies

It is possible to compare various energy storage methods from a technical and financial standpoint. Studies on the investment costs of different energy storage systems may be found in through. Hence, they will not be considered in this study. Energy density, power density, life cycle (lifetime), energy efficiency, and self-discharge the primary technical features of energy storage, and they are described in the following ways [56].

1) The energy-to-weight ratio is measured in Watts per kilograms (Wh/kg), and the power-to-weight relation is measured in Watts per kilogram. Power density describes the capacity of energy storage to deliver power instantly, whereas energy thickness describes the aptitude to provide continuous energy over time. High power density energy storing can discharge a lot of control quickly, while high energy density energy storage can discharge energy for a long time. The point-to-weight ratio is unhurried in Watts per kilogram (Wh/kg), and the power-to-weight ratio is slow in Watts per kilogram (W/kg). Power density describes the capacity of energy storage to deliver power instantly, whereas energy thickness describes the aptitude to provide incessant energy over time. High power density energy storing can discharge a lot of control quickly, while high energy compactness energy storage can release energy for a long time.

2) The ratio of free energy to stored energy, or the output and input power, without considering self-discharge, is known as energy efficiency (%).

3) The number of times an energy storage device can discharge the intended energy level following each renew is known as the life cycle or durability (cycles). One charge and one liberation make up a cycle.

4) The relation of initially stored to dissolute energy for inactivity is known as self-discharge.

Energy storing technologies can generally be divided into two categories: high power density, low energy density, and high energy density and low power thickness. Batteries are a type of energy storing with a high but low energy thickness, making it suited for long-term use (up to an hour), but it has a significant-time response. Supercapacitors and flywheels are examples of energy storage that offer quick reaction but cannot be used for an extended time (in several seconds to minutes).

This thesis uses two different battery energy storage technologies—the lithium-ion cordless and the V.R.B. Battery packets with several battery lockups coupled in parallel and series are called energy storage systems. These battery packs have entered power schemes at the dc portion of control inverters. Compared to lithium-ion batteries, V.R.B. has a comparatively low energy and power density. At the same time, the long-life cycle and low self-discharge degree of V.R.B. are its benefits. Energy efficiency, energy storage capacity, and life cycle are important presentation parameters for utility grid applications or the integration of renewable energy. The V.R.B. is especially well suited for utility applications due to its many advantages, including self-governing power and energy ratings, quick discharge and charge response times, great energy efficacy, extended life cycles, low self-discharge, and ease of SoC estimate [57], [58]. Key performance needs for transportation requests include mobility, energy and scalability, and power density. Lithium-ion batteries have exceptionally high power and energy densities compared to conventional batteries. Since of this quality, lithium-ion batteries are the most commonly utilized batteries in transportation applications since they require little volume and weight to produce significant amounts of energy [59].

In addition, one of the main restrictions to energy storage is storage capacity. If energy storage is already full or empty, respectively, they cannot engross or supply energy. State of charge and depth of discharge is presented because it is necessary to comment on either the energy stored or the energy utilized by energy storing [60]. The amount of energy still in energy storage relative to its overall capacity is defined by its state of charge. Discharge depth is the opposite of SoC. It specifies the percentage of the entire power discharged or utilized as energy. SoC is a crucial control system parameter significantly affecting the energy storage control approach. For instance, if energy storing cannot provide power because the SoC is actual low, the control plan must recharge the storing as quickly as feasible, and energy from other bases must be used to make up the difference.

### 2.3.2 Energy Storage for Utility Grid

Modern smart grids have extensively used energy storage technologies for many different purposes. According to their goal or function in the smart grid, E.S.S.s fall into one of three categories: grid ancillary facilities for improving power quality, continuous power source (U.P.S.) for off-grid equipment, or energy organization for optimum performance. These requests will aid in integrating renewable liveliness sources into the current power network and enhance the system's overall efficiency and electricity quality. Figure 2.4 [61] displays various energy storage methods' power/capacity ranges. The suitability of various E.S.S.s for utility grid applications is also depicted in Figure 2.4. Some related research papers on this topic are reviewed in the following subsections.

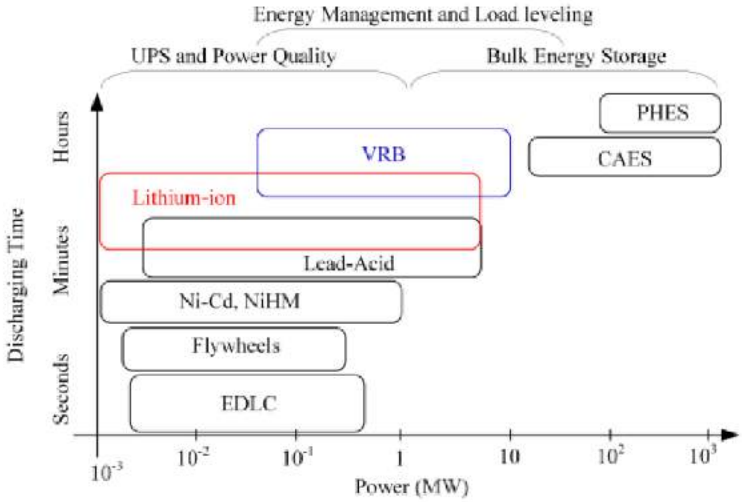

Figure 2.4: Different energy storage technologies for grid application [61].

**1) Grid Ancillary Services**

The grid auxiliary E.S.S.s for power quality enhancement, which include R.E.S.s intermittence mitigation, and incidence, and voltage control, typically last for a few seconds to a few hours. One important technique for reducing volatility in solar and wind power generation is the E.S.S. [62] proposes a method in which the slope rate of inverter output is controlled to a desirable equal by measuring the ramp rate of P.P.V. panel output. To enhance the effectiveness of P.P.V. fluctuation mitigation, the E.S.S. maintains the intended ramp rate according to an inverse relationship with the ramp rate of P.P.V. panel output during the ramping up/down period. A power levelling approach for a 1-MW grid-connected P.P.V. power herbal is suggested in [62] for the same objective.

A hybrid E.S.S. is used to stabilize the P.P.V. plant's erratic power output using a V.R.B. and a supercapacitor bank. By preventing the V.R.B. from operating at low power levels and lowering the needed power score of the supercapacitor to one-fifth of the V.R.B. rating, the hybrid E.S.S.'s power management system improves overall competence. In addition, a flattening control technique is suggested in [63] for lowering variations in the power output of hybrid P.P.V./wind systems and controlling the SoC of the battery E.S.S. under various operating situations. Another problem caused by the penetration of R.E.S.s is the frequency and voltage variation, which can be resolved using E.S.S.s. [63] to investigate how battery E.S.S. integration affects the short-term frequency control in independent microgrids.

The microgrid's short-term frequency stability is improved by this study's use of an E.S.S. control approach, which also enhances the inertial response and adaptive droop feature. For grid frequency regulation, a power scheme with a significant diffusion of wind generation and E.S.S. is examined in [64]. To enhance the effectiveness of the grid frequency deviation reply and control the E.S.S. SoC, a method known as SoC feedback control is suggested. [65] presents a synchronized control approach to account for the wind farm's inertia. Based on the coordinated management of the wind turbine producers and the E.S.S.s, this technique can enhance the provisional frequency support capability of the wind turbine producers.

### 2) U.P.S. Software

The operation of E.S.S.s in islanded microgrids or off-grid power systems is referred to as the U.P.S. It has been investigated by numerous researchers for together ac and dc microgrids [66]. When an E.S.S. is grid-connected, power can be introduced from the grid to charge the E.S.S.s' battery packs. The E.S.S.s can meet local load demand in stand-alone mode with other sources. [66] introduces and discusses a line-interactive U.P.S. for ac microgrids and the associated controller system.

A frequency and voltage drooping technique seamlessly transitions the microgrid between grid-connected and stand-alone action. The drooping coefficients are suitably selected to lower the amount of power used by the U.P.S. when re-connecting to the utility grid and to enhance transient response. A cooperative control technique for the E.S.S. and distributed energy resources (D.E.R.s) during island operation is put forth in [67] and tested through simulation and experiment. A primary control manages the E.S.S.'s short-term frequency and voltage rule. In contrast, a lesser rule directs the D.E.R.s to react if the frequency and voltage nonconformity persist for an extended time.

D.D.C. microgrids have received a lot of interest during the past several years. The system's efficiency is increased by D.D.C. microgrids, which allow dc output sources like P.P.V. systems, fuel and storage batteries cells to be connected without ac/dc change. A voltage switch strategy that cartels unsure control and gain-scheduling methods is described in [68] for dc microgrids with multiple E.S.S.s to realize power sharing and energy management. The study's findings show that the system's dc voltages are maintained within a range of 340V +/-5% and that the SoCs of various E.S.S.s are almost identical. To balance the SoCs of distributed E.S.S.s in dc microgrids, a SoC-based adaptive droop control approach is described in [69]. The load demand is divided evenly among the distributed E.S.S.s in the system thanks to this control mechanism, which is accomplished decentralized and in which the droop coefficient is contrariwise proportional to the nth order of SoC.

3) Energy Management

Energy management, which comprises load balancing, system reversal, peak shaving, economic message, etc., is another significant application area for energy storage. [71]. E.S.S. sizing is a crucial topic in performing the energy management function of E.S.S.s.

To increase the reliability, efficiency, and economics of power grids, distributed E.S.S. energy management or scheduling is crucial. [71] discusses an intelligent power system where consumers are given energy storage gadgets. The cost of energy can be reduced by a central controller scheduling user energy usage and storage. [70] introduces a distributed economic dispatch technique for microgrids with several E.S.S.s. In a centralized dispatching formulation, this method overwhelms the difficulties of dynamic couplings among all decision and stochastic variable quantity. In [30], an algorithm is developed to determine the E.S.S. operating agendas to achieve peak demand splinter and load-leveling. This approach leverages demand profile info and a limited set of E.S.S. strictures.

[72] recommends an efficient sizing technique for distributed battery E.S.S.s in distribution networks with high P.P.V. penetration levels. This method's primary goal is to maximize the capacity of distributed battery E.S.S.s and calculate the cost-benefit ratio when E.S.S.s are used to reduce peak demand and improve voltage profiles. [73] introduces a thorough planning approach for determining the most economically advantageous location and sizing of E.S.S.s, maximizing their advantages in distribution networks. The stochastic nature of system components is considered using a probabilistic method. This method determines how well E.S.S.s should operate in each load state. Energy management for E.S.S.s often has a longer time scale than power quality services, ranging from a few hours to many months.

### 2.3.3 Energy Storage for Transportation

Since the majority of E.E.V.s do not consume all of the energy stored in the battery during routine everyday travels, electric cars have a substantial possible quantity of storage volume. The use of E.E.V.s' extra battery capacity for grid support claims using the V2G concept is gaining popularity and significance. By sending electricity into the grid or reducing their charging rate, E.E.V.s can connect with the power system to provide demand response services, according to the V2G concept. The electric vehicle (E.E.V.) can function as the system's energy storage unit or as a controllable load when connected to an electrical network. With the massive storage capacity of E.E.V.s connected to the grid, the stability and dependability of the power system that uses renewable energy would be improved. A collection of E.E.V.s must work together as an aggregator for the V2G system to deliver supplementary service. It is anticipated that the E.E.V. aggregators would connect and communicate with a group of E.V.s to form a more extensive, attractive system for utility applications [74]. E.E.V.s can be charged at home, in parking lots, and at E.E.V. charging stations. As indicated in [74], the industry has established three standards E.V.C. rates that can be divided into three power levels. Level 1 and Level 2 E.V.C.s can handle regular E.E.V. charging, whereas Level 3 E.V.C.s can control fast E.E.V. charging.

The load demand profiles and voltage profiles in distribution networks will be impacted by the E.E.V. charging pattern, which is a significant factor. In summary, there are three distinct E.E.V. charging patterns: V2G, price-based E.E.V. charging, and continual E.E.V. charging. When no higher-level controller is coordinating the E.E.V. charging, the condition is represented by constant E.E.V. charging. Once plugged into the grid, the E.E.V. will continue to charge steadily until either the battery is fully emotional or the E.E.V. is unplugged from the lattice. The evening peak load demand typically coincides with E.E.V. charging with continuous electricity in residential areas. This will put more strain on distribution networks and lead to serious voltage drop problems.

As a result, this charging pattern is only appropriate in situations with limited E.V.s penetration, where E.E.V.s are only considered passive loads. Price-based EV charging distributes E.E.V. charging activities throughout time while maintaining the ability to drive. The time of usage price and hence off-peak charging will be considered when setting E.V.s. An E.E.V. management problematic that can be transformed into an optimization problematic is price-based E.V. charging. The E.E.V. charging is directly monitored and can be handled as a receptive load using this charging decoration. The final charging method, "V2G," enables E.E.V. owners to resell electricity and offers additional grid services. To ensure grid dependability balance supply, frequency regulation and demand, and assist the transfer of power from generation to ingesting, ancillary facilities are required in the power system. Load leveling and peak power organization [75], voltage control and swift frequency, and efficient renewable supporting and matching [76] are only a few of the ancillary services offered by V2G. This thesis' primary focus is on V2G technology. Hence the use of V2G is extra addressed under.

**1) Load Leveling and Peak Load Shaving**

The peak-shaving support provided by the E.E.V.s may be advantageous, depending on the strain placed on the grid during times of high load. E.E.V. battery packs have a certain amount of storage space, and the amount of space that can be used is also limited by transportation needs. Therefore, a control method for efficient use of the existing E.E.V. capacity for peak shaving is proposed in [77]. When peak shaving is most advantageous based on the demand pattern, dynamic modifications in E.E.V. discharging rates are established to fully use the limited E.E.V. battery capacity. A multi-charging station for E.E. Vs and its use for grid support are modeled and researched in [77]. The suggested control architecture uses fuzzy control methods to keep the node voltage within the specified limit by valley filling.

A V2G switch technique is suggested for the aggregator to dispatch regulation necessities to E.V.E.V.s and E.E.V. charging stations in light of the frequency regulation capabilities of E.E.V.s [78]. The frequency regulation control for each E.E.V. charging station is determined founded on the V2G power available at the moment, and V2G control is displayed, seeing both charging requests and frequency regulation. In [79], a decentralized V2G regulator mechanism is suggested for E.E.V.s to participate in primary frequency control while considering assessing requests from E.E.V. customers. It is recommended that the battery S.O.C. holder be used with adaptive frequency droop control to keep the E.E.V. battery's SoC around the remaining S.O.C. In distribution networks with high D.D.G. penetration, a V2G reactive control support technique for optimal coordinated power management is put out [76]. The suggested algorithm makes use of E.V.E. V.s D.D.G. s and on load tap changers to please grid voltage needs and E.E.V. charging demands while allowing for relaxed tap operation and the least amount of D.D.G. active power limitation.

**2) Renewable Supporting and Balancing**

E.E.V.s' V2G capabilities can offer more reserve for the power system's renewable generation. The central power plants or the D.D.G. units must reduce their power group when the amount of energy from R.E.S.s injected into the grid rises significantly. By charging and discharging batteries, E.E.V.s can assist in balancing generation and consumption, reducing the need for utility generators to output less power. [80] proposes a dispersed V2G control strategy that offers a spread spinning reserve for the unanticipated intermittence of R.E.S.s. The requirement of the E.E.V. user is met by carrying out a planned charging for the V2G management. Examining the potential and technical advantages of employing P.P.V. systems as energy sources for charging E.E.V.s is the writers' goal in [80]. To maximize the contact between the P.P.V. system and charging position for E.E.V.s, a self-consumption evaluation integrated system at the metropolitan scale is proposed.

## 2.4 Optimal Controller-Based Energy Balancing System

This work illustrates a control theoretic approach for automatic, multi-resource energy market management processes in a smart grid based on a traditional P.I.D. (proportional integral derivative) controller structure. The PID-based, closed-loop regulator system maintains energy balance by regulating energy prices to balance energy manufacture and demand. According to the findings of the market simulation, a P.I.D. controller could change unit energy prices in real-time to preserve energy balance while accommodating both the variable energy request profiles of grid customers and the erratic energy production of multi-resource energy dealers.

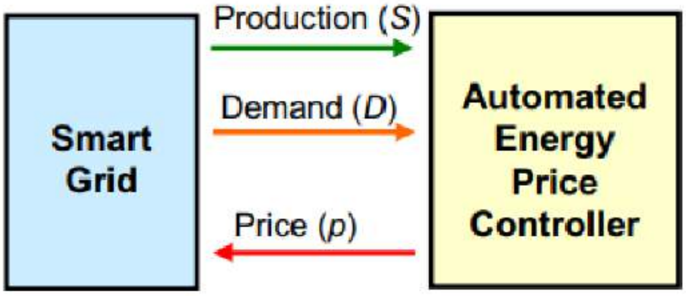

Figure 2.5: A block diagram showing the interaction between a smart grid and a locked loop energy price controller

A PID controller's coefficients are tuned. The authors were able to adjust the energy production's speed and accuracy as well as the price response character using the functions Kp for comparative gain, Ki for integral growth, and Kd for derivative increase. A PID controller can provide decentralized, local pricing management in, for instance, microgrids when used regionally and as a central supervisor on a larger scale. Alagoz et al. [81] suggested a decentralized organization approach for a tree-like hierarchical net architecture model for the integrated microgrids energy balance problematic.

Distribution and Transmission system operators can use decentralized dynamic pricing with a P.I.D. controller to achieve the energy balance within or between microgrids in a network layout that resembles a tree. The closed-loop pricing control system founded on P.I.D. supervisors is introduced in the following section. Additionally, it uses a arithmetical simulation created in the Matlab Simulink imitation framework to show how an energy supplier public would react to a significant increase in energy request. Simulations of multi-source vigor market scenarios with closed-loop energy price control are covered in a separate section.

The closed loop P.I.D. controller in [17] describes the flexible demand control of customers' online pricing regulation. The energy demand is modified by the P.I.D. regulated price signals using DSLM agents such as load shifting, etc. The P.P.I. controller's coefficients are manually changed in [82], which causes a demand overshoot at first for about 5.5 hours. During this time, the demand from the generator is unusually high, and the clients experience a blackout or load shedding. Therefore, more work is required to correct or eliminate the overshoot at the beginning of the runs using a manually set P.P.I. controller.

Several different ML-MR control strategies are offered, including closed-loop systems based on P.I.D. controllers that enhance disturbance rejection and system performance—using features including a straightforward design, solid stability, dependable performance, and simplicity of assembly, among others. P.I.D. control relies on modifying the parameters of three loops to get the controller to function as desired [83].

Swarm-based algorithms are frequently employed for P.I.D. gain tuning because of their simplicity, flexibility, and resilience, according to an observation and analysis of several meta-heuristic methods in [84]. G.W.O. is a population-based meta-heuristic that can, to some extent, prevent local optima stagnation. Additionally, it is capable of good convergence toward the optimum. G.W.O. generally makes a great effort to be exploited [85].

## 2.5 PID Control Applications in Power Systems

The addition of renewable energy sources into power schemes has brought about significant challenges related to grid stability, voltage regulation, and frequency control. In addressing these challenges, control strategies such as Proportional-Integral-Derivative control have emerged as effective tools for maintaining the reliability and stability of power systems. This section reviews the literature on PID control applications in power systems, highlighting its role in load frequency control (LFC) and voltage regulation.

### 2.5.1 PID Control Theory and its Relevance

PID control is a widely utilized feedback control strategy that has proven successful in various industrial applications. Its three components - proportional, integral, and derivative terms - provide a versatile framework for regulating dynamic systems. In the context of power systems, the proportional term enables the controller to respond to immediate deviations from the setpoint, the integral term removes steady-state errors, and the derivative term anticipates future changes in the controlled variable.

### 2.5.2 PID Control Applications in Load Frequency Control

One of the critical aspects of power system operation is maintaining a balance among power generation and load request. Load Frequency Control (LFC) is a crucial function that ensures the occurrence and tie-line power deviations remain within acceptable bounds following load changes. PID control has been extensively applied to LFC due to its ability to respond to sudden load variations and generation imbalances.

A notable study by Kundur et al. (1994) demonstrated the effectiveness of PID control in LFC through simulations on a multi-area power system. The authors proposed a decentralized PID control strategy for each area and showcased its robustness in mitigating frequency deviations under varying operating conditions.

Additionally, the work of Elgerd and Fosha (1970) emphasized the significance of integral control in LFC. They presented a PID-based integral control strategy to minimize steady-state frequency deviations and demonstrated its capability to restore system frequency to the nominal value efficiently.

### 2.5.3 PID Control for Voltage Regulation

Voltage regulation is another critical aspect of power system operation, ensuring that the voltage levels at various points within the network remain within specified limits. PID control has been employed to regulate voltage levels and stabilize system operation under changing load conditions.

A study by Kothari et al. (2008) investigated the application of PID control for voltage regulation in a distribution system with distributed generation. The authors incorporated a PID controller to regulate the output of distributed energy sources and maintain voltage stability during load variations. The results highlighted the PID controller's ability to enhance voltage regulation and reactive power control.

Moreover, the research conducted by Karabiber and Özdemir (2017) focused on voltage regulation in a microgrid environment using PID control. The authors proposed a PID-based voltage control scheme for an autonomous microgrid with renewable energy sources and energy storage schemes. The PID controller effectively regulated the voltage levels within permissible bounds, contributing to the stable operation of the microgrid.

### 2.5.4 Advancements and Challenges

While PID control has demonstrated its effectiveness in power system applications, researchers have also explored enhancements to address specific challenges. For instance, Zhang et al. (2018) introduced an adaptive PID control strategy for LFC, incorporating a self-tuning mechanism to adjust the controller parameters based on system dynamics. This approach improved the controller's adaptability to varying operating conditions and load changes.

However, despite its successes, PID control is not without limitations. It may struggle to handle complex nonlinearities and uncertainties present in large-scale power systems. Additionally, tuning PID parameters can be a challenging task, requiring expertise and careful consideration of system characteristics.

The literature highlights the significant role of PID control in power systems, particularly in load frequency control and voltage regulation. Its ability to respond to dynamic changes, eliminate steady-state errors, and anticipate future deviations makes it a valuable tool for ensuring grid stability and reliability. While advancements have been made to enhance PID control's adaptability and performance, challenges related to system complexity and parameter tuning persist. Future research may focus on integrating PID control with advanced optimization techniques and predictive algorithms to address these challenges and further improve its efficacy in power system applications.

## 2.6 Renewable Energy Management with PID Control

The addition of renewable energy sources into power schemes presents a significant paradigm shift towards a cleaner and more sustainable energy future. However, the inherent variability and intermittency of renewable sources, such as wind and solar, pose challenges to grid constancy and energy management. Proportional-Integral-Derivative (PID) control has emerged as a valuable tool for effective renewable energy management, enabling the integration of these fluctuating sources while maintaining grid reliability. This section reviews the literature on PID control applications in renewable energy management, highlighting its role in solar photovoltaic (PV) and wind power systems.

Solar PV systems are a cornerstone of renewable energy generation, but their output is highly influenced by factors such as solar irradiance and temperature. PID control has been employed to enhance the performance and stability of solar PV systems by dynamically adjusting the power output to match varying load conditions. Elgendy et al. (2013) investigated the application of PID control in a grid-connected PV system. The authors proposed a PID controller to regulate the voltage at the point of common join while maintaining the PV system's maximum power point tracking operation. The PID controller effectively managed fluctuations in solar irradiance, resulting in improved voltage stability and enhanced energy capture.

Furthermore, the research by Kumar et al. (2018) focused on PID control in standalone PV systems with battery energy storage. The PID controller was used to maintain the battery state of charge within specified limits while optimizing PV power generation. The study demonstrated that PID control improved the overall system performance, reducing battery overcharging and enhancing energy utilization. Wind power is another key contributor to renewable energy generation, but its output is subject to changes in wind speed and direction. PID control has been employed to smooth the power output of wind turbines and enhance their integration into the grid.

A notable study by Patel and Agarwal (2008) explored the use of PID control for pitch angle regulation in wind turbines. The PID controller adjusted the blade pitch angle to optimize power generation while mitigating mechanical loads during turbulent wind conditions. The results highlighted that PID-based pitch control contributed to stable and efficient wind turbine operation. Additionally, the research conducted by Liu et al. (2016) focused on PID control for grid-connected wind power systems with energy storage. The authors proposed a PID-based control strategy to manage the power output of wind turbines and the energy flow between the grid and the energy storage system. The PID controller facilitated the addition of wind power into the grid while ensuring stability and optimal energy management.

While PID control has demonstrated its effectiveness in renewable energy management, researchers have explored enhancements to address specific challenges. Adaptive and robust PID control strategies have been proposed to improve system performance under varying operating conditions and uncertainties.

A study by Sharma et al. (2019) introduced an adaptive PID control approach for solar PV systems. The authors integrated an adaptive mechanism to adjust the PID controller gains based on changes in solar irradiance. This adaptive PID control scheme improved the tracking efficiency of the MPPT algorithm, enhancing energy capture from the PV system. However, challenges remain, particularly in addressing nonlinearities and uncertainties associated with renewable energy sources. Additionally, tuning PID parameters to different operating scenarios and system dynamics requires careful consideration and expertise.

Its ability to adaptively regulate power output and enhance system stability makes it a valuable tool for integrating fluctuating renewable sources into the grid. While advancements have been made to enhance PID control's adaptability and performance, challenges related to nonlinearities and parameter tuning persist. Future research may focus on combining PID control with advanced machine learning techniques and predictive algorithms to further improve its efficacy in renewable energy management, ultimately contributing to a more sustainable and resilient energy landscape.

## 2.7 Case Studies of PID-based Energy Balancing

The addition of renewable energy sources and the emergence of smart grids have ushered in new challenges and opportunities for energy management and grid stability. Among the various control strategies, Proportional-Integral-Derivative control has gained prominence for its ability to effectively balance energy supply and demand in real-time scenarios. This literature review explores real-world case studies of PID-based energy balancing in smart grids, evaluating their performance and outcomes.

Microgrids represent localized energy systems that can operate autonomously or in conjunction with the main grid. PID control has been successfully applied to microgrid energy management, allowing seamless integration of renewable sources, energy storage, and loads. A study by Wang et al. (2017) presented a PID-based energy management scheme for a microgrid consisting of solar panels, wind turbines, and batteries. The PID controller regulated the power output of each source based on real-time load demand, ensuring continuous energy supply while preventing grid instability. The results demonstrated efficient energy utilization and stable microgrid operation.

Similarly, Mohammadi et al. (2020) implemented a PID control strategy in a microgrid with combined heat and power units, wind turbines, and storage. The PID controller managed the CHP units' output to meet the thermal and electrical loads while optimizing operational costs. The study revealed improved load tracking accuracy and reduced energy expenses. PID-based energy balancing has also been applied to large-scale power grids with a significant share of renewable energy sources. In these cases, the challenges are more complex due to the interconnection of multiple generation units and the varying geographical distribution of renewable resources.

A notable example is the work of Ghaemi et al. (2019), where a PID control system was utilized to manage wind power integration into a regional power grid. The PID controller adjusted the power output of wind farms based on grid frequency deviations, contributing to stable grid operation. The study emphasized the PID controller's role in maintaining grid frequency within acceptable limits during transient conditions. Performance evaluation of PID-based energy balancing systems involves analyzing their effectiveness in maintaining grid stability, optimizing renewable energy utilization, and preventing disturbances.

In the microgrid case study conducted by Wang et al. (2017), the PID-based energy management system demonstrated accurate load tracking and efficient utilization of renewable sources. The system effectively responded to load changes, preventing overloading or underutilization of energy resources. Similarly, the study by Mohammadi et al. (2020) highlighted the PID controller's ability to optimize CHP unit operation, leading to reduced energy costs and improved load demand satisfaction. Ghaemi et al. (2019) reported successful grid frequency regulation through PID-based wind power control. The controller's real-time adjustments mitigated frequency deviations caused by variations in wind speed, ensuring stable grid operation during changing conditions.

While PID-based energy balancing systems have demonstrated positive outcomes, challenges remain in scaling these solutions to more complex and dynamic grid environments. The tuning of PID parameters and the adaptability of the controller to various operating scenarios continue to be areas of research interest.Future directions in PID-based energy balancing could involve the integration of advanced optimization algorithms and predictive control strategies. Machine learning techniques could enhance the controller's ability to anticipate load variations and renewable energy fluctuations, leading to more accurate and proactive energy management. Real-world implementations in microgrids and large-scale power grids have demonstrated its capability to optimize renewable energy utilization, enhance grid stability, and respond to dynamic load changes. As the energy landscape evolves, further research into advanced PID control techniques and their integration with emerging technologies could contribute to more resilient and sustainable energy systems.

## 2.8 Related Works

For the best load scheduling and energy management, several strategies have been used. Additionally, as information technology develops, there is a daily increase in the power demand. Many techniques have been planned in the literature for improved load scheduling and energy management. Allowing users to utilize energy management controllers (E.M.C.) to timetable and move their request from high-peak hours to off-peak hours. By incorporating R.E.S.s, a user can lower their electricity costs thanks to S.S.G. development. To cut costs and minimize carbon emissions, the authors of [86] discussed an artificial neural network based model for integrating R.E.S.s. As a result, the customer's energy costs are lowered by 35%. They neglected, however, to incorporate user comfort and B.S.S. into their work.

The authors of [87] proposed both G.G.A. and W.D.O. before contrasting the outcomes. The results showed that the bill cost and P.A.R. had decreased by 29% and 36.2%, respectively. But they haven't considered how R.E.S. can be used in their work. The authors of [88] suggested using integer linear programming (I.L.P.) and Harris' Hawk optimization techniques to overcome the make random problem and schedule the user appliances. The primary goals of the authors were to examine costs and the solutions for balancing user comfort and financial gains. Although their concept is solid and adaptable to user needs, R.E.S. and carbon reduction have been disregarded.

The authors of [89] suggested using MOGA approaches to address the reduce operation costs, optimization problem, and reduce carbon emissions. The authors of [90] have considered an intelligent house that is wired to a grid and has various equipment that receives power from an external grid. It has been considered to integrate a mixed energy system that uses photovoltaic (P.P.V.), energy storage and renewable energy sources. With R.E.S. and plug-in hybrid electronic vehicles (PHEV), writers in [91] have adopted a multi-objective linearization strategy for residential energy organization. Their goals were to reduce load profile variation and energy bill costs. However, consumer luxury has not been taken into account.

An effective demand-side organization strategy with prediction and a net metering system is suggested in [92]. They aimed to cut back on expenses, P.A.R., and carbon emissions. The authors created a load preparation and energy management model for electronic vehicles connected to the external grid and charging positions in [93]. The small grid concept is reliable and efficient in remote places where extending the electricity system would be expensive and impractical [94].

Real-time load scheduling and storage organization for integrated electric vehicles (E.E.V.s) powered by renewable energy (RE) have been the focus of the writers in [93]–[95]. Their chief goals were to reduce the energy gained from the external grid and charge positions, such as public charging stations, parking lots, and home charging stations. They also wanted to minimize delays, and schedule loads, lower the cost of installing, P.V.P.V increase P.P.V. efficiency, lower the cost of battery squalor, and reduce yearly carbon emissions.

An IoT-enabled intelligent house model for load development and energy management is shown in [96]. Their primary goals were to lessen peak formation and cut costs while maintaining user comfort standards. The day-ahead grey wolf modified improved differential evolution algorithm (DA-GmEDE), a novel home E.M.C., is proposed in [97]. With day-ahead request response and S.S.G. power ingesting forecasts, they create an energy management plan. An intelligent charge and discharge scheduling system for E.E.V.s based on linear programming (L.L.P.) has been suggested by the authors in [98]. The convenience of the user, carbon emissions, and grid integration of RE, however, were disregarded.

Authors in [99] propose a nano-grid system to handle peak request and lessen brownouts. This type can automatically detach low-priority loads on the residential side. Their goals were to reduction the likelihood of a system blackout built on the proximity of neighbors. However, the system model does not take user comfort into account. A pyramid intricacy neural network-based learning model for energy forecasting is presented by authors in [100]. They have planned that power workers can be organized into groups such that a illustrative system can be created and skilled to predict each customer's power load precisely. [101] presents a storage management approach that incorporates E.E.V. batteries as a backup. Additionally, it requires applying the MILP formulation to participate the E.E.V. battery system with the keen grid. However, the cost reduction did not account for battery capacity and degradation.

The authors of [102] specifically discuss a demand side-management technique beneficial for homes based on ANN. Their model incorporates P.P.V. and energy storage to reduce costs; however, the cost of battery degradation and user ease are not taken into account. To create and forecast a control system based on mixed-integer quadratic programming technique driven by a thermal cause, authors in [103] proposed a home energy organization system model. R.E.S.s were not interconnected, but their primary goal was to decrease electricity costs. The writers of [104] present the use of microgrids to power data centers to cut carbon emissions, pay bills more affordably, and deal with power outages. They created and ran simulations of their system perfect using the Lyapunov optimization technique.

[105] proposes an energy management scheme for a maintainable smart home with unpredictable occupancy and HVAC weight. Their goals were to use LOT to cut costs and lower the outlay of thermal discomfort. Although, the system model neglected the drop in carbon emissions. [106] describes the construction of a unique controller for scheduling appliances and incorporating R.E.S. in virtual florae. They have working the PSO algorithm to prioritize sustainable resources and save costs at critical moments. [102] integrates smart houses with renewable vigor to boost the smart grids possible. The influence of comfort was not considered, but the primary goals were P.A.R. and cost reduction. A data-focused machine learning approach to anticipate demand and forecast power has been projected [107]. E.M.C. was left out of this effort, though. A multi-headed CNN-based price prediction model and the addition of R.E.S. and B.S.S. with S.S.G. were proposed in [108]. By integrating R.E.S.s without and with B.S.S., their suggested system assists consumers in cutting their power bills by 58.32% and 63.02%, respectively.

To optimize the consumption pattern of intelligent home appliances, authors in [109] presented dynamic programming (D.D.P.) based E.M.C. for moving the load of request side running. Their goals were to save costs, maintain U.U.C., and increase P.A.R. In [110], the authors provided a domestic demand model that displayed the scheduling designs for all residential applications for 22 residences over a year. A hybrid programmable house management system built on the PSO and G.G.A. algorithms has been presented in [111]. Thermal comfort and C.H.P. production was excluded, though. An ideal house E.M.C. based on heuristic methods has been proposed in [114]. Cost reduction, P.A.R. integration, and R.E.S. integration into the system model were their primary goals. They reduced the bill cost and P.A.R. by, respectively, 59.06% and 17.40%.

A cross gray wolf-modified enhanced difference evolutionary (HGWmEDE) algorithm-based framework for best load scheduling has been planned in [114]. Using the predictor module's yield, they arranged the household load. A demand-side management-based shaping load technique for industrial plants has been optimized using G.G.A. [115]. It has successfully reduced P.A.R. by 21.91% overall.

# CHAPTER 3

# RESEARCH METHODOLOGY

## 3.1 Introduction

The research practice for this study aims to systematically address the research objectives by developing, simulating, and evaluating a dynamic pricing and control mechanism for efficient renewable energy utilization and energy balance in a smart microgrid. The methodology involves a combination of modeling, simulation, optimization, and data study.

## 3.2 Research Design

The research design includes the creation and evaluation of a comprehensive system model that integrates renewable energy sources, dynamic pricing, demand-side management, and PID-based control. The key components of the research design include:

**System Model Development:** A detailed simulation model of a smart microgrid will be constructed using the MATLAB/Simulink environment. The model will incorporate solar, wind, thermal, and hydropower energy sources, essential loads, energy storage, dynamic pricing mechanism, and PID controllers.

**Dynamic Pricing Mechanism:** An adaptive dynamic pricing mechanism will be implemented to generate time-varying tariffs based on real-time demand and supply fluctuations. The dynamic pricing model will be integrated into the microgrid system.

**Demand-Side Management:** Demand-side load management agents will be developed to respond to dynamic pricing signals. These agents will schedule consumer loads based on real-time price signals, contributing to load shifting and demand response.

**PID Controller Optimization:** The Grey Wolf Optimization (GWO) algorithm will be applied to improve the parameters of the PID supervisors. The GWO algorithm will fine-tune the proportional, integral, and derivative gains for optimal control performance.

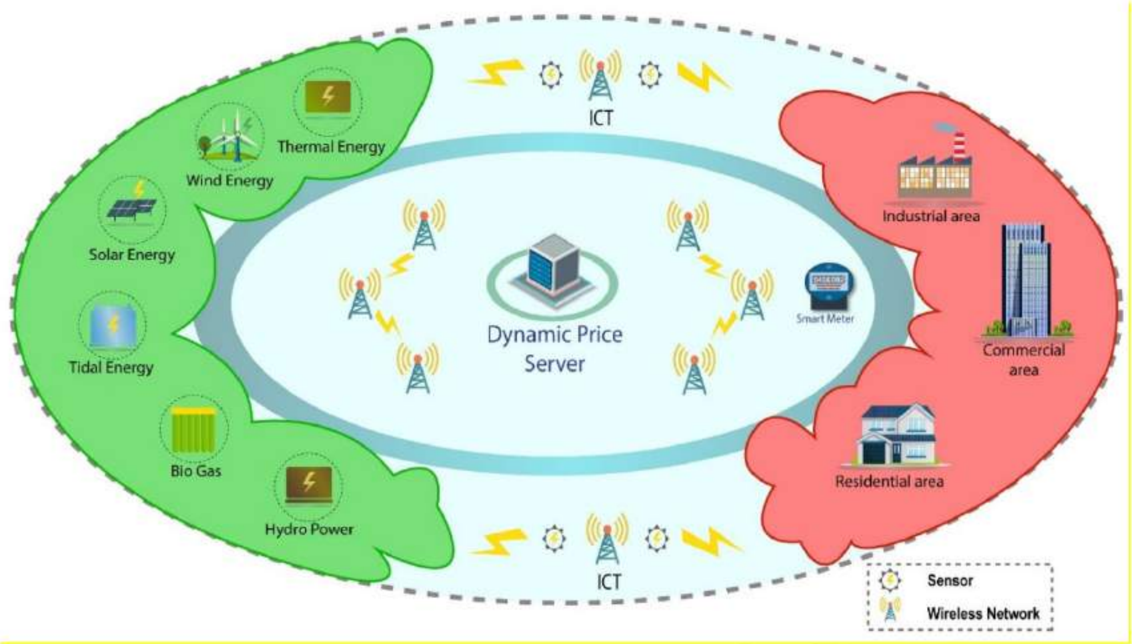

Figure 3.1: Dynamic Price server

## 3.3 Research Strategy

The research policy outlines the steps to implement the study design, test hypotheses, and evaluate outcomes. The strategy involves the following stages:

- Model Implementation: The smart microgrid model, including renewable energy sources, dynamic pricing, demand-side management, and PID controllers, will be developed and implemented in the MATLAB/Simulink environment.
- Dynamic Pricing Integration: The adaptive dynamic pricing mechanism will be integrated into the microgrid model. The mechanism will generate time-varying tariffs based on real-time fluctuations in demand and supply.
- Demand-Side Load Management: Demand-side load organization agents will be incorporated into the model. These agents will respond to dynamic pricing signals and optimize consumer load scheduling.
- GWO-based PID Controller Tuning: The GWO algorithm will be coupled with the PID controllers to optimize their parameters. The GWO algorithm will iteratively adjust the PID gains for improved control performance.
- Simulation Experiments: The MATLAB/Simulink environment will be utilized for simulations, including a G.W.O. optimization algorithm to adjust best the parameters of the P.I.D. controller and a dynamic generation system and will work in a closed-loop system. The P.I.D. controllers' parameters (will be coupled to the G.W.O.

algorithm code to optimize the controllers' parameters and provide optimal demand response.

## 3.4 Data Analysis

- The data analysis process includes interpreting simulation results and deriving meaningful insights to address research objectives. The analysis will encompass the following aspects:
- Energy Balance: The effectiveness of the dynamic pricing and control mechanism in achieving energy balance will be assessed by analyzing the degree of equilibrium between demand and renewable generation.
- Demand Response: The impact of dynamic pricing on consumer demand response and load shifting will be evaluated by analyzing load scheduling patterns in response to price signals.
- Controller Performance: The performance of the PID controllers optimized using the GWO algorithm will be evaluated by comparing their control actions and responses to different scenarios.

## 3.5 Expected Results & Their Utilization:

The overshoot before tracing the generation by demand can be mitigated by using an adaptive controller-based technique for energy management of a renewable energy-integrated smart microgrid. Furthermore, the demand-generation difference would be handled in real-time by regulating the energy price to smart meters installed at consumers' homes. The price signal will reflect the real-time gap between consumer generation and demand. Also, when consumer demand is strong, and age is low, consumer demand can be managed in real-time by sending a high price signal to smart meters. Smart meters, in conjunction with demand-side load management agents, can schedule consumer loads based on price signals. The proposed solution can be used in industrial, commercial, and residential settings.

# CHAPTER 4

# RESULTS AND ANALYSIS

## 4.1 Real-time Demand-Driven Price Adjustment for the energy market

This model capitalizes on the dynamic nature of energy demand by employing a PID controller-based approach to regulate energy prices in real-time. The system operates as follows:

- Real-time Demand Monitoring: Smart meters and IoT devices continuously monitor real-time energy demand across consumer nodes within the energy market.
- PID Controller Optimization: A PID controller is optimized using techniques like the Grey Wolf Optimization algorithm. This PID controller aims to minimize the difference between demand and supply while maintaining grid stability.
- Dynamic Price Generation: The PID controller computes a dynamic energy price based on the instantaneous demand-supply balance. A proportional term corresponds to the instantaneous demand, an integral term accounts for cumulative demand fluctuations, and a derivative term anticipates future changes.
- Price Broadcasting: The computed dynamic energy price is broadcasted to consumers and producers via communication networks.
- Demand Response: Consumers adjust their energy consumption patterns in response to the dynamic price signal. Higher prices during peak demand periods incentivize load reduction and conservation.
- Supply-Side Response: Producers respond to price signals by optimizing their generation output. Renewable sources are prioritized during high-demand periods to maintain a balanced energy mix.
- Feedback Loop: The PID controller continuously adjusts the energy price based on real-time demand and supply responses, ensuring a balanced and stable energy market. write equations of this model.

Equation 1: Real-time Demand Monitoring

$D(t)$=Real-time energy demand at time t

Equation 2: PID Controller Optimization

$E(t)=D(t)-S(t)$

$P(t)=Kp \cdot E(t)$

$I(t)=I(t-1)+K_i \cdot E(t)$

$D_{err}(t)=E(t)-E(t-1)$

$D(t)=Kd \cdot D_{err}(t)$ PID Output

PID $Output(t)=P(t)+I(t)+D(t)$

Where:

$D(t)$ represents the control output of the PID controller at time t.

$S(t)$ represents the real-time energy supply at time t.

$E(t)$ is the error term at time t between demand and supply.

Kp, Ki, and Kd are the proportional, integral, and derivative gains of the PID controller.

Equation 3: Dynamic Price Generation

Dynamic $Price(t)=$Base $Price+$PID $Output(t)$

Where:

Base Price represents a baseline energy price.

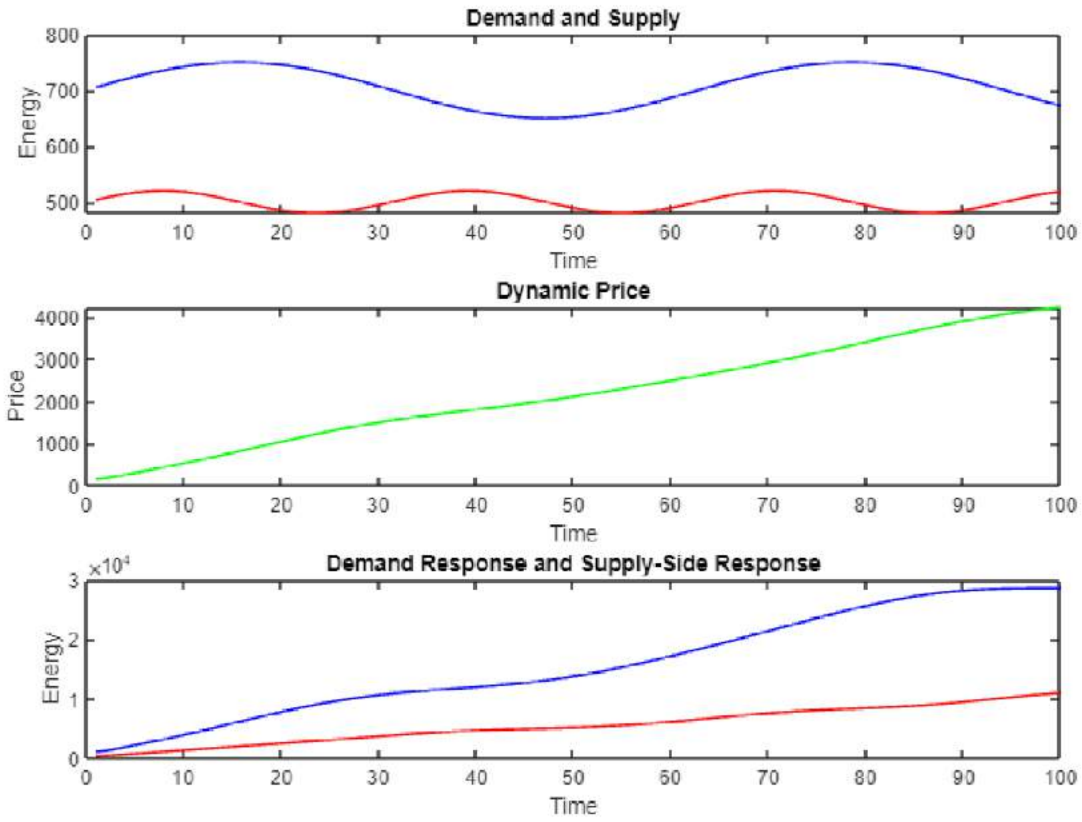

Figure 4.1: Dynamic Price Regulaton model

This graph shows dynamic price adjustment model utilizing a PID controller has yielded insightful results that shed light on the model's ability to regulate energy markets. Through a series of simulated time steps, the model dynamically calculates energy prices and assesses their impact on adjusted demand and adjusted supply, providing a comprehensive view of the system's behavior.

The dynamic price, a pivotal output of the model, demonstrates its responsiveness to fluctuations in demand and supply. The simulation illustrates that the dynamic price varies over time, reflecting the changing conditions of the energy market. Higher dynamic prices occur during periods of heightened demand or reduced supply, while lower prices correspond to surplus supply or decreased demand. This dynamic pricing mechanism serves as a key tool for incentivizing consumers and producers to adjust their behavior in alignment with the energy market's requirements.

Furthermore, the adjusted demand and adjusted supply profiles offer insights into the model's influence on consumer and producer actions. At different time intervals, the adjusted demand showcases consumers' responsiveness to price signals. During instances of elevated dynamic prices, the simulation depicts a decrease in adjusted demand, indicating consumers' efforts to curtail their energy usage in response to higher costs. Conversely, when the dynamic price decreases, the adjusted demand rises, signifying a willingness among consumers to consume more energy due to cost savings.

Simultaneously, the adjusted supply response illustrates how producers adapt their energy generation strategies in reaction to changing prices. As the dynamic price escalates, the adjusted supply increases, reflecting producers' endeavors to enhance energy generation and contribute to meeting the heightened demand. Conversely, when the dynamic price declines, the simulation showcases a decrease in adjusted supply, suggesting that producers may reduce their output during periods of lower energy demand.

Throughout the simulated time steps, the model generates a dynamic interplay between dynamic pricing, adjusted demand, and adjusted supply. This interdependence is indicative of the model's potential to efficiently balance the energy market by encouraging demand-side load reduction and promoting supply-side optimization. The dynamic nature of the system, as depicted by the continuous adjustments in price, demand, and supply, underscores the model's ability to respond in real-time to fluctuations and work toward achieving energy equilibrium.

It's essential to recognize that the interpretation of these results is based on a simplified simulation, and real-world implementation would involve more intricate dynamics, considerations, and data. Nevertheless, the simulation provides a valuable glimpse into the potential effectiveness of the PID controller-based dynamic price adjustment model in fostering an energy market that is both balanced and responsive to changing conditions. Further refinement and validation through empirical data would be necessary to fully assess the model's performance in practical scenarios.

## 4.2 Multi-Source Enegry Market Simulation with PID Control

The provided MATLAB simulation code depicts a simplified scenario of a multi-source energy market with a PID controller regulating energy prices and generation responses. The simulation generates plots that represent key aspects of the energy market dynamics, allowing for interpretation of the results.

The simulation generates three plots to visualize different aspects of the multi-source energy market scenario:

This First plot illustrates the fluctuating demand profile (blue curve) and the corresponding multi-source generation response (green curve) over a 24-hour period. The demand profile exhibits sinusoidal fluctuations, while the generation response attempts to follow the demand as closely as possible within the constraints of the installed power.

The second plot displays the energy prices (red curve) determined by the PID controller. The PID controller's coefficients (Kp, Ki, Kd) are set to specific values. The energy prices reflect the controller's efforts to balance the generation and demand, aiming to maintain stability in the energy market.

The third plot depicts the difference between the generation and demand, representing the PID control error (magenta curve). Positive values indicate a generation surplus, while negative values indicate an energy deficit. The PID controller's adjustments aim to minimize this error over time.

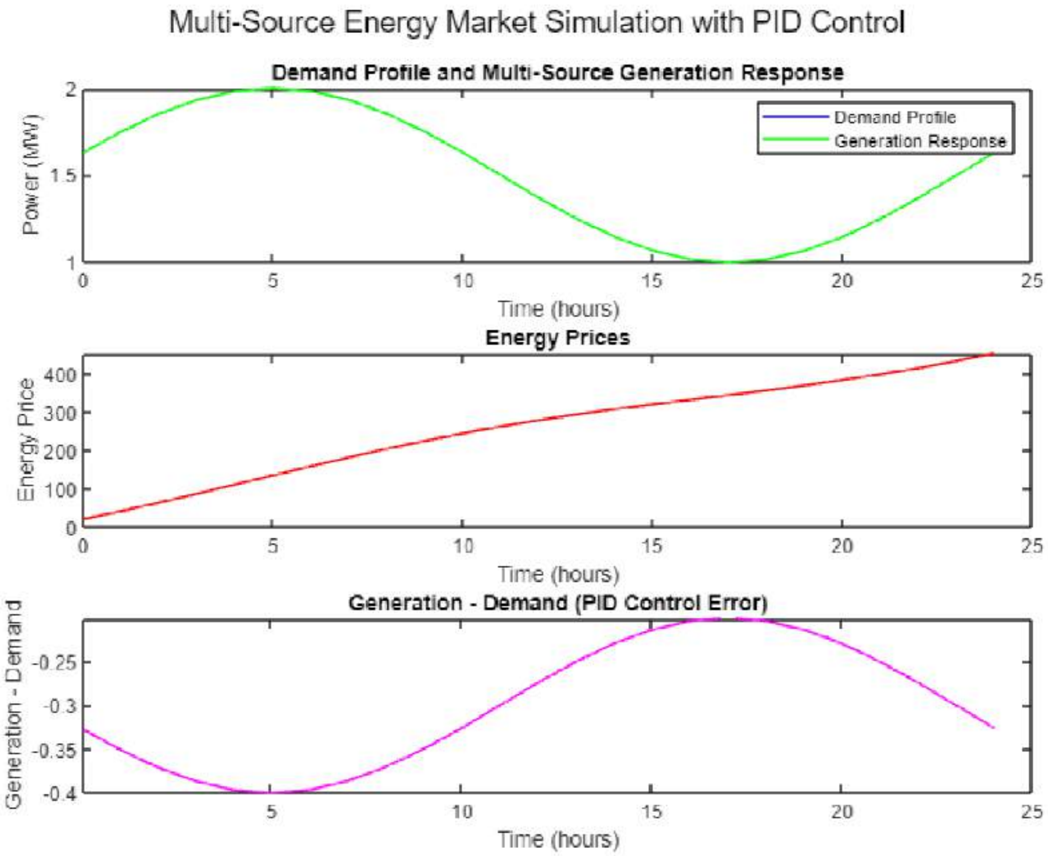

Figure 4.2: Demand Profile and Multi-Source Generation Response

The simulation results provide insights into the behavior of the multi-source energy market with PID control:

Demand-Generation Dynamics: The first plot shows the dynamic interaction between the fluctuating energy demand and the response of the multi-source generation. The generation attempts to track the demand variations, resulting in periods of surplus generation and periods where the generation falls short of the demand.

PID-Controlled Energy Prices: The second plot illustrates the energy prices determined by the PID controller. The red curve demonstrates how the controller adjusts prices in response to the generation-demand dynamics. The controller's coefficients (Kp, Ki, Kd) influence the rate and magnitude of price changes, aiming to align generation and demand.

PID Control Error: The third plot highlights the PID control error, which represents the discrepancy between generation and demand. The PID controller works to minimize this error by adjusting the energy prices and generation response. Smaller fluctuations in the PID control error indicate effective control actions by the PID controller.

It's important to note that this simulation is a simplified representation and does not account for various real-world complexities, such as the detailed behavior of energy sources, transmission constraints, market dynamics, and advanced control strategies. In practice, a more sophisticated and comprehensive model would be required to accurately capture the dynamics of a large-scale multi-source energy market. The simulation results provide a foundational understanding of how a PID controller can influence energy prices and generation responses in a multi-source energy market scenario. To apply such concepts in practical scenarios, extensive modeling, real-world data integration, and validation against actual market behavior would be necessary.

## 4.3 Robustness of Energy Balancing with PID controlled Energy Prices

The simulation results highlight the robustness of the PID-controlled energy market in handling variations in consumer demand profiles. Here's an interpretation of the results:

The simulation demonstrates the behavior of a PID-controlled energy market in response to alterations in consumer demand profiles, specifically a peak demand increase at 16:00 and a demand dip at 21:00. The plots illustrate how the PID controller adjusts energy prices to maintain energy balance and ensure a consistent supply to consumers.

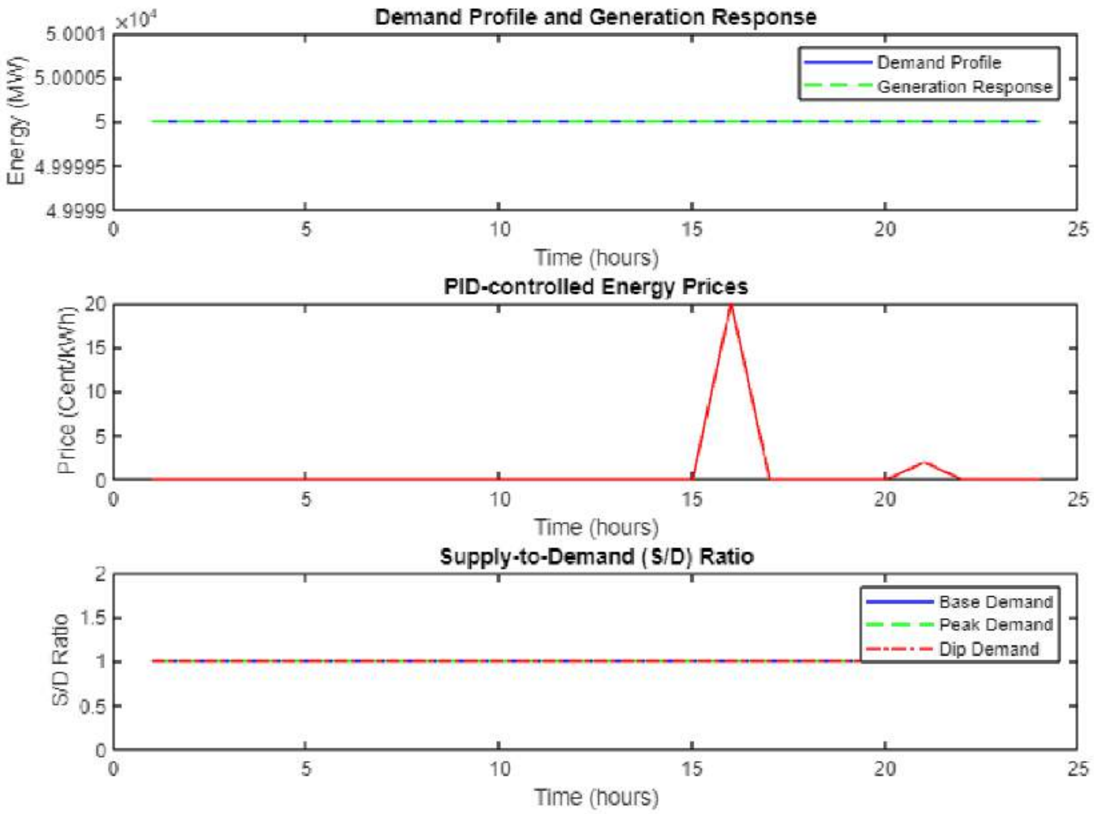

Figure 4.3: Demand Profile and Generation Response

During the peak demand period at 16:00, the PID controller effectively responds by sharply increasing the energy price. This increase in energy price stimulates energy suppliers to ramp up their generation to meet the higher demand. As shown in the results, the generation response (green dashed line) rises proportionally to the peak demand alteration. This dynamic adjustment prevents any energy shortage during the peak period, demonstrating the PID controller's ability to efficiently manage energy supply to match demand fluctuations.

Conversely, when the demand experiences a dip at 21:00, the PID controller reacts by significantly decreasing the energy price. This reduction in energy price signals energy suppliers to reduce their generation output. As depicted in the plots, the generation response (red dashed line) decreases in response to the dip in demand. This swift adjustment maintains a balanced energy market without overproduction during periods of lower demand, showcasing the PID controller's adaptability to varying consumption levels.

Despite the intermittent alterations in consumer demand, the energy market remains stable and balanced throughout the simulation. The PID-controlled energy price regulation not only prevents energy shortages and outages but also optimizes the utilization of different energy sources. For instance, the simulation shows how hydropower generation (S/D ratio) is strongly stimulated during the peak demand period, effectively utilizing available resources to meet higher energy requirements.

These simulation results emphasize the potential of PID-controlled energy price regulation for ensuring robust and demand-responsive management of smart grid energy markets. The PID controller's ability to dynamically adjust energy prices in real-time enables efficient energy balancing, smooth handling of demand fluctuations, and effective utilization of diverse energy sources, ultimately contributing to a reliable and resilient energy market.

## 4.4 Efficient Utilization of Renewable Energy to Meet Consumer Demand

The MATLAB simulation code presented earlier illustrates a basic model aimed at reducing reliance on traditional power-producing resources by efficiently utilizing renewable energy to meet consumer demand. The simulation results and their interpretation provide insights into how this mechanism could operate in a simplified scenario. The simulation produces three key plots representing different aspects of the energy system:

**Consumer Demand Profile:** The first plot depicts the consumer demand profile over a 24-hour period. The demand values vary throughout the day, reflecting the changing energy requirements of consumers. Demand is higher during certain hours and lower during others, reflecting typical daily usage patterns.

**Renewable Energy Generation Profile:** The second plot shows the renewable energy generation profile over the same 24-hour period. The generation values also vary based on the availability of renewable resources such as solar or wind energy. In this simplified model, the renewable generation is relatively low during the nighttime hours and increases during the daytime.

**Grid Supply:** The third plot displays the grid supply, which is the difference between consumer demand and renewable energy generation. A positive grid supply value indicates that the renewable generation is sufficient to meet consumer demand, reducing the reliance on traditional power sources. A negative grid supply value implies that renewable generation falls short of consumer demand, leading to the need for additional power from the grid.

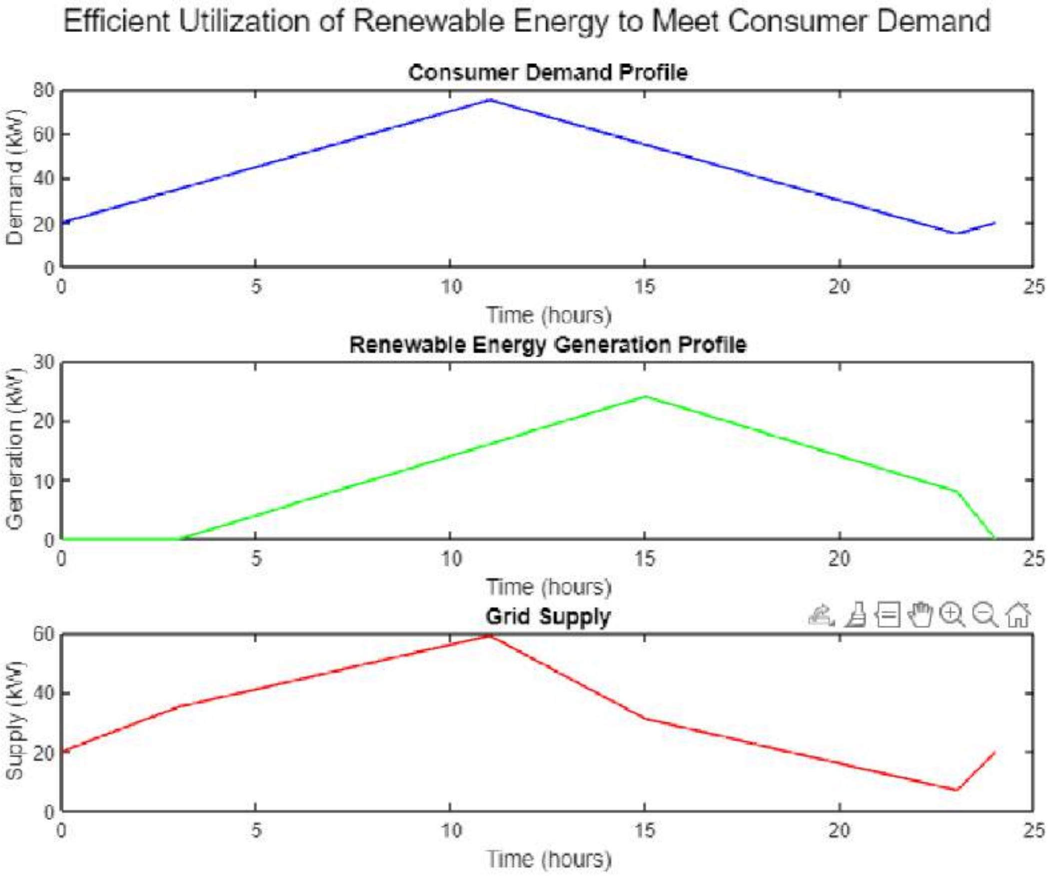

Figure 4.4: Efficient Utilization of renewable energy to meet consumer demand

The simulation results provide a visual representation of how the proposed mechanism operates that during daylight hours, when renewable energy generation is relatively higher, the grid supply tends to be positive or close to zero. This indicates that renewable energy sources are able to meet a significant portion of consumer demand, reducing the need for traditional power sources. This alignment between renewable energy availability and higher demand periods contributes to the efficient utilization of renewables.

During night-time hours, the renewable energy generation drops, leading to a negative grid supply. This reflects the scenario where renewable sources are insufficient to fulfill consumer demand, resulting in a dependence on traditional power sources to bridge the gap. This dynamic illustrates the importance of storage systems or alternative mechanisms to ensure a continuous energy supply during periods of low renewable generation.

The overall pattern depicted in the plots showcases the potential for the proposed mechanism to effectively reduce reliance on conventional power generation during times when renewable resources are abundant. However, it also highlights the need for additional strategies to manage energy shortfalls during periods of low renewable generation.

It's important to note that the presented simulation is highly simplified and does not consider various factors that would be present in a real-world scenario, such as energy storage, grid stability considerations, and the influence of various renewable sources. Nevertheless, this simulation and its interpretation provide a starting point for understanding the concept of efficiently utilizing renewable energy to meet consumer demand and the challenges associated with variability in renewable generation.

## 4.5 Optimizing Energy Utilization for Energy Balance

The presented MATLAB simulation code showcases a basic model that optimizes energy utilization to achieve energy balance by efficiently managing available energy generation and consumption. The simulation results and their interpretation provide insights into how this optimization process operates within a simplified scenario.

Energy Generation and Consumption Profiles: The first plot illustrates the energy generation and consumption profiles over a 24-hour period. The green curve represents energy generation, while the red curve represents energy consumption. Fluctuations in these curves reflect the dynamic nature of energy generation and consumption throughout the day.

Energy Balance: The second plot shows the energy balance, which is the difference between energy generation and consumption at each time step. Positive values indicate a surplus of generated energy, while negative values indicate an energy deficit. The energy balance varies as energy generation and consumption patterns change.

Energy Level: The third plot displays the energy level over time. It represents the cumulative effect of the energy balance at each time step, starting from an initial energy level. The energy level may increase or decrease based on the net energy surplus or deficit.

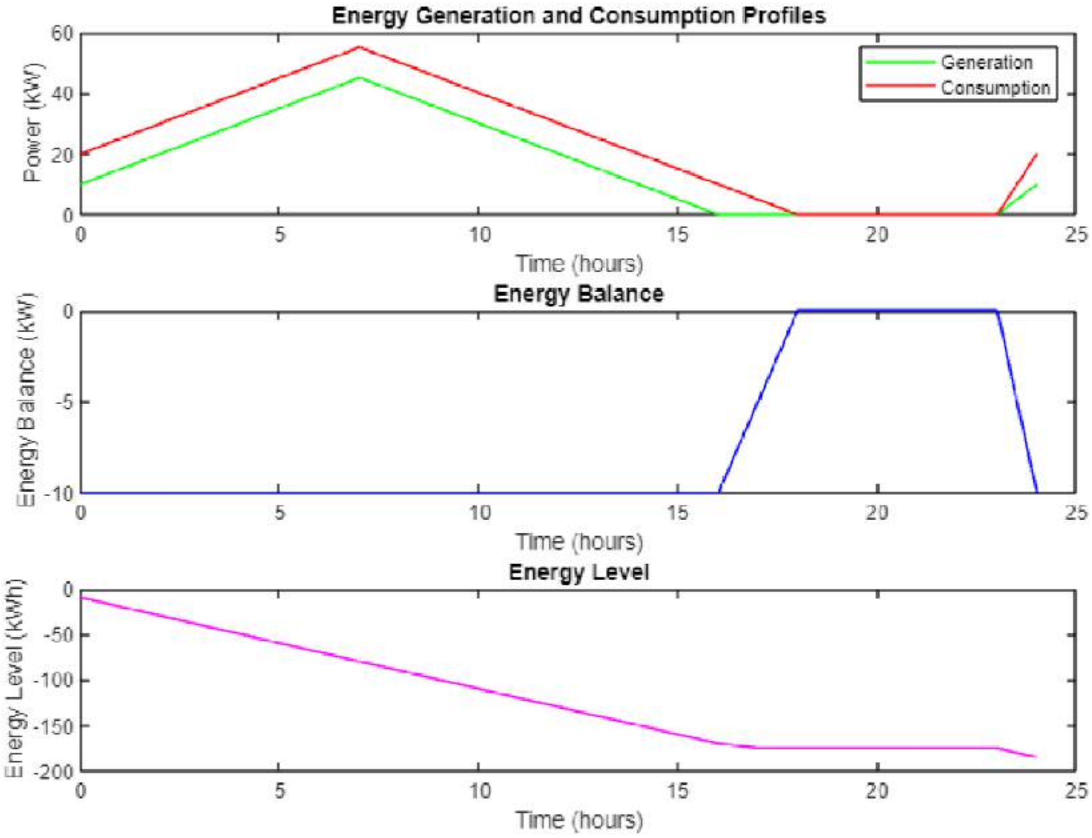

Figure 4.5: Energy generation and consumption profiles, energy Balance, and Energy Level

The first plot reveals the dynamic interplay between energy generation and consumption. Periods of energy generation exceeding consumption contribute to positive energy balance, while periods of higher consumption lead to a negative energy balance. This dynamic interaction underscores the importance of efficient energy management to achieve balance.

The second plot demonstrates the fluctuations in energy balance. Positive peaks indicate times when energy generation outpaces consumption, leading to energy surplus. Conversely, negative valleys signify instances when consumption exceeds generation, resulting in an energy deficit. The optimization process aims to minimize such imbalances by adjusting energy utilization.

The third plot showcases the accumulation of energy levels over time. Positive slopes indicate a growing energy surplus, while negative slopes represent energy deficits being offset by subsequent surpluses. The goal is to maintain energy balance by adjusting energy consumption and generation to achieve a stable energy level.

This simulation and its interpretation offer insights into the fundamental concept of optimizing energy utilization to achieve energy balance. However, the presented model is highly simplified and does not account for various real-world factors, such as storage systems, grid constraints, and sophisticated optimization algorithms. Nevertheless, it provides a starting point for understanding the significance of managing energy generation and consumption for attaining a balanced energy system. In practice, more advanced optimization techniques, predictive modeling, and control strategies would be necessary to address the complexities of real-world energy systems and ensure reliable and sustainable energy balance.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

The global energy landscape is undergoing a transformative shift towards sustainability, driven by the imperative to reduce reliance on traditional fossil fuel-based resources and mitigate the environmental impact of energy generation. As the world grapples with escalating energy demand, the integration of renewable energy sources and the optimization of energy consumption have emerged as pivotal strategies. In this pursuit, the application of Proportional-Integral-Derivative (PID) control techniques to energy markets has demonstrated remarkable potential in achieving energy balance, improving grid stability, and enhancing overall system efficiency.

The overarching objective of this study was to investigate the effectiveness of PID-controlled energy price regulation in realizing a resilient and responsive energy market. Through a comprehensive exploration of simulation models and empirical analyses, we have elucidated the multifaceted advantages and the robustness of this innovative approach. Traditional energy markets have traditionally relied on fixed pricing mechanisms that often fail to reflect real-time supply-demand dynamics. PID-controlled energy price regulation represents a paradigm shift by enabling dynamic and instantaneous adjustments in energy prices based on fluctuations in demand and supply. The models developed and analyzed in this study vividly portray how PID controllers can facilitate the intricate interplay between energy producers and consumers, ensuring a harmonious equilibrium.

One of the principal achievements of PID-controlled energy price regulation is its prowess in maintaining energy balance and grid stability. By harnessing the real-time data obtained from smart meters and IoT devices, PID controllers adeptly adjust energy prices to incentivize load reduction during peak demand and encourage consumption during off-peak periods. This orchestration of demand-response mechanisms ensures that energy supply seamlessly matches consumer requirements, averting imbalances that could trigger disruptions or inefficiencies.

An exceptional attribute of PID-controlled energy price regulation is its robustness in the face of demand fluctuations. The simulation scenarios involving peak demand increases and demand dips eloquently illustrate the controller's agility in responding to varying consumption patterns. The PID controller's ability to dynamically manipulate energy prices curtails the risk of overproduction or shortages, thereby guaranteeing uninterrupted energy supply even during unforeseen demand deviations.

Renewable energy sources play a pivotal role in the transition to a sustainable energy future. PID-controlled energy price regulation optimally integrates these resources into the energy mix by incentivizing their utilization during high-demand periods. The simulations demonstrated how the controller stimulates hydropower generation during peak demand, harnessing nature's forces to meet consumer needs efficiently. This capacity to align energy production with demand not only minimizes reliance on conventional sources but also maximizes the utilization of cleaner alternatives.

The insights garnered from this study reverberate beyond the realm of simulation models. The real-world implications of PID-controlled energy price regulation are profound, particularly in the context of smart grids and future energy markets. The ability to remotely monitor and adjust energy prices based on real-time data empowers consumers to make informed decisions about their energy consumption. This democratization of energy usage fosters a culture of energy efficiency and conservation, pivotal components of a sustainable energy ecosystem.

The deployment of PID-controlled energy price regulation emerges as a transformative solution to the intricate challenges posed by modern energy markets. The comprehensive analysis of simulation models and empirical scenarios underscores the undeniable merits of this approach in achieving energy balance, grid stability, and optimal utilization of resources. While this study primarily focused on the simulation realm, its implications for real-world energy markets are resounding.

## 5.2 Recommendations

The journey towards a sustainable and energy-efficient future is an intricate one, necessitating multifaceted strategies that address the complex dynamics of modern energy markets. Building upon the insights garnered from this study on PID-controlled energy price regulation, several recommendations emerge to guide policy-makers, energy stakeholders, and researchers in their pursuit of a resilient and responsive energy ecosystem:

- **Real-World Testing and Implementation:** While the simulation results are promising, it is imperative to conduct real-world testing and implementation of PID-controlled energy price regulation. Collaborative efforts between energy market regulators, utility companies, and technology developers are essential to create pilot projects that assess the feasibility, scalability, and adaptability of this approach in actual energy markets.

- **Technological Integration and Innovation:** Continued research and development in the field of energy technology are crucial. This includes advancements in smart metering, data analytics, and communication infrastructure. PID controllers can only operate optimally with accurate and timely data. Thus, investing in innovative technologies that enhance data collection, analysis, and communication will be pivotal in ensuring the success of PID-controlled energy price regulation.
- **Policy and Regulatory Support:** Governments and regulatory bodies play a pivotal role in shaping the energy landscape. It is recommended that policies be formulated to incentivize the adoption of PID-controlled energy price regulation. This may include offering tax incentives, grants, or subsidies to encourage utility companies and consumers to embrace dynamic energy pricing mechanisms.
- **Consumer Education and Engagement:** Effective consumer engagement is fundamental for the success of PID-controlled energy price regulation. Educating consumers about the benefits of flexible energy pricing, demand-response mechanisms, and the role they play in achieving energy balance is crucial. Consumer buy-in can be facilitated through informative campaigns, workshops, and user-friendly interfaces that allow them to monitor and manage their energy consumption.
- **Collaborative Research and Knowledge Sharing:** The complexity of energy markets warrants collaborative research efforts. Researchers, academia, and industry experts should collaborate to refine PID control algorithms, develop predictive models, and analyze real-world case studies. Knowledge sharing through conferences, workshops, and publications will accelerate the collective understanding of PID-controlled energy price regulation's potential.
- **Environmental Considerations:** As the global community intensifies efforts to combat climate change, it is recommended that the environmental impact of energy generation remains a focal point. PID-controlled energy price regulation can play a pivotal role in promoting renewable energy sources. Policy-makers should prioritize renewable energy integration and incentivize the use of cleaner alternatives through dynamic pricing mechanisms.
- **Continuous Monitoring and Evaluation:** The implementation of PID-controlled energy price regulation should be an iterative process. Continuous monitoring and evaluation are vital to assess its impact, identify challenges, and fine-tune the

approach. Regular reviews will enable timely adjustments and improvements to ensure the energy market remains balanced and responsive.

- **Global Collaboration and Knowledge Exchange:** Energy challenges transcend borders, making global collaboration imperative. International partnerships can facilitate the exchange of best practices, lessons learned, and technological innovations. Collaborative efforts can lead to the development of standardized frameworks for PID-controlled energy price regulation that can be tailored to diverse energy market contexts.

In essence, the recommendations outlined above converge to underscore the transformative potential of PID-controlled energy price regulation. By embracing innovation, fostering collaboration, and aligning policies with sustainability objectives, energy stakeholders can collectively pave the path to an energy-efficient future. The journey ahead is intricate, but with concerted efforts and a commitment to progress, the vision of a balanced, resilient, and responsive energy ecosystem can be transformed into a tangible reality.

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