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Techno-Economic Modelling and Optimization of Grid Connected PV-BESS Using a Linear Programming

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ABSTRACT:

With the worldwide turn to sustainable energy systems, photovoltaic (PV)-battery energy storage systems (PV-BESS) are at the center of elimination of grid-dependence and the maximization of energy use. By combining solar, wind energy and battery power, such systems are not only going to help reduce the emissions of carbon but also increase the efficiency of energy. The difficulty in maximizing energy use, grid tariffs, and integration of renewable energy is a serious problem despite its potential. The current optimization techniques are usually unable to resolve the intricacies of cost analysis and grid dependence in systems and this is where the gap that our research seeks to fill.

I applied Linear Programming (LP) optimization to optimize energy expenses and minimize the reliance on grid power, as well as enhance the overall energy efficiency of grid-connected PV-BESS systems. In particular, the study examines the roles of LP optimization in energy consumption optimization, economic effects of time-of-use (TOU) grid pricing, and battery storage system performance. Through the use of LP, the research should be employed to improve the cost-efficiency of energy systems and to incorporate renewable sources of energy in a more effective manner. The economic feasibility of the PV-BESS systems was analyzed by PV-BESS optimization models and real-world data were taken over Finnish Meteorological Institute and Vaasan Sähkö Distribution Company during the months of January to December 2020. The great importance of LP optimization in the way to gain a high level of cost savings with operating efficiently of renewable energy and battery storage. The LP model was discovered to minimize the costs in terms of exploiting less expensive energy in the off-peak periods, especially when TOU grid pricing is employed. Also, battery storage was imperative in minimizing grid power consumption, particularly when it is in peak demand.

These results imply that the tool of LP optimization is an efficient one in the management of energy costs and maintenance of the cost-effective and sustainable energy system. The study will make a contribution to the energy optimization research by providing a new tool of using LP optimization in combination with grid-connected PV-BESS systems particularly in terms of TOU price schedule along with clustering renewable energy to minimize grid dependence and lower the expenditures on energy. It offers worth to both energy system designers, utility companies and policymakers in evolving on the economics of renewable energy systems. The current research opens the door to future developments in real-time dynamic pricing, battery degradation, and more sophisticated forecasting models to optimize energy systems even more towards a more sustainable future.

KEYWORDS: Grid-connected PV-BESS, Linear Programming (LP), Cost Optimization, Time-of-Use (TOU) Pricing, Battery Energy Storage System (BESS), renewable energy Integration, energy consumption optimization, Grid Pricing

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background and Motivation

The world is changing its energy profile immensely with the growing demand of an eco-friendly and clean source of energy. The replacement of fossil fuels by renewable energy marks a turning point to solving the problem of climate change, energy security, and environmental degradation (Sovacool, 2014). Photovoltaic (PV) and battery energy storage systems (PV-BESS) are particularly important in this scenario as they contribute to decarbonization of electricity generation, increase resiliency in the grid, and decrease the reliance on traditional energy generation (Boruah & Chandel, 2024). As one of the most widespread and strongest renewable sources, solar energy has taken a central part in the process of forming renewable energy systems that are sustainable. Solar power generation is spreading globally with the growing investment on wind energy which collectively compose a large percentage that constitutes renewable energy mix (IRENA, 2020). Solar as well as wind energy however is by nature intermittent i.e. it can be generated or is slowed down by the weather, time of day and seasonal changes. This intermittency also provides a challenge to the grid operators who are required to manage the balance between supply and demand in real-time so as to maintain the continuous stability of the grid and reliability even in the event of changes in the renewable generation (Sharma et al., 2025).

Battery energy storage system (BESS) plays a critical role in reducing intermittency of solar and wind power as excess energy is stored when production rises more than when required and released when production is lower than required (IEA, 2025). Batteries are critical in the integration of renewable energy into grid as well as availing such advantageous features like load shifting, frequency regulation and voltage control, which improve stability and efficiency of the grid. Yet the PV-BESS system integration presents new complexities to the energy management, particularly in the optimization of the energy production, storage, and consumption (Muhsin & Hassan, 2025).

Cost optimization is among the key dynamic challenges of present-day-energy systems. The management of energy systems is further complicated by the fluctuating character of grid prices, in recommendations of time-of-use (TOU) pricing. When electricity prices repeatedly vary in the areas, timing on whether to consumed electricity over the grid, which store surplus energy of a renewable source, or discharge stored energy can lead to cost reduction on a large scale (M. Ren et al., 2021). These decisions are vital and need to be managed effectively, especially in the system where the demand of energy and the prices of energy fluctuate during the day.

The difficulties this present can be overcome through the use of linear programming (LP) optimization models. LP models have been extensively applied in the field of energy to determine the most economical operation of PV-BESS systems and reduce the dependence on the grid at the expense of greater exploitation of renewable energy (Superchi & Bianchini, 2026). Such models are capable of integrating several restrictions which may include battery storage capacity, grid demand and grid charges to determine optimal solutions of energy generation, storage and use. LP models can offer valuable information by solving these optimization problems on how to effectively operate PV-BESS systems and lower the cost of using energy and therefore become a valuable tool in future energy systems.

The goal of the study is to fill in the gaps to optimize grid-connected PV-BESS systems under dynamic grid prices with the help of LP optimization. This research aims at using LP models in order to optimize the interplay of solar generation, battery storage and grid utilization eventually lowering the cost of energy and increasing efficiency of the system. The rationale behind the study is based on the desperate need to enhance economic sustainability of renewable energy systems and also to guarantee reliable and sustained operation of the grid at the age of rising integration of renewable energy (Georgiou et al., 2020).

1.2 Research Problem

The growing infiltration of renewable energy resources, specifically, solar and wind power into the global electricity grid, has playful opportunities and challenges. Although renewable energy sources can minimize loss of fossil fuel consumption and emission of greenhouse gas, its intermittency renders instability in the energy grid. This is particularly common in grid-connected photovoltaic (PV) systems and battery energy storage systems (BESS) where the fluctuations in renewable energy generation have to be offset by consumer demand and grid demand (Zheng et al., 2021).

The research problem in this study can be discussed in the form of the optimization of the work of grid-connected PV-BESS systems, in particular, in terms of the cost optimization and grid pricing policies. Although the PV-BESS systems have the potential of decreasing the costs of electricity and increasing energy efficiency, to fully achieve the integration of the renewable energy with battery storage, superior optimization methods are needed to ensure efficiency in using the available resources (Mößle et al., 2025). The key difficulty is to limit the use of costly grid power, maximize battery storage operation, and balance the variability of renewable energy production.

The most recent studies with respect to grid-connected PV-BESS systems have been on the individual optimization of the system components that include PV panel efficiency, battery performance, and grid integration (Affonso & Kezunovic, 2019). Nevertheless, a clear gap in thorough research that includes time-of-use (TOU) grid pricing, linear programming (LP) optimization, and economic cost analysis to operate the system in real-time is noticeable (Carreras & Kirchsteiger, 2023). Regularly available studies generally ignore dynamic grid pricing, which discourse during the day, and the effect on the cost-effectiveness of PV-BESS systems of optimizing the energy storage and consumption. Moreover, the conventional tools in most cases do not offer the best solutions to reduce the cost of energy during grid prices decreasing in real time, and therefore cannot take advantage of the possible economic gains of deploying PV-BESS systems in energy management (Muhsin & Hassan, 2025).

Furthermore, the current approaches to optimization usually fail to utilize the numerous system constraints, including battery aging within timeframe, variability of solar production, or random energy supply-demand dynamics. Most research concentrates on unchanging assumptions which cannot explain the fluctuation in renewable energy supply and grid prices on a day-to-day basis, which in turn results in inefficiencies in the real-life situation in solutions (Lin et al., 2024).

Moreover, grid power in time-of-use (TOU) pricing in cost savings and energy efficiency has not been well studied with respect to the mutual interaction involving solar generation, battery storage, and the impact of both factors (Kumar & Kumar, 2022).

The current study would help to overcome these weaknesses by optimization of grid connected PV-BESS system by using linear programming (LP) in order to model the system and optimize it with consideration of time of use (TOU) pricing as well as real time grid price data (Luengo-Baranguan et al., 2026). This research will help occupy the research gap in the optimization of the economic functioning of PV-BESS systems by looking at the complete range of system constraints such as battery degradation, the changing nature of energy demands and the dynamic nature of prices. Moreover, the study will have informative insights in regards to how optimization of LP can enhance cost savings, energy-saving and system reliability by reducing grid dependence and a better utilization of renewable energy.

1.3 Research Objectives

The primary aim of this study is to create an efficient optimization model of grid-connected photovoltaic (PV) and battery energy storage systems (BESS) applying Linear Programming (LP) tools. The following research goals are developed to find solutions to the fundamental issues of energy consumption optimization, cost minimization and including renewable energy in the grid.

1. To optimize the use of energy and reduce costs with the help of LP models in grid connected PV-BESS.
2. The aim of this research is to examine the economic effect of time-of-use (TOU) pricing on energy system cost optimization.
3. To determine the effectiveness and the cost-efficiency of battery storage in decreasing dependence on grid power.
4. To determine the economic feasibility of using renewable energy sources (solar and wind) combined with battery storage in the cost optimization models.

1.4 Research Questions

The research questions in the given research attempt to resolve the key points involved in the cost optimization, energy management, and the combination of grid-connected photovoltaic (PV) systems and battery energy storage systems (BESS). The questions should assist in the research of the effect of Linear Programming (LP) optimization, time-of-use (TOU) pricing, and battery storage performance on the overall cost and efficiency of the energy systems. The following are the research questions:

1. What are the ways in which the optimization of the LP can be used to save costs in grid-connected PV-BESS systems?
2. How does time-of-use (TOU) grid pricing help to optimize the pattern of energy consumption and lower the total costs?
3. What impact does battery storage performance have on the dependency on grid electricity and cost optimization in renewable energy systems?

1.5 Scope of the Study

The area of study can be determined by the main aspects such as the geographical area of interest, the time period, and limits of the system. The study particularly aims at grid-connected photovoltaic (PV) and battery energy storage systems (BESS) with the view to optimizing the cost efficiency and enhancing energy management.

1.5.1 Geographical Focus

The research is on the energy systems of Finland since the country has been commendable in enforcing the integration and sustainability targets of renewable energy (Wali et al., 2023). The situation in Finland is interesting as it is highly dependent on renewable energy production, including wind and solar energy, and is implementing grid-connected PV-BESS systems (Lieskoski et al., 2024). These systems are tested in performance concerning Finnish energy conditions and policy (Such as the time-of-use (TOU) grid pricing system of the country) which is fundamental to analyze cost optimization.

1.5.2 Time Frame

The data reviewed in this paper is between January and December 2020. This time was chosen because it provides a detailed account of the seasonal changes in the amount of solar power produced, availability of wind energy, and the patterns of grid demand. It can also be used to analyze how the time-of-use pricing will influence the cost optimization of energy systems, particularly in the different seasons when there is a variation in the production of renewable energy owing to weather patterns (Finnish Ministry of Economic Affairs and Employment, 2019).

1.5.3 System Boundaries

It specifically looks at grid-connected PV-BESS systems and discusses Linear Programming (LP) optimization tool to reduce the cost of energy and enhance the efficiency of the energy system. The article assesses an energy system with a battery stored, and without a battery stored to understand how battery storage could lessen the dependence on the grid and simultaneously achieve cost savings especially at periods of high demand and peak costs. Also, time-of-use pricing is the only demand as the grid pricing model which is a key aspect of cost optimization (Pan et al., 2021; Zhuo & Savkin, 2019). Other pricing models like real-time pricing, demand-side management are not within the scope of this study.

1.6 Methodology Overview

The analysis also uses a Linear Programming (LP) optimization framework to assess and optimize the performance and cost of grid-connected photovoltaic (PV)-battery energy storage systems (BESS). Their primary aim is to reduce costs of energy and maximize on the use of renewable energy sources like solar and wind energy and the efficient use of the accumulated energy in the battery system.

1.6.1 LP Optimization Model

The fundamental algorithmic basis is a mathematical optimization strategy named Linear Programming which is broadly employed to facilitate the solution of problems with linear constraints and an objective function uses LP to make an optimal choice regarding integrating battery storage and renewable energy in the power grid. The LP model is designed in a way that it does the minimum amount of energy consumption by maximizing the use of grid power, solar PV, wind energy, and battery storage as a response to Time-of-Use (TOU) grid prices.

The optimization model accounts several variables, the State of Charge (SOC) of the battery, power production of solar (PV) and wind, and load demand. The end goal is to lessen use of grid electricity at high expenses by utilizing the saved energy of the battery or generated energy of solar and wind when possible. Limitations of the LP model would be battery charge/discharge limit, battery storage limit and renewable energy availability at various times of the day.

1.6.2 Cost Analysis

The cost analysis is carried out by delivering the total energy costs in two cases; as always, in one case of the system running without any optimization (baseline scenario), and in the other case of the application of LP optimization. The cost analysis will entail computing the cost of consuming grid power taking into consideration the energy consumption and time-of-use grid prices. An important detail of the analysis will be the assessment of the savings, which will be made available by the battery storage and integration of renewable energy, especially at peak grid price hours.

1.7 Chapter Summary

The increasing demand of green energy and the stress of having to include the intermittent renewable energy sources such as solar and wind in the grid. It characterizes the variability in the operation of renewable generation, and time-of-use grid prices by centering upon grid-connected PV-BESS systems in Finland and analyzing data over a year to understand these swings. The study shows that energy usage, battery storage and grid dependency can be updated through Linear Programming optimization, to be cheaper and more efficient. The study not only addresses key research questions that concern the cost savings and energy management but also provides a practical framework of how to optimize the integration of renewable energy by taking into account such constraints of the system as battery, seasonal variations, and dynamic prices. On the whole, this piece of work is important to highlight the economic and operational significance of PV-BESS system in aiding the reliable, economical, and sustainable energy transition.

2 Literature Review

2.1 Introduction

The growing energy requirements in the world, the need to mitigate the release of greenhouse gases has initiated striking changes towards green energy, including solar photovoltaic (PV) and battery energy storage system (BESS). With the global shift towards green and more sustainable energy, the inclusion of renewable energy technologies into the current power grid has attracted interest since they can alleviate climate change and reduce the consumption of fossil fuels. Among various renewable energy technologies, solar energy with battery storage systems has proved a feasible alternative to overcome intermittence in energy generation as well as grid instability. When solar and wind energy is combined with the storage facilities, the energy supply reliability can be enhanced, thereby alleviating the need to rely on the traditional power plants (Mohamad et al., 2021).

The adoption of such technologies (especially solar PV with battery storage) on the power grid has provided new challenges and debates. These systems not only lessen the reliance of traditional grid power but they also enhance reliability and efficiency of energy supply, especially during times of peak demand. This bilateral combination of renewable energy and storage will make energy management more sustainable, providing a way out of the negative consequences of the traditional energy production infrastructure, including variable fuel prices, emissions, and environmental footprint (Behabtu et al., 2020). Nevertheless, these systems also have attractive advantages, but they also need advanced optimization methods that will guarantee cost-efficiency and the difficulty level in integrating them into the current grid systems (Ahmad Khan et al., 2025).

We cover available literature on the optimization of grid-connected PV-BESS, with respect to their economics, technical performance and economic feasibility. The objective is to offer a detailed insight to the strategies employed to improve grid performance by applying the best models of optimization despite the emphasis on the Linear Programming (LP) models towards the minimization of operational costs and optimized production and consumption of energy. Specifically, the papers that have investigated the effect of time-of-use pricing (TOU), battery use, and grid interaction will be reviewed in terms of their impact on the general efficacy of these systems (Mohamad et al., 2021). This study is of significance because it not only aims at maximizing the energy expense but also enhancing energy security and minimizing environmental footprints.

2.2 Global Importance of Grid-Connected PV-BESS Systems

Energy is increasing as population, urbanization and industrialization continue to rise. Conventional energy systems, which depend on fossil fuel, are increasingly deficient in terms of their ability to offer a sustainable, economical and environmentally friendly supply of energy. As a response to these difficulties, there has been renewed research and policy interest as to how renewable energy sources such as solar energy and battery energy storage systems (BESS) can be integrated into the power grid. Such technologies have a great potential to reverse the effects of the energy production on the environment and solve the major energy security challenges. With the impending shift in a decarbonized energy future, grid-connected PV-BESS systems could be a great solution as the world works hard to lower greenhouse gas emissions in the atmosphere (Mulenga et al., 2023).

Most of the nations in the world have a goal of cutting down carbon emissions and switching to clean energy. Like the European Union, which has pledged to go carbon neutral by the year 2050 with emphasis on the application of renewable energy and energy storage technologies. Likewise, other nations such as China and the United States are also spending a lot of money on solar and wind energy technologies to sustain their power demands in addition to decreasing on their carbon footprints. The transformation to smart grids and renewable energy worldwide is not just an action to combat climate change but a strategy to create energy autonomy and decrease dependence on imported fuels and increase energy security (Dawn et al., 2026).

One of the essential elements of this transition is the evolution of grid-connected PV-BESS systems. Such systems have many benefits such as being able to counter the fluctuations in energy prices, streamline energy generation and consumption and increase resiliency in the grids. Additionally, PV-BESS systems are not only economically sustainable in environmental sustainability. Storing the solar power and maximizing the utilization of the same would allow huge cost benefits to the consumers, especially with time-of-use (TOU) price plans in place. Such systems can also provide a substantial reduction in electricity costs since they can allow consumers to use stored renewable energy when electricity prices are highest on the grid, therefore, decreasing the amount of electricity they must use when the cost of electricity is high. Moreover, their scalability and modularity can be easily integrated into both residential and commercial environments, which is why they can be used in a vast number of applications (Yuan et al., 2022). The grid-connected PV-BESS systems are increasingly being an inseparable part of the energy transition worldwide, as it can potentially provide an answer to issues of the rising demand of clean, dependable, and affordable energy. They are a key milestone in the implementation of sustainable development goals (SDGs) especially SDG 7: Affordable and Clean Energy. With the global community moving towards a low-carbon economy, the combination of renewable energy sources and energy storage solutions represents an avenue to energy independence, a lowered number of emissions, and an enhanced energy grid stability (Dawn et al., 2026).

2.3 Local Importance: Focus on Finland

Similar to several other nations in Northern Europe, Finland leads the transition towards the world of renewable energy. Being part of the European Union, Finland has already made ambitious climate targets that should result in net-zero carbon emissions by 2035, and one of the most ambitious in the world (Cederlöf, & Siljander, 2020). The energy policies of Finland are in line with these objectives, with a more apparent focus on increasing renewable energy production, enhancing its energy efficiency, and decreasing its reliance on fossil fuels.

Decarbonization of the energy sector has been highlighted by the Finnish government as one of the main solutions to tackle climate change and enhance energy security (Finnish Ministry of Economic Affairs and Employment, 2019).

The significance of grid-connected PV-BESS systems within the country of Finland can be traced to the geography and weather of this country. Although Finland receives relatively high amount of solar irradiance as compared to other countries in the northern region of Europe, it also has limited potential to produce energy as solar energy is seasonal. The long winters which give little sunlight also pose a challenge to the production of solar power and it is therefore important to get the maximum of the available solar energy in the summer months. Meanwhile, during the summer months, Finland enjoys the benefits of having long daylight hours which gives a chance to store surplus energy produced by solar photovoltaic (PV) systems at such times that can be tapped during dark months in the winter.

BESS can provide a feasible solution to this dilemma. Through combining solar PV systems and battery storage the variation of energy production seasonally can be removed and the additional energy stored in the summer months and utilized later on during the winter. Such a method will not only aid in energy self-sufficiency but also assist Finland to achieve its renewable energy-related goals in the EU. The issue of the green transition in Finland is also demonstrated by the energy taxation policies implemented in the country as tax breaks and renewable energy installation subsidies are provided, and the country has favorable regulatory climate towards battery storage systems (Heenatigala Kankanamge et al., 2026).

The ongoing research and pilot installations in Finland have proven the possibility and the financial advantages of introducing PV-BESS systems. By way of illustration, VTT Technical Research Centre of Finland has carried out several researches on how solar energy can be combined with a battery storage in homes and businesses. These reports have indicated that battery storage can decrease the cost of energy, add stability to the grid, and increase the security of energy by offering standby power during grid failures and maximizing energy use of power during peak hours (Pasonen et al., 2012).

With the goal of delivering on carbon neutrality, the design of PV-BESS systems should be included in the grid, as one of the key elements that would sustain the far-reaching climate objectives of the country. These systems are able to offer flexible and scalable and sustainable energy solutions that facilitate the energy transition in Finland as well as contribute substantially to carbon reduction initiatives. Additionally, with ongoing innovation of renewable energy and further expansion of its use in Finland, the relevance of a grid-connected PV-BESS system is going to become more important towards the realization of the long-term sustainability goals (Lieskoski et al., 2024).

2.4 Time-of-Use Pricing and Cost Optimization

TOU - Time-of-Use (TOU) is the platform that has become relevant in the planning of optimal use of energy and the productive incorporation of the renewable energy system, including solar PV and battery storage. TOU pricing is a pricing model in which rates of electricity change based on the time of the day with rates generally being higher during times of high demand, and lower during times of low demand. The idea behind this pricing model is that the price of electricity generation does not remain the same during the day with some being higher during those hours when demand is greater than supply, and lower during those parts of the day when supply is high (Li et al., 2020).

TOU pricing in grid-connected PV-BESS systems is an essential factor to influence customers in selecting the consumption pattern of the grid, solar power or battery supplies. The key to energy utilization in these systems lies on the possibility of storing surplus energy when the grids prices are low and consuming them when they rise to high values. This combination of renewable energy and battery storage enables the consumer to change their consumption pattern in accordance to the lower cost, off-peak times, and thus maximize cost savings. One of the advantages of TOU pricing is that it will motivate consumers to change their energy consumption habits to lessen the dependence on the grid and broaden their self-consumption of solar energy. The authors suggest that TOU pricing can be implemented alongside PV-BESS systems, which results in substantial cost savings as, in this case, the consumers can store the solar energy on the day when the electricity costs are lower and can take it at the evening or night when the cost of the electricity is higher (Li et al., 2020). This is due to the fact that by using battery storage they are able to bypass buying electricity at the grid when the rates are the highest and use that stored renewable energy. (Gabr et al., 2021) estimated that time-shifting energy consumption with battery storage can save residents of a large area on the cost of expensive grid power especially when power demand peaks in the evening.

TOU pricing can be more efficiently applied with smart grid technologies to achieve greater effectiveness in cost optimization. Smart grids are able to dynamically regulate the level of electricity usage depending on real time price changes, weather, and demand. This real-time optimization makes better integration of renewable energy sources and efficient operation of a battery storage system possible. Furthermore, modernized models of solar generation and load demand can open the possibility of making more accurate adjustments to the battery charge/discharge cycles, resulting in more cost savings, and more sensible use of solar power (Sepúlveda-Mora & Hegedus, 2021).

However, in spite of such obvious advantages, there are no difficulties associated with the implementation of TOU pricing. The introduction of TOU prices in most areas necessitates extensive modification of current energy pricing structures and grid facilities. In order to take full advantage of the TOU pricing, consumers need to invest in sophisticated energy management systems that would be able to program the charging and discharging of batteries in response to pricing signals. Moreover, local energy market forces, such as subsidies on renewable energy and storage systems and the regulations, affect TOU pricing efficiency (M. Ren et al., 2021). Combinations of dynamic pricing and energy storage systems are still in their maturing stages and there is much potential that will yet be covered in practical applications.

2.5 Linear Programming (LP) for Optimization in Energy Systems

LP is typically applied to optimize energy generation, storage and load dispatching in a renewable energy system taking into account a number of operational constraints, such as the demand of energy, the fuel price, and the environmental objectives, among other factors. LP assists in defining optimum level of renewable energy production to be stored or dispatched to fulfill the load demand due to the intermittent character of renewable energy sources like wind and solar (Georgiou et al., 2020). The limiting flexibility of LP is that it allows different kinds of constraints to be applied, including battery storage capacity, generation limits, and time-of-use (TOU) pricing, in order to produce solutions that optimize cost savings and optimization of the grid.

The grid-connected PV-BESS models based on LPs strive to maximize the timing of energy production and storage. The objective function generally aims to reduce the overall cost of obtaining electricity off the grid, this can be modeled to the aggregate of energy costs associated with each hour/ time period. The limitations are the relationship between solar PV energy generation, battery charge/discharge and grid consumption, and the battery state of charge (SOC) signals the constraints, and provide the battery with discharge and charge limits. Besides, it is possible to expand LP models to take into consideration more complex parameters such as battery degradation with time, renewable energy curtailment, and weather-related uncertainty (H. Ren et al., 2010).

Moreover, the optimization of LP models in the energy systems can as well include real-time pricing signals by the grid, that change during the day depending on the supply and demand. Through this, it is possible to decide when to charge and discharge the battery storage to take advantage of cheap electricity prices and to evade periods of high cost using LP to ensure economic efficiency. The time-of-use (TOU) pricing models are commonly modelled into the LP objective function and in that case the hourly price of electricity is considered to calculate the best strategy to use grid power or store energy (Pan et al., 2021).

LP based optimization has been found to be extremely useful in overcoming the difficulties of renewable energy integration, and especially solar PV coupled with battery storage. Nevertheless, nonlinearities promoted by the complexities of real-world systems tend to elude LP. As an example, the requirement to use more complex optimization methods such as mixed-integer linear programming (MILP) that can be used to consider both continuous and discrete decision variables may be caused by factors such as battery degradation, weather variability, and dynamic grid prices. Nonetheless, LP is still an essential optimization tool because of its simplicity, efficiency, and capacity to generate scalable solutions to energy systems that are well-large and intricate (Mazzoni et al., 2026). Linear Programming (LP) thus, offers a powerful and effective address to optimization of grid-connected PV-BESSs to enable minimization of cost, maximization of energy use and better grid integration. By determining the complex interactions between solar energy, battery, and grid interaction.

2.5.1 LP for Grid-Connected PV Systems

The facilitation of the adoption of solar photovoltaic (PV) systems into the current power grid has emerged as a foundation block in the move towards achieving a low-carbon and sustainable energy future. Nevertheless, the intermittency of solar power generation poses great grid stability and optimization issues of energy. Linear Programming (LP) has proven to be an effective way out of these issues by ensuring optimization of the functioning of grid connected PV systems. Linear Programming (LP) is specifically the most appropriate method to grid-connected PV systems, as it is capable of optimization of a plethora of system parameters, including energy generation, battery storage and grid interaction, with a number of constraints. The object of the application of LP in this case is usually the reduction of the cost of electricity acquisition in a grid, the efficient use of renewable energy and the overall power system throughput. LP is used to simplify the aspects of grid-connected PVs because it models how solar power generation, battery storage and grid power interact, and is inexpensive to buy electricity supplies at the high-demand times.

Moreover, it is possible to apply LP to grid-connected PV systems to multi-objective optimization, where several variables, including energy savings, same-grid stability, and emissions reduction, will be optimized together. The integration of renewable energy by taking into account these multiple objectives can be more comprehensive by having LP models do so. It is especially applicable to the example of the energy transition, at which insourcing solar power usage could become one of the tools to reach the objectives of decarbonization and environmentally-friendly energy use (Georgiou et al., 2020). When implemented with sufficiently relevant considerations, including TOU pricing, and battery efficiency, LP models will be important in reducing energy expenses, promoting the efficiency of renewable energy systems and ensuring a more sustainable and more affordable energy future. This fact is demonstrated by the high performance of the LP as a tool to optimize grid-connected PV systems, which contributes to the importance of this tool in helping to shift over to renewable energy and climate targets.

2.5.2 LP in Hybrid Energy Systems

Hybrid energy systems (which can be defined as the combination of various renewable energy sources e.g. solar photovoltaic (PV) and wind energy with battery energy storage systems (BESS)) These systems are expected to capitalize on the strengths of the various energy sources so that a constant, reliable and cost-effective supply of energy is achieved, which will also help minimize the dependence on fossil fuels. When buildings are hybrid and use a combination of solar, wind, and battery storage, these complexities must be considered and the optimal approach must be taken to make the best use of this energy and reduce the expenses. Linear Programming (LP) is one of the best ways to solve these optimization problems. These systems can be modeled by the application of LP models to establish the best power generation, storage, and dispatching plans. LP can also find the most cost-efficient solutions to satisfy the energy demand overtime by solving the linear equations that describe the relationship between the energy generation, storage and consumption. The objective function commonly used in LP models of hybrid systems aims at optimizing costs, or energy efficiency. The limitations of these models are generation capacity, battery storage capacity, energy demand, time-of-use pricing, and its operations like charge/discharge capacity of batteries and maximum power limit of the renewable energy sources (Vaccari et al., 2019).

The solar PV with the wind energy is a typical hybrid system, which comprises of the most common and complementary energy sources in renewable energy. During the day, solar energy is produced and during the night or overcasting seasons, the wind energy tends to be much and hence the intermittency of each source of energy is evened out. Hybrid systems can ensure that there is a continual power supply even in situations when one or more sources are out of service by combining these sources with battery storage that stores surplus energy produced during peak production periods. As an illustration, the wind can be used to battle up the battery at night; and the battery could be discharged during the daytime where there is solar power to supply the demand.

The use of LP to hybrid systems has been extensively developed in recent literature. (Vaccari et al., 2019) used LP to optimize the functioning of hybrid solar-wind-battery and discovered that LP helped to save a considerable amount of money related to grid electricity by way of optimizing the battery charging and discharging schedule. On the same note, (Derrouazin et al., 2017) developed a solar-wind-storage hybrid system, which is designed by using LP, and demonstrated that the system could offer a cost-effective approach and enhance energy security by saving expensive grid electricity in peak hours. The findings of such studies show that LP models are effective in the optimization of hybrid energy systems at the interaction of various sources of energy and the storage systems.

As a second factor of hybrid energy system, time-of-use (TOU) pricing should be involved in the process of optimization. TOU pricing is a difference between the price of electricity at various times in response to demand and supply. TOU pricing can be implemented in LP models with renewable energy systems and battery storage to analyze when to store the energy and when to discharge the battery, maximizing energy use and energy savings. Combining renewable energy with the use of TOU pricing will not only guarantee a cost decrease, but also grid efficiency and decreased dependence on fossil fuels (Najafi Ashtiani et al., 2020).

2.6 Empirical Literature Review

Part of the international studies on grid-connected PV-BESS will give the insights on the adoption of grid-connected PV-BESS systems in different regions and countries that have a different opportunity and challenge in their respective energy sector which estimated the economic value of grid-connected PV-BESS systems in the United States (Affonso & Kezunovic, 2019). The paper has analyzed the economic opportunities of incorporating solar energy with battery storage to reduce utilization of grid energy during a peak period and consequently, the electricity bills. (Keck et al., 2019) conducted another study of battery storage system in Australia, and the impact it made in facilitating lie of solar PV on the grid. The solar resources of Australia are reputed to be some of the best in the world and Australia has achieved a rapid growth in solar PV installations. The study came up with the conclusion that grid-connected PV-BESS systems were critical to reduce the energy costs to the consumers and improve the stability of the grid by providing power at the peak demand seasons.

A range of studies have been conducted in China, one of the biggest markets of solar PV globally, to enhance the energy security of remote areas and optimize energy prices in urban areas using PV-BESS. (Li et al., 2020) conducted research in their work to optimize grid-connected PV systems with a battery store in rural China. They focused the study on its energy independency and the potential of green facilities of solar-wind-batteries to provide a stable energy supply. It emerged that the battery storage systems played a significant role towards keeping a balance between supply and demand of energy in areas characterized by high solar penetration and low grid connection.

The studies on grid connected PV-BESS systems in the global context have exposed the potential of such systems to achieve optimal performance in terms of maximizing energy utilization, reducing the cost of energy and increasing grid resilience. These mechanisms prove to be particularly valuable in areas which have large solar potential and/or intermittent renewable energy resources, where battery storage can iron out intermittencies in energy supply. In addition, integrated time-of-use pricing with the smart grid technologies and hybrid energy systems can be useful towards enhancing the economic sustainability and performance of such systems. As the world gets ready to shift to cleaner forms of power, PV-BESS would still be an unlocking of energy sustainability and cost savings.

2.6.1 Regional Studies

There are a few studies investigating the role of PV-BESS systems in solving energy security and minimizing cost in Europe. As an example, a study by (Meriläinen et al., 2023) was held in Germany where it was attached to the integration of grid-connected PV systems with battery storage and evaluated the possibility to save costs in urban regions. Correspondingly, (Uddin et al., 2017) did a study of solar PV and battery storage implementation in residential and commercial areas in the United Kingdom. The significance of grid-connected PV-BESS systems was also highlighted in this study as they can help lower the cost of electricity and in stabilizing the grid especially where the residential adoption of solar is high. The researchers reported that battery storage played a critical role in preceding to allow the solar PV systems to cover the demand at peak hours and decrease the cost of electricity at peak hours. The research also was keen on the economics of the TOU pricing which stimulated the consumers to accumulate solar energy during low demand and consume it during the high demand time. Countries such as China and India in Asia that have fast rising energy demand have also incorporated grid-connected PV-BESS units in its push to satisfy its ever-increasing electricity demand and less dependence on fossil fuels. As an example, (Li et al., 2020) carried out a study in China to assess the feasibility of solar PV and battery storage in residential and business settings. The researchers concluded that solar energy production in China, which was propelled by the mega-solar farms and the home installations, was complemented efficiently by battery storage in lowering the energy expenses. The results highlighted that the battery storage was useful in overcoming the intermittence of solar generation, which assured consistent power supply in times when solar power would not be obtained.

Solar PV systems have been widely used in the Middle East region especially in countries like the United Arab Emirates (UAE) and Saudi Arabia which have much solar radiation. (Alfalah, 2025) conducted the study assessing the feasibility of solar PV and battery storage systems in Saudi Arabia and the UAE in terms of the urban environment and commercial buildings.

Chile has emerged as one of the most important actors in the integration of solar PV in Latin America, based on the high solar irradiance and government policies to encourage renewable energy. (Zurita et al., 2018) conducted a study to assess PV systems and battery storage within the Chilean markets of energy. The study determined that hybrid PV-battery systems also enabled an optimal utilization of energy during the daytime since surplus energy is stored in order to be used later. The analysis demonstrated that battery storage also assisted to minimize dependence on the grid during peak demand periods. Also, the paper proposed that TOU pricing would be an addition to consumer motivations to install PV-BESS systems to increase the financial profitability of such systems in the area.

2.6.2 Local Studies

Regarding the context of Finland, the possibility of the integration of grid-connected PV-BESS systems has been studied by local studies that have examined the viability, performance and cost-effectiveness of solar photovoltaic (PV) systems with battery energy storage systems (BESS). Since Finland is a country with a high latitude (to the North), the energy landscape creates particular challenges and possibilities in using renewable energy sources, mainly, solar power. The relatively low sunlight hours in winter do not mean that solar PV systems cannot be exploited effectively, although the strong quality of solar radiation in summer months will enable the use of this system to its maximum capacity with the incorporation of battery storage to ensure they make the most out of the energy and minimize their dependence on electricity produced through power grids.

One of the most important studies by (Derrouazin et al., 2017) was on the cost optimization and energy savings in the residential sectors of Finland through installing grid-connected PV-BESS. The research question looked into the economic feasibility of these systems in response to the specific climatic conditions and time-of-use (TOU) pricing schemes in Finland. The findings showed that PV-BESS systems decreased the energy expense very much annually, particularly when combined with TOU pricing that promoted use of solar power during low cost off-peaks. Other findings of this study were that battery storage assisted it in controlling this daily variation of energy, therefore, maintaining a steady supply of energy even during windless solar radiation. In the Finnish environment, solar energy proved to be more advantageous in energy consumption optimization and an energy-related decrease in the use of fossil fuels in summer months when the pressure on the grid electricity was decreased and solar radiation was more intense.

In a different investigation by (Heenatigala Kankanamge et al., 2026), authors emphasized conversely on the large-scale PV-battery hybrid systems used in the northern areas of Finland. The paper has examined how a battery storage can be an option to offer back-up power to remote locations where the infrastructure to support the grid is either inadequate or expensive to put up. In Finland local investigations on time-of-use pricing have demonstrated that despite the relatively low cost of energy in the country, the combination of a TOU pricing with grid-connected PV systems may considerably yield high economic returns. Formally, electricity rates in Finland are usually lower when demand is low, implying that by adding battery storage to TOU charges, it may be possible to maximize the cost savings by charging the battery during low-price periods of the day and discharging it during high-price periods. (Aksbi et al., 2025) carried out a study whose objective was to investigate how TOU pricing affects the functioning of grid-connected PV systems in Finland. The findings revealed that TOU pricing was an incentive to consumers to change their energy consumption habits and thus using the maximum amount of solar energy and save on the purchase of some costly grid electricity.

2.7 Research Gaps

Although there have been major breakthroughs in grid-connected PV-BESS systems and their optimization, a number of research gaps still exist, which must be filled in to enhance the efficiency, economic feasibility and scalability of such systems. A long-term performance and degradation of the battery storage systems in grid connected applications is another one of the major research gaps. Despite the considerable attention paid to battery energy storage in terms of its use to enhance energy efficiency and reduce cost, there is a considerable lack of literature that addresses long-term degradation of batteries owing to factors like cycling, changes in temperature, and depth of discharge (Tu et al., 2025). Due to battery deterioration with time, the cost-efficiency of PV-BESS systems will have diminished, which will result in poor cost calculation in the long-term application. New studies should concentrate on simulating battery deterioration and its effects on the total system output to have more realistic estimates of the life-cycle costs and advantages of such systems. There is another research gap related to the application of the models of the real-time pricing to the systems of grid-connected PV-BESS. Although a number of studies have focused on the use of time-of-use (TOU) pricing in the optimization of energy consumption and costs minimization, dynamism and real-time dynamic pricing and market-based pricing signals have hardly found their way into optimization models. Real-time pricing that is adjusted during the day according to supply and demand can be considered the more accurate reflection of the energy costs than fixed TOU rates.

Besides pricing models, another significant research gap would be uncertainty and variability of the renewable energy sources, specifically the solar power and wind power. Although current models of grid-connected PV system are inclined to believe that the energy production can be determined in a relatively predictable manner, the fact is much more complicated. The solar production is very sensitive to weather patterns, change of seasons and location (Li et al., 2020; Yuan et al., 2022).

The other important research gap is the incorporation of hybrid systems where solar PV, wind energy, and battery can be incorporated together. In spite of a few studies focusing on solar-wind-battery hybrids, little knows the interaction of the hybrids with the grid especially in different climatic conditions. Additionally, the potential of the grid-connected PV-BESS systems even at higher levels (residential, commercial, and industry) is under-researched. The PV-BESS big box systems would considerably reduce the costs and enhance the performance since the economies of the large-scale systems would be quite appealing to the industrial consumers, particularly in areas with high electricity prices and even high demand fees. Study of the viability and cost advantage of large-scale (Mohamad et al., 2021)grid-based PV-BESS system may help in shaping policy and the investment plans of commercial and industrial energy consumers.

Lastly, grid-connected PV-BESS systems do not provide certain information on their effects on the environment, which also serves as a research gap. Although the economic advantages of solar PV systems and battery storage are well-recorded, there are no in-depth researchers that assess the environmental footprint of these systems, especially regarding battery production and end-of-life disposal. Lithium, cobalt and nickel are some of the critical materials used in battery manufacturing and may have a significant environmental impact. Moreover, recycling and discarding of old batteries is problematic to the environment. The next research topic should be on life-cycle assessment (LCAs) of PV-BESS systems, based on the not only energy generation of the products but also the impact on the environments over the product life cycle.

3 Methodology

3.1 Research Approach

The research methodology used in this study is the quantitative research methodology that concentrates on optimization methods of grid-connected PV-BESS systems (Doroudchi et al., 2015). The main problem of this study is to test the economic viability and cost efficiency of solar PV systems-battery energy storage systems (BESS) employing the tool of linear programming (LP) as a method of optimization. This will enable systematic analysis of the energy consumption patterns, battery discharging/charging cycles as well as integrating solar energy into the grid together with minimizing costs incurring in their operation and maximizing on self-use of renewable energy (Rahmani & Mostefai, 2022). The analysis will model the relationships among different elements of a grid-connected PV-BESS system such as generation of solar PV, battery and electricity supply on the grid. The characterization of the problem as an LP optimization problem. In order to conceive such a method of research, a few crucial aspects are taken into consideration:

1. Linear Programming Model: Linear programming approach will be used, making the minimization of this total energy cost along with meeting the energy demand of the load constituting a mix of solar PV, battery storage and grid electricity. The model takes into account the major variables of decisions, including grid power consumption, the rate of battery charge/discharge, and excess renewable energy. The goal optimization problem is to reduce the total cost of electricity through optimal planning of the electricity storage and consumption (Vaccari et al., 2019).
2. Data-Driven Inputs: PV, wind, and grid prices of imbalance price is based on real-life data. The input-data includes the information between the year period of January 2020 and December 2020 and time-of-use (TOU) of grid electricity, which allows the model to add economic incentives to use renewable energy during the off-peak hours. Such inputs play a pivotal role in making economic sense of PV-BESS systems in the context of real-world conditions (Sepúlveda-Mora & Hegedus, 2021).

3. Energy System Modeling: The research model is the energy system modeled based on technical constraints and economic objectives. These are battery storage limitations, like those imposed by state-of-charge (SOC) and the balance between supply and demand; the power produced by the solar PV systems is consumed to fulfill the demand and excess energy is stored in the battery or wasted. The time-of-use pricing of grid electricity, which is time of day dependent, and the grid interaction is also implemented in the study such as when to pull or send to the grid (Mazzoni et al., 2026).

3.2 System Design and Configuration

The grid-connected PV-BESS system design and layout to implement the present study are important in fulfilling the objective of minimizing the costs and maximizing the energy. The system is made up of three main parts where there are the solar photovoltaic (PV) panels, battery energy storage system (BESS), and the grid interface. The components are collaborating to provide maximization of the utilization of solar energy, minimization of grid dependency, and minimization of energy costs (Ahmad Khan et al., 2025).

The solar PV system will be such that, it produces electricity using solar energy that will be utilized directly to serve the load demand or saved in the battery to be used in future. In this case, the size of the solar panel is determined according to the average solar irradiance available on the site of the interest and the system will be programmed to maximize self-consumption when there is a daylight since at that time, the production of solar is optimally high. The battery storage is used as a reserve of the extra energy produced by the solar PV system throughout the day, and used at night or between weather conditions when the solar generation is deficient such as pollutants or other ad hoc conditions. The battery capacity is set to balance the compromise between the cost and energy autonomy, whereby, enough energy is stored so that the load demand is not fulfilled at the expense of the use of too much capital with respect to installing the battery infrastructure.

The system will be tied to the electric grid, where excess power can be fed back to the grid when there is an excess power generation, and power can be imported to the electric grid when there is a load demand exceeding the ability of the solar PV system and battery storage. Time-of-use (TOU) price controls the interaction of the grid, PV, and battery, which also affects the optimization strategy of both energy consumption, charge and discharge. Linear Programming (LP) is used to optimize the configuration of the system to limit the expenses on grid electricity and use as much of the renewable energy presented by the solar PV system as possible (Georgiou et al., 2020).

3.2.1 Photovoltaic (PV) System

The Photovoltaic (PV) system used in this experiment, is one of the important elements of the grid-connected PV-BESS system, which produces electricity using solar radiation. The PV system is made to immediately turn sunlight into electricity via solar panels, comprised of photovoltaic cells. The levels of irradiance, the capacity of the solar panels, and the solar panel efficiency are the main factors that determine the solar energy conversion efficiency. Local solar radiation has a huge impact on the performance of the PV system and is affected with geographic location, time of year, or weather conditions (Sadat & Pearce, 2025). The solar irradiance (G) is modeled, in this work, on the basis of the past weather and the calculation of electricity output (P) of the solar PV panels is made by the next equation:

$$P_{PV} = A \cdot G \cdot n_{p_v} \tag{1}$$

Where:

- P_{PV} = Power generated by the PV system (W)
- A = Area of the PV panels (m^2)
- G = Solar irradiance (W/m^2), which varies throughout the day and year
- n_{p_v} = Efficiency of the PV panels (unitless), typically ranging from 0.15 to 0.20 for commercial panels

The size of the solar panels installed and the capacity of the system is directly proportional to the amount of installed solar panels and directly related to the available solar irradiance. Solar irradiance data will be obtained in this study through solar radiation databases or weather agencies whereby an hourly or a daily solar irradiance value is available based on the geographical place of study. The power produced by the PV system consumer is consumed to produce the load directly or can be stored in the battery to be utilized later. The quantity of the surplus solar that remains after powering up the load is known as the surplus PV power and is stored in the battery storage system that can be availed when the load demand is low (Yuan et al., 2022).

The solar generation profile is a daily cycle and its output is normally maximized in broad daytime when the irradiance of the sun is maximized and minimalized in the morning and evenings when the irradiance of the sun is less. Solar production curve plays a vital role in optimizing the PV-BESS system because it has a direct impact on the battery charging and discharging cycle and interaction with the grid. The amount of energy that the PV system produces at any given time period (usually every 15 minutes or an hour) is modeled in our dataset and then utilized in the optimization problem to ensure minimum use of energy and maximum use of solar energy that is self-produced. The time-of-use price is also essential in optimization of charging and discharging the battery with the price of grid electricity varying according to the time of the day (Sepúlveda-Mora & Hegedus, 2021).

3.2.2 Battery Energy Storage System (BESS)

Battery Energy Storage System (BESS) is a part of the complete connected grid-based PV-BESS system, and is meant to store surplus energy created by the solar PV system and use it later. The BESS facilitates better energy use, minimizes grid dependence and increased energy security by offering the stored energy in seasons when the solar generation is low or when electricity in the grid is costly. The variables that can affect the overall behavior and the cost-efficiency of the system are the storage capacity and the charging/discharging cycles of the battery. The State of Charge (SOC) that is the amount of energy stored by the battery at any point in time that is expressed as a percentage of the maximum storage capacity rules the performance of the battery (Meriläinen et al., 2023). Two processes, namely charging and discharging, affect the SOC (when the battery gains power and when the battery releases power, respectively). The equation below can be used to describe the dynamics behind the SOC:

$$\mathrm{SOC(t)} = \mathrm{SOC(t\text{-}1)} + \frac{n_{charge} \cdot P_{charge(t)\,.\,\Delta t - \frac{P_{discharge\,(t)\,.\Delta t}}{n_{discharge}}}}{C_{battery}} \tag{2}$$

Where:

- $\mathrm{SOC(t)}$ = State of Charge at time (t) (Wh or %)
- $\mathrm{SOC(t\text{-}1)}$ = State of Charge at the previous time step (t-1) (Wh or %)
- $\mathrm{P_{Charge}(t)}$ = Charging power at time (t) (W)
- $\mathrm{P_{discharge}(t)}$= Discharging power at time (t) (W)
- $\mathrm{n_{charge}}$ = Charging efficiency (unitless, typically 0.95)
- $\mathrm{n_{discharge}}$ = Discharging efficiency (unitless, typically 0.95)
- Δt = Time interval (hours or minutes)
- $\mathrm{C_{battery}}$ = Total battery capacity (Wh)

This equation demonstrates how the SOC varies with time as per the charging and discharging operations with the efficiency factors taking into consideration the loss ratio during the two processes.

BESS capacity is often set by how much power is likely to be needed, how the sun is predicted to shine, and how long the battery is needed to go without power grid support (often in terms of hours). The peak charge and discharge rates of the battery also have a influence on the responsiveness to the changes in demand of the battery and these limitations are added to the optimization model. The life cycle of the battery and its degradation should also be taken into consideration to guarantee the reliability and economic performance of the system (Mazzoni et al., 2026). With time repetitive charging and discharging processes result in a decline in the capacity of the battery and hence may influence the cost-effectiveness of the system in the long term. Battery degradation is not part of the basic optimization models, but can be added to the model to enhance the ability of the model to give an accurate result in the long run in financial analysis.

3.2.3 Grid Connection

The grid connection is a vital part of the grid-connected PV-BESS mechanism that enables the combination of solar energy, battery storage and grid energy to maximize the energy use and cost-effectiveness. The grid interface is effective in allowing the system to be connected to the grid so that the system can take in energy during low levels of solar generation and release excess energy to the grid during times of overproduction (Derrouazin et al., 2017). Such an interactive process with the electric grid can be used to minimize grid dependency and costs of electricity through the use of solar PV and the battery storage at the most opportune time possible. The energy balance between the grid and PV-BESS system may be represented as the following equation:

$$P_{load} = P_{pv} + P_{battery} + P_{grid} \tag{3}$$

Where:

- P_{load} = Power required by the load (W)
- P_{pv} = Power generated by the solar PV system (W)
- $P_{battery}$ = Power discharged from the battery to meet load demand (W)
- P_{grid} = Power imported from the grid to meet load demand (W)

The grid connection can accommodate two-way power flow, where the system may take electricity when the solar PV, and battery storage are not adequate to supply the demand and supply excess energy when the battery is fully charged and the solar generation is more than the demand. The energy change with the grid is determined by the following equation:

$$P_{grid} = P_{load} - (P_{pv} + P_{battery}) \tag{4}$$

Where:

- P_{grid} is the power imported from or exported to the grid (W)

Connection can be based on time-of-use (TOU) pricing or which can be dynamic pricing, wherein the price of electricity delivered over the grid can change based on the time of day. The grid pricing in this study is defined as hourly charges depending on the demand and supply characteristics that will guide the best strategy to charge and discharge the battery and utilize the grid electricity (Pan et al., 2021). The aim is to reduce the overall grid cost by maximizing the utilization of solar energy and battery storage and reduce the acquisition of grid electricity at peak periods. The grid cost can be computed according to the formula:

$$\text{Grid Cost} = P_{\text{grid}} \,.\, \text{Grid Price} \,.\, \Delta t \quad (5)$$

Where:

- Grid Cost = Total cost of importing energy from the grid (USD)
- P_{grid} = Power imported from the grid (W)
- Grid Price = Cost of electricity per unit (USD/kWh)
- Δt = Time interval (hours)

The grid price normally is of a time-of-use scheme where the cost of electricity is high in peak times and low in off-peak times. The model has been included with the linear programming optimization model to establish the optimal patterns of energy usages that would minimize electricity expenditures and maximize solar and battery usages.

3.3 Linear Programming (LP) Model for Optimization

In the current study, the Linear Programming (LP) model will be used to optimize the working of the grid-connected PV-BESS system, which will strive to minimize the cost of energy and meet the load demand. The aim is to establish the optimal energy dispatch model, including the solar PV system, battery, and grid electricity, given the time-of-use (TOU) pricing. The LP model effectively accounts for optimization of cost and power balance of the system through linear relationships (Vaccari et al., 2019). Minimizing the overall cost (including the costs of imported grid electricity, battery charging and discharging) is the idea, i.e.:

$$\min Z = \sum_{t-1}^{n} P_{\text{grid}}(t) \,.\, \text{Grid Price}(t) \,.\, \Delta t + P_{\text{charge}}(t) \,.\, \text{Charge Price}(t) \,.\, \Delta t + P_{\text{discharge}}(t) \,.\, \text{Discharge Price}(t) \,.\, \Delta t \quad (6)$$

Where:

- P_{grid} is the power imported from the grid.
- P_{charge} is the battery charging power.
- $P_{discharge}$ is the battery discharging power.

Constraints

1. Power Balance: Energy equal supplied by the combination of solar pv, battery releases and grid energy.

$$P_{load}(t) = P_{pv}(t) + P_{discharge}(t) + P_{grid}(t) \tag{7}$$

2. Battery SOC Dynamics: State of Charge (SOC) of the battery is updated depending on charging and discharging:

$$SOC(t) = SOC(t-1) + \frac{n_{charge} \cdot P_{charge(t)} \cdot \Delta t - \frac{P_{discharge\,(t)}}{n_{discharge}} \cdot \Delta t}{C_{battery}} \tag{8}$$

3. Grid Power Limits: The maximum grid import capacity restricts the power that can be imported using the grid:

$$P_{grid}(t) \leq P_{grid}, \max \tag{9}$$

4. Solar Power Generation: The maximum power that can be produced by the PV system is the same as that produced by the available solar energy:

$$P_{pv}(t) \leq G(t) \cdot A \cdot n_{pv} \tag{10}$$

5. Non-Negativity: The power variables should be non-negative.

$$P_{grid}(t) \geq 0, P_{charge}(t) \geq 0, P_{discharge}(t) \geq 0 \tag{11}$$

3.4 Data Collection and Sources

The information employed in this investigation is mainly obtained in the Finnish Meteorological Institute and Vaasan Sahko Distribution Company. In particular, temperature, solar radiation (global, diffuse, and direct), wind speed, and air temperature data were taken at Finnish Meteorological Institute. Furthermore, the data on the load demand in the case of a mediumvoltage (MV) transformer was received in Vaasa Sahko Distribution Company. The data is essential in modelling and optimization of grid connected photovoltaic-battery energy storage system (PV-BESS), which forms the required real-world parameters to simulate the performances of the system. The data will be one year of data between January 2020 and December 2020 to provide hourly data on solar output, load demand and grid pricing.

3.5 Limitations

Although the assumptions make the modeling process straightforward, there are some limitations associated with it and need to be factored in the interpretation of the results. First, the factor of constant sun radiation ignores effects of cloud cover, change in seasons and weather conditions which influence production of solar energy. Also, the model of the load demand is calculated using previous data, and the unexpected change in energy consumption is not taken into consideration (e.g., the decrease in economic activity or an emergency situation). Another weakness is the simplification of battery degradation as in real-life, batteries become degraded with time since they undergo a number of charge-discharge cycles. This will result in diminished efficiency and capacity which may affect the overall economic operation of the system in the long-term. In addition, the assumption of 100 percent charging and discharging efficiencies does not indicate the real-world energy losses in these processes. Impact of real-time grid price and dynamic price is also not included in the model; it may influence the operating approach and the economic performance. Finally, the geographic coverage of research is restricted to a certain area and findings cannot be extended to the other regions with alternative solar irradiance patterns or grid-based pricing plans. These drawbacks are important when interpreting the outcomes of the model, and future research might fill in these limitations by using more sophisticated model assumptions and uncertainties to enhance the accuracy and applicability of the results.

4 Results

4.1 Introduction

The grid-connected Photovoltaic-Battery Energy Storage System (PV-BESS) optimization model and simulation that dwell upon the economic performance, cost savings, and load satisfaction of the system after a 24-hour time. This research aims to determine the efficiency of Linear Programming (LP) model to minimize the energy or power usage and costs optimization in a grid-tied system and meet the demand. Here, the outcomes of the system performance in terms of energy generation, storage application, and the entire cost implication of the system are elaborated. The system is demonstrated to be effective in getting desired results through different numbers such as time-of-use grid price curve, hourly comparison of the cost, load satisfaction breakdown, and cumulative costs. The outcomes are compared to the baseline system that is based on only grid electricity to emphasize the advantages and cost efficiency of utilizing renewable energy sources and storage systems.

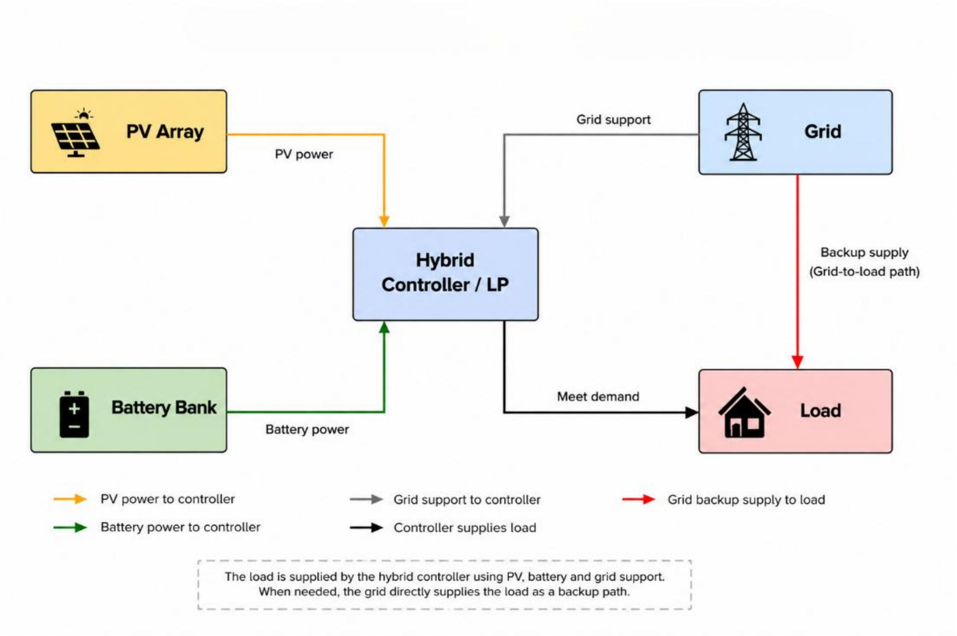

Figure 1. Hybrid energy system with load connected grid

The hybrid energy system whereby the PV array, battery bank and the grid interact to provide the load. The hybrid controller or linear programming unit is in charge of the power flow; they utilize the PV power first followed by battery power when this is not available as well as grid support as back-up in figure 1. The load is straight up with the grid thus the grid can provide electricity whenever the renewable sources are not available. By so doing, the system provides reliability and continuity in the delivery of power to the load by coordinating the energy management.

4.2 Time-of-Use Grid Price (First 24 Hours)

Time-of-Use (TOU) grid price figure 2 shows the change in the price of electricity during the day with regards to the demand and the supply aspect in the grid. Here we discussed grid prices in terms of the hourly values over the initial 24 hours of system operation data obtained from the Finnish Meteorological Institute and Vaasan Sahko Distribution Company. Identity of price curve When the insurance of time-varying electricity costs, the price curve is an important factor in the optimization choices we will make in the grid-connected PV-BESS system when the grid prices are rather low during the early morning periods, midnight to 6 AM which is the off-peak period when the renewable energy demand is low in figure 2 and large amounts of renewable energy which is often free, like wind or solar is There is a sharp rise of the grid price at the time of noon, reaching its highest value at 12 PM, which can be attributed to the fact that there is a high demand in the middle of the day and this fact may explain why renewable energy generation is also high, hence costs are higher. Following this peak, the grid price moves slowly downwards but changes and swings during the afternoon and early evening hours, probably, because of other demand patterns during the day. Later real-time pricing increases a bit in the evening after 9 PM, which might be caused by the higher need in energy expenditure on activities such as heating or cooling. This type of time of use grid pricing curve reproduces typical demand variability and indicates major periods when energy storage might save considerable costs by allowing lower-cost electricity to be used during off-peak demand periods, and causing less use of costly grid power during peak times.

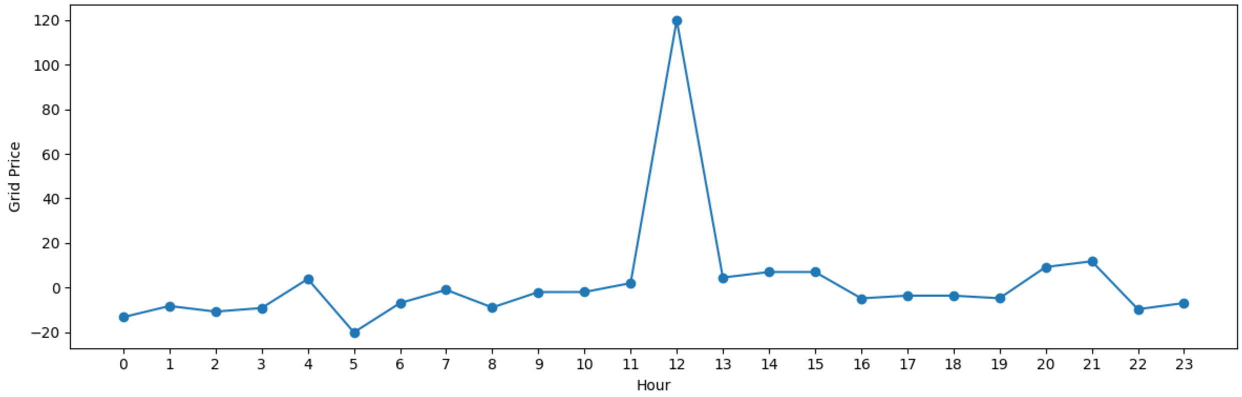

Figure 2. Time-of-Use Grid Price (First 24 Hours)

The TOU grid price is usually arranged so as to represent the times of high demand when electricity prices are highest (e.g., in the midday and early evening) and times when there is low demand, and the electricity price is much less (e.g., at night or in the early morning).

4.3 Hourly Cost Comparison for the First 24 Hours (Baseline vs. LP)

The current situation is that in the conventional system, the load power is mostly supplied by the grid and there is no effort to time when the power is used, or to incorporate renewable energy sources. The grid electricity prices have a fixed pattern according to TOU pricing; costs are higher during peak demand hours (usually during the midday and early evening) and lower during off-peak hours (usually during the night). The Baseline Cost (blue bars) and the LP Cost (orange bars) can be viewed as in the hourly cost comparison figure 3. The Baseline Cost is that of the system where it operates with no optimization or battery storage, but only use grid power to satisfy the load demand. Conversely, the LP Cost indicates a case when the Linear Programming (LP) optimization is used, which can include battery storage and more efficient energy management, including its use of renewable energy, namely PV and wind. The graph demonstrates that the costs are greatly rolled around 12 PM, which corresponds with the high demand and grid prices, and the LP model cost-reduces the cost, during the peak, by using the cheaper energy options. The LP Cost is also significantly lower than the Baseline Cost throughout the rest of the day, especially during off-peak times, which illustrates the advantages of LP optimization of cost-reduction. During certain off-peak periods the two costs become negative meaning that the excess renewable power is being used more effectively in the LP case, which may be stored or sold back into the grid. Altogether, this number testifies to the fact that the optimization of LP will be able to result in significant saving of costs, especially, when it comes to battery storage and renewable energy being effectively combined when high prices occur in the grid.

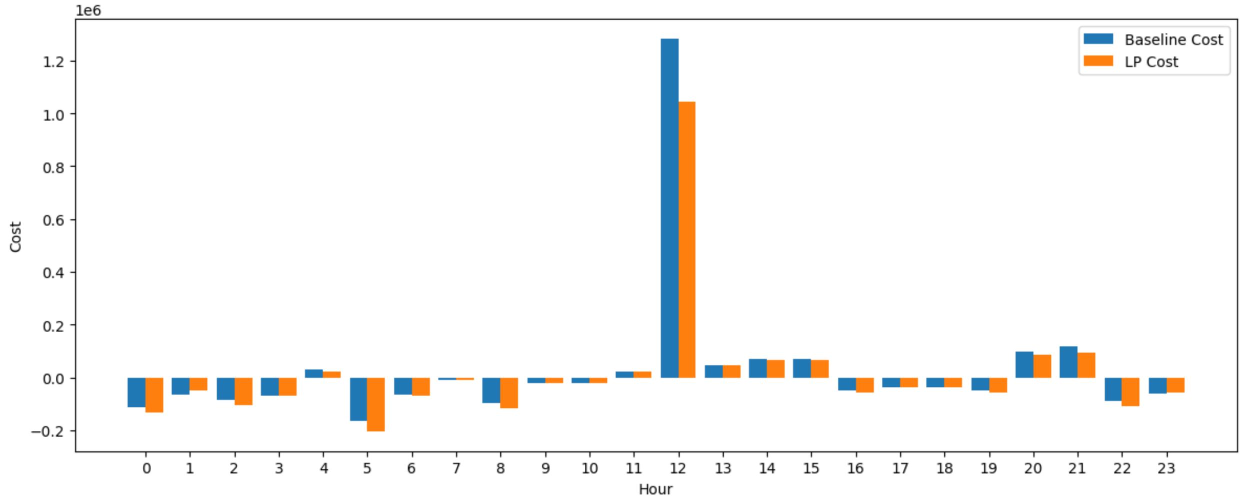

Figure 3. Hourly Cost Comparison for the First 24 Hours

The comparison of the hourly cost also shows the cost savings obtained due to the LP optimization where data obtained from the Finnish Meteorological Institute and Vaasan Sahko Distribution Company. The savings of the costs can be illustrated as the disparity between the base cost and the LP-optimal cost especially within the peak pricing seasons. As an example, in peak grid price times, the LP system minimizes the use of relatively costly grid power, using as much stored energy as possible in the battery, and unused solar energy. The optimization saves a lot of money in the 24 hours period because the system makes purchases to the grid in the most expensive hours.

4.4 Load Satisfaction Breakdown

4.4.1 PV Generation and Load Satisfaction

The system mostly relies on the solar PV system as its primary source of energy. The solar generation is used to directly supply the load demand as illustrated in the breakdown figure 4. The PV system is the largest source of energy generated during the day, specifically 9:00 AM - 3:00 PM, which is the peak solar production time so that most of the energy needed to serve the load is met inside the daylight hours. The system is to place greater emphasis on using renewable energy instead of grid-supplied electricity and make sure that as much of the load as possible is taken care of by solar energy. This Load Satisfaction Breakdown is a diagram that depicts the power allocation to satisfy the load to operate within a grid-connected PV-BESS system given a certain duration. The graph illustrates how the solar power generation (PV), the battery storage (Pbattery) and the grid (Pgrid) could contribute to the load demand (Pload). The energy provided by the solar generation, which is most active in the sunny days when the solar radiation is the best. Conversely, the discharged power in the battery which is applied when generated solar power is not adequate or in a peak time.

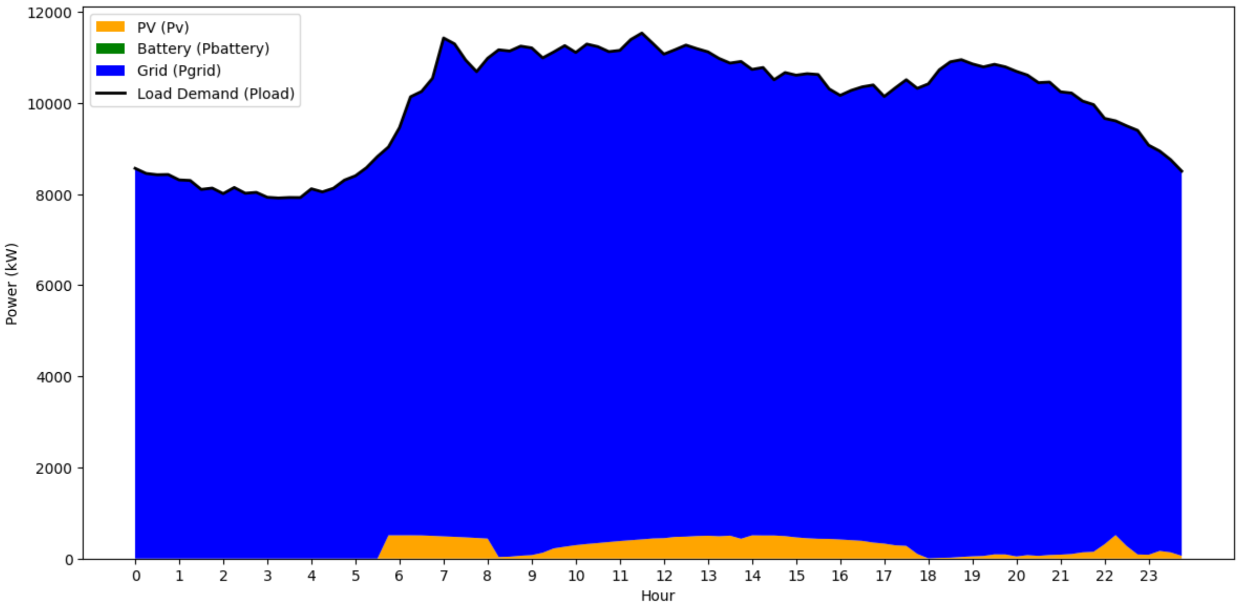

Figure 4. Load Satisfaction Breakdown

The grid supply available when the solar production and battery discharge slow down to access the demand especially at night or during cloudy days. This sum of the load demand which varies with time. This analysis shows clearly how this system can be used to reduce dependence on the grid, particularly in times of peak demand, through a combination of renewable energy (solar) and battery storage, to reduce energy usage costs and increase its efficiency.

4.4.2 Grid Electricity as a Supplementary Source

Although PV and battery storage have been integrated, the PV-BESS system sometimes runs out of power to sustain the load demand. Long periods with high demand or the inadequacy of solar generation as well as battery storage, grid energy is utilized to make up the system. The amount of energy supplied by the grid was represented by equation which we utilized in chapter 3.

4.5 Battery State of Charge (LP Model)

In the grid-connected PV-BESS, the SOC is important in determining the operational efficiency and effectiveness of the battery energy storage system (BESS). The level of energy stored in the battery at any given time is measured using SOC that has a direct impact on the ability of the system to respond to the load demand and decrease grid dependence. Figure 5 illustrates the state of charge (SOC) of the battery during 24 hours, with the help of Linear Programming (LP) optimization model. When there are surplus renewable capacities (solar or wind) which are stored in the battery (daily), it raises the SOC. This can be seen in spikes of SOC particularly in the midday and afternoon. The SOC on the other hand reduces when the battery is discharged to satisfy the load demand especially during the night or at times when the renewable generation is low. The LP model of optimization assists in balancing between charging and discharging of the battery so that it is running efficiently to reduce depending on the grid. The cyclical quality of a battery being charged and discharged is also emphasized by this graph as the SOC has a tendency of a high point and a low point happening on the same day after the peak on solar power generation or when the grid power is employed.

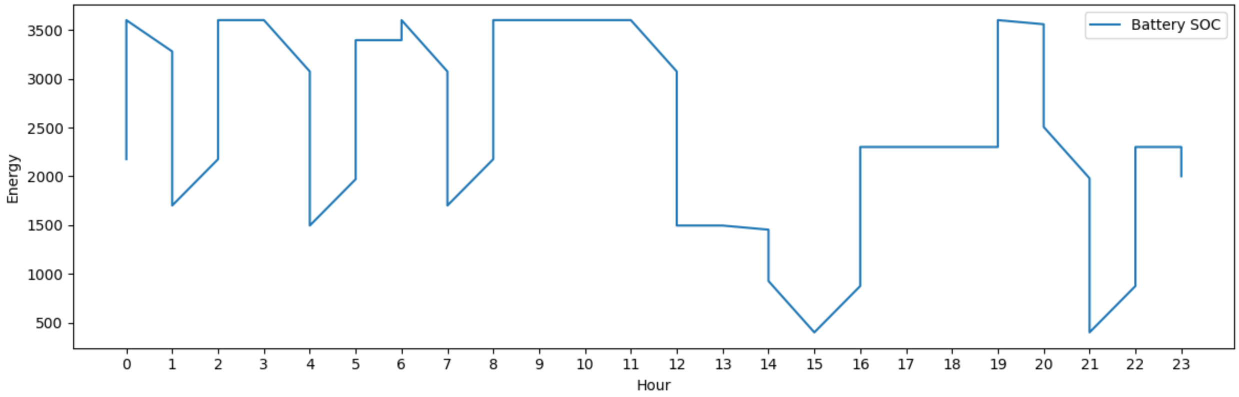

Figure 5. Battery State of Charge (LP Model)

The SOC trends reveal the way the battery is charged when there is surplus solar generation and discharges when there is low solar generation or elevated grid prices. In the initial 24 hrs., the battery SOC will be varying according to the pattern of solar and load demand.

4.5.1 Optimization and SOC Trends

To make the SOC dynamics suitable to the time-of-use pricing mechanism, the optimization model makes sure that the battery is charged during off-peak periods and discharged during high-cost periods. This plays a crucial role in minimizing overall cost of a system and maximizing the use of renewable energy. To illustrate, during bright day periods (midday) the battery is charged making the SOC to its full capacity, and during dark periods (night time) the battery is discharged so, the demand is supplied without having to use grid electricity as a secondary source of power at its full capacity.

This SOC management is an important aspect in decreasing the consumption of grids and the cost of energy in general. The graph 5 indicate that under time of peak prices (later afternoon and evening), the battery is charged to supply demand, therefore not drawing expensive grid electricity.

4.5.2 Battery Performance and System Efficiency

Storing and release of energy is an important factor in the system as it is by the battery. The SOC curves of the figure 5 will give a clear overview of how the battery can manage the charge cycles as a response to the time-of-use pricing and variability of solar generation. The SOC is also elevated when there is excess generation (e.g., at noon), and during discharging cycles which illustrates the ability of the battery to be used in load balancing and cost optimization. Moreover, the efficiency of the battery is maximized according to the linear programming (LP) model that tends to reduce grid dependency and take advantage of solar energy. Because when the battery is charged the event is off-peak and the opposite applies on the times of high cost of electricity, the system manages to save the money spent on the electricity grid and utilize the renewable reserves to their maximum capacities.

4.6 Cumulative Cost Comparison (Baseline vs. LP)

We understand that energy is provided mainly by the grid in the baseline system, with no efforts to optimize time-of-use pricing or energy storage. The overall price of the system is added to the grid consumption, particularly when prices are higher in high-cost periods (high3pm and early evening), when electricity prices are greater. The cumulative cost curve of the base system demonstrates a linear growth though the steepest increments are made at times of high demand and a high grid price. This indicates how the system needs costly grid electricity when solar power is minimal or not readily available. The base cumulative connection curve shows direct correlation between the energy cost and the amount of grid power that is consumed and it shows that using grid power alone to obtain the load demand may be very inefficient. This increases the cost because in high-cost periods, the system will import more electricity into the grid.

On the contrary, the LP optimized model is used to exploit the production and storage of solar energy to reduce the rate of grid consumption, particularly at expensive times. The LP model will maximize the use of energy by discharging the battery when the demand rises, charging the battery when the power is cheap, and using excess solar energy to cover the load demand. Due to this, the cumulative cost curve of the LP system rises at a very low rate than the baseline system. In figure 6 we compare the cumulative cost in 24 hours of two cases: the Baseline Cost and the LP Optimized Cost. As the cost with which the system will be optimized, the Baseline Cost is the total cost at which the system is not optimized to achieve the load demand, it will be also dependent on the grid to fulfill the load demand. The LP Optimized Cost on the other hand represents the cost with the use of Linear Programming (LP) optimization, which includes the use of battery storage as well as renewable energy to decrease grid dependency and to optimize cost.

Figure 5 reveals that at the beginning of the day, the two costs are quite similar. Nonetheless, there is a steep rise in the cost of the LP at about 12 PM indicating that during the peak times of the day, the grid price increment due to the load increases even though the LP optimization aims at balancing the load. The Baseline cost on the other hand exhibits a lower spike, since the system is wholly dependent on the grid during peak hours. Both costs begin to be equalized after 12 PM, the LP cost having a slight drop caused by improved energy management (i.e. stored battery power and renewable energy sources). The cost analysis by cumulative comparison indicates that the financial gain of the optimization of LP leads to a potential reduction of costs, as the use of grid power is reduced in general, and especially at high-demand times when the use of costly grid power is minimal.

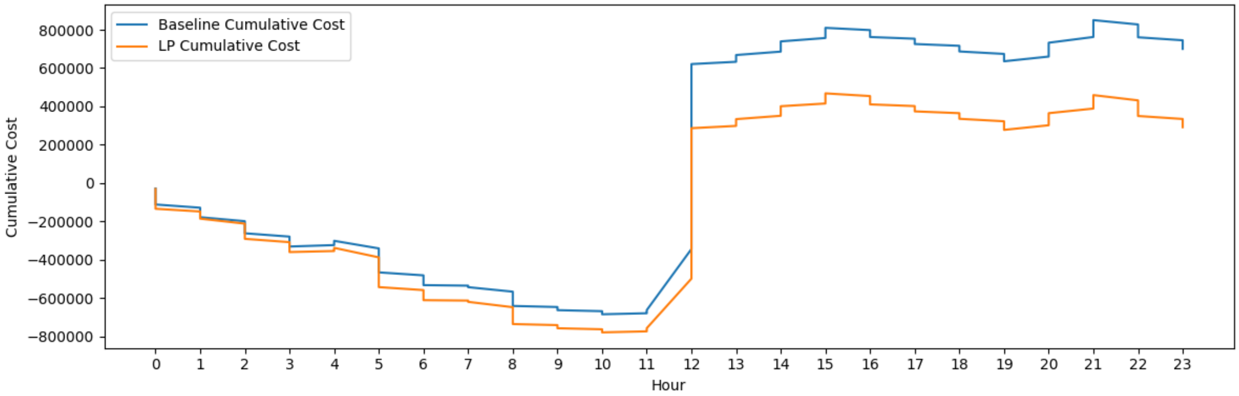

Figure 6. Load Satisfaction and Cost (LP Model)

4.6.1 Cost Savings from LP Optimization

The major highlight of the cumulative cost comparison was the cost saving obtained in the LP optimization model. The system optimized by the LP helps to achieve a lower overall cost of energy procurement as it helps to minimize political grid dependence and make use of solar energy stored. The savings are greater in the high-price periods as shown by the figure 6 since the system receives maximum benefits by ensuring that renewable energy and battery storage is maximally utilized to meet the load demand. The difference between the cumulative cost curves of the baseline and the LP-optimized systems is a cumulative savings realized by the optimization model. The cost efficiency of the LP model is clear since the optimized system will still be cost-effective even when the demands are high. The LP model presents a considerable cut in the overall cost of the system by minimizing grid usage at times with high costs and maximizing the utilization of renewable energy.

4.7 Total Power Generation

We looked at the cumulative power production and the input of each of these components, particularly that of solar PV, wind, battery storage and grid electrical production to the load demand of the system during the first 24 hours of operation with respect to how each energy source helps in meeting the overall load demand of the system. Figure 7 reproduced the input of various sources of power to satisfy the demand of the load during a 24-hour cycle. The solar (PV) generation that becomes dominant during the day particularly around mid-noon, with the peak production of solar power. The wind power production that could offer a consistent contribution, but in this instance, this is less important than the solar power. The grid power that is going to be used to supply the load demand, especially at low periods of renewable generation like in the early morning (1 to 6) and late evening (19 to 24) where both the solar and the wind generation is at a minimum or non-existent. Battery discharge that provides power in cases where the renewable sources become inadequate especially during peak hours. The load requirement that varies during the day is requirements fulfilled by a combination of solar and wind, battery storage and grid power. This graph shows how the system is efficient with regard to using energy resources in the renewable form, as well as storage to limit the use of the grid particularly when the load is at its peak, through the concept of the LP optimization in minimizing the cost and maximizing the overall energy efficiency.

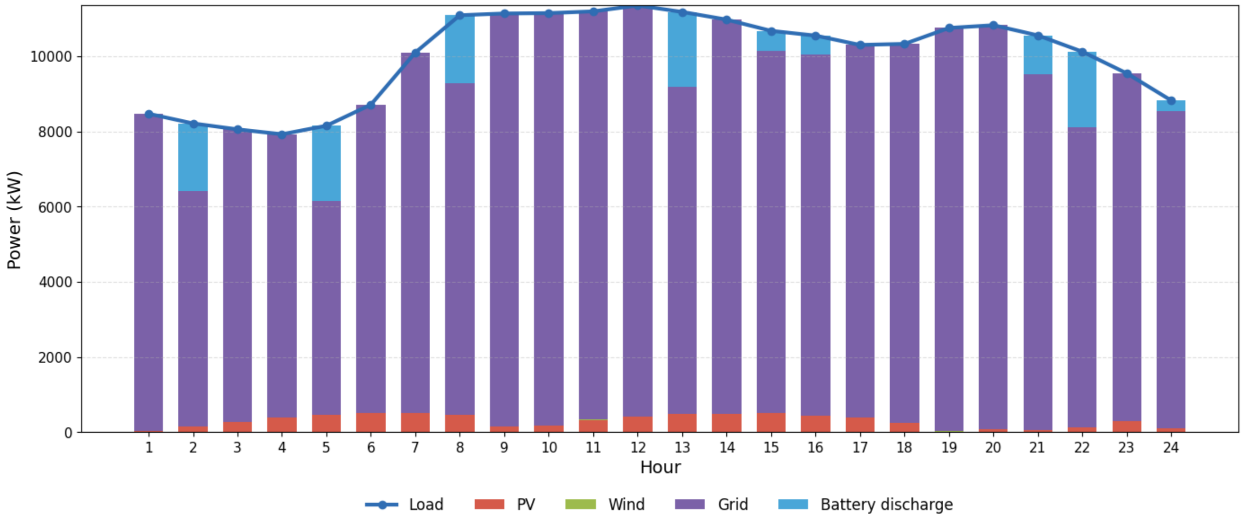

Figure 7. Total Power Generation

The initial 24 hours indicate that the system has high dependence on solar energy in the daytime high-energy spots, with a reduced dependence on wind energy, except where there are high wind velocities. This is a real-life scenario of what is observed in the real world when solar generation is more predictable and predictable during the day when compared to wind generation, which is more intermittent and location specific.

4.8 Hourly Cost Comparison (LP vs. Baseline) in USD

The load demand is fulfilled mainly by buying energy over the grid with no optimization on TOU-pricing and integration of renewable energy source such as solar PV or battery storage. Peak costs in the baseline system are largest during peak hours when there is peak demand and peak grid prices, when it is midday and in the early evening. These peak hours are the most expensive to the consumer because the system will solely use grid electricity, which is at its highest during such peak hours in figure 8. We take the hourly cost of two scenarios, LP Cost, and the savings in comparison with the baseline, which is Figure 8. Total cost that is optimal when the system is optimized based on Linear Programming (LP) is called LP Cost and includes the cost of battery storage and managing renewable energy and the cost not to optimize the system is called the baseline cost and just uses grid power. The LP Cost is higher in daytime with a high of 12 PM 6 PM, probable because demand is high and the grid price is high. The orange bars are the savings made by the LP model in terms of cost. Such savings are mostly visible in high-periods (particularly, the ones in the late afternoon and evening), when the optimization of the LP can be utilized to decrease the grid-based operation and decrease the dependency on renewable energy and batteries. Interestingly, the LP model gives maximum savings at evening (8 PM to 11 PM) suggesting that the optimization saves a lot of money when the grid prices are high. In this way, then we can say that using this figure illustrates the economic benefit associated with the deployment of LP optimization of energy systems can apply to the model on cost savings by the efficient utilization of renewable energy and battery storage in particular during peak grid prices.

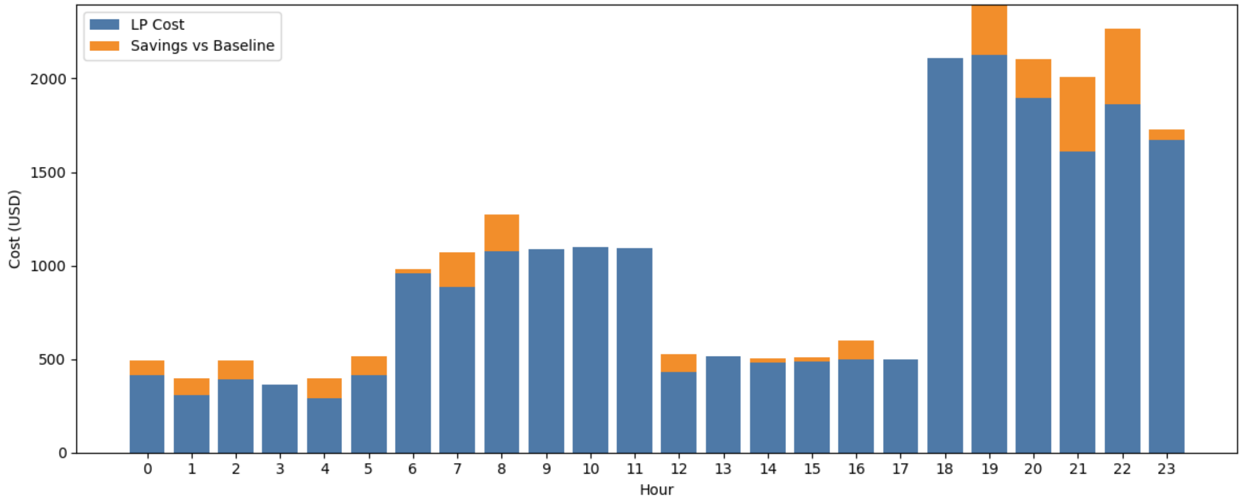

Figure 8. Hourly Cost Comparison (LP Cost vs. Baseline) (USD)

An hourly cost comparison vividly illustrates that the LP-optimized system accrues lower costs during hourly periods that the grid prices are at their peak.

4.9 LP in Hybrid System

The hybrid system is most efficiently working on the grid with the majority of the load fed by the grid with the PV input and battery discharge significantly less than the demand. The battery state size remains nearly steady about zero which implies that the battery is either not being utilized much or not permitting any significant charging and discharging. In this case, the load scale will be far larger than that of PV and battery flow and thus the LP effect will be difficult to observe. In Figure 9, the optimal supply mix, as a portion of load and in the battery SOC, in a separate diagram is plotted. That renders the LP result straightforward and beautiful. Thus, the outcome is now a hybrid energy system optimization, only instead of a balanced PV-battery-grid hybrid the system is now acting like a grid-dominated dispatch.

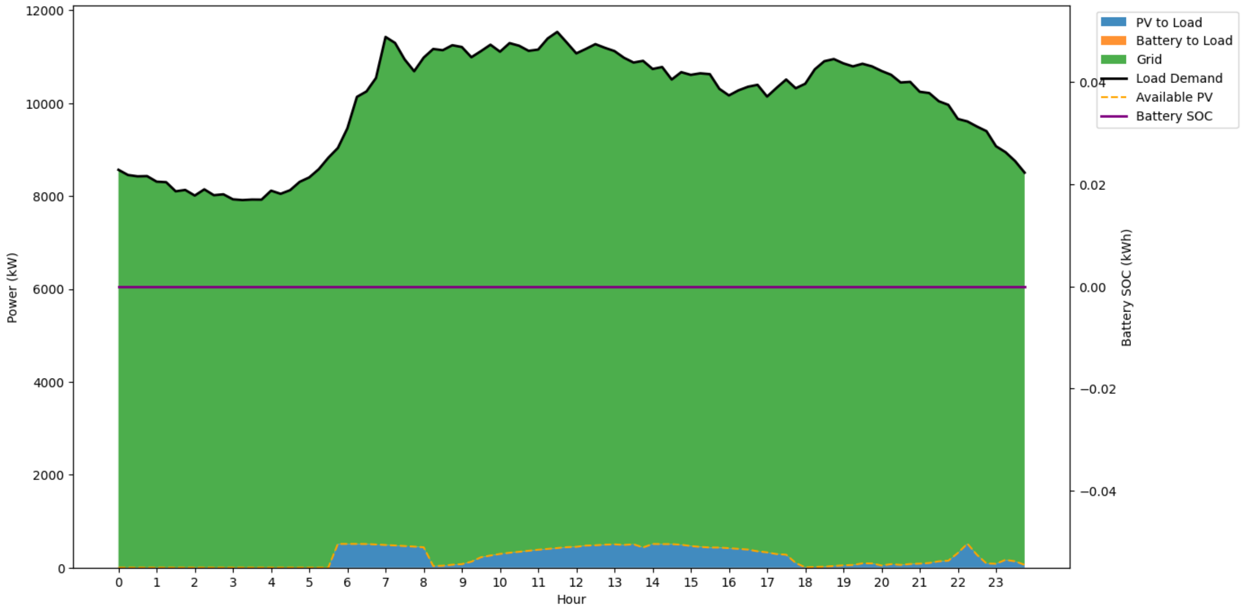

Figure 9. LP in Hybrid System

4.10 Hourly Summary of Energy Usage and Costs

Table 1 refers to one 24-hour time corresponding to different parameters of an energy system, including load demand, solar (PV) generation, wind generation, battery state of charge (SoC) and grid power and grid price of time-of-use (TOU) and grid cost.

Table 1. Hourly summary table in USD

hour	Load	PV	Wind	SoC	Grid	TOU Grid Price USD	Grid Cost USD
0	8467.69	25.156	3.2625	2888.593	8439.271	0.0489	103.074
1	8210.29	158.409	3.2625	2490.416	6242.935	0.0494	77.043
2	8052.33	264.704	3.2	2888.593	7784.426	0.0504	98.091
3	7922.42	382.721	3.55	3601.363	7536.149	0.0484	91.274
4	8149.02	464.607	4.9125	2285.075	5678.743	0.0516	73.190
5	8709.36	506.923	3.4375	2683.252	8199.000	0.0505	103.569
6	10096.9	506.842	2.9625	3447.357	9587.095	0.1003	240.466
7	11087.56	470.367	0.9125	2336.410	8810.597	0.1008	222.103
8	11133.32	143.951	1.6625	2888.593	10987.707	0.0979	268.905
9	11143.44	171.820	3.675	3601.363	10967.945	0.0993	272.304
10	11190.3	329.662	3.4125	3601.363	10857.226	0.1014	275.212
11	11346.06	412.470	3.1375	3601.363	10930.453	0.1000	273.346
12	11174.79	474.649	3.3	2285.075	8696.084	0.0493	107.163
13	10970.52	481.969	3.1625	1495.303	10485.389	0.0493	129.357
14	10672.2	503.714	3.575	1058.295	9624.707	0.0498	119.894
15	10545.37	444.217	2.675	400.151	9598.289	0.0505	121.177
16	10297.1	390.599	2.3625	1588.101	9904.138	0.0502	124.326
17	10325.26	250.011	2.225	2300.871	10073.024	0.0493	124.128
18	10749.2	18.546	2.875	2300.871	10727.779	0.1966	527.348
19	10821.58	72.085	2.9625	2919.855	10746.533	0.1978	531.391
20	10551.42	64.552	2.6625	2901.098	9443.812	0.2008	473.984
21	10116.48	117.514	3.4375	1189.924	7994.772	0.2013	402.303
22	9539.97	299.178	3.2125	1588.101	9237.579	0.2015	465.232
23	8818.26	111.541	3.575	2225.842	8418.036	0.1988	418.396

The load demand is varying during the day, with highest load around hour 7 at 11087.56 kW and hour 19 at 10821.58 kW indicating more power is being consumed in the afternoons and evenings. The peak generator rate of the solar generation (PV) is at hour 11 at 412.470 kW as a result of intense sunshine with wind generation marginally stable with a 4.9125 at hour 4 and

0.9125 at hour 7. The battery SoC will peak at 3601363 kWh in various hours across (3, 9, 10, 11) during the day, as excess renewable energy is stored to peak and will fall during the evening with the battery discharging in accordance with the demand. The more grid power consumption would be in the early morning and in the late evening when there is low renewable energy production. The price on the TOU grid fluctuates across the day where at hour 1 the price is 0.0494 USD/kWh, and at hour 12 the price stands at 0.0493 USD/kWh, showing that the cost of electricity via the grid is higher during the time of peak demand. This results in an increased grid cost in these periods, with values such as 77.04 USD at hour 1 and 107.16 USD at hour 12 and indicates that using the grid is economical particularly on days of high demand. In general, the relationship among renewable energy production, battery storage and grid-based power consumption, and highlights the significance of energy management optimization to minimize grid costs, especially at times when prices are highly expensive.

5 Discussion

5.1 Introduction

The value and originality of the present study is due to the extended economic discussion of the system that is being optimized by the application of LP including the introduction of these renewable sources and storage to reduce the use of the costly grid power. Especially necessary in the periods of peak demand when grid prices normally increase. This research will illustrate how a significant amount of cost reductions can be achieved using LP optimization versus the conventional grid-dependent systems by optimizing solar power, wind power, and battery storage. The only difference is that this new strategy provides a new solution to the expensive grid dependency, especially in terms of proper strategies of time-of-use (TOU) pricing and battery storage use. We dwelt on the effects of LP optimization on energy consumption behavior, system behavior and cost regime, with the findings and numbers of the analysis.

5.2 Key Findings

We pay attention to the economic optimization of a grid-connected PV-BESS system with the help of Linear Programming (LP). The findings suggest that optimization in terms of LP can efficiently minimize the use of energy, in terms of grid dependence, particularly during peak hours when grid prices are the highest. This part explores the crucial outcomes experienced in last chapter, shedding light on the economic consequences, system efficiency, and general efficiency of the LP. Among the biggest discoveries is the cost reduction that the LP model offers in comparison to a baseline system, which does not work with optimization or a battery storage. Lower costs always take place with the LP model and during high demand, (8 PM to 11 PM) which is high grid pricing. To a large extent this decrease owes to the control of battery storage and renewable energy (solar and wind) performed within the framework of the LP optimization model. In particular, by recharging the battery as the grid prices are low (off-peak periods), and in contrast to that, leaving the battery to discharge in the peak demand times, the system can reduce the amount of grid purchases and optimize energy costs. This cost-cutting plan emphasizes the possibility of battery storage as a buffer of energy, but also as an economic resource that would help lower the operating expenses dramatically because it would even the load throughputs. The results of this paper indicate that the stored energy can be effectively used to optimize the LP, which will require less grid power and hence a more cost-efficient energy management system.

5.2.1 Impact of Time-of-Use (TOU) Grid Pricing

Time-of-Use (TOU) pricing analysis is vital in appreciating the economic effects of grid pricing to energy prices. Time-of-Use Grid Price Curve was used to illustrate the variations in prices according to time of day with off-peak hours (midnight to 6 AM) and peak periods (8 PM to 11 PM) having low prices and high price increases respectively. Such pricing structure allows a possibility of having cost-saving, particularly when the LP optimization is incorporated as a way of storing any excess energy during off-peak and producing it during the high costly peak.

Through effective control of the energy storage and incorporation of renewable sources the LP model can take advantage of the low grid prices during off-peak periods and reduce dependence on the high-cost grid power during high-price periods. The time sensitivity function of this optimization shows how crucial pricing strategies are in lowering the costs of operations and enhancing the overall efficiency of the energy systems. These results indicate that Time-of-Use pricing, in conjunction with the LP maximization, may serve as a means to reach a lower price, as well as make the system more profitable, thus the integration of renewable energy becomes cost-efficient.

5.2.2 Battery Performance and Efficiency

Battery storage, which is used effectively, is another major finding. The Battery State of Charge (SOC) graph is a good depiction of how the SOC rises when renewable energy is produced (midday and afternoon) and falls when the battery is being discharged to supply the load, especially at night. Balancing the charging and discharge life of the battery makes the LP model efficient so it can form an important part of the energy management plans of the system.

This economical battery functioning is a core contributor to the minimization of grid-reliance. The system is able to provide energy needs with the least use of the grid because they store surplus renewable energy (e.g., solar or wind) when it is daylight, and release it when it is needed. The capability of the LP model to maximize charge/discharge cycles is again going to boost the economic sense of battery storage to make sure the system is cost-effective and at the same time allows a consistent supply of energy.

5.2.3 Load Satisfaction and Energy Management

Depending on the Load Satisfaction Breakdown, we expect the grid connected PV-BESS system to depend on a mix of solar power (PV), battery discharge, and grid power as a means to satisfy the load demand. The system first concentrates on consumption of solar energy during the daylight and the rest of the battery storage is done when the solar output is inadequate. When there is no renewable generation (or low renewable generation) in time (e.g. at night or during clouding), the system uses grid power. The analysis indicates that the system can reduce the dependency on the grid because it can control the power of the sun and battery storage efficiently, especially at the time when the demand is high. This brings out the cost-efficiency aspect of integrating renewable energy since the system can be in a position to generate demand effectively without over depending on the grid hence resulting in increased energy expenses.

5.2.4 Sensitivity to Key Parameters

Finally, the paper considers how the LP optimization model is sensitive to a number of parameters, including solar generation and battery efficiency, as well as grid prices. As the results indicate, changes in these parameters, particularly, the solar generation and battery efficiency are highly sensitive to the achievement and cost reductions of the system. This implies that uncertainties in renewable energy production (e.g., fluctuation in sunlight and wind) can affect the outcome of the optimization.

Nonetheless, the LP model seems to be sound in its capability of handling such uncertainties undertaking that the system is still economically feasible as long as the crucial input parameters vary. This observation highlights the versatility of LP optimization to real-world situations, where uncertainty is embedded in the renewable energy system.

5.2.5 Novel Contribution and Implications

The originality of the present study is the combination of the Linear Programming (LP) and grid-connected PV-BESS systems in the optimization of costs, especially when Time-of-Use Pricing is considered. The outcomes of this research illustrate how the optimization of LP can decrease the costs of energy, help the system to operate more efficiently, and increase the use of renewable energy. With an inclusion of battery storage, the system would be in a position to maximize energy consumption, lower utility dependence on the grid, and eventually incurred economic savings, thereby adding to the emerging body of research in the renewable energy systems.

Its implications, especially on policy makers, utilities and consumers of energy, are also very important, as it provides them with important indications of how their use of LPO can help make renewable energy systems economically viable, particularly in areas where grid prices are fluctuating and renewable energy generation may be variable.

To conclude, the results of the study confirm the hypothesis that Linear Programming optimization is a valuable tool in cost saving, energy efficiency enhancement and reliance on a renewable energy source when connected to a grid, and that battery storage is a key factor in balancing the energy supply and demand, thus optimizing costs.

5.3 Cost Implications and Feasibility

Economic viability of this technology can be assessed in the context of its cost implications and practicality as a grid-connected PV-BESS system and its optimization via Linear Programming (LP), implemented. With the constantly increasing energy cost billed and being highest during peak hours, energy optimization by combining solar photovoltaics (PV) and battery energy storage systems (BESS) is a feasible idea. The results of the current study prove that, not only the LP optimization approach can be used to decrease grid reliance but is also a main contributor to cost savings, especially in the areas of Time-of-Use (TOU) pricing.

5.3.1 Financial Viability of Investment in PV-BESS

The overall energy costs minimization through an effective application of renewable energy sources and battery storage support the feasibility of investing in a grid-connected PV-BESS system further supported with the LP optimization. The overall cost of using energy can be very low, as the consumer will be able to cut off some of the grid as the total energy is reduced, and when demand is at its peak.

TOU pricing fundamentally affects the affordability of this system because this system aims to maximize the utilization of low-cost electricity during off-peak demand and store excess renewable energy to be used during the time of high-cost electricity. The optimization algorithm allows to achieve peak shaving where the system decreases its peak grid purchases resulting in lower energy costs. The LP optimization is always more effective than the Baseline model as demonstrated in the hourly cost analysis between the two models, since during peak hours, the Baseline model uses energy that is stored up more effectively when compared to the LP optimization. The option used in the LP model of minimizing purchasing in the grid during peak costs is translated to the reduction of expenditure in electricity bills monthly or annually thereby making the system less expensive to the consumers. The return on investment (ROI) of the system increases over time since savings of costs are going on accruing.

5.3.2 Scalability and Long-term Savings

The scalability of the PV-BESS system is another factor that is important in determining its cost implications. The system is very versatile as the LP optimization can support various sizes and layouts of PV-BESS systems. Its capability to scale up or down to the requirements of certain energy consumption and the budget constraints has made it a desirable choice to use at homes and in a business context. In addition, the savings that would accrue over the long-run by using a PV-BESS system are high. With the increased costs of energy projected to shoot up, renewable energy systems with battery storage offers some form of advertising against the costs of electricity, and offers a more appealing financial assurance to people. The LP optimization helps make the system as always in as cost-effective way as possible, using renewable sources and battery storage to reduce the reliance on the grids.

5.3.3 Policy and Incentive Implications

The government policies and incentives designed to promote the adoption of renewable energy will also contribute to the economic feasibility of grid-connected PV-BESS system. The initial cost of these systems can be greatly subsidized through incentives available as subsidies, tax breaks and feed-in tariffs and as a result, they can be offered at a lower cost to consumers and become more widely available faster. Moreover, renewable energy credits/ certificates (RECs) also offer supplementing benefits to installing renewable energy systems making the PV-BESS a more financially appealing undertaking. Government policies and incentives can be significant by lowering the cost of solar panels, batteries, and other parts to make the PV-BESS systems cheaper to implement particularly in residential applications or with small businesses who may otherwise find the initial investment unaffordable. The cost-reduction associated with the LP optimization, along with these incentives, allows the PV-BESS system to become a viable and sustainable profitable choice of banks.

5.4 Impact of Grid Prices and Time-of-Use (TOU) Pricing

Combination of grid price and Time-of-Use (TOU) price is also very important in deciding the effectiveness and cost savings of grid connected PV-BESS systems. TOU pricing is a pricings technology in which the electricity prices can change with the time of the day, the price will be higher and higher at the time of peak hours and lower at the time of off-peak hours. This type of pricing offers a strong incentive to the consumer to redirect their energy use to off-peak periods so that they do not rely on high-cost grid power during peak periods, and make the fullest use of the lower cost electricity during off-peak periods.

5.4.1 Role of Grid Prices in Energy Consumption Optimization

One of the key determinants of the costs of energy in a grid-connected PV-BESS is grid prices, particularly during peak demand periods. The grid price curve as seen in the findings of this study consistently moves and peaks substantively during the day with a particularly sharp spike seen upon noon indicating the high demand for power and possibly the decreased renewable production during this period. This difference in the grid price also is in a way captured in the LP model and helps the system optimize the usage of the energy by utilizing renewable energy and battery stores during periods of high cost and storing excess energy that can be used in times of peak demand. The system minimizes its dependence on the grid and energy bills by moving energy load to off-peak periods during which the grid charges are low.

The LP optimization model offers an effective tool to control the interaction of solar production, wind generation and the use of grid electricity, thereby minimizing the overall expenses of using a highly priced grid electricity. This combination of the sources of renewable energy and battery storage is critical in reducing costs and improving the overall energy efficiency of the system, particularly in dynamic pricing regions like in TOU pricing.

5.4.2 Economic Benefits of TOU Pricing for PV-BESS Systems

TOU pricing scheme has profound cost impact on the cost-effectiveness of PV-BESS systems as they are more cost-effective. As the diagrams and outputs of this research demonstrate, the LP optimization is able to exploit the shifts in grid prices. Economic gains are noticeable especially in the afternoon and evening when the grid prices are high because of the high demand. At this time of high costs, the system resorts to battery storage to satisfy the demand at relatively cheaper renewable energy stored during off-peak periods.

This cost-shifting approach will help the system to reduce grid purchase in periods of peak thereby cutting down the energy spending. The findings of the study also reveal that during certain off-peak periods, the system even has negative costs implying that excess renewable energy is being used or resold to the grid, which makes the system even more cost-effective. This demonstrates that TOU prices are critical to the profitability and financial viability of PV-BESS system. Using energy in a more strategic way will enable consumers to take advantage of the reduced rate that is offered during off peak hours and minimize on excessive usage of the costly grid electricity during peak hours.

5.4.3 Influence of TOU Pricing on Energy Storage and Grid Power Use

TOU pricing can influence battery storage and grid power consumption as well in maximizing the pattern of energy consumption. The results of this research project suggest that in times of high grid prices, battery storage is a scarce resource given priority whereby the system will consume the stored energy before it will tap into the grid. The LP optimization model is crucial in balancing the energy requirements of the system by seeing to it that battery charging is done at times when the grid prices are low and the battery discharging is done during times when the grid prices are high. This system works around the need to prevent expensive grid electricity in peak hours and the battery storage is, therefore, an invaluable means of tariff reduction. Moreover, excess renewable energy can be stored efficiently and used subsequently when the price increases in the grid by the great advantages of greatly lowering costs. The best pooling of renewable energy and battery storage is that not only the dependence on the grid decreases, but the system is also operated in a cost-efficiency mode because it reacted flexibly to changes in the costs of the grid.

5.4.4 Strategic Use of Energy Storage During High-Price Periods

The system also uses battery discharge to supply energy requirement when the grid prices are high. The system store of energy during periods of low demand and low grid prices optimally utilizes the renewable energy at times of high price to bypass the costly grid electricity. This does not only assist in reducing the electricity bills, but also the economic viability of the PV-BESS system by offering a predictable and affordable power system to consumers. This flexibility and economic potential of the optimized system of the LP is demonstrated by the ability to react to the TOU pricing schemes at the effective combination of battery storage and renewable energy sources. The flexibility gives the consumers the opportunity to maximize their electrical usage and storage energy as it gives a sustainable solution that aids to minimize the usage of the energy and helps to enhance the overall usage of renewable energy.

5.4.5 Conclusion on the Impact of Grid Prices and TOU Pricing

The effectiveness of grid prices and Time of Use (TOU) pricing on grid-connected PV-BESS system has far-reaching implications on the system costs and optimization. Optimization of LP can be successfully used to minimize energy expenses by employing renewable energy and battery storage at times when the grid price is high and by moving the load to non-peak times. Such a mechanism is not only effective to reduce the dependence on grids, but also to save a lot of money intended for customers, so TOU pricing can play a crucial role in enhancing the economic feasibility of PV-BESS systems. Through effective energy consumption management, the consumer is able to optimize on his financial savings and achieves improved overall sustainability of his energy system.

5.5 Comparison with Previous Studies

5.5.1 Comparison with Studies on Grid-Connected PV Systems

A number of works have been done to optimize grid-connected PV systems, which address cost-saving, management of energy, and the incorporation of renewable energy. According to Carreras & Kirchesteiger (2023) where Linear Programming (LP) optimization significantly decreased the operating expenses of grid-connected PV systems utilized in the most cost-effective manner of utilizing energy held by solar panels and battery storage during peak periods. As with our results, the LP optimization was demonstrated to allow managing the renewable energy through a better approach, minimizing the dependence on grid electricity and minimizing the expenses related to high grid prices at high loads. Nevertheless, this paper is unique because it focuses specifically on Time-of-Use (TOU) pricing, which maximizes the cost-saving capacity by both using grid pricing variations and further optimization of energy storage and use according to grid price signals.

Unlike previous studies, including Zhuo & Savkin (2019), which modified their research based primarily on empirical models to measure cost optimization without considering the battery storage systems, the present study is the first to consider battery energy storage (BESS) as a crucial variable in the optimization procedure. This combination plays a critical role in enhancing the performance of the economy by better utilization of renewable energy when the grid price is low, which has not been extensively researched. Our optimization with LP provides insight into the fact that not only battery storage prevents the use of the grid, but also minimizes costs during peak grid price periods, underpins the significance of dynamic energy management.

5.5.2 Comparison with Studies on Battery Energy Storage Systems (BESS)

The impact of battery storage systems on energy optimization has been addressed and researchers have explored the question of how a battery can reduce grid reliance, and enhance the economic viability of renewable energy systems. Similar to the results of this study, Mohammad et al., (2021) discovered that combining battery storage with grid-connected systems increases the possibilities of the grid, as well as the utility of energy consumption. Nevertheless, the study is more extended, as it incorporates the optimization of PV and battery storage and Time-of-Use (TOU) pricing, which has been barely discussed in the literature to date. Conversely in this study, it is shown that LP optimization offers a more dynamic and far less expensive solution, by dynamically utilizing energy storage as well as renewable energy when the grid price is high and the switching of demand to off-peak periods to maximize cost saving. The findings of this experiment demonstrate that there was a drastic drop in the grid power usage particularly in the high prices that have not been adequately considered in past research mainly on the battery size or efficiency enhancement.

5.5.3 Comparison with Studies on Time-of-Use Pricing Optimization

Time-of-Use (TOU) studies have established the significance of balancing energy usage and price indicators on the grid to maximize cost of energy. According to Zhuo & Savkin (2019), TOU pricing is important to better control energy consumption patterns, particularly when it comes to battery storage systems. Also, this research discovered that TOU pricing greatly cut down on the energy expenses, particularly when battery storage was incorporated in the optimization process. But at the same time, our research contributes to the existing body of literature, as it determines the formulation of linear programming (LP) and provides an opportunity to take a more specific (granular) approach to optimize both energy use and the utilization of renewable energy resources, such as solar and wind.

The vast majority of former studies of TOU price optimization are based on the concept of demand-side management that overlooks the entire implementation of battery storage and renewable energy. Using LP optimization, this paper presents a valuable approach to the optimization of demand peaks, minimized grid power during high-price times, and redistribution of energy-consumption to low-price times. The study is also a groundbreaking one in terms of exploring the strategic application of battery storage, with the aim of helping to decrease energy expenses and increase grid autonomy; a part where the previous research was not even fully examined.

5.5.4 Contribution to the Field

The primary input of this study in the field is the innovation of combination Time-of-Use (TOU) pricing, battery storage, and Linear Programming (LP) optimization. Though the available literature discusses these components separately, in this study, we will demonstrate how these components can be planned to be used in a synergistic manner to enhance the economic performance of grid-connected PV-BESS systems. This paper reveals that a significant cost saving can be achieved by optimizing power consumption when the price of power is high, eliminating grid power requirements and optimal use of any surplus renewable energy supply by using batteries.

In addition, this study gives a valuable contribution to the cost-effectiveness of PV-BESS facilities in the areas with fluctuating grid prices and it presents a concrete data-based model to simulate the real-world situation with the energy consumption patterns and prices. The results are important in the growing body of knowledge, which focuses on energy optimization and economic viability, and practical implications to consumers, utilities and policy makers interested in encouraging renewable energy use and cost-effective energy systems.

Finally, the paper offers innovative understanding of cost optimization, grid pricing, and energy storage control, with concrete recommendations on how to enhance the financial operations of grid-connected PV-BESS systems.

5.6 Limitations of the Study

Among the main restrictions of the study is the simplified assumptions that are made about the structures of the system and about their working conditions. An example of this is the model presumes that production of solar generation and wind power is pegged on historical averages, without taking the chances of variability caused by change in seasons or unexpected alterations in renewable energy production. The overlook of battery degradation and lifetime impacts of the battery storage system is another important limitation. The model also assumes that the battery would be full-efficiency during the lifetime of the battery and no further consideration of loss of battery capacity due to aging. As a matter of fact, battery performance degrades with usage because of cycling effects which causes the amount of energy to be stored and discharged by the battery to reduce with use. It may create a more complex cost structure since, due to degradation of batteries, the long-term operation cost would be more, especially when the system has to undergo battery replacement throughout the lifecycle of the battery. It may be utilized in future research by adding battery degradation models and making a more accurate statement on the long-term feasibility and cost-effectiveness of PV-BESS systems.

Conversely, the model also presupposes the predictability of the load demand and the renewable energy production that are not always appropriate to the real situation. The pattern of load demands is subject to change depending on the external factors like the economic activities, user behavior as well as weather conditions which are not perfectly reflected in this study. In the same spirit, there are supposedly stable patterns of generation of renewable energy which are not always true (weather variability, unstable outages, intermittent nature of solar and wind power). Real-time data be included or stochastic forms of modeling the uncertainty in the demand and the generation may give an even better overview of the efficiency of the system in various conditions.

The analysis is done on historical Time-of-Use (TOU) grid prices, which generally are subjected to variance based on numerous economic and regulatory and environmental factors. The omission of real-time dynamic grid pricing might constrain the model to apply to real-life operational scenarios where grid prices may change more often than available in the historical TOU data. A more accurate insight into the effects of price changes in the optimization of PV-BESS systems could be done with the help of real-time grid pricing information, which would be especially necessary when the grid prices vary quickly because of the market conditions or extreme changes in the demand.

Finally, the study is focused on a selected geographical area (Finland) and a time frame (January 2020-December 2020). These findings may consequently not be generalized to areas where the climatic conditions are not similar, grid-based pricing systems, or potential renewable energy sources. The amount of solar radiation, patterns of wind, and cost-efficient consumption of electricity across the different regions can have a significant impact on the performance and cost-efficiency of PV-BESS systems. The study could be expanded to multiple regions that are in varying climate zones and energy policies to give an insight into the global applicability and transferability of the optimization framework.

5.7 Conclusion

Nevertheless, the paper is valuable in also giving insights on the economic viability and optimization of grid-connected PV-BESS system based on Linear Programming. It shows how much money can be saved in battery storage and renewable energy management interconnection, as well as the importance of demonstrating more vivid and real data that could enhance the stability and applicability of this model. More studies in the future need to consider the above-presented limitations so that precision and applicability of the results can be improved, and in this respect, the financial sustainability of the system, as well as the incorporation of real-time grid pricing in the studies, can be mentioned.

6 Conclusion and Recommendations

6.1 Conclusion

This study has been able to establish the utility of Linear Programming (LP) optimization when approaching improved economic performance, efficiency, and sustainability of grid-connected photovoltaic-battery-based energy storage systems (PV-BESS). The results provide an importance in practical combination of renewable energy sources, namely, solar and wind power with battery storage to decrease the given relevance and yet decrease the expenses on the functioning. Through energy use optimization, particularly at high demand times and peak rates, we note how the LP optimization can successfully decrease grid reliance and end up saving a lot of costs. TOU pricing further enhances the optimization advantages with the analysis indicating that strategically operating storage of energy during off peak hours and releasing it at peak demand periods can both reduce the costs of energy dramatically. This mix of LP optimization and OTOU pricing does not only contribute to a cost-effective system, but also shows that this type of renewable energy can be used in balancing supply and demand without triggering a decrease in the stability of the grid.

Also, the study presented useful information on battery performance and storage efficiency, highlighting an effective regulation of state of charge (SOC) cycles. The combination of wind energy and solar energy with optimal utilization to enable the use of the LP corresponds to the overall objective of minimizing carbon emissions and favoring a low-carbon energy infrastructure. The long-term economic sustainability of the LP model lies in its optimality in using renewable energy, battery storage and grid electricity, which also helps in the current global change to cleaner, more sustainable energy systems. The study opens the door to more cost-effective energy management solutions by demonstrating how LP optimization can enhance an economic feasibility of renewable energy systems. In addition, it helps in the local and global energy policies to reduce the reliance on fossil fuels, carbon footprints and increase energy security.

Although the study offers helpful information, it has its limitations, including disregard of battery degradation, real-time grid pricing and environmental impact assessment. These are restrictions that can be targeted in future research. Implementing grid pricing in real-time, modeling the generation and demand stochastically and the impacts of policies will make optimization models that are more robust and can also bring about more comprehensive and adaptive energy solutions.

Finally, the LP optimization becomes a potential tool to address the operational and economic challenges of PV-BESS systems that are connected to the grid. With the energy landscape ever-changing, this study highlights the need to optimize energy systems to achieve a cost-saving and sustainability balance. As the field of research and optimization evolution continues, LP optimum can help progress towards further integration of renewable energy and push the world toward more efficient and cleaner energy sources.

6.2 Key Findings

The remarkable results of this study are as follows:

1. Cost Reduction through LP Optimization: It was found out that substantial cost reduction can be achieved with the help of applying the LP optimization. The LP model effectively reduced grid power dependence particularly when demand was high and when the price was high. The LP approach allowed minimizing the use of battery storage and renewable energy, such as solar power (PV) and wind, so that the system would be cost effective in terms of energy use compared to the base case scenario, in which the system would operate under grid power only. This saved a lot in grid reliance and this is a test of the economy of using battery storage together with solar and wind energy systems.
2. Effect of Time-of-Use (TOU) Pricing: The next significant finding is that time-of-use (TOU) pricing is another important step making the system work even better. The grid price curve analysis indicated that the grid prices were minimal in off-peak periods (early morning and late night), and peak (midday and early evening) periods. The LP optimization model

maximized the energy use by storing more energy during these times of low prices, and discharging the battery during the times of high prices, which helped the model save energy costs. This is in line with previous studies which note that time-of-use pricing is important in promoting smart use of energy and also maximizing the cost effect of renewable energy integration.

3. Battery Performance and Storage Efficiency: The other important aspect of the optimization of the system was the battery energy storage system (BESS) performance. The state of charge (SOC) of the battery changed throughout the 24-hours, rising during the day when the excess renewable energy was stored and dropped during the times the battery was going through load demand to the system. These charging and discharging cycles were optimized via the LP model which ensured that the battery was utilized efficiently to satisfy the load with minimum consumption of grid electricity. The model revealed how battery storage is useful in weaning ourselves off grid power, and in offering the cost-effective solutions to dealing with renewable energy.
4. Renewable Energy Integration (PV and Wind): The solar PV, and wind energy integration played a major role in the performance of the system. The solar generation (PV) played an important role during the day period particularly when the sun radiation was intense. The contribution wind power made was fairly consistent although it was a minor contribution in comparison with solar power. A combination of battery storage with these renewable energy sources and LP optimization made the system meet load demands with a minimum use of the grid. This integration of renewable energy also minimized operational cost, and in tandem with the goal to realize a low-carbon cost-effective energy system.
5. Cumulative Cost Savings: The cumulative cost analysis between the normal system and the LP-optimized system was another way of highlighting the economic gains of optimization in the long run. During the 24-hour process, the cumulative cost in the LP model remained below that of the baseline scenario. This is particularly important with the consideration of the ever-rising grid prices at the peak times. The optimization of battery storage, renewable energy and grid electricity that the LP model achieved led to

saving of the overall costs and hence the LP model proved to be a more feasible option to take control of the energy in grid-connected PV-BESS systems.

6.3 Significance of the Study

The research has relevance to the field of economic analysis, cost saving measures, and optimization of energy systems, especially when using grid-connected PV-BESS systems. An understanding of the reasons why Linear Programming (LP) optimization is one of the tools that can be used to reduce costs in the energy system through the incorporation of renewable energy sources, including solar and wind energy, as well as energy storage options, like batteries. This paper will contribute to the better comprehension of managing energy cost efficiency in different situations and the ways of how best energy costs will be managed, lesser reliance on grids and increased overall efficiency of the energy systems. The results highlight how LP optimization can be used to enhance the economic viability of renewable energy systems, thereby rendering them more competitive than conventional grid-based systems which typically are more costly since the system is susceptible to changing energy prices.

The relevance of the present piece of work on the global and local importance of the optimization of energy systems can also be seen in the fact that the topic has been covered in the literature review. The transition to sustainable energy systems across the world is important in fighting climate change and ensuring energy security. This study will substantiate that shift by giving realistic insights on how renewable energy together with battery storage systems can be introduced into the grid to curb the use of fossil fuels, lower the energy cost, and enhance economic stability of energy systems. The results also highlight the importance of time-of-use grid pricing to improve the efficiency of energy systems through the encouraging consumption of cheaper off-peak electricity that has valuable effects on both consumers and the utility that seeks to lower the cost of energy.

Locally, the research has so much relevance to the Finnish energy market where the pressure to enhance the penetration of renewable energy resources and mitigate the consumptions of carbon emissions is very high. The energy policy of Finland has revolved around the effort to switch to cleaner energy sources, such as solar, wind, and storage systems, as well as address the issue of balancing intermittent generation of renewable energy to the load needs. The research has a local significance to energy optimization through proving how the combination of battery storage with time-of-use pricing and LP optimization can maximize the cost effectiveness and reliability of the energy system in Finland. This will be extremely important to the current energy transformation in Finland, as the potential to efficiently balance renewable resources and optimize the energy expenses will contribute significantly to the realization of the ambitious climate targets in Finland.

6.4 Implications of the Study

The implications of this study on the real world relate broadly to the design and operation of energy systems, utility companies, policymakers interested in optimizing the integration of renewable energy systems and energy storage systems, specifically in grid-connected PV-BESS systems. Linear programming (LP) optimization of the design and operation of these systems have been a strategic way of lowering the cost of the energy supplied, decreasing the reliance on the grid and increasing the overall rate of energy distribution networks. These implications are especially effective in influencing future energy policy and informing the energy infrastructure development, particularly in areas with a high penetration of renewable energy.

To the designers of energy systems, the research highlights the need to pay attention to cost-effective energy management practices, like the efficient use of solar and wind energies, used together with battery storage. With an appropriate system design based on the use of LP optimization, it is possible to manage the time-of-use grid pricing in a more efficient way meaning that more energy would be stored when it is most economical and consumed when it is most expensive. Not only does this save energy to consumers but it also enhances stability and reliability of the grid by reducing the amount of costly grid power that is needed when there is peak demand. Also, the results of the study can be used by energy system designers to improve the functionality of future grid-connected PV-BESS systems, offering a multifaceted solution to energy supply balancing the generation of renewable energy within a grid with storage and consumption trend.

In the case of utility companies, the article points to the future opportunities of cost savings and better efficiency of systems on adoption of LP optimization and time of use grid pricing plans. Through such optimization strategies, utilities will be able to limit the necessity of expensive peaking power plants since the system will be better at addressing the energy consumption demands during high-price hours via the use of stored renewable energy. This as well could result to a decline in the total grid stress; because renewable energy and battery storage can be used to balance supply and demand in a more efficient manner. Moreover, the findings of this research can help utilities create more dynamic pricing schemes that could motivate consumers to consume energy at off-peak times which will only alleviate the pressure on the grid and will enhance effective allocation of the existing resources.

The findings of the study can offer important lessons to policymakers who can formulate future regulations and incentives to boost the use of renewable energy and energy storage systems. The research illustrates economic benefits of streamlining the energy systems, which might also be used as a foundation to design policies that would promote the application of LP optimization in residential, commercial, and industrial realms. The results of the study can also be used to inform policymakers on the decision-making regarding subsidies, incentive schemes, and tax rebates of the energy storage systems and renewable energy installations that promote a shift to more viable and sustainable energy infrastructure. Moreover, a possible approach to national strategies that may involve inclusion of LP optimization into energy grid management will be the de-carbonization of national reserves since most countries with a widespread level of renewable energy in their energy mix tend to be more energy secure.

The implications that this research will have on the future of grid-connected PV-BESS systems, in areas where large fractions of the renewable energy are currently utilized, e.g., in Finland or in other places in Europe and North America, are also significant. The great irregularity of renewable energy sources such as solar and wind needs novel solutions to achieve reliable and consistent energy supply. These systems can also deal with the varying periods of renewal energy better by adding battery storage and LP optimization so that the extra energy produced on sunny or windy days can be stored to be used during periods of less generation. This is especially significant in regions where renewable energy has a high representation in the grid, and grid stability may be influenced by the intermittency of renewable generation. Consequently, the research offers a guide on how grid-connected PV-BESS can be improved and utilized in the future to utilize optimally renewable energy, decrease reliance on the grid, and eventually reduce energy expenses.

6.5 Recommendations for Future Research

According to the results, there are a number of recommendations on future studies to expand on the current research and to take the optimization of the grid-connected PV-BESS systems to the next level. These suggestions will fill in the gaps uncovered in the analysis and offer that more detailed and realistic models can inform the policy, design and operational choices in the energy systems.

The real-time grid pricing was not incorporated in the optimization model was one of the primary limitations of this study. Indicators of daily changes in price based on time-of-use pricing were contrasted but the actual changes in grid prices on a real-time basis due to such factors as market volatility, grid congestion, and imbalances in supply-demand were not considered. The incorporation of dynamic grid pricing into the optimization model in future research can be helpful. This would allow the system to re-response to real-time price adjustments and have a more realistic and flexible method of optimizing the cost and energy control. The analysis supposes that load demand and the generation of solar energy follow the predictable models using past data. But in practice, these variables are subject to stochastic variations which occur owing to weather conditions, consumer behavior and cold grid unexpectedness. Further research may consider the use of stochastic modeling to consider such uncertainties. The method had the potential to employ probabilistic modeling to model a number of load and generation scenarios, which would be useful to optimize the performance of a system in different conditions, as well as the robustness of the LP optimization model.

Pricing of grids, energy production, and consumption using real-time data can greatly enhance the accuracy and optimization model. Future studies would be capable of gathering and analyzing real-time data of renewable sources, battery storage, and grid systems by connecting smart grid technology and devices of the Internet of Things (IoT). This would allow the LP model to dynamically respond to the dynamic demand, generation as well as pricing pattern and the system would become more receptive to the changing demand. Real-time data integration would enable to manage the peak load conditions in a more efficient way and make PV-BESS systems more economical. The progress and implementation of advanced forecasting models of solar generation, wind generation and load demand is another field of interest to research in the future. More complex methods like machine learning and artificial intelligence may be utilized to enhance the accuracy of forecasting and this may particularly assist in intermittent renewable energies. Such models might be able to better forecast energy availability and demand, with the model of planning then able to anticipate ahead and store energy during demand low periods or times of large renewable generation. This paper touched upon sensitivity analysis, but can be extended to how the optimization model reacts to different conditions. The sensitivity analysis of the most important parameters (battery efficiency, rates of solar and wind generation, grid prices) could be more profound in the future research. This would give a better insight of the factors that have the greatest impact on the performance of the system and cost- efficiency. The potential risks and uncertainties could also be determined through sensitivity analysis and enhance the resilience and robustness of PV-BESS optimization to future challenges.

The impact of regulatory frameworks and policy incentives on the economic viability of PV-BESS systems would be explored in future research. Significant changes in the cost-benefit analysis of renewable energy systems can be achieved by combining government subsidies, tax incentives and carbon pricing systems. Implementing policy scenarios into the optimization models will enable researchers to evaluate the importance of government support in providing facilitation to PV-BESS technology adoption and the conversion of energy systems towards more sustainable ones. This study did not present the full benefits of environmental cost optimization of the system despite the fact that the economic factor was the theme of the study. Future studies may incorporate concerns of life cycle assessments (LCA) to gauge the carbon footprint reductions and environmentally sustainable PV-BESS systems. This would provide a better picture of the performance of the system and allow seeing the possible impacts not only on cost savings, but also future contributions to climate change mitigation.

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Appendix: Code

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import linprog

# Upload data
from google.colab import files
uploaded = files.upload()

# READ, AND CLEAN
# Fix: Extract the filename from the uploaded dictionary
df = pd.read_excel(list(uploaded.keys())[0])
df.columns = df.columns.str.strip().str.lower()

# Rename columns to simple names
df = df.rename(columns={
    "imbalance price": "grid_price",
    "load demand": "load_demand",
    "pv": "pv",
    "wind": "wind"
})

required_cols = ["grid_price", "load_demand", "pv", "wind"]
missing = [c for c in required_cols if c not in df.columns]
if missing:
    raise ValueError(f"Missing required columns: {missing}")

# Convert to numeric and clean
for col in required_cols:
    df[col] = pd.to_numeric(df[col], errors="coerce")

df = df.dropna(subset=required_cols).reset_index(drop=True)

print("Cleaned dataset shape:", df.shape)
print(df.head())

# dataset is truly hourly, change dt = 1.0
```

```
dt = 0.25   # hours per row (15 minutes)

# First 24 hours = 96 rows if dt=0.25
n_steps_24h = int(round(24 / dt))

if len(df) < n_steps_24h:
    raise ValueError("Dataset does not contain enough rows for the first 24 hours.")

day = df.iloc[:n_steps_24h].copy()
# Create time and hour
day["time"] = pd.date_range("2026-01-01 00:00:00", periods=n_steps_24h, freq="15min")
day["hour"] = (np.arange(n_steps_24h) * dt).astype(int)

import matplotlib.dates as mdates
print("Generating plots and tables...")
# Descriptive statistics: Histogram/Box plot
# Histogram of Load Demand
plt.figure(figsize=(10, 6))
plt.hist(day['load_demand'], bins=20, edgecolor='black', alpha=0.7, color='#7b61a8')
plt.title('Histogram of Load Demand (First 24 Hours)')
plt.xlabel('Load Demand (kW)')
plt.ylabel('Frequency')
plt.grid(axis='y', alpha=0.75)
plt.tight_layout()
plt.show()

# Energy production: time series plot
# Stacked Bar Chart of Raw PV and Wind Production (Hourly average)
hourly_prod = day.groupby("hour", as_index=False).agg({
    "pv": "mean",
    "wind": "mean"
})
x = np.arange(len(hourly_prod))
x_labels = [f"h{i}" for i in range(len(hourly_prod))]

plt.figure(figsize=(14, 6))
plt.bar(x, hourly_prod["pv"], label="PV Production", color="#d55a4a")
plt.bar(x, hourly_prod["wind"], bottom=hourly_prod["pv"], label="Wind Production", color="#9dbb4c")
plt.title("Hourly Average PV and Wind Production (First 24 Hours)")
```

```
plt.xlabel("Time (hr)")
plt.ylabel("Power (kW)")
plt.xticks(x, x_labels)
plt.legend(loc="upper center", bbox_to_anchor=(0.5, -0.12), ncol=2, frameon=False)
plt.grid(axis='y', linestyle='--', alpha=0.75)
plt.tight_layout()
plt.show()

# TIME-OF-USE GRID PRICES
# Use the dataset's imbalance price as the grid price
day["tou_grid_price"] = day["grid_price"]

# POWER DEFINITIONS
# Since the dataset has both PV and wind, I combine them into the renewable side.
# In the breakdown plot below, this combined renewable power is used as "Pv".
day["p_pv_total"] = day["pv"] + day["wind"]

# Renewable power directly serving the load
day["p_pv_to_load"] = np.minimum(day["load_demand"], day["p_pv_total"])

# Surplus renewable power (can charge battery or be curtailed)
day["p_surplus_pv"] = np.maximum(day["p_pv_total"] - day["load_demand"], 0)

# Residual demand after direct PV/wind contribution
day["p_residual_load"] = np.maximum(day["load_demand"] - day["p_pv_total"], 0)

# GRID PRICE CURVE (FIRST 24 HOURS)
hourly_price = day.groupby("hour", as_index=False)["tou_grid_price"].mean()
plt.figure(figsize=(12, 4))
plt.plot(hourly_price["hour"], hourly_price["tou_grid_price"], marker="o")
plt.title("Time-of-Use Grid Price Curve (First 24 Hours)")
plt.xlabel("Hour")
plt.ylabel("Grid Price")
plt.xticks(range(24))
plt.grid(True)
plt.tight_layout()
plt.show()

# BASELINE COST (NO BATTERY)
```

```
# Baseline:
# - PV/wind directly serve load first
# - remaining deficit comes from the grid
day["p_grid_baseline"] = day["p_residual_load"]
day["interval_cost_baseline"] = day["p_grid_baseline"] * day["tou_grid_price"] * dt
# BATTERY SETTINGS
avg_load_24h = day["load_demand"].mean()
battery_power_max = 0.20 * avg_load_24h    # battery power rating
battery_capacity = 2.0 * battery_power_max # 2-hour battery
eta_charge = 0.95
eta_discharge = 0.95

soc_init = 0.50 * battery_capacity
soc_min = 0.10 * battery_capacity
soc_max = 0.90 * battery_capacity

# Small throughput penalty to reduce unrealistic simultaneous charge/discharge in LP
throughput_penalty = 1.0

print("\nBattery settings used:")
print(f"battery_power_max = {battery_power_max:.2f}")
print(f"battery_capacity  = {battery_capacity:.2f}")
print(f"soc_init          = {soc_init:.2f}")
print(f"soc_min           = {soc_min:.2f}")
print(f"soc_max           = {soc_max:.2f}")

# LINEAR PROGRAMMING MODEL
# Decision variables for each interval t:
#   g_load[t]   = grid power used to serve load
#   g_ch[t]     = grid power used to charge battery
#   ch_pv[t]    = surplus PV/wind used to charge battery
#   dis[t]      = battery discharge power used to serve load
#   soc[t]      = battery state of charge
#   spill[t]    = curtailed surplus renewable power
# Load equation:
#   Pload = Ppv + Pbattery + Pgrid
# where:
#   Ppv      = p_pv_to_load
#   Pbattery = dis
```

```
#   Pgrid    = g_load

price = day["tou_grid_price"].to_numpy(dtype=float)
residual_load = day["p_residual_load"].to_numpy(dtype=float)
surplus_pv = day["p_surplus_pv"].to_numpy(dtype=float)
n = len(day)

# Variable indexing
idx_g_load = np.arange(0, n)
idx_g_ch   = np.arange(n, 2*n)
idx_ch_pv  = np.arange(2*n, 3*n)
idx_dis    = np.arange(3*n, 4*n)
idx_soc    = np.arange(4*n, 5*n)
idx_spill  = np.arange(5*n, 6*n)

num_vars = 6 * n

# Objective:
# minimize total grid cost
c = np.zeros(num_vars)
c[idx_g_load] = price * dt
c[idx_g_ch]   = price * dt + throughput_penalty * dt
c[idx_ch_pv]  = throughput_penalty * dt
c[idx_dis]    = throughput_penalty * dt

# Equality constraints
A_eq = []
b_eq = []

# (a) Residual load must be met by battery discharge or grid
# g_load[t] + dis[t] = residual_load[t]
for t in range(n):
    row = np.zeros(num_vars)
    row[idx_g_load[t]] = 1.0
    row[idx_dis[t]] = 1.0
    A_eq.append(row)
    b_eq.append(residual_load[t])

# (b) Surplus PV can charge battery or be spilled
```

```
# ch_pv[t] + spill[t] = surplus_pv[t]
for t in range(n):
    row = np.zeros(num_vars)
    row[idx_ch_pv[t]] = 1.0
    row[idx_spill[t]] = 1.0
    A_eq.append(row)
    b_eq.append(surplus_pv[t])

# (c) Battery SOC dynamics
# soc[0] = soc_init + eta_charge*(g_ch[0] + ch_pv[0])*dt - dis[0]*dt/eta_discharge
row = np.zeros(num_vars)
row[idx_soc[0]] = 1.0
row[idx_g_ch[0]] = -eta_charge * dt
row[idx_ch_pv[0]] = -eta_charge * dt
row[idx_dis[0]] = dt / eta_discharge
A_eq.append(row)
b_eq.append(soc_init)

# For t >= 1
for t in range(1, n):
    row = np.zeros(num_vars)
    row[idx_soc[t]] = 1.0
    row[idx_soc[t-1]] = -1.0
    row[idx_g_ch[t]] = -eta_charge * dt
    row[idx_ch_pv[t]] = -eta_charge * dt
    row[idx_dis[t]] = dt / eta_discharge
    A_eq.append(row)
    b_eq.append(0.0)

# (d) End-of-day SOC = initial SOC
row = np.zeros(num_vars)
row[idx_soc[n-1]] = 1.0
A_eq.append(row)
b_eq.append(soc_init)

A_eq = np.array(A_eq)
b_eq = np.array(b_eq)

# Inequality constraints
```

```
A_ub = []
b_ub = []

# Total charge power limit:
# g_ch[t] + ch_pv[t] <= battery_power_max
for t in range(n):
    row = np.zeros(num_vars)
    row[idx_g_ch[t]] = 1.0
    row[idx_ch_pv[t]] = 1.0
    A_ub.append(row)
    b_ub.append(battery_power_max)

A_ub = np.array(A_ub)
b_ub = np.array(b_ub)

# Bounds
bounds = []

# g_load
bounds += [(0, None)] * n

# g_ch
bounds += [(0, battery_power_max)] * n

# ch_pv
bounds += [(0, battery_power_max)] * n

# dis
bounds += [(0, battery_power_max)] * n

# soc
bounds += [(soc_min, soc_max)] * n

# spill
bounds += [(0, None)] * n

# Solve LP
result = linprog(
    c=c,
```

```
    A_ub=A_ub,
    b_ub=b_ub,
    A_eq=A_eq,
    b_eq=b_eq,
    bounds=bounds,
    method="highs"
)
if not result.success:
    raise RuntimeError(f"Optimization failed: {result.message}")

# STORE LP RESULTS
x = result.x
day["p_grid_lp"] = x[idx_g_load]
day["p_grid_to_battery"] = x[idx_g_ch]
day["p_battery_charge_from_pv"] = x[idx_ch_pv]
day["p_battery_discharge"] = x[idx_dis]
day["soc"] = x[idx_soc]
day["p_spill"] = x[idx_spill]

# LP total purchased grid power = grid to load + grid to battery
day["p_grid_total_purchase_lp"] = day["p_grid_lp"] + day["p_grid_to_battery"]

# LP interval cost
day["interval_cost_lp"] = day["p_grid_total_purchase_lp"] * day["tou_grid_price"] * dt

# HOURLY COST COMPARISON FOR THE FIRST 24 HOURS
hourly = day.groupby("hour", as_index=False).agg(
    hourly_grid_price=("tou_grid_price", "mean"),
    hourly_cost_baseline=("interval_cost_baseline", "sum"),
    hourly_cost_lp=("interval_cost_lp", "sum"),
    p_pv_used=("p_pv_to_load", "mean"),
    p_battery_used=("p_battery_discharge", "mean"),
    p_grid_used=("p_grid_lp", "mean")
)

plt.figure(figsize=(12, 5))
width = 0.4
hours = hourly["hour"].to_numpy()
```

```
plt.bar(hours - width/2, hourly["hourly_cost_baseline"], width=width, label="Baseline Cost")
plt.bar(hours + width/2, hourly["hourly_cost_lp"], width=width, label="LP Cost")
plt.title("Hourly Cost Comparison for the First 24 Hours")
plt.xlabel("Hour")
plt.ylabel("Cost")
plt.xticks(range(24))
plt.legend()
plt.grid(True, axis="y")
plt.tight_layout()
plt.show()

from pulp import LpProblem, LpMinimize, LpVariable, lpSum, LpStatus
# Battery parameters
battery_capacity = 500  # Maximum battery capacity (kW)
battery_state = 0       # Initial battery state (kW)

# Ensure 'PV' column is numeric, coercing errors to NaN
df2['PV'] = pd.to_numeric(df2['PV'], errors='coerce')
# Fill any NaN values that resulted from coercion, for example, with 0 or a suitable mean/median
df2['PV'] = df2['PV'].fillna(0)

# Compute Pbattery and Pgrid
Pbattery_list = []
Pgrid_list = []

for index, row in df2.iterrows(): # Changed df to df2 here
    load = row['Load demand']
    pv = row['PV']

    # PV first satisfies the load
    remaining_load = load - pv

    if remaining_load < 0:
        # Surplus PV charges the battery
        surplus = -remaining_load
        battery_charge = min(surplus, battery_capacity - battery_state)
        battery_state += battery_charge
        Pbattery = 0
        Pgrid = 0
```

```
    else:
        # Battery discharges to cover remaining load
        Pbattery = min(remaining_load, battery_state)
        battery_state -= Pbattery
        Pgrid = remaining_load - Pbattery

    Pbattery_list.append(Pbattery)
    Pgrid_list.append(Pgrid)

# Add computed columns to dataframe
df2['Pbattery'] = Pbattery_list
df2['Pgrid'] = Pgrid_list

# Calculate the hour of the day for each time step
# There are 96 15-minute intervals in 24 hours (24 * 4 = 96)
df2['hour_of_day'] = (df2.index % 96) // 4

# Plot stacked area figure
plt.figure(figsize=(12,6))
plt.stackplot(df2.index, df2['PV'], df2['Pbattery'], df2['Pgrid'], # Changed df.index to df2.index
              labels=['PV (Pv)', 'Battery (Pbattery)', 'Grid (Pgrid)'],
              colors=['orange', 'green', 'blue'])
plt.plot(df2.index, df2['Load demand'], color='black', linewidth=2, label='Load Demand (Pload)') # Changed df.index and df['Load
demand'] to df2.index and df2['Load demand']

plt.title('Load Satisfaction Breakdown: Pload = Pv + Pbattery + Pgrid (First 24 hours)')
plt.xlabel('Hour')
plt.ylabel('Power (kW)')
plt.legend(bbox_to_anchor=(1, 1), loc='upper left') # Adjusted legend position
plt.grid(True)



# For 1 day (96 time steps), 96 time steps per day
hour_ticks = np.arange(0, len(df2), 4) # Every hour (4 15-min intervals)
hour_labels = [f'{int(tick / 4)}' for tick in hour_ticks]

plt.xticks(hour_ticks, hour_labels)

plt.tight_layout()
```

```
plt.show()

import matplotlib.dates as mdates

# LOAD SATISFACTION AND COST (LP MODEL)
plt.figure(figsize=(12, 4))
plt.plot(day["hour"], day["soc"], label="Battery SOC")
plt.title("Battery State of Charge (LP Model, First 24 Hours)")
plt.xlabel("Hour")
plt.ylabel("Energy")
plt.grid(False)
plt.legend()
# Format x-axis to display hours
plt.xticks(range(24))
plt.tight_layout()
plt.show()

plt.figure(figsize=(12, 4))
plt.plot(day["hour"], day["interval_cost_baseline"].cumsum(), label="Baseline Cumulative Cost")
plt.plot(day["hour"], day["interval_cost_lp"].cumsum(), label="LP Cumulative Cost")
plt.title("Cumulative Cost Comparison (First 24 Hours)")
plt.xlabel("Hour")
plt.ylabel("Cumulative Cost")
plt.grid(False)
plt.legend()
# Format x-axis to display hours
plt.xticks(range(24))
plt.tight_layout()
plt.show()


# Required columns in `day`:
#   load_demand
#   p_pv_to_load
#   p_battery_discharge
#   p_grid_lp
#   pv
#   wind
#   hour
```

```
# Then aggregate to hourly average power
hourly_plot = day.groupby("hour", as_index=False).agg({
    "pv": "mean",
    "wind": "mean",
    "p_grid_lp": "mean",
    "p_battery_discharge": "mean",
    "load_demand": "mean"
})

# Rename for plotting
hourly_plot = hourly_plot.rename(columns={
    "pv": "PV",
    "wind": "Wind",
    "p_grid_lp": "Grid",
    "p_battery_discharge": "Battery discharge",
    "load_demand": "Load"
})
# 2) Create x labels t1 ... t24
x = np.arange(len(hourly_plot))
x_labels = [f"{i+1}" for i in range(len(hourly_plot))]

# 3) Plot stacked bars + line
plt.figure(figsize=(14, 6))
bar_width = 0.65

# Stacked bars
plt.bar(x, hourly_plot["PV"], width=bar_width, color="#d55a4a", label="PV")
plt.bar(x, hourly_plot["Wind"], width=bar_width,
        bottom=hourly_plot["PV"],
        color="#9dbb4c", label="Wind")
plt.bar(x, hourly_plot["Grid"], width=bar_width,
        bottom=hourly_plot["PV"] + hourly_plot["Wind"],
        color="#7b61a8", label="Grid")
plt.bar(x, hourly_plot["Battery discharge"], width=bar_width,
        bottom=hourly_plot["PV"] + hourly_plot["Wind"] + hourly_plot["Grid"],
        color="#49a6d8", label="Battery discharge")

# Load line
plt.plot(x, hourly_plot["Load"], color="#2f6db3", linewidth=3, marker="o", label="Load")
```

```
# 4) Formatting
plt.title("", fontsize=20, fontweight="bold")
plt.xlabel("Hour", fontsize=14)
plt.ylabel("Power (kW)", fontsize=14)
plt.xticks(x, x_labels, fontsize=11)
plt.yticks(fontsize=11)
plt.grid(axis="y", linestyle="--", alpha=0.4)
plt.legend(loc="upper center", bbox_to_anchor=(0.5, -0.12), ncol=5, frameon=False, fontsize=12)

plt.tight_layout()
plt.show()
# Hourly Cost Comparison with USD annotations
hourly = day.groupby("hour", as_index=False).agg(
    hourly_cost_baseline=("interval_cost_baseline_usd", "sum"),
    hourly_cost_lp=("interval_cost_lp_usd", "sum")
)
# Calculate hourly savings
hourly["hourly_savings"] = hourly["hourly_cost_baseline"] - hourly["hourly_cost_lp"]
plt.figure(figsize=(12, 5))
x = hourly["hour"].to_numpy()
# Stack LP cost and savings to show baseline cost
plt.bar(x, hourly["hourly_cost_lp"], label="LP Cost", color="#4e79a7")
plt.bar(x, hourly["hourly_savings"], bottom=hourly["hourly_cost_lp"], label="Savings vs Baseline", color="#f28e2b")
plt.title("")
plt.xlabel("Hour")
plt.ylabel("Cost (USD)")
plt.xticks(range(24))
plt.legend()
plt.grid(False, axis="y")
plt.tight_layout()
plt.show()

import matplotlib.pyplot as plt
import matplotlib.dates as mdates

# LOAD SATISFACTION BREAKDOWN FOR LP MODEL IN HYBRID ENERGY SYSTEMS
# Where:
#   P_PV_to_load      = PV and wind power directly serving the load
```

```
#   P_Battery_Discharge = Battery power discharged to serve the load
#   P_Grid_to_Load    = Grid power purchased specifically to serve the load

plt.figure(figsize=(14, 6))

# Stacked area plot for power sources contributing to the load
plt.stackplot(
    day["time"],
    day["p_pv_to_load"],
    day["p_battery_discharge"],
    day["p_grid_lp"],
    labels=["PV (to load)", "Battery Discharge (to load)", "Grid (to load)"],
    colors=["#d55a4a", "#49a6d8", "#7b61a8"]
)

# Line plot for the total load demand
plt.plot(day["time"], day["load_demand"], linewidth=2.5, color="#2f6db3", label="Total Load Demand")

plt.title("Linear Programming in Hybrid System", fontsize=16)
plt.xlabel("Time", fontsize=12)
plt.ylabel("Power (kW)", fontsize=12)
plt.legend(loc="upper left", ncol=4, frameon=False, fontsize=10)
plt.grid(True, linestyle='--', alpha=0.6)

# Format x-axis to display time more clearly
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter('%H:%M'))
plt.xticks(rotation=45)
plt.tight_layout()
plt.show()
import pandas as pd

# Assume `day` DataFrame exists
# Hourly aggregation
hourly_summary = day.groupby("hour", as_index=False).agg({
    "load_demand": "mean",
    "pv": "mean",
    "wind": "mean",
    "p_grid_lp": "mean",
    "soc": "mean",
```

```
    "tou_grid_price_usd": "mean"
})
# Rename columns
hourly_summary = hourly_summary.rename(columns={
    "load_demand": "Load",
    "pv": "PV",
    "wind": "Wind",
    "soc": "SoC",
    "p_grid_lp": "Grid",
    "tou_grid_price_usd": "TOU_Grid_Price_USD"
})

# Calculate Grid cost in USD
dt = 0.25
hourly_summary["Grid_Cost_USD"] = hourly_summary["Grid"] * hourly_summary["TOU_Grid_Price_USD"] * dt

# Reorder columns
hourly_summary = hourly_summary[[
    "hour", "Load", "PV", "Wind", "SoC", "Grid", "TOU_Grid_Price_USD", "Grid_Cost_USD"
]]

# Display nicely
pd.set_option('display.width', 1000)
pd.set_option('display.max_columns', 20)
pd.set_option('display.float_format', '{:,.2f}'.format)

print("\n================ Hourly Summary Table ================")
print(hourly_summary)

# Save to Excel
output_file = "hourly_summary_table_usd.xlsx"
hourly_summary.to_excel(output_file, index=False)
print(f"\nHourly summary table saved to: {output_file}")
```