REPUBLIC OF TÜRKİYE
ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY UNIVERSITY

GRADUATE SCHOOL
ELECTRICAL AND ELECTRONIC ENGINEERING DEPARTMENT

TECHNO-ECONOMIC FEASIBILITY ANALYSIS OF A BATTERY ENERGY STORAGE SYSTEM ASSISTED SOLAR PHOTOVOLTAIC POWER PLANT: A CASE STUDY

TÜRKER AŞKIN KABADAYI

M.Sc.

ADANA 2025

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THESIS ADVISOR
ASSOC. PROF. DR. ÖZGÜR ÇELİK

ADANA, 2025

DECLARATION OF CONFORMITY

In this thesis study, which was prepared following the thesis writing rules of Adana Alparslan Türkeş Science and Technology University Institute of Graduate School, I declare that I provide all the information, documents, evaluations and results in accordance with scientific ethics and moral codes without resorting to any means or assistance that would be contrary to scientific ethics and traditions. I also declare that I refer to all of the articles I used in this study with appropriate references and accept all moral and legal consequences if a situation is found contrary to my statement regarding my work.

29/08/2025

[Signature]

Türker Aşkın KABADAYI

ÖZET

BATARYA ENERJİ DEPOLAMA SİSTEMİ DESTEKLİ FOTOVOLTAİK ENERJİ SANTRALİNİN TEKNO-EKONOMİK UYGULANABİLİRLİK ANALİZİ: BİR VAKA ÇALIŞMASI

Türker Aşkın KABADAYI
Yüksek Lisans, Elektrik-ElektronikAnabilim Dalı
Danışman: Doç. Dr. Özgür ÇELİK
Ağustos 2025, 55 sayfa

Bu çalışmada, 1 MW çıkış gücüne sahip iki büyük ölçekli arazi tipi güneş enerjisi santralinin kapsamlı bir performans ve ekonomik analiz karşılaştırması sunulmaktadır. Projelerin aynı ekipmanlarla kurulduğu ve aynı lokasyonda bulunduğu varsayılmaktadır. Projelerden biri geleneksel fotovoltaik (FV) enerji santrali olarak değerlendirilirken, diğeri geleneksel sisteme bir batarya enerji depolama sistemi (BEDS) entegre şekilde değerlendirilmiştir. BEDS ile entegre edilen sistem tepe-traşlama yöntemi ile çalışmakta olup temel amaç gündüzleri 1 MW üzerindeki enerjiyi depolayarak gün batımından sonraki tepe talep döneminde FV sisteminin sürdürülebilirliğini sağlamak ve enerji talebine cevap vermektir. Her iki sistem de ortak bir benzetim programında ayrı ayrı tasarlanmış, performans ve tekno-ekonomik açısından değerlendirilmiştir. Uygulama sonucunda, BEDS entegrasyonu uygulamasının şebekeye verilen enerji miktarını yılda 153,18 MWh arttırdığı ve performans oranını %4,8 oranında iyileştirdiği görülmüştür. Fakat fizibilite çalışmaları sonucunda ekonomik açıdan önemli maliyet artışı olduğu tespit edilmiştir. Teknik bulgular, BEDS entegrasyonunun FV sistemleri üzerinde olumlu bir etkiye sahip olduğunu ve depolamalı FV sistemlerinin batarya teknolojisindeki gelişmelerle sürekli bir enerji kaynağı olma potansiyeli olduğunu göstermektedir. Bu çalışma, sistem tasarımcılarına, yatırımcılara ve araştırmacılara FV sistemlerine BEDS entegrasyonu konusunda önemli teknik bilgiler sunmaktadır.

Anahtar Kelimeler: Tepe-traşlama, BEDS entegrasyon, FV, Enerji depolama

ABSTRACT

TECHNO-ECONOMIC FEASIBILITY ANALYSIS OF A BATTERY ENERGY STORAGE SYSTEM ASSISTED SOLAR PHOTOVOLTAIC POWER PLANT: A CASE STUDY

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August 2025, 55 pages

This study presents a comprehensive comparison of the performance and economic analyses of two large-scale, 1 MW-output, ground-mounted solar power plants. The projects are assumed to be constructed with the same equipment and located at the same location. One project is a conventional photovoltaic (PV) power plant, while the other is evaluated with a battery energy storage system (BESS) integrated into the conventional system. The system integrated with the BESS operates using a peak-shaving method, with the primary objective of storing more than 1 MW of energy during the daytime to ensure PV system sustainability and provide energy demand during peak demand periods after sunset. Both systems were designed separately in a common simulation program and evaluated from a performance and techno-economic perspective. The results showed that the BESS integration increased the amount of energy injected to the grid by 153.18 MWh per year and improved performance by 4.8%. However, feasibility studies revealed a significant increase in economic costs. Technical findings demonstrate that BESS integration has a positive impact on PV systems and that PV systems with storage have the potential to become a continuous energy source with advancements in battery technology. This study provides important technical insights for system designers, investors, and researchers regarding BESS integration in PV systems.

Keywords: Peak-shaving, BESS integration, PV, Energy storage

Dedication

To my family.

ACKNOWLEDGEMENTS

I would like to acknowledge my advisor Assoc. Prof. Dr. Özgür Çelik for his support throughout this academic process, which was a driving force. His insightful guidance, constructive feedback, and constant motivation contributed significantly to my progress and success. I am grateful for his expertise in the field and the time he devoted to my work. I would also like to express my gratitude to the distinguished jury members for their time, comments, and suggestions.

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LIST OF ABBREVIATIONS

AC	: Alternating Current
BESS	: Battery Energy Storage System
DC	: Direct Current
DOD	: Depth of Discharge
IRR	: Internal Rate of Return
kW	: Kilowatt
kWh	: Kilowatt-hour
LCOCE	: Levelized Cost of Consumed Electricity
LCOE	: Levelized Cost of Electricity
MC4	: Multi-Contact, 4 millimeters
MPP	: Maximum Power Point
MW	: Megawatt
NPV	: Net Present Value
NREL	: National Renewable Energy Laboratory
PCS	: Power Conversion System
PE	: Protective Earth
PR	: Performance Ratio
PV	: Photovoltaic
ROI	: Return on Investment
SOC	: State of Charge
STC	: Standard Test Conditions
TL	: Turkish Lira
UTC	: Coordinated Universal Time
USD	: United States Dollar
YEKA	: Yenilenebilir Enerji Kaynak Alanları
YEKDEM	: Yenilenebilir Enerji Kaynakları Desekleme Mekanizması

LIST OF SYMBOLS

%	: Percent / Percentage
±	: Plus/minus
→	: Indicates direction or relation
A	: Ampere
°C	: Degrees Celsius
m²	: Square meter
V	: Volt
Wp	: Watt-peak
≥	: Greater than or equal to

1. INTRODUCTION

In this chapter, firstly, the importance of renewable energy sources, the development of solar energy in the world and in Türkiye, the role of storage in solar energy systems are mentioned and finally, this chapter will be concluded with the aim and scope of the thesis.

1.1. The Importance of Renewable Energy Sources

In the recent past, with the developing industry led by the industrial revolution and the rapidly increasing population, the need for energy has increased at very high rates. Today, most of this increasing energy need is obtained from fossil fuels. The use of fossil fuels threatens environmental and economic sustainability. As a result of the burning of fossil fuels, harmful gases such as carbon dioxide and methane are released into the atmosphere, which directly threaten the environment and human health. In this context, renewable energy sources offer great hope for the future of the ecosystem by meeting sustainable, environmentally friendly and low-cost energy needs (Çelik et al., 2018).

Solar energy systems, which are the main subject of this thesis among renewable energy sources, stand out with some advantages compared to other sources. The main advantage of solar energy is that its negative environmental impact is minimal because solar energy systems do not cause carbon emissions in the energy production process and do not emit other pollutant gases, thus having a positive effect on air quality, and since solar energy systems do not need water in the production process, they do not consume and pollute water resources. Therefore, solar energy is the most suitable energy production method for regions that may experience possible water shortages in the future. As a result, the fact that solar energy does not require any fuel or raw materials during production and is a clean energy source directly ensures the protection of natural resources (Çelik et al., 2016).

Since the sun continuously supplies energy to the earth, solar energy is assumed to be infinite in theory, and therefore energy can be produced using solar energy systems in the future. In addition, a major advantage of this sustainable energy source is that it is suitable for installation and production on any scale, thus making access to energy more equal.

When analysed economically, the high initial investment cost is balanced with long-term low-cost energy generation and low operating costs. Since sunlight does not require a cost, this investment cost is entirely installation and equipment costs, but since these costs are limited to installation, the energy unit cost, which gradually decreases in the long term, provides a great advantage. In fossil fuel dependent countries like Türkiye, solar energy production with domestic resources directly contributes to economic growth as well as keeping foreign currency within the country.

For the main reasons mentioned above, solar energy has great advantages over fossil fuels with its environmental, economic and sustainability features. By eliminating the environmental damage caused by fossil fuels, reducing energy costs and ensuring sustainable energy production for the future, it keeps the environment cleaner and increases the level of welfare.

1.2. Development of Solar Energy in the World and Türkiye

The solar energy sector and basic system components in the world have made great progress compared to the 1950s, when it was first pronounced and studies were assumed to have started, taking its share from the rapidly developing technology and renewable energy policies of governments.

Looking back in terms of the development of solar energy technologies, three critical turning points and events before the millennium stand out. The first of these is the attempt to generate energy from solar radiation with PV cells developed in the 50s, and in the 70s, due to the global oil crises, this technological initiative gained momentum by attracting the attention of governments and authorities. In the 90s, solar energy technologies became more important in order to reduce the carbon footprint with the increasing awareness of ecological degradation of society. Especially in this period, the main actors in the field of renewable energy are seen as United States, Japan and Germany. Total installed PV capacity in the world is given in Figure 1.1 (IEA, 2025).

After the millennium, this realisation has spread worldwide and today large-scale installations and components for the industry are being developed in pioneer countries as well as in China, India and the European Union. As of 2020, China has the world's highest installed capacity and is also the market leader in PV panel production. The European Union, on the other hand, is making large investments with the goal of net zero carbon emission in the region in 2050 within the scope of the Green Deal.

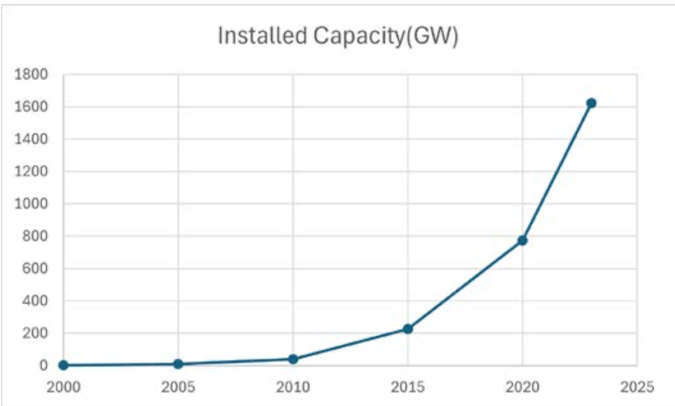

Figure 1.1. Installed PV capacity in the world

As a result of these global efforts, installation costs have been reduced and the unit energy cost has been reduced. thus, solar energy systems have become a more reasonable and sustainable option.

Türkiye is a very favourable country for solar energy due to its geographical location and has focused on this field after the 2000s in order to follow a sustainable energy policy by reducing its dependence on foreign energy with solar energy. Although investments progressed quite slowly until the 2010s, they gained momentum in the mid-2010s. While the sector first attracted attention with large-scale licensed projects implemented in 2013, it has become a very popular investment with YEKA (Renewable Energy Resource Areas) and various state-supported incentives introduced by the government in 2014.

While exceeding 10 GW installed capacity as of 2023, it is predicted that the installed capacity will continue to increase in the near future. Total installed PV capacity in Türkiye is shown in Figure 1.2 (Alparslan, 2025).

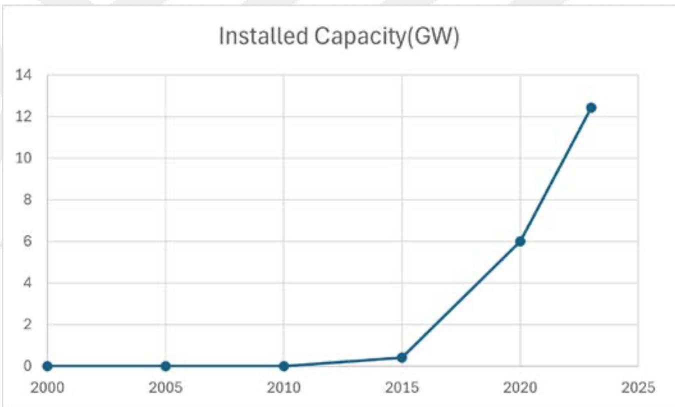

Figure 1.2. Installed PV capacity in Türkiye

1.3. The Role of Energy Storage in Solar Energy Systems

In the previous sections, the advantages of solar energy in general have been discussed, but by its nature, solar energy varies according to sunlight and weather conditions and therefore it has a discontinuous resource characteristic. This disadvantage prevents solar energy systems from meeting the continuity and supply in full time. Right here, this disadvantage can be eliminated with storage systems. Storage systems have a critical importance in the sustainability of solar energy by balancing the different energy supply and demand times (Çelik et al., 2022).

Energy storage systems allow more energy to be produced by increasing efficiency. While solar energy systems can produce at the highest level during daylight hours by nature, energy demand generally increases in the evening and early morning hours. Storage systems, on the other hand, establish the energy supply-demand balance and store the surplus energy produced during the day and ensure that it is ready for consumption in case of need. In this context, storage systems provide a more flexible characteristic to solar energy, enabling it to respond to instantaneous demands and gain a fully sustainable identity.

The most common storage methods used in solar energy systems are batteries, but pumped hydroelectric storage and thermal energy storage methods are also preferred today. Among the battery systems, the most preferred battery type is lithium ion batteries. Batteries store surplus energy during the day and respond to the energy demand by pressing the stored energy to the grid during the hours when the power plant does not have sunlight, making the system more sustainable, flexible and efficient. The main reasons for the preference of lithium ion batteries can be listed as high efficiency, low maintenance costs and gradually decreasing production costs (Bozkurt et al., 2024).

The pumped hydroelectric storage method is a storage technique applicable in large-scale power generation facilities and offers effective solutions in integration with solar energy. With this method, water is stored in a reservoir at an upper level by using the extra energy produced, and in case of energy demand, turbines are rotated with this stored water and energy is provided and energy demand is met full time.

The purpose of thermal energy storage systems is to store solar energy in the form of hot water or steam. In this system, heated water or another substance is stored and this heat is used in electricity generation to provide supply when energy demand increases. Long-term energy storage can be provided with this method.

2. LITERATURE REVIEW

In this section, a literature review has been conducted on the subject and the study topic and the final study results regarding the relevant documents are conveyed. The studies consist of academic articles, master's theses and doctoral theses. In order to reach more consistent results while conducting a literature review, the following keywords were used in the search instructions. Solar energy, battery storage system, techno economic analysis on solar, lithium-ion batteries, solar power plant design, solar power plant operation.

2.1. Related Documents

Uzun (2010) discussed theories of storing solar energy as heat energy in and above the soil and analysed with experiments. Solar energy, by its nature, varies depending on sunlight during the day and also changes seasonally. and has difficulty in responding to demand especially in winter months. In order to neutralize this disadvantage, some researches were conducted in this study. Storage methods of heat energy, heat losses until the reuse of heat energy when stored and energy savings provided when heat energy is stored in and above the soil were investigated and the importance of insulation was emphasized. As a result of the study, the author conveyed with detailed analyses that it would be more appropriate to store heat energy underground since soil is a natural insulation material and it was recommended that this method be widespread.

Hill et al. (2012) discussed the integration of solar energy into the system in order to overcome the problems that may arise from the intermittent nature of solar energy in the integration of these two systems as solar energy becomes more popular and the transition to smart grids. Batteries can alleviate problems related to solar energy generation, such as frequency and voltage problems, and make the system more stable.

Li et al. (2017) presented a brief overview of the traditional applications of solar energy was made and new types of applications for rechargeable batteries. As a result, it is suggested that the development of solar energy rechargeable batteries can make a great contribution to the construction of a resource-saving society.

Cervantes and Choobineh (2018) proposed a stochastic mixed integer optimization model in order to optimally size a solar power system and battery storage. The main objective of the model is to minimize the total cost associated with solar power system investments and grid-provided electricity. Analysis shows that the size of the solar system is affected by labour cost and load size, while the battery storage size is sensitive to load size and battery cost.

Gürtürk (2019) performed the cost analysis of the solar power plant located in Elazığ province of Türkiye according to the levelized cost analysis method. When the results obtained from this study are evaluated in a general framework, it is seen that high interest rates in developing countries will negatively affect investments in solar power plants.

Li and Wu (2020) determined the optimum size of PV panels, the optimum capacity of BESS, and the optimum timing of BESS charging/discharging, thus aiming to minimize both electricity bills and long-term total cost including PV system. As a result, it was applied to real data from a commercial user in San Francisco, and it was found that the system reached the balance point in 66 months, and the total system cost was reduced by 29.3%.

Karahan (2021) discussed stabilization of the grid operation using energy storage systems and the effects of this system on the grid in detail. Since energy must be consumed as soon as it is produced, it is necessary to establish a supply-demand balance continuously in order to establish a balance instantly in the system and to prevent possible problems. When energy storage systems integrated into the grid are actively used, the supply-demand balance can be largely balanced through battery systems and grid stability can be achieved by preventing possible problems. In this study, mobile battery storage systems were proposed as a result of the analyses made by the author.

According to Mohamad et al. (2021), battery energy storage systems (BESSs) are typically installed at buses hosting solar farms, enabling direct storage of surplus PV generation at the source. This configuration prevents unnecessary transmission of excess energy through power lines and thereby reduces line losses. By extension, this placement method considers that each of the deployed BESSs is allocated to local solar farms only. In other words, BESSs are deployed without considering the network topology, and the cooperation between BESSs is limited by combining all their capacities to store excess solar energy. Therefore, this paper proposes a method that optimally deploys BESSs and determines their capacities in a two-part framework to minimize the solar energy constraint by considering the network topology and power flow constraints. The results show that the proposed method is more efficient than the traditional distribution strategy in that it manages to store more excess solar energy.

Sicim (2022) conducted a study on the integration of energy storage systems in wind power plants. Since the main source considered in this study is wind, it is directly dependent on wind without being dependent on any raw material for energy production, as in solar energy, and for this reason, some disadvantages arise in scenarios where storage systems are not used in terms of flexibility and sustainability in terms of supply-demand balance. As a result of the study, energy storage systems can consistently serve the purposes of smoothing and flattening the active power outputs of renewable energy sources such as wind turbines. In this way, more controllable wind energy systems in terms of balancing production and consumption, and the effect of active power on frequency. On the other hand, when viewed for domestic consumption purposes, the need can also be met with the energy to be provided from the battery in cases where wind energy is insufficient.

Iriogbe (2023) mentioned the Nigerian economy and stated that the primary motivation for the concept of solar energy systems was the provision of energy in remote areas where existing power supply sources are inefficient and transmission line extension is impractical or possibly economically inefficient.

Aksu (2024) presented the comparison of the BESS systems with solar power plants designed according to the laws and regulations of different countries. The aim of the study is to observe the laws and approaches of different countries in terms of BESS sizing and to suggest the most suitable system in financial terms with sizing and technology selection studies. It has been determined that flexible BESS sizes and energy sales price supports for BESS installations have a positive impact in terms of financial feasibility.

Elmas (2024) addressed the analysis of investments made for residential solar energy systems with various economic models as a field study. In this context, hourly anonymous electricity consumption data was collected from a residence in Gökçeada, Çanakkale for one year. Then, this data was modeled and analysed using the System Advisor Model (SAM) software provided by the National Renewable Energy Laboratory (NREL). Different metrics such as levelized cost of electricity (LCOE), levelized cost of electricity consumed (LCOCE), internal rate of return (IRR) and return on investment (ROI) were used to perform techno-economic analysis. It is concluded that LCOCE has more potential for residential usability analysis for renewable energy investment decisions.

Geçgil (2024) mentioned the factors affecting the efficiency of solar power plants in the operating phase and the importance of maintenance. In addition, the effect of the pollution coefficient was emphasized. Three different scenarios were considered based on panel pollution, ambient and module temperature, and efficiency evaluation was made. As a result, the importance of the panel washing process was emphasized.

Kölemenoğlu (2024) discussed the issue of preventing or reducing to minimum damage levels the errors, faults and negativities determined during the design, installation and operation stages with some precautions to be taken. As a result, in this study, the plant design, installation errors and possible faults during the operation stage were evaluated and suggestions and information were presented about what to do against these negativities.

Oruçoğlu (2024) investigated the pre-license and license acquisition process, which is the first stage of solar energy investments. The requirements were also discussed in detail.

Şahin (2024) examined the land structure, meteorological data and installation of a solar power plant in Cizre-Şırnak-Türkiye. As a result, the real production data and simulation data were analysed together and the consistency of the results was emphasized.

Almassak (2023) aimed to optimize an off-grid, fully renewable and generator-connected PV system to feed a household with 20 kW/day electrical load in Babel, Iraq, using HOMER and MATLAB software.

Çiftçi, (2024) presented a review on the integration of solar and hydraulic energy. It is a case study to determine whether the storage of solar energy and conversion to hydraulic energy during peak hours when energy demand is highest is technically and economically possible with a sample field analysis in the light of previous publications and studies. The locations on the right bank of Sarıyar Dam reservoir were investigated and the technical and economic results of a project to be carried out in the selected locations were shared. Three topographically suitable locations were determined in the examined area.

Dirlik, (2024) evaluated the common simulation programs and the simulation outputs were compared with the real-time data. As a result, it was stated that the PVsyst outputs were -3.30%.

Karmiris & Tengnér (2013) proposed a method to calculate the optimal shaving level based on recorded historical load data. In the study, an optimization algorithm combined with statistical analysis is developed for the energy storage peak shaving application. As a result, the computational time is significantly shorter compared to other proposed methods and one does not have to deal with large integration errors.

3. THEORETICAL BACKGROUND

Detailed information about PV systems and energy storage systems will be given in the subheadings of the theoretical background section.

3.1. Photovoltaic (PV) Systems

PV systems are basically formed by connecting PV cells in series-parallel configurations, because an average PV cell alone has a DC voltage of 0.5-1.0 and its output power is less than 3.0 watts. Today, the output power of PV modules designed to be used in solar power plants can reach up to 650-700 watts .

The output of modules and even arrays formed by serial-parallel connection of modules is DC, and in order for this to be injected into the grid or to provide energy to AC-powered devices in the plant, energy conversion from DC to AC is required. Solar inverters perform this mentioned energy conversion. We can basically classify solar inverters into two groups as string inverters and central inverters (Çelik et al., 2022).

In the subheadings of the section, the two basic components of PV systems, PV cell/module/array and solar inverters, will be explained in detail.

3.1.1. PV Cell

PV cells are the most basic components of PV systems. The crystal-based PV cell, which is widely used in PV systems, has a p-n junction, which is formed by connecting two different semiconductors of p and n type, and when this cell is exposed to solar radiation, a DC voltage is generated between the positive and negative probes. This voltage is around 0.5-1.0 V. The configuration of a PV cell is shown in Figure 3.1 (Lameirinhas et al., 2022).

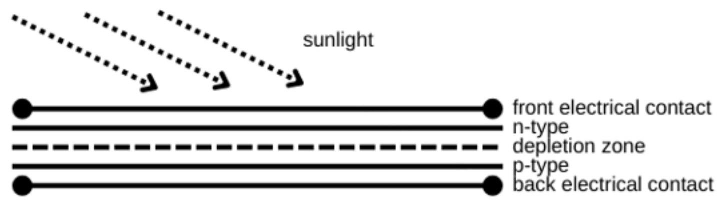

Figure 3.1. Basic PV cell layers

3.1.2. PV Module

PV cells have a very weak and fragile structure in their initial state. PV cells are connected to each other in series or parallel to be used in solar power plants, this connection is usually in series. To make the PV cells connected in series more durable and suitable to used in outdoor conditions, some industrial processes such as lamination are applied. Tempered glass is used on the upper surface so that the sunlight can reach the semiconductors inside the PV module without being blocked. Tempered glass allows 95% of the light to reach the semiconductor directly.

Current PV modules produced by combining PV cells are usually 72 PV cells connected in series to each other and these PV cells consist of 24 separate sub-series. By-pass diodes are used parallel to the sub-series and these by-pass diodes prevent local overheating on the PV module. There is a junction box on the back of these PV modules and the plus/minus DC connectors are produced integrated into the PV module. Figure 3.2 shows the main components of the PV module. (Parida et al., 2011)

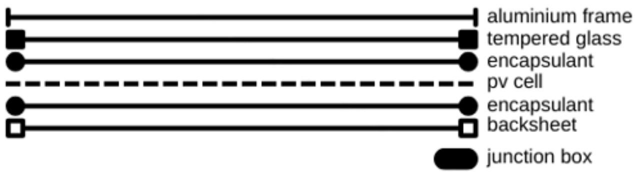

Figure 3.2. Basic PV module layers

3.1.3. PV Array

The structures formed by connecting PV modules in series/parallel are called PV arrays. If higher currents and voltages are required, PV modules should be connected in series/parallel arrays. If high current is needed, PV modules are connected in parallel, but if high voltage is needed, PV modules are connected in series. (Luque & Hegedus, 2011)

In addition, string inverters have a certain minimum DC voltage lower limit for operation. In order to reach this lower limit, PV modules are connected in series in the number determined according to the inverter technical specifications during the design phase and form series called PV arrays. Figure 3.3 shows series/parallel PV array configurations.

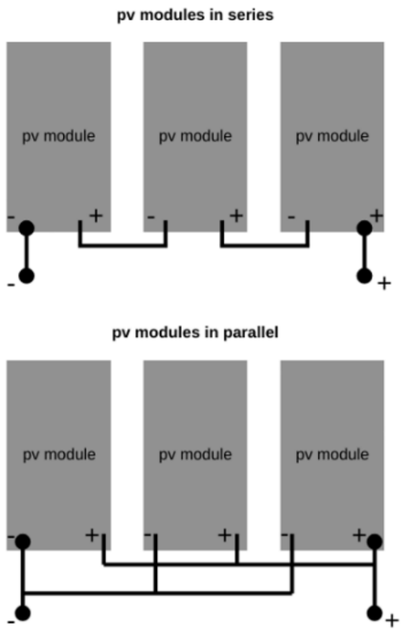

Figure 3.3. Series/parallel pv array configurations

3.2. PV Module Technology

PV modules are classified under three main headings as shown in the diagram below. Each type has its own advantages and disadvantages. The most frequently preferred PV module technology in today's PV power plants is crystalline silicon technology. PV module technology with different types are shown in Figure 3.4 (Lameirinhas et al., 2022).

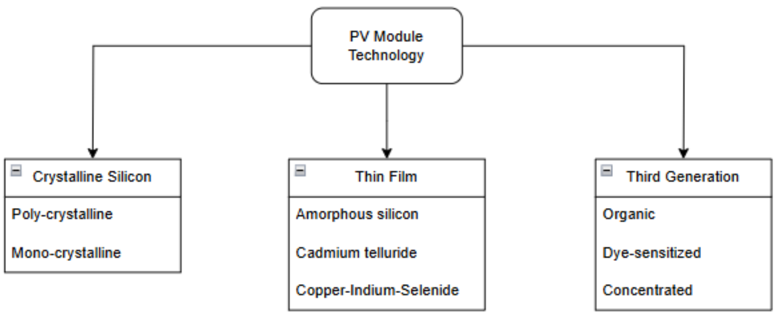

Figure 3.4. PV module technology

3.2.1. Crystalline Silicon

It is divided into two classes according to the production material. If single crystal silicon is used as a material, it is called monocrystalline, if multi crystal silicon is used as a material, it is called polycrystalline. Monocrystalline PV modules have higher efficiency than polycrystalline PV modules. While monocrystalline panels have a maximum efficiency of 25%, polycrystalline PV modules have a maximum efficiency of approximately 20%. As can be understood from the efficiency, monocrystalline PV modules are more costly and require a smaller installation area. Under high temperatures, monocrystalline PV modules are more durable and can be produced effectively. As a result, unless the investment cost of the project is the first priority, using monocrystalline PV modules promises less installation area and higher efficiency (Green, 2005).

3.2.2. Thin Film

It is produced from thin semiconductor materials. It has approximately 10% lower efficiency than crystalline PV modules. With its thin and flexible structure, it can be applied to a wide variety of surfaces, for example; backpacks, building facades. Its efficiency does not decrease as much as other types of PV modules in shadowing and high temperatures. It is rarely used in large-scale PV power plants (Chopra et al., 2004).

3.2.3. Third Generation

It is a relatively newer technology compared to the other two PV module technologies. The aim of this technology is to use organic-inorganic based materials other than silicon, thus providing high efficiency, flexibility and ease of design. In addition, it is aimed to reduce production costs. It can be summarized as a PV module type that is not seen much in PV plants today but is expected to be actively used in the future and studies are carried out in this direction.

3.3. Inverter Technology

Solar inverters are basically devices that convert the direct current provided by PV modules into alternating current suitable for the grid or domestic consumption. They are divided into three groups according to their areas of use.

3.3.1. String Inverter

String inverters are the most widely used inverters today. Strings formed by PV modules connected in series are connected to string inverters to provide energy conversion. Since PV modules are connected in series, all PV modules in a string operate at the same voltage. This value varies according to the string inverter model and power, but for medium-large-scale inverters, the DC input voltage varies between 700-1400 volts. AC output power is directly dependent on the inverter size and power, and today there are inverters with AC output power up to 350-400 kW. Although there are many string inverter manufacturers globally, energy conversion efficiency is over 98% for all products. String monitoring efficiency can also be achieved through string inverters. As a result, easy installation and relatively low cost, ease of fault detection, low-cost maintenance and repair are the main advantages of string inverters. Since PV modules are connected in series, if any inverter in the string does not work, the entire string is directly affected and efficiency can easily decrease, which is its main disadvantage (Boscaino et al., 2024).

3.3.2. Micro Inverter

Micro inverters are small inverters that are integrated into all PV modules in the system separately. They are generally used in small-scale projects and their output power varies between 0.15-0.55 kW depending on their model and the PV module they are connected (Çelik et al., 2022). They generally operate between 15-65 volts according to the PV module operating voltage. Energy conversion efficiency is over 96 percent. Thanks to micro inverters, all PV modules in the system can be monitored separately and PV modules can operate at maximum efficiency without affecting each other. The main advantage is that PV modules can be monitored separately and operate at maximum efficiency and can be easily detected in case of failure, while the main disadvantage is the high installation cost and complex design (Sharma et al., 2025).

3.3.3. Central Inverter

Central inverters are generally preferred in large-scale projects. They can convert DC input power up to 3-4 MW at very high power into AC output power. The most common usage is to collect the strings in DC boxes and collect them in the central inverter in DC boxes to provide energy conversion. The most important advantages are reducing costs in large-scale projects, high efficiency of around 97-98 percent, easy design, while the main disadvantages are the need for a large installation area, complete halt of production in the event of a failure, and the difficulty of detecting failures at the PV module level (Ali Khan et al., 2020).

3.4. Performance Factors and Causes of Loss

The efficiency of solar energy systems depends on many factors. These factors are mainly land selection, design, component selection. The main factors affecting the performance of the system during the operation phase after installation are dust, dirt, shading, maintenance, grid connection and electrical losses. These factors are briefly discussed in the subheadings.

3.4.1. Irradiation Factor

Land selection is made carefully according to the direct radiation factor. Rainfall and cloudy sky directly reduce energy production. For this reason, suitable land selection is made by using annual radiation maps in the feasibility phase.

3.4.2. Component Selection

Selecting PV modules and inverters in accordance with the project budget is a very important factor for system efficiency. In an average area, mono-crystalline modules are more durable and operate with high performance and low loss, but they are a bit more expensive than other options. For inverters, the DC loading ratio suitable for the region should be well determined during the design phase, the inverter should not be overloaded, and the AC/DC conversion ratio should be taken into account by considering the inverter's own technical specifications when it comes out of the factory.

3.4.3. Environmental Loss Factor

The main factors that directly affect efficiency and loss are dust, dirt, and precipitation. In dusty and dirty environments, an extra layer of dust and dirt forms on the PV modules and this layer prevents all sunlight from reaching the pv module, thus decreasing efficiency and causing energy production loss. On rainy days, production loss occurs because the amount of radiation decreases. In the event of snowfall and blizzard, since the surface of the PV modules is covered with snow mass, production loss occurs because sunlight cannot reach the PV module surface until this snow mass is cleaned or completely melted by natural means.

3.4.4. PV Module Direction and Tilt Angle

If the optimum installation angle and direction cannot be determined by carefully simulating the PV modules after the land survey before installation, this factor will cause very serious and irreversible energy loss as the PV modules cannot absorb sunlight sufficiently.

3.4.5. Periodic Maintenance Factor

Preventive maintenance is very important to maintain the system condition after installation and to keep the system efficiency at an optimum level. These maintenances are carried out as short-term and long-term maintenances. In general, all components and electrical connections are checked and thermal measurements are made in these maintenances. Maintenances sometimes include PV module washing process and the aim is to keep the system at maximum availability and efficiency. Systems where the maintenance factor is ignored age prematurely and maximum efficiency cannot be obtained from the system.

3.4.6. Grid Factor

In some cases, even though the system is available, grid-sourced energy production may be disrupted and production loss may occur. The most common of these situations are energy outages and the national grid operator deactivating the energy production plant to ensure supply-demand balance.

3.5. Energy Storage Systems

Energy storage is an increasingly important issue today. Especially with the wider use of renewable energy sources, the role of energy storage systems is increasing. Here are some important points about the future of energy storage and renewable energy:

3.5.1. Why Should We Store Energy?

Considering the demands that arise for different purposes in different time periods, it is of great importance to use electrical energy efficiently and store it when necessary. Energy storage provides many benefits for the efficient use of electrical energy and has a critical role in the sustainability of energy resources.

3.5.2. Energy Storage Solutions

3.5.2.1. Correcting Fluctuations from Renewable Energy Sources

Renewable energy sources that generate power depending on meteorological conditions, such as solar and wind energy, have an intermittent and variable production profile by nature. If the amount of energy produced by these sources in the variable profile is higher than the demand, the energy storage system can store the excess energy for later use. In this way, unnecessary use of excess energy production is prevented and economic contribution is provided.

3.5.2.2. Reducing Peak Loading

Peak load refers to instantaneous high increases in energy demand. Energy storage systems meet these intense demands with the energy stored in previous time periods in peak load situations. Thus, it provides a smooth distribution of energy demands and contributes to more efficient operation of energy systems.

3.5.3. Renewable Energy and the Future of Energy Storage

While the reports focus on how to store renewable energy, they show that storage systems for solar and wind energy are still being developed that will allow them to be used long after the sun stops shining or the wind blows. Energy storage systems play an important role both in the integration of renewable energy sources and in maintaining resilient and reliable electricity systems. Energy storage technologies will become even more important in the energy sector in the future and will support the efficient utilisation of renewable energy sources.

3.5.4. Technical and Economic Advantages of Energy Storage

Energy storage systems play an important role in the power generation sector. The technical and economic advantages of these systems are given under the subheadings as below.

3.5.4.1. Regulating Energy Production

Energy storage systems are used to regulate energy production depending on time. In particular, these systems are preferred to eliminate the energy production forecast errors of renewable power plants during or after the day. Thus, energy production is realised in a more efficient and balanced manner (Zakeri & Syri, 2015).

3.5.4.2. Ensuring Grid Balance

Energy storage systems ensure balanced operation of the grid by providing ancillary services support. Especially in countries where wind and solar power plants are dense, energy storage systems have become inevitable to manage grid stability and energy supply/demand balance.

3.5.4.3. Economic Advantages

When the investment, operating costs and environmental impacts of the energy produced using renewable energy sources are evaluated, it is known that energy storage systems have an important place economically. These systems provide more added value to the national economy.

3.5.4.4. Large Scale Instantaneous Energy Demand

On the energy distribution side, with the integration of vehicle charging stations, which will be used more intensively in the future, energy storage systems play a supporting role as a ready and fast energy source in large-scale instantaneous energy demand.

Energy storage systems offer significant potential to increase security of supply, operate energy systems more efficiently and effectively manage large-scale energy transfer. It is expected that these systems will be more widely used in the future (Dunn, Kamath, & Tarascon, 2011).

3.6. Electric Energy Storage

The force created by the electrons moving in the atomic structure is called the electric energy force. Storing electricity ensures the security of energy supply and the electrical energy stored when it is cheap can be used when electricity is expensive. Storage of electricity allows mobile use of electrical energy.

Electric energy storage methods; batteries, ultra-capacitors, fuel cells, superconducting magnetic energy storage (Larcher & Tarascon, 2015).

3.6.1. Batteries

Batteries are one of the oldest methods of storing electrical energy. Batteries are a system that produces electricity as a result of chemical reactions. In general, batteries consist of two parts. One of them is negative charge the cathode with a positive charge and the anode with a positive charge. When the batteries are connected to a device, they start to flow from negative to positive. These positive and negative charges are surrounded by a medium called electrolyte. Batteries differ from each other according to their production characteristics and usage methods. This is due to energy and power output, capacity, lifetime and efficiency when the battery is produced. Batteries are most commonly composed of nickel, lithium, lead and sodium types (Nitta et al., 2015).

3.6.1.1. Lead Acid Batteries

It has been the most widely used battery in the world until today. Lead acid batteries have lead (Pb) cathode, lead dioxide (PbO_2) anode and sulfuric acid (H_2SO_4) electrolyte. The most common place of use of lead acid batteries is the batteries in vehicles. Studies to increase the efficiency of these batteries, which operate in the efficiency range of 72% to 78%, have been ongoing (Barnhart & Benson, 2013).

3.6.1.2. Sodium Nickel Choloride Batteries

There are sodium and nickel coloride electrodes in its structure. It can reach temperatures between 270 °C and 350 °C as operating range. By the high energy density of sodium nickel chloride batteries, it has provided an advantage for systems where large batteries are used (Ourici, 2023).

3.6.1.3. Nickel Cadmium Batteries

It has metal cadmium and nickel oxide hydroxide electrodes. It has an output voltage of 1.2 V and operates with an average efficiency of 75%. Thanks to its long cycle life, low maintenance requirement and high energy density compared to lead acid batteries, it has taken a lot of place in our daily lives. Due to its high environmental damage, it was replaced by nickel metal hybrid and lithium ion batteries after 1990 (Ourici, 2023).

3.6.1.4. Nickel Metal Hydride Batteries

Nickel metal hydride cells utilise nickel hydroxide positive electrodes. Since there are no harmful substances such as mercury, lead and cadmium in their structure, they are less harmful to the environment than lead acid and nickel cadmium batteries. Energy density is 25% to 30% more intense than nickel cadmium batteries. If it is necessary to compare energy density with lithium ion batteries, it lags behind in this regard. Therefore, it has remained in the shadow of lithium ion batteries (Ourici, 2023).

3.6.1.5. Sodium Sulphur Batteries

Sodium sulphur batteries are made with liquid salt sodium and sulphur. It is processed at 300 °C as processing temperature. Since it can reach temperatures such as 300 °C, it works without any problems at high temperatures. It has the ability to work so efficiently that its efficiency is accepted as 100%. Sometimes an extra heat source is required to operate. A disadvantage of the sodium sulphur battery is its high cost (Wikipedia, 2025a).

3.6.1.6. Lithium-Ion Batteries

Lithium ion batteries used in many fields were first produced by Sony in 1991. It is also known as rechargeable battery. While these batteries are discharging, lithium ions pass from negative to positive electrode, while charging, the opposite is the case. Lithium ion batteries are frequently used in portable technological devices, mobile phones and laptops that we use in our daily lives. It is also one of the most important actors in the storage of renewable energy. Lithium ion batteries have close to 100% efficiency and higher energy density compared to other batteries. The disadvantage of lithium ion batteries is the high initial investment cost and different charging structures due to the sensitivity in operating limits. Damage to the battery structure occurs when it stays in charge longer than other batteries. Lithium ion batteries have a sensitive structure. Studies are being carried out to strengthen the sensitive chemical structure of these batteries. Studies are being carried out to improve this issue in electric vehicle studies where durability is very necessary. In general, these studies are trying to develop new materials to be used in the electrolyte structure of the battery and to reduce the production price (Luo et al., 2015).

3.6.1.7. Fluidised Batteries

These batteries are connected to multiple electrochemical cells and serially interconnected ion exchange. This configuration is used to determine the power of the cell. Electrolytes control is with the help of chemical tanks. The output cell voltage of these batteries is up to 1.8 V. Fluid batteries have a high energy potential. Due to the high cost of fluid batteries, the necessary studies to reduce this cost are still ongoing. The most widely used type of fluid batteries are iron vanadium batteries (Ruan et al., 2020).

3.6.2. Ultra Capacitors

Ultra capacitors store energy by separating it into positive and negative. The basic structure of the ultra-capacitors is an electro-chemical double-layer structure, with a surface electrode on top of the structure and a surface separating this surface. The purpose of the separating surface is to prevent physical deformations occurring on the surface electrodes. The separating surface also allows ion transitions. Ultra capacitors have a high capacity. This is because their surface electrodes are nano-sized. Although ultra-capacitors are generally used in small systems, ultra-capacitors provide great advantages when used in electric vehicles (Bharti, et al., 2021).

3.6.3. Fuel Cells

Fuel cells are electrochemical converters that convert the chemical energy of fuel directly into electrical energy without any combustion process. Their specific internal energy is higher than batteries. The specific power value is lower than batteries. The disadvantage of fuel cells is that they are expensive and cannot adapt to sudden load changes. Therefore, high power compared to other electrical energy storage systems, they are inferior in terms of capacity (Çelik et al., 2025).

3.6.4. Superconducting Magnetic Energy Storage

In the structure of the superconducting magnetic energy storage system, energy is stored in the magnetic current field formed by the current flowing in the coil. In the internal structure of the superconducting magnetic energy storage system, there is a superconducting coil, cooling system and energy storage system. It works at 97% efficiency. Short response times, active and reactive power can be used separately and long life.

3.7. Use of Lithium-Ion Batteries in PV Power Plants

In PV power plants, it is aimed to store the excess energy of the power plant's license upper limit or excess energy. In addition to these, energy storage systems are also very important for grid stabilization and play an important role in balancing the grid frequency. Today, in order to fulfil these stated purposes, energy storage systems consisting of lithium-ion batteries are generally preferred. The technical study and application principles of lithium-ion batteries were discussed in the subheadings (Mulolani & Mwaanga, 2024).

3.7.1. Charge and Discharge Process

During the charging process, the DC energy obtained from the PV modules is transferred from the cathode to the anode by the charge controller and stored in the graphite anode material by lithium ions. In case of overcharging, the charging voltage should be carefully monitored to prevent heating and damage to the batteries. The fully charged charging voltage of an average lithium-ion cell is 4.0-4.5 volts. The charging current can be up to fifty percent of the charging capacity, that is, if we assume fifty percent, the full capacity is filled in two hours.

During the discharge process, lithium ions return from the anode to the cathode and exit the battery. The DC energy coming out of the battery is converted to AC energy by inverters and injected into the grid or consumed directly. High-current discharges shorten the life of the lithium-ion cell, and the voltage of an average fully discharged lithium-ion battery is around 3.0 volts (Planella et al., 2022).

3.7.2. DOD (Depth of Discharge)

DOD indicates how much of the battery's full capacity is used, and is usually expressed as a percentage. For example; 100 percent DOD indicates that the battery's full capacity is used. Lithium-ion storage systems, which are preferred in PV plants, are usually operated with 80/90 percent DOD. When the battery is operated with 100 percent DOD, excessive discharge damages the battery's chemical structure, shortening its capacity and life. As the DOD percentage decreases, the battery's cycle life increases. An average lithium-ion battery is expected to operate at 80 percent DOD for approximately 1800-2000 cycles.

3.7.3. SOC (State of Charge)

SOC is simply the ratio of a battery's current capacity to its total capacity. SOC is expressed as a percentage. 100 percent SOC means the battery is fully charged, while zero percent SOC means the battery is completely discharged. SOC is vital in preventing battery overcharging and discharging. In addition, when lithium-ion batteries are operated at 20/80 percent, the chemical structure of the batteries is preserved and the cycle life is extended. At the same time, the system's reserve power capacity is also provided through SOC. For lithium-ion storage systems to be integrated into PV plants for energy storage activities, a 20/80 percent SOC range is widely recommended, considering the battery life and the number of cycles.

3.7.4. Relationship Between SOC and DOD

There is an inverse relationship between DOD and SOC.

- %80 SOC → %20 DOD (battery mostly full)
- %20 SOC → %80 DOD (battery mostly empty)

SOC and DOD are two very important parameters for the life, performance and reliable operation of lithium-ion batteries. When evaluated correctly and operated with the right parameters, safe and long-lasting operation of lithium-ion batteries will be ensured.

3.7.5. Charge and Discharge Rate

The C rate defines the charge and discharge rate of a battery in proportion to its own capacity. For example; a charge/discharge rate of 0.25 C means that the current battery will be fully charged/discharged in 4 hours. Charge/discharge rates above 0.5 C are not recommended for storage systems to be integrated into PV plants, the reason for this is to prevent overheating and ensure longer battery life.

3.7.6. Efficiency and Losses in Lithium-Ion Batteries

The energy conversion efficiency of lithium-ion cells is approximately 95 percent. Since temperature changes, i.e. temperature increases during conversion, negatively affect efficiency, various cooling systems such as air-water are used in today's battery technologies. The ideal operating temperature for lithium-ion batteries is 20-25 degrees Celsius. At high temperatures, the energy conversion efficiency and life of the battery decrease, while at low temperatures, the movements in the electrolyte slow down and the battery may be damaged.

3.8. Reasons for Using Lithium-Ion Batteries in PV Power Plants

Lithium ion battery technology is generally used for energy storage in solar power plants, and the main reasons for this are examined in the subheadings.

3.8.1. Energy Density

Lithium ion batteries have a very high energy storage capacity per unit volume. A typical lithium ion battery has 5-6 times more energy density than a typical lead acid battery. The high energy density increases the mobility of the system and takes up less space in the area of use.

3.8.2. Charging/Discharging Efficiency

The charging and discharging efficiency of a typical lithium ion battery is over 90%. Thus, most of the stored energy is utilised with low losses. Solar energy and other renewable energy plants aim for high performance and this high efficiency charge/discharge feature makes lithium ion batteries stand out in this field.

3.8.3. Cycle Lifespan

In investments with high investment costs such as solar energy, this performance should be long-lasting and sustainable as well as performance is important. In general, when batteries are considered, their low lifetime is one of the prominent disadvantages. However, unlike other batteries, lithium ion batteries have the ability to make more than 4500 efficient cycles. With this advantage, it is an unrivalled storage component for solar power plants today.

3.8.4. Rapid Charging and Discharging Feature

Lithium-ion batteries are capable of rapid charging and discharging with high efficiency compared to other battery types. Especially in solar power plants that store with peak-shaving strategy, maximum efficiency can be obtained from the sun thanks to this feature during peak hours. Furthermore, thanks to its rapid and efficient discharge feature, it provides higher financial return per unit energy to the investor during peak hours of consumption.

3.8.5. Operation Temperature Range

A typical lithium-ion battery operates efficiently without damage in the -20/+60 Celsius temperature range. With this feature, lithium ion batteries have a universal operating capability regardless of temperature conditions in different geographies and climates of the world.

3.8.6. Security Features

Today, lithium-ion battery containers used for energy storage in power plants are equipped with safety precautions against overheating and thermal/electrical leakage and are highly optimised in terms of system and environmental safety.

In addition to all these features, lithium ion batteries are very suitable for use in solar power plants with their self-discharging feature below 2% and this technology is widely used today.

3.9. Energy Storage Strategies in PV Power Plants

There are three storage strategies commonly used in PV power plants. These strategies are; peak shaving, load shifting and frequency regulation. These three energy storage strategies are detailed in the subheadings.

3.9.1. Peak Shaving

For PV systems, excess energy produced during peak energy production hours, when energy demand is low and energy production costs are high, is stored in the storage system. Stored energy is injected into the grid during peak energy production hours, when consumption is high, usually in the evening. In energy markets where electricity unit prices are priced hourly, considering the supply-demand balance, with the peak shaving strategy, energy with low unit prices is sold to storage during hours when demand is high, i.e. when the energy unit price is high, thus reducing energy production costs. Especially since PV power plants can sell energy during the day due to their nature, storage systems and this strategy provide flexibility to investors in terms of energy sales.

3.9.2. Load Shifting

It aims to store the energy produced during periods when energy demand is low and to use this stored energy during periods when demand is high. It focuses on balancing consumption and production times by distributing energy over time. It is similar to the peak shaving method in terms of operation, but it is a more complex strategy in terms of operation because peak shaving strategy applications aim to store excess energy by shaving the peaks in the production curve. In the load shifting strategy, the focus is on storing the energy to be injected into the grid in line with the energy demand and shifting the time for the demand period.

In short, while the load shifting strategy provides longer-term energy management, peak shaving focuses on sudden loads on the grid.

3.9.3. Frequency Regulation

The main purpose is to balance the grid frequency to ensure stable operation of the grid. The grid frequency in question is directly related to the balance between supply and demand. The disruption of the balance can cause the grid frequency to deteriorate and cause grid failures, i.e. power outages. Integrated or external energy storage systems in PV systems aim to keep the grid frequency constant by injecting previously stored energy into the grid when the grid frequency drops, and when the grid frequency increases, they draw energy from the grid and store it in batteries, thus reducing the grid frequency. The main reason why lithium-ion batteries are preferred is their ability to respond quickly.

In short, the frequency regulation strategy is responsible for helping to ensure grid stability and focuses on keeping the grid frequency as close to the target frequency as possible.

3.10. Energy Storage Regulation for PV Power Plants in Türkiye

The legal regulations regarding storage PV power plants in Türkiye are determined by the regulations published by the Energy Market Regulatory Authority (EPDK). The relevant regulations determine the installation, operation and market activities of the storage plant. In this field, the relevant institution has created a clear legal framework with the legal update made on November 19, 2022.

In the current legal order in Türkiye, production facility licenses are granted by competition, but with this legal regulation, the right to obtain a license without competition has been granted in return for the commitment to establish an energy storage facility to be established for production facilities within the borders of production facilities. In this context, applications can be made with an installed power between 10 MWe-250 MWe.

It is allowed to put into operation a storage unit as much as the main source power, but if the storage unit cannot be put into operation within the committed period, its license is cancelled.

The energy subsequently injected into the grid in energy storage units is sold at the same pricing as the energy injected into the grid by the plant after production, and there is no different pricing policy in this regard (Energy Market Regulatory Authority [EMRA], 2022).

4. MATERIAL AND METHODS

In the subheadings of this section, collected data, determination of system components, simulation parameters and economic analysis criteria were explained in detail.

4.1. Data

4.1.1. Climate and Site Data

A land suitable for PV power plant installation in Karaman, Türkiye with coordinates of 37.50 °N 33.21 °E was selected as the project site. The altitude of the land is 1112 meters. The land is included in the UTC+2 time zone. Meteonorm 8.1 (2006-2013) - Synthetic data package was used in the simulation. According to the data package, annual global horizontal irradiation is 1833.8 kWh/m2, annual average ambient temperature is 12.36 °C. Site climate data are shown in Table 4.1.

Table 4.1. Site climate data

	GlobHor[kWh/m²]	DiffHor[kWh/m²]	T_Amb[°C]	Alb_Inc[kWh/m²]
January	72.90	30.87	-0.33	1.14
February	90.70	40.95	1.68	1.42
March	136.90	51.20	6.83	2.14
April	173.50	59.57	11.20	2.72
May	222.60	72.10	16.31	3.49
June	238.60	57.52	21.04	3.74
July	238.90	65.89	25.09	3.74
August	215.90	53.12	24.85	3.38
September	172.10	45.48	19.55	2.69
October	124.10	38.34	13.47	1.94
November	81.40	29.63	6.55	1.27
December	66.30	29.43	1.37	1.04
Year	1833.80	574.09	12.36	28.70

In line with the main climate data, high solar radiation, low precipitation rate due to arid climate and ease of finding land that is unsuitable for agriculture were effective in the selection of the region and land.

4.1.2. Determining System Components

The same number and same brand-model components will be used for PV power plants with and without storage. In the storage scenario, a 1305.60 kWh storage unit will be used as the energy storage unit.

4.1.2.1. PV Module, Inverter and Battery Pack

The PV module to be used in the project has been determined as HT-SAAE/HT66-18X-500, the irradiance of the PV module is 1000W/m^2, module temperature is 25, the electrical characteristics in the factory test environment are shown in Table 4.2.

Table 4.2. PV module electrical characteristics

Maximum Power at STC (P_{max})	500W
Open - Circuit Voltage (V_{oc})	45.55V
Short - Circuit Current (I_{sc})	13.93A
Optimum Operating Voltage(V_{mp})	38.37V
Optimum Operating Current (I_{mp})	13.04A
Module efficiency	21.1%
Power Tolerance	0 ~ + 5W
Maximum System Voltage	1500V DC
Maximum Series Fuse Rating	25A
Operating Temperature	-40 °C to +85 °C

Mechanical characteristics of PV module are shown in Table 4.3.

Table 4.3. PV module mechanical characteristics

Solar Cells	Monocrystalline 182 × 91mm
Number of Cells	132 (6 × 22)
Dimensions	2094mm × 1134mm × 30mm
Weight	25.0kg
Front Glass	High transmission tempered glass; thickness; 3.2mm
Frame	Anodized aluminium alloy
Junction Box	IP68
Cable	4mm2 (UL / IEC) length; (+) 400mm (-) 200mm / length can be customized
Connectors	MC4 / MC4 compatible

Huawei/SUN2000-100KTL-M1 string inverter was used in the project. Technical specifications of the inverter are shown in Table 4.4.

Table 4.4. Inverter specifications

Max. Efficiency	98.8%
Max. Input Voltage	1100 V
Start Voltage	200 V
Rated Input Voltage	600 V
Rated AC Active Power	100000 W
Rated AC Apparent Power	100000 VA
Rated Output Voltage	400 V, 3W + PE
Rated AC Grid Frequency	50 Hz / 60 Hz
Operating Temperature Range	-25°C ~ 60°C
DC Connector	Staubli MC4
Protection Degree	IP66
Topology	Transformerless

BYD/ Battery Box HVS 12.8 battery pack was used in the project. Technical specifications of the inverter are shown in Table 4.5.

Table 4.5. Battery pack specifications

Battery Module	HVS(2.56kWh, 102.4V, 38kg)
Number of Modules	5
Usable Energy	12.8 kWh
Max Output Current	25 A
Nominal Voltage	512 V
Operating Voltage	400~576 V
Dimensions	1411x585x298 mm
Weight	205 kg
Operating Temperature	-10/+50 °C
Battery Cell Technology	Lithium Iron Phosphate
Round-trip Efficiency	≥96%

4.1.3. System Configuration

The numbers of system components and a simple single line diagram are given under subheadings for two separate scenarios.

4.1.3.1. PV System without Storage System

General and technical details of the project are shown in Table 4.6.

Table 4.6. PV system component list for without BESS

Component	Manufacturer	Model	Unit nominal power	Number of component	Total power
PV module	HT-SAAE	HT66-18X-500	500 Wp	2772 units	1386 kWp
Inverter	Huawei Technologies	SUN2000-100KTL-M1-400VAC	100 kWAC	11 units	1100 kWAC

Basic PV single line diagram of the project is shown in Figure 4.1.

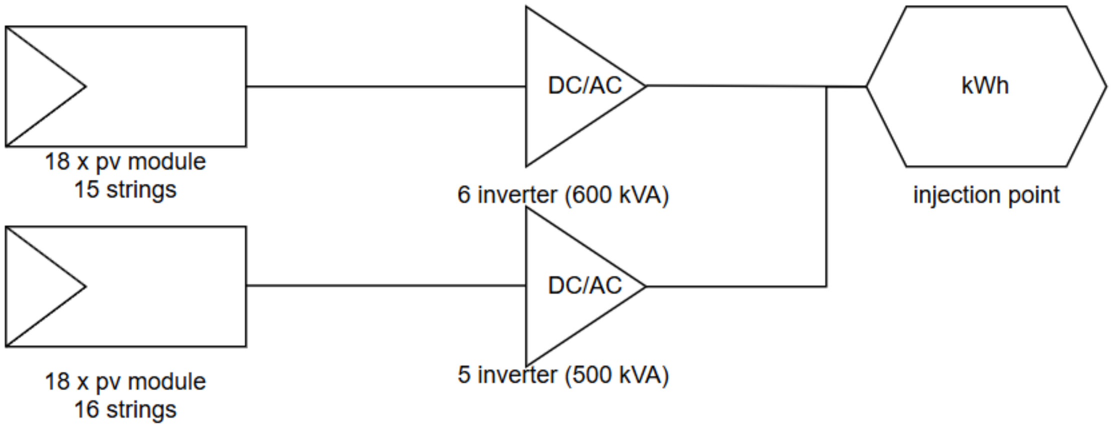

Figure 4.1. PV system single line diagram

4.1.3.2. PV System with Storage System

General and technical details of the project are shown in Table 4.7.

Table 4.7. PV system component list for with BESS

Component	Manufacturer	Model	Unit nominal power	Number of component	Total power
PV module	HT-SAAE	HT66-18X-500	500 Wp	2772 units	1386 kWp
Inverter	Huawei Technologies	SUN2000-100KTL-M1-400VAC	100 kWAC	11 units	1100 kWAC
Battery pack	BYD	Premium HVS 12.8	12.8 kWh	102 units	1305.6 kWh

Basic PV single line diagram of the project is shown in Figure 4.2.

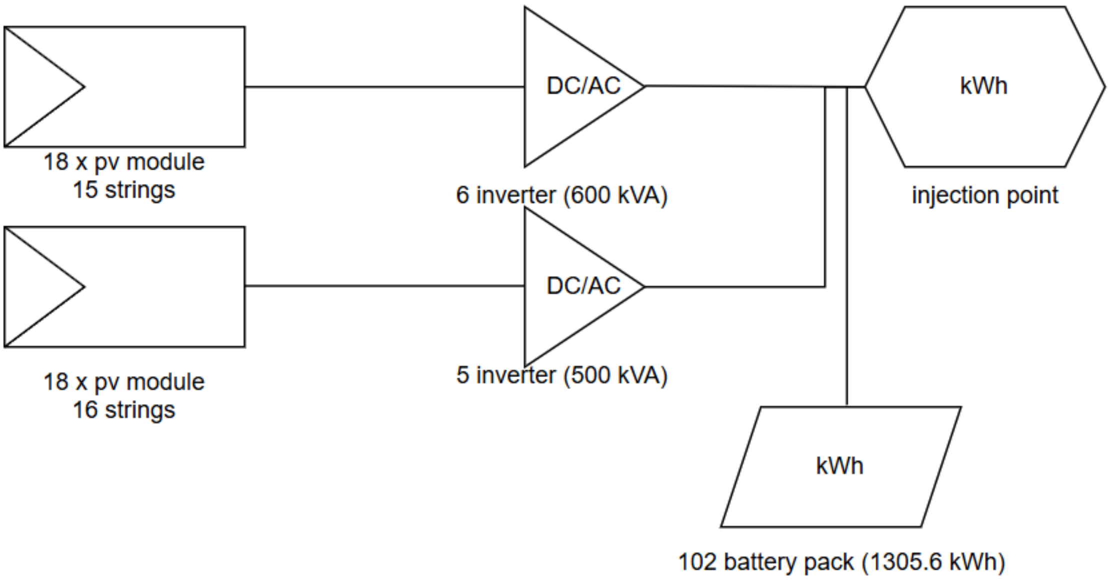

Figure 4.2. PV system with BESS single line diagram

Since this study focuses more on performance analysis and comparison rather than economics, the PCS system has not been included.

4.1.4. Project Overview

General information of the project designed in Karaman, Türkiye is shown in the table. In a second scenario with energy storage, the PV system side will remain as it is and the energy storage system application will be integrated into the existing system. It is assumed that the AC output power of the power plant from the grid connection point is maximum 1 MW within the scope of the connection agreement. Project general informations are shown in Table 4.8.

Table 4.8. Project overview

City/Country	Karaman/Türkiye
Latitude/Longitude	37.50°N/33.21°E
Altitude	1112 m
Weather data package	Meteonorm 8.1 (2006-2013) - Synthetic
Grid status	on-grid
Plane	fixed
Tilt/Azimuth	32.5°/0°
Grid Connection Agreement nom. power	1.0 MW

4.2. Simulation Preferences

Common parameters were chosen to be the same in systems with and without storage. Details are available in the subheadings.

4.2.1. Simulation Parameters for Without Storage Project

The simulation parameters are shown in two separate tables. The first table includes PV field orientation, tilt/azimuth, horizon, shadow, grid power limitation and DC/AC ratio. Domestic energy consumption is ignored as it has no impact on the project. Due to the connection agreement, 1 MW power limitation is set from the grid connection point, there is no power limitation at the inverter level. There is no shadow element in the project area. Simulation parameters are shown in Table 4.9.

Table 4.9. Simulation parameters

Orientation	Fixed plane
Tilt/Azimuth	32.5/0 °
Horizon	Free Horizon
Near Shadings	No Shadings
Grid power limitation	1000 kWAC
Pnom ratio after grid power limitation	1.386
Domestic energy consumption	0 MWh per year

The next table shows the project losses. These losses include thermal loss factor, module mismatch losses, incident angle modulation loss factor, DC wiring losses, module quality loss and are defined in the project parameters. Simulation loss factors parameters are shown in Table 4.10.

Table 4.10. Loss factors parameters

Thermal loss factor(module temperature according to irradiance)- Uc (const)	20.0 W/m²K
Thermal loss factor(module temperature according to irradiance)- Uv (wind)	0.0 W/m²K/m/s
Module mismatch loss fraction	2.0 % at MPP
DC wiring losses- Global array res.	5 mΩ
DC wiring losses- Loss Fraction	1.5 % at STC
IAM loss factor 0°	1.000
IAM loss factor 30°	0.998
IAM loss factor 60°	0.948
IAM loss factor 90°	0.000

4.2.2. BESS Design and Simulation Parameters

In this section, the BESS design suitable for the project is evaluated in line with the outputs of the storage-free power plant, and a design and capacity that will use the cost and current capacities of the batteries as efficiently as possible is targeted.

4.2.2.1. Analysis of Peak Shaving Needs

The main goal in the Peak Shaving strategy is to store the energy amount above 1000 kWAC in lithium-ion batteries for this project, so as not to exceed the grid power limitation during peak production hours. The energy stored in the batteries will be injected into the grid in the evening hours after sunset.

The main goal is to implement the strategy correctly and to ensure that the BESS capacity operates at the highest capacity possible and that the excess energy produced is as close as possible to the BESS storage capacity, otherwise the cost of the BESS will not be reasonable. As a result, the excess power will be calculated correctly and a design will be made in accordance with the amount of energy that will remain above the grid limit.

4.2.2.2. Determination of Excess Power, BESS Capacity, Charge/Discharge Capacity

The maximum DC energy production capacity of the PV system is 1530 kWDC and the inverter output power is 1100 kWAC when the tolerance is ignored. The grid maximum AC output power is determined as 1000 kWAC. When the maximum limit is ignored, the DC/AC ratio of the plant is 1.39, which is within the inverter DC loading limits. This value was selected by slightly increasing the DC loading ratio for the climatic conditions of the land where the plant will be installed and the possible BESS design. The main purpose of the selection is to ensure that the output power reaches the peak as quickly as possible and charges the batteries. In addition, the ability to produce as much as possible during periods when radiation is low is taken as a basis.

In line with these values, the peak clear day power output of the plant is approximately 1300 kW. This value is approximately 300 kW above the grid limit. From this calculation, it is estimated that the power surplus will be approximately 300 kWh per hour. It is assumed that the peak production period will be an average of 3 hours per year. In this case, a BESS with a storage capacity of approximately 900 kWh will be needed. Considering that the SOC value of the BESS will be set to 20 percent, a storage system of minimum 1080 kWh is needed.

After determining the BESS capacity, the charge/discharge power should be determined. The maximum charge power should not be below the excess power value, for this reason the maximum charge power will be set as 380 kW, and the maximum discharge power has been determined as 280 kW, considering the life and health of the batteries. These values have been determined with tolerance, considering the energy conversion losses. BESS simulation parameters are shown in Table 4.11.

Table 4.11. BESS simulation parameters

Discharging minimun SOC	20.0 %
Stored energy maximum	1044.5 kWh
Maximum charging power	380.0 kWDC
Maximum discharging power	280.0 kWAC
Maximum/Euro efficiency	97.0/95.0 %
Temperature	Fixed 20 °C

4.3. Economic Analysis

In the first subheading, PV project installation and operating costs will be calculated. In the second subheading, economic return criteria will be discussed.

4.3.1. Construction and Operational Costs

For the cost calculation of the PV power plant, the costs will be evaluated as six different cost items with their average percentage slices. Project cost percents are shown in Table 4.12.

Table 4.12. Project cost percent

Cost type	Average rate (%)
PV modules and inverters	60
Construction	20
Cables and connectors	10
Workmanship	5
Others (permits, insurance, etc.)	5

The land cost will be ignored in this cost calculation. After the PV module and inverter costs are calculated, other costs will be calculated using the percentages in the table.

4.3.1.1. PV modules and Inverters Costs

PV module cost will be calculated based on unit price. Inverter cost will be calculated based on unit inverter price.

- PV modules (HT66-18X-500): avg. 0.145 USD/Wp
  PV modules cost= (500 Wp×3060 modules×0.145 USD/Wp)**= 221,850.00 USD**

- Inverters (SUN2000-100KTL M1-400VAC): avg. 5750 USD/inverter
  Inverters cost= (11 inverters×5750 USD/inverter)= **63,250.00 USD**

Since taxes are included in the unit prices, no taxes will be added to these costs again.

4.3.1.2. Construction, Cables and Connectors, Workmanship and Other Costs

After the cost calculation of PV modules and solar inverters is made, other cost items will be calculated according to the percentages explained in the above heading.

Approximately 60 percent of the system cost consists of PV module and inverter costs. In the cost calculation of this project, the cost slice table is adhered to and after the PV module and solar inverter costs are clarified, other items are calculated approximately based on these figures. The 1% cost corresponds to 4751.67 USD in line with the calculation explained in detail above.

- Construction constitutes 20 percent of the total cost
  Construction cost= 20×4751.67 USD= **95,033.33 USD**
- Cables and connectors constitute 10 percent of the total cost
  Cables and connectors cost= 10×4751.67 USD= **47,516.67 USD**
- Workmanship constitutes 5 percent of the total cost
  Construction cost= 5×4751.67 USD= **23,758.33 USD**
- Others (permits, insurance, etc.) constitute 5 percent of the total cost
  Others (permits, insurance, etc.) cost= 5×4751.67 USD= **23,758.33 USD**

In addition to all these expenses, it is assumed that a 15-acre land suitable for installing a PV plant is purchased for the establishment of the project, and the cost of this land is approximately **60,000.00 USD** for that region.

4.3.1.3. Grand Total Cost with BESS

As previously stated, the costs calculated under two separate subheadings include taxes, and when these costs are added together, the total project cost is calculated as **535,166.70 USD**.

In line with the current unit prices taken from the Turkish market, the installation cost of 1 MWh BESS is 180,000.00 US dollars + 30% tax. Based on this price, the cost of 1,305.6 MWh BESS is calculated as **305,604.00 USD** including taxes. When this cost item is added directly, the total cost of the energy storage PV plant is calculated as approximately **840.770,70 USD**.

4.3.2. Economic Return Criteria

In this section, the analysis methods to be used in the techno-economic feasibility analysis are detailed. In the techno-economic analysis of the PV plant, the analysis will be carried out by applying the net present value, internal rate of return and payback period methods.

4.3.2.1. Net Present Value (NPV)

This method is interpreted based on the cash flow that the investment will provide during its operating period and the result obtained by subtracting the investment cost from its present value. If the result is greater than zero, the project is profitable, otherwise the project has suffered a loss.

4.3.2.2. Internal Rate of Return (IRR)

The rate that expresses the return of an investment as a discount rate, making NPV zero. In other words, it shows what percentage return the project will provide. The smaller the percentage result obtained, the more attractive the investment.

4.3.2.3. Payback Period

It shows the recovery period of the investment; i.e. how many years it takes to payback the initial cost. The result obtained by dividing the investment cost of the power plant by the annual income expresses the payback period in years.

5. FINDINGS

The simulation outputs of PV plants with and without storage, which are simulated using the PV plant designs and simulation parameters shared in the previous section at the specified location, will be focused on and a technical infrastructure will be provided for the discussions in the next section.

In addition, after the simulation outputs are shared, economic analysis will be made on this production data and the section will be presented under two sub-headings and these headings will be presented with their subheadings.

5.1. Simulation Results for Systems with and without Storage

The focus will be mainly on energy production data, efficiency and performance comparisons, energy continuity and the impact of your storage on the system.

5.1.1. Energy Production Data

Table and graph containing monthly production data for PV plants with and without storage compare monthly production data within a calendar year. About 6.5% of the total produced energy is injected into the grid by the energy storage system. Monthly energy productions are shown in Table 5.1.

Table 5.1. Monthly energy production

	Production [MWh]	Production with BESS [MWh]
January	153.4	162.0
February	167.3	174.6
March	205.7	219.4
April	223.5	238.4
May	259.7	275.5
June	256.7	274.3
July	266.6	280.8
August	260.7	277.9
September	240.1	256.8
October	207.1	221.5
November	168.4	176.9
December	152.7	157.0
Year	2561.9	2715.0

Monthly energy production chart is shown in Figure 5.1.

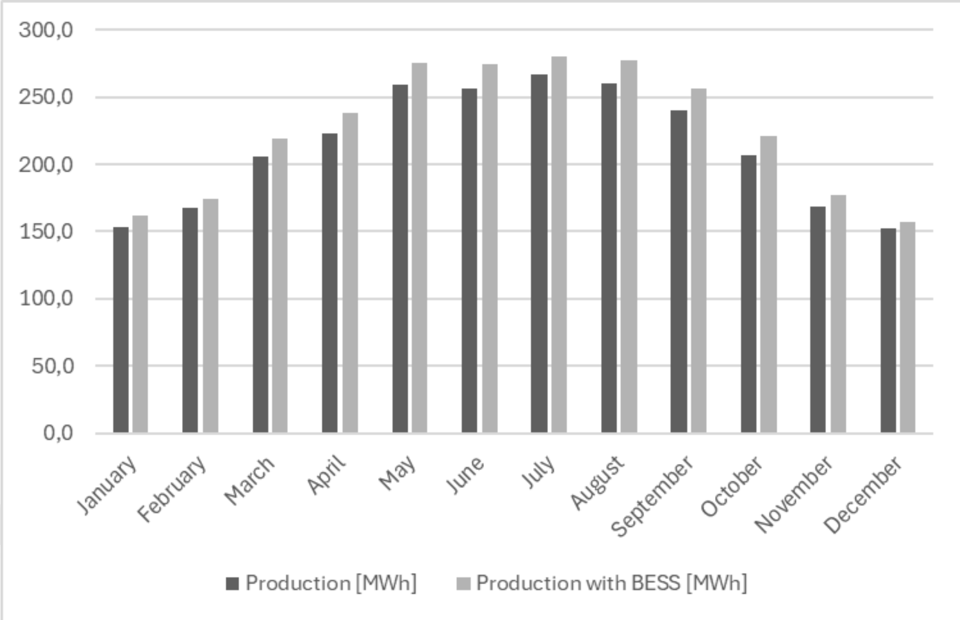

Figure 5.1. Monthly energy production chart

It is seen in the table that the storage system works more effectively on days when the sunshine duration is longer. Besides 153.1 MWh more energy is injected into the grid annually in PV plant with BESS.

5.1.2. Performance Ratio Comparison

The performance ratio is accepted as the basic parameter to measure the efficiency of PV plants. PR measures the difference between the energy that the plant can theoretically produce and the energy it actually produces.

PR is calculated automatically with simulation tools and monitoring systems in operating PV plants, but the simplest calculation of PR is obtained by dividing the energy injected into the grid by the sum of the radiation falling on the module surface and the product of the nominal capacity of the plant.

It is evaluated between 0 and 1 or can also be evaluated as a percentage. The higher the value, the higher the efficiency. In the ideal PR evaluation, between 0.7 and 0.8 indicates acceptable performance, while between 0.8 and 0.9 indicates high performance.

Performance ratio comparison is shown in Table 5.2.

Table 5.2. PR comparison

	PR	PR with BESS
January	0.87	0.92
February	0.87	0.90
March	0.81	0.86
April	0.78	0.84
May	0.79	0.84
June	0.77	0.82
July	0.78	0.82
August	0.76	0.81
September	0.77	0.82
October	0.79	0.85
November	0.85	0.90
December	0.91	0.93
Year	0.80	0.85

Performance ratio comparison graph is shown in Figure 5.2.

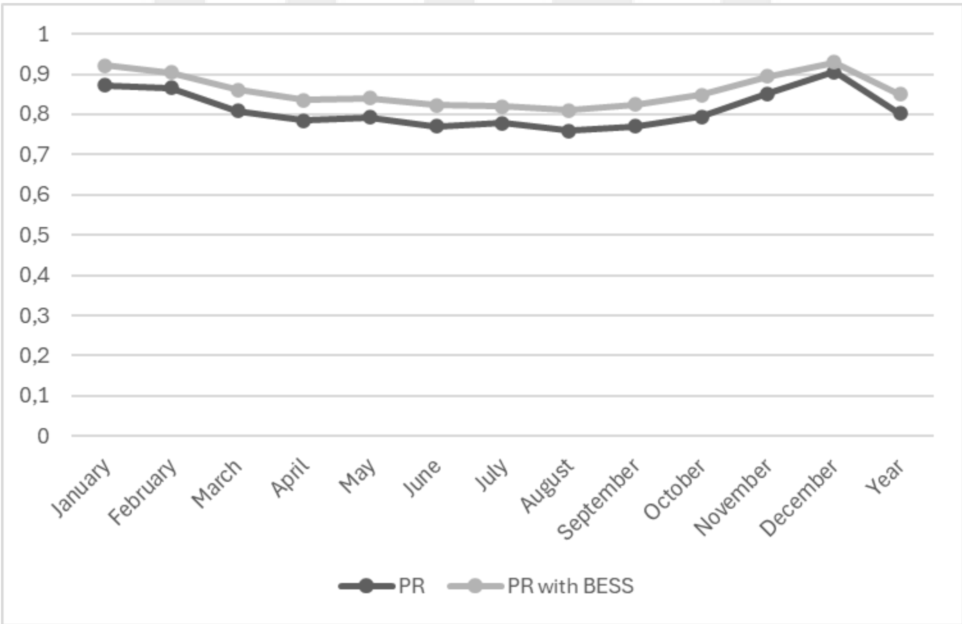

Figure 5.2. PR comparison graph

According to the simulation results, when BESS is added to the PV plant, it increases by 5%.

5.1.3. System Losses

The purpose of the table is to analyse the energy losses of the PV system and the energy flow up to the inverter output. Energy losses from the PV side to the inverter output directly affect the performance ratio.

Energy losses occur at various stages during the energy production and conversion stages, and the tables show losses for two different scenarios. Energy loss table for without BESS is shown in Table 5.3.

Table 5.3. Energy loss table for PV system without BESS

Stage	Value [kWh]	Loss (%)	Description
Array nominal energy (at STC effic.)	3115777	-0.50%	PV loss due to irradiance level
		-6.19%	PV loss due to temperature
		+0.75%	Module quality loss
		-2.05%	Mismatch loss, modules and strings
		-1.13%	Ohmic wiring loss
Array virtual energy at MPP	2837765	-1.68%	Inverter Loss during operation (efficiency)
		-8.17%	Inverter Loss over nominal inv. power
		0.00%	Inverter Loss due to max. input current
		0.00%	Inverter Loss over nominal inv. voltage
		0.00%	Inverter Loss due to power threshold
		0.00%	Inverter Loss due to voltage threshold
		-0.01%	Night consumption
Available Energy at Inverter Output	2561851		
Energy injected into grid	2561851		

Energy loss table for with BESS is shown in Table 5.4.

Table 5.4. Energy loss table for PV system with BESS

Stage	Value [kWh]	Loss (%)	Description
Array nominal energy (at STC effic.)	3115777	-0.50%	PV loss due to irradiance level
		-6.19%	PV loss due to temperature
		+0.75%	Module quality loss
		-2.05%	Mismatch loss, modules and strings
		-1.13%	Ohmic wiring loss
Array virtual energy at MPP	2837765	-1.82%	Inverter Loss during operation (efficiency)
		-1.64%	Inverter Loss over nominal inv. power
		0.00%	Inverter Loss due to max. input current
		0.00%	Inverter Loss over nominal inv. voltage
		0.00%	Inverter Loss due to power threshold
		0.00%	Inverter Loss due to voltage threshold
		-0.01%	Night consumption
Available Energy at Inverter Output	2740193	-0.04%	Unused energy (battery full or conv. overload)
		-0.25%	Battery IN, charger loss
		+0.02%	Battery Stored Energy balance
Battery Storage		-0.38%	Battery global loss (6.28% of the battery contribution)
		-0.27%	Battery OUT, inverter loss
Energy injected into grid	2715034		

5.1.4. Injection from BESS to the Grid and Battery Efficiency

Table 5.5 shows the charge/discharge energy amounts and efficiency of the BESS in monthly periods.

Table 5.5. Monthly BESS energy flow data

	EBatCh[MWh]	EBatDis[MWh]	BatEff [EBatDis/EBatCh]
January	9.05	9.02	0.945
February	8.15	7.65	0.939
March	15.26	14.34	0.940
April	16.67	15.68	0.941
May	17.58	16.50	0.939
June	19.63	18.43	0.939
July	15.86	14.86	0.937
August	19.28	18.10	0.939
September	18.64	17.51	0.939
October	16.04	15.09	0.941
November	9.49	8.90	0.938
December	4.80	4.49	0.935
Year	170.44	160.58	0.942

In addition to the monthly charge/discharge energy amounts in the Figure 5.3, the battery efficiency with the mathematical formula (=discharge/charge) is added as a line graph to the second axis.

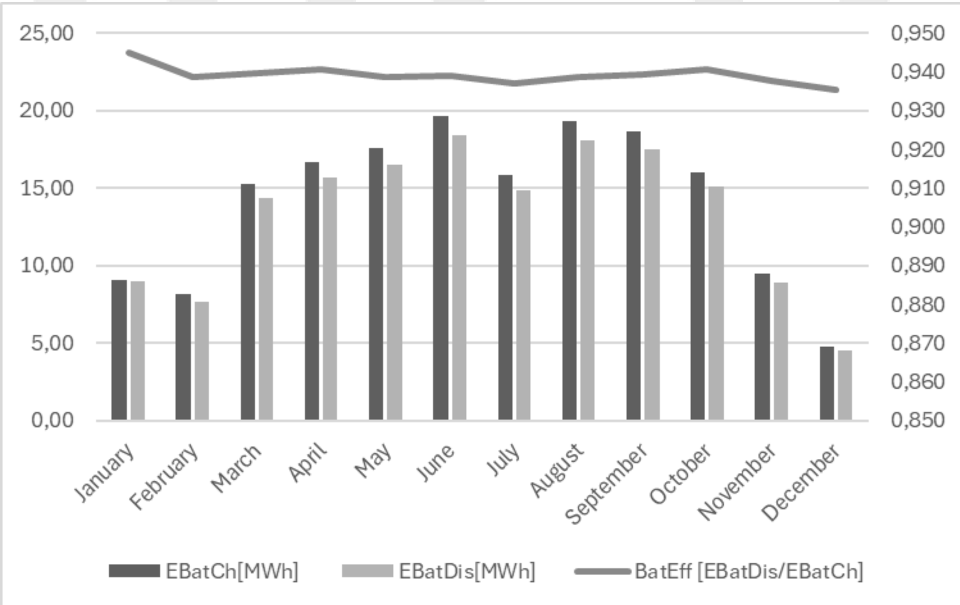

Figure 5.3. Monthly charge/discharge amount and battery efficiency

The total annual BESS charging amount is 170.44 MWh, and the discharge amount, that is, the amount of energy to be injected from the BESS to the grid, is 160.58 MWh. Based on this, the annual battery efficiency is calculated as 94.21%.

5.2. Economic Analysis Results

5.2.1. Techno-Economic Feasibility Analysis for PV Plant without BESS

This part presents the techno-economic feasibility analysis of a 1 MW PV power plant located in Karaman, Türkiye, under the scenario of not including BESS. The plant is expected to produce approximately 2,561.90 MWh/year under the YEKDEM feed-in tariff scheme. The project has been financially evaluated according to key performance indicators such as total investment cost, payback period and return on investment (ROI), and all monetary values have been exchanged to USD at the exchange rate of 1 USD = 34 TL.

5.2.1.1. Analysis Parameters

- Location: Karaman, Türkiye
- Installed capacity: 1 MW
- Annual energy production: 2,561.9 MWh
- Tariff Scheme: YEKDEM (1,941.10 TL/MWh + local component support 527.80 TL/MWh) or (7.26 cents/kWh)
- Land requirement: 15 acres
- Operational Model: No on-site personnel required, site visit for maintenance and troubles
- Annual operation and maintenance cost 100,000.00 TL or 2,491.18 USD
- TEİAŞ System Usage Fee: 147,764.06 TL/MW-year + 82.90 TL/MWh or 4,346.00 USD/MW-year + 2.44 USD/MWh
- TEİAŞ System Operation Fee: 45.38 TL/MW or 1.33 USD/MWh
- The life of the PV plant is assumed to be 25 years.
- The YEKDEM tariff is assumed to remain constant.
- The annual discount rate is assumed to be 10%.
- The annual operation and maintenance repair costs of the PV plant are assumed to increase by 2%.

5.2.1.2. Financial Analysis

Table 5.6 briefly shows the investment cost.

Table 5.6. Project cost

Cost Component	**Amount (USD)**
EPC (Engineering, Procurement, and Construction)	475,166.70
Land Purchase	60,000.00
Total Investment Cost	535,166.70

Table 5.7 shows annual revenue and expenses.

Table 5.7. Project annual revenue and expenses

Parameter	**Value (USD)**
Total Annual Revenue	186,107.85
O&M (Operation & Maintenance) Cost	2,941.18
System Usage Fee	4,333.71
System Operation Fee	3,415.02
Total Annual Expenses	10,689.91
Net Annual Profit	175,417.94

5.2.1.3. Economic Return Analysis

The payback period is calculated by dividing the total project cost by the annual net profit.

$$Payback\ period = \frac{Total\ project\ cost}{Annual\ net\ profit} = \frac{535{,}166.70}{175{,}417.94} \approx 3.05\ years$$

The return on investment (ROI) is calculated by dividing the annual net profit by the total project cost and this part is multiplied by one hundred and the result is expressed as a percentage.

$$ROI = \frac{Annual\ net\ profit}{Total\ project\ cost} \times 100 = \frac{175{,}417.94}{535{,}166.70} \times 100 \approx 32.78\%$$

The net present value (NPV) is calculated as in Table 5.8.

Table 5.8. 25 year cost table

Year	Profit (USD)	Expense (USD)	Net Cashflow (USD)	Discounted net cashflow (USD)
1	186,107.85	10,689.91	175,417.94	159,470.85
2	186,107.85	10,903.71	175,204.14	144,959.76
3	186,107.85	11,121.78	174,986.07	131,789.85
4	186,107.85	11,344.22	174,763.63	119,868.56
5	186,107.85	11,571.11	174,536.74	109,106.30
	...	...	...	...
25	186,107.85	17,245.21	168,862.64	15,641.80

$$NPV = \sum_{t=1}^{25} \frac{Net\ cashflow_t}{(1 + 0.10^t)} - Initial\ project\ cost = 1{,}040{,}751{,}34\ usd$$

The internat rate of return (IRR) is calculated as;

$$0 = \sum_{t=1}^{25} \frac{Net\ cashflow_t}{(1 + IRR)^t} - Initial\ project\ cost = 32.62\%$$

5.2.2. Techno-Economic Feasibility Analysis for PV Plant with BESS

This part presents the techno-economic feasibility analysis of a 1 MW PV power plant located in Karaman, Türkiye, under the scenario of including BESS. The plant is expected to produce approximately 2,715.00 MWh/year under the YEKDEM feed-in tariff scheme. The project has been financially evaluated according to key performance indicators such as total investment cost, payback period and return on investment (ROI), and all monetary values have been exchanged to USD at the exchange rate of 1 USD = 34 TL.

5.2.2.1. Analysis Parameters

- Location: Karaman, Türkiye
- Installed capacity: 1 MW
- Annual energy production: 2,715.00 MWh
- Tariff Scheme: YEKDEM (1,941.10 TL/MWh + local component support 527.80 TL/MWh) or (7.26 cents/kWh) <u>There is no special tariff for BESS.</u>
- Land requirement: 15 acres

- Operational Model: No on-site personnel required, site visit for maintenance and troubles
- Annual operation and maintenance cost 150,000.00 TL or 4,411.76 USD
- TEİAŞ System Usage Fee: 147,764.06 TL/MW-year + 82.90 TL/MWh or 4,346.00 USD/MW-year + 2.44 USD/MWh
- TEİAŞ System Operation Fee: 45.38 TL/MW or 1.33 USD/MWh
- The life of the PV plant is assumed to be 25 years.
- The YEKDEM tariff is assumed to remain constant.
- The annual discount rate is assumed to be 10%.
- The annual operation and maintenance repair costs of the PV plant are assumed to increase by 2%.

5.2.2.2. Financial Analysis

Table 5.9 briefly shows the investment cost.

Table 5.9. Project cost

Cost Component	Amount (USD)
EPC (Engineering, Procurement, and Construction)	840,770.70
Land Purchase	60,000.00
Total Investment Cost	900,770.70

Table 5.10 shows annual revenue and expenses.

Table 5.10. Project annual revenue and expenses

Parameter	Value (USD)
Total Annual Revenue	197,118.35
O&M (Operation & Maintenance) Cost	4,411.76
System Usage Fee	4,333.71
System Operation Fee	3,415.02
Total Annual Expenses	12,160.49
Net Annual Profit	184,957.86

5.2.2.3. Economic Return Analysis

The payback period is calculated by dividing the total project cost by the annual net profit.

$$Payback\ period = \frac{Total\ project\ cost}{Annual\ net\ profit} = \frac{900{,}770.70}{184{,}957.86} \approx 4.87\ years$$

The return on investment (ROI) is calculated by dividing the annual net profit by the total project cost and this part is multiplied by one hundred and the result is expressed as a percentage.

$$ROI = \frac{Annual\ net\ profit}{Total\ project\ cost} \times 100 = \frac{900{,}770.70}{184{,}957.86} \times 100 \approx 20.50\%$$

The net present value (NPV) is calculated as in Table 5.11.

Table 5.11. 25 year cost table

Year	Profit (USD)	Expense (USD)	Net Cashflow (USD)	Discounted net cashflow (USD)
1	197,118.35	12,160.49	184,957.86	168,143.51
2	197,118.35	12,403.70	184,714.65	152,480.59
3	197,118.35	12,651.77	184,466.58	138,109.44
4	197,118.35	12,904.80	184,213.55	124,935.86
5	197,118.35	13,162.89	183,955.46	112,871.97
	...	...	...	...
25	197,118.35	19,623.15	177,495.20	16,261.31

$$NPV = \sum_{t=1}^{25} \frac{Net\ cashflow_t}{(1 + 0.10^t)} - Initial\ project\ cost = 800{,}384.12\ usd$$

The internat rate of return (IRR) is calculated as;

$$0 = \sum_{t=1}^{25} \frac{Net\ cashflow_t}{(1 + IRR)^t} - Initial\ project\ cost = 23.15\%$$

6. RESULT AND DISCUSSIONS

In this section, the financial and technical analyses of PV plants with and without storage will be compared. The advantages and disadvantages of the storage scenario will be evaluated from a technical perspective according to the simulation results.

The results of integrating BESS into PV plants in Türkiye, where the plants are assumed to be established, in line with the current energy markets and regulations, and the conclusions on how attractive this investment is in the current situation will be made and the section and the study will be concluded with idea suggestions.

6.1. Performance Analysis

Table 6.1 shows the important technical simulation results as a summary.

Table 6.1. Performance summary

	without BESS	**with BESS**
Injected energy into grid	2561.99 MWh	2715.00 MWh
Performance ratio	0.80	0.85

It is seen that the energy injected into the grid is approximately 6-7% higher in the storage scenario. The reason for this is that in the scenario without storage, the instantaneous energy above 1.00 MW is prevented from passing to the grid at the grid injection point due to the connection agreement of the plant and therefore this energy is evaluated as loss. On the other hand, since the energy above the peak-shaving limit of 1.00 MW is stored in the batteries in the storage scenario, this energy is injected into the grid after sunset without being lost and without being subject to any connection agreement limit. Except for the losses during charging/discharging of the batteries, the energy remaining above the connection agreement limit is managed well in accordance with the simulation results and the loss at the grid injection point is minimized to near zero.

When the performance ratio results of the plants are evaluated, it is seen that the storage scenario works with 5% more performance. As explained before, since PR focuses on the usable size of the total energy produced in the plant and since the losses are lower in the storage scenario, it directly gives a higher PR output. However, when the general classification of PV plants is taken into account, both plants provide good PR outputs. In short, both plants are suitable for investment in terms of performance ratio.

When the energy injected into the grid on a monthly basis is examined, BESS has stored variable amounts of excess energy in all months of the year and injected it into the grid during the hours when demand is high. BESS has technically created an advantage in terms of supply flexibility and energy losses.

In Figure 6.1, the area graph and the production data injected into the grid on a monthly basis are shown.

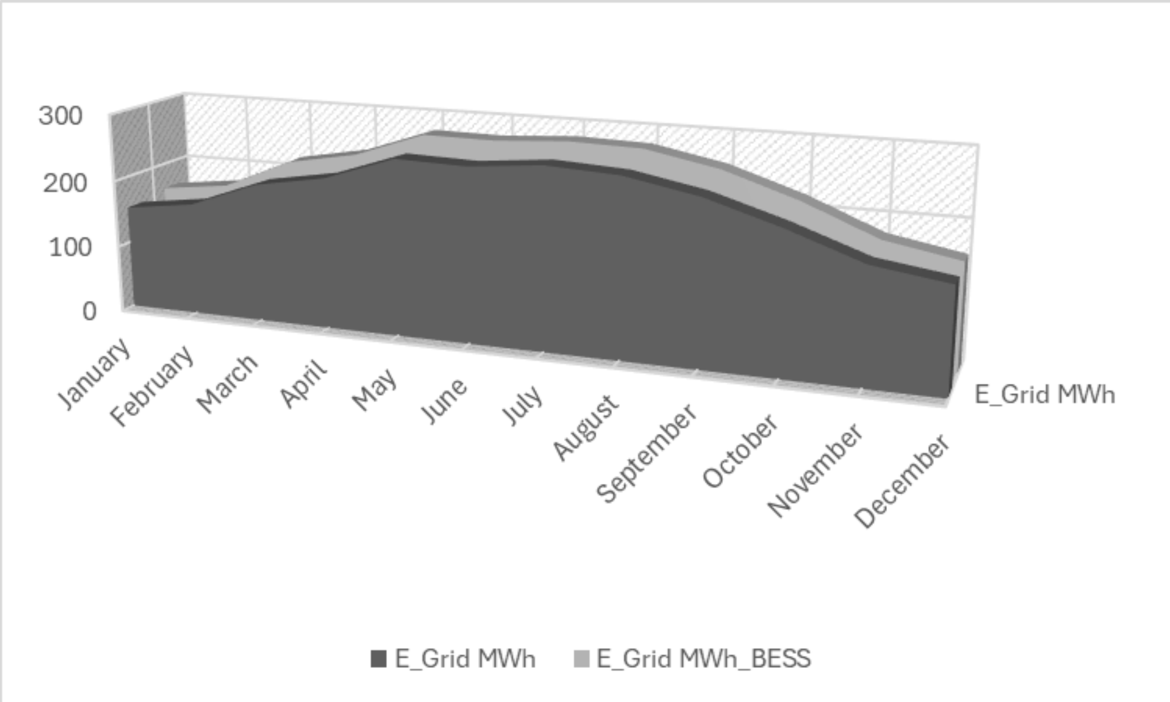

Figure 6.1. Monthly injected energy into grid area graph

6.2. Comparison of Financial Analysis Results

The payback period, ROI, NPV, IRR results used in the previous section on economic return analysis are shown comparatively in Table 6.2 for two separate projects.

Table 6.2. Economic return analysis comparison

	without BESS	**with BESS**
Payback period (years)	3.05	4.87
ROI (%)	32.78	20.50
NPV (USD)	1,040,751.34	800,384.12
IRR (%)	32.62	23.15

6.2.1. Payback Period

While the payback period for the scenario without storage is 3.05 years, this period is extended to 4.87 years for the scenario with BESS integration.

Since the payback period is a basic financial metric that shows how long it will take for the investment to pay for itself, the PV plant project without storage is undoubtedly more reasonable in today's conditions. The disadvantages of BESS integration are the high initial investment cost, the need for various additional equipment and the increase in maintenance costs.

The fact that the payback period is long today does not mean that the project is completely unreasonable or a bad project. Since the PV plant project with storage is a long-term investment, incentive increases in the unit price injected into the grid from BESS can shorten this period, in other words, the increase in income over time can make the investment more profitable in the long term.

6.2.2. Return on Investment (ROI)

In the scenario without storage, ROI is calculated as 32.78%, and in the scenario with BESS integration, ROI is calculated as 20.50%.

ROI is a basic finance metric that measures how profitable the investment is. The main reason why ROI is high in a PV plant without storage is that the investment is lower. The reason why BESS integration reduces ROI is that the additional income provided by the system and batteries while the investment is high does not cover this cost.

ROI can be increased in the long term with possible incentives in the regulations and energy markets, along with unit price increases

6.2.3. Net Present Value (NPV)

Net present value is a financial metric that calculates the current value of a project based on future revenues. All revenues to be obtained during the investment operation period are reduced to the present and show the total value. The storage system quickly amortizes itself and provides cash flow in a shorter time, resulting in a higher NPV.

There are three main reasons why the NPV of a storage system is low. These reasons are high investment cost, the system's revenue generation process takes time, and batteries wear out and lose capacity over time.

How NPV will shape in the long term depends on market conditions. Considering the variable market conditions, the increase in the unit price of the energy stored and injected from the batteries into the grid during high demand hours can make NPV advantageous.

6.2.4. Internal Rate of Return (IRR)

Internal rate of return is a financial metric that shows how much return an investment provides annually. A high internal rate of return indicates that the investment is attractive.

While the internal rate of return is calculated as 32.62% in the scenario without storage, the internal rate of return is calculated as 23.15% in the scenario with storage. The results indicate that storage PV plant is more profitable in the short term.

The internal rate of return is lower because the investment in the integration of BESS provides long-term returns and the fixed energy unit price reduces the profit margin in this area.

6.3. Avoided CO_2 Emission Comparison and Environmental Factories

In a PV plant without storage, the energy produced during energy production hours is injected into the grid within the scope of the connection agreement conditions and meets a portion of the energy demand. Since the CO_2 emission of renewable energy plants is assumed to be zero, the amount of energy injected into the grid, as well as the CO_2 emission that would occur when the energy is obtained from fossil fuels, represents an environmental parameter as the prevented CO_2 emission. When evaluating the amount of CO_2 emission prevented by the BESS integrated project, it is assumed that the excess energy produced during the day is stored with the peak-shaving method and injected into the grid during the hours when the supply is at its peak after sunset, preventing further CO_2 emission. In this way, energy demand is met by supply without producing energy using fossil fuels. Avoided CO_2 emissions and reduction are shown in Table 6.3.

Table 6.3. Avoided CO_2 emissions and reduction

	Avoided_CO2_emission without BESS kgCO2	Avoided_CO2_emission with BESS kgCO2	Reduction
Coal	2.433.805,00	2.579.250,00	5.98%
Natural Gas	1.152.855,00	1.221.750,00	5.98%
Oil	1.985.472,50	2.104.125,00	5.98%

PV plants provide different environmental benefits in addition to preventing CO_2 emissions. Energy production will help improve air quality as a result of obtaining it from the sun without burning fossil fuels. In addition, a large amount of water is used as a cooling material in energy production plants that produce energy from fossil fuels, and there is no need for water as a coolant when obtaining energy from the sun.

The ecosystem is protected by preventing CO_2 emissions, increasing air quality, and preventing water pollution.

When environmental factors are taken into account, the PV plant with BESS integration provides more environmental benefits than the PV plant project without storage, as it injects more energy into the grid.

7. RESULTS

In the previous sections of this thesis, performance and economic analyses of scenarios without BESS and with BESS integration of a PV power plant with 1 MW output power were performed and comparative results were presented. Both systems were simulated on the same location and basic PV power plant equipment were selected as the same and with equal simulation parameters using the same simulation software.

Technically, the annual energy amount injected into the grid as a result of BESS integration increased by 153.18 MWh, the main reason for this increase is that the excess energy that cannot be injected into the grid during the day within the connection agreement can be stored and integrated into the grid at the end of the day. In terms of performance ratio, the annual PR result of the traditional PV power plant increased by 5%. Energy losses naturally decreased as a result of storage and injection into the grid after sunset and positively affected the system, thus increasing PR. The extra charge/discharge efficiency for the scenario with BESS was 94.2%, which shows that the BESS system is technically integrated into the main system with high efficiency and operates as intended. Finally, in technical and environmental terms, the prevented carbon dioxide emissions decreased by 5.98% inversely proportional to the increase in energy injected into the grid, and the integration of BESS into the system had a positive environmental impact.

As a result of BESS integration, while the technical gains are quite obvious, when the economic feasibility results are examined and compared. It is seen that the obtained results are disadvantageous to the investors and the project developers. As a result of battery integration, the investment cost has increased by approximately 47%. While the return period of the investment cost of the system without storage to the investor, namely the amortization period, is calculated as 3.05 years, the amortization period of the system with storage is calculated as approximately 4.87 years. Based on these findings, it is seen that the unit cost of electricity in the system with storage is approximately one and a half times higher than the system without doping. This situation shows that the storage system is still high-cost in terms of investment.

When the technical and economic analysis results are examined together, it is obvious that BESS integration into PV power plants improves system performance and energy continuity and is important in approaching net zero carbon emission targets, while when viewed from the point reached by current battery technology, high investment costs and maintenance costs still pose an economic problem. However, when we consider the rate of development of the sector in the last 15 years and consider that costs have decreased rapidly in parallel with this development, it can be foreseen that BESS integration can be implemented with more reasonable costs in the near future.

8. RECOMMENDATIONS

Based on the findings obtained as a result of this thesis, the following suggestions are presented:

Integration of BESS into PV systems in terms of energy continuity is recommended. The main reason is that PV plants can create supply for energy demand during sunset hours and support grid stability, thus ensuring energy continuity and allowing more use of renewable energy sources.

Battery management systems can also be added to the system externally, increasing the life of the batteries and facilitating the financial management of energy for investors, but this also creates an extra cost.

Research and development activities should be encouraged for domestic cell and battery production, and domestic production should be provided. In this way, BESS integration costs for power plants to be established in Türkiye will decrease, because while there are domestic production options for basic PV system components, it is quite obvious that there is complete external dependence on batteries.

No contribution margin or incentive is currently applied in the energy markets for PV power plants with BESS integration, and energy is sold at the same unit price as plants without storage. With state support and incentives based on unit prices, BESS integration investment costs, which are quite high, may become more attractive for investors.

This study addresses the comparison of systems over a 1 MW power plant, but according to current regulations, the licensed system must be at least 10 MW, this lower limit can be lowered and access to this technology can be opened for small and medium-sized systems and investors.

According to the regulation that came into force in 2022, obtaining a license is quite easy and offers investors an opportunity for the future, but unfortunately, most of these licenses have not yet been implemented as projects in the past years, the process can be accelerated with changes to be made in the procedures in practice.

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