ECONOMICS OF ENERGY STORAGE SYSTEMS: A REAL OPTIONS APPROACH FOR INVESTMENT APPRAISAL

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ABSTRACT

ECONOMICS OF ENERGY STORAGE SYSTEMS: A REAL OPTIONS APPROACH FOR INVESTMENT APPRAISAL

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Energy storage systems (ESSs) are gaining more importance with the increase in demand for a change in the patterns of energy generation and consumption associated with decarbonization and energy independence concerns. To promote further deployment of storage systems, Türkiye implemented significant regulatory measures in recent years. Despite those regulatory measures taken in recent years, there is a lack of investment especially in large-scale ESS deployments. Given their importance in enabling the increased penetration of renewable power sources, it is critical to understand the factors affecting ESS investment decisions and develop a realistic investment appraisal model. To meet both needs, this study adopted an integrated approach by mixing qualitative and quantitative methods to evaluate the investment appraisal of ESSs.

The qualitative analysis showed that contrary to a positive net present value for the hybrid battery ESSs (BESSs), investors defer their investment decisions for more favorable conditions due to uncertainties stemming from the volatility in

electricity price and investment costs, frequent changes in legislation, and the ever-changing nature of battery technology. Based on that background, a real options framework for option to wait is developed in the thesis considering electricity price and investment cost uncertainties. Results of the real options model revealed that the optimal investing strategy for a hybrid BESS is to invest immediately and not postpone the investment decision for a cost decrease and/or a revenue increase. The investment would be profitable anyway. The results are also robust to the most anticipated change in legislation.

Keywords: Energy storage systems, battery energy storage systems, real options framework, option to wait, mixed approach

ÖZ

ENERJİ DEPOLAMA SİSTEMLERİ EKONOMİSİ: YATIRIM DEĞERLENDİRMESİNDE REEL OPSİYON YAKLAŞIMI

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Enerji Depolama Sistemleri (EDS'ler), karbon azaltımı ve enerji bağımsızlığına yönelik endişelerle birlikte enerji üretim ve tüketim kalıplarında değişim talebinin artmasıyla giderek daha fazla önem kazanmaktadır. Depolama sistemlerinin yaygınlaştırılmasını teşvik etmek amacıyla Türkiye son yıllarda önemli düzenleyici önlemler almıştır. Alınan bu düzenleyici önlemlere rağmen, özellikle büyük ölçekli EDS yatırımlarında eksiklikler devam ettiği görülmektedir. Yenilenebilir enerji kaynaklarının şebekeye entegrasyonunun artırılmasındaki önemi göz önüne alındığında, EDS yatırım kararlarını etkileyen faktörleri anlamak ve gerçekçi bir yatırım değerlendirme modeli geliştirmek kritik hale gelmektedir. Bu iki ihtiyacı karşılamak amacıyla bu çalışmada EDS yatırımları nitel ve nicel yöntemleri birleştiren bütünleşik bir yaklaşım ile değerlendirilmektedir.

Nitel analiz, yenilenebilir enerji santraline bütünleşik hibrit batarya EDS'lerdeki (BEDS'ler) pozitif net bugünkü değere rağmen, yatırımcıların daha elverişli koşullar için yatırım kararını ertelediğini göstermiştir. Bunun temel nedenleri; elektrik

fiyatlarındaki dalgalanmalardan, yatırım maliyetlerinden, mevzuattaki sık değişikliklerden ve batarya teknolojisinin sürekli gelişen doğasından kaynaklanan belirsizliklerdir. Bu temelden hareketle, tezde elektrik fiyatı ve yatırım maliyeti belirsizliklerini dikkate alarak bekleme opsiyonu için bir reel opsiyon modeli geliştirilmiştir. Modelin sonuçları, hibrit bir BEDS için en optimal yatırım stratejisinin yatırımı ertelememek ve derhal gerçekleştirmek olduğunu ortaya koymaktadır. Yatırım, maliyetlerin düşmesi veya gelirlerin artması beklenmeden de kârlı olacaktır. Ek olarak, analiz sonuçları beklenen yasal değişikliklere karşı sağlamdır.

Anahtar Kelimeler: Enerji depolama sistemleri, batarya enerji depolana sistemleri, reel opsiyon yaklaşımı, bekleme opsiyonu, bütünleşik yöntem

To my beloved mother, my dear sister, and my dear father

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LIST OF ABBREVIATIONS

BESSs	Battery Electric Energy Storage Systems
BS	Bachelor of Science
BPM	Balancing Power Market
BTM	Behind-the-Meter
CAES	Compressed Air Energy Storage
DAM	Day-ahead Market
DCF	Discounted Cash Flow
EGR	Electricity Grid Regulation
EMBSR	Electricity Market Balancing and Settlement Regulation
EMCSU	Electricity Market Connection and System Utilization Regulation
EML	Electricity Market Law
EMLR	Electricity Market License Regulation
EMRA	Energy Market Regulatory Authority
EMS	Energy Management Systems
EPİAŞ	Enerji Piyasaları İşletme Anonim Şirketi
ESSs	Energy Storage Systems
FFR	Fast Frequency Response
FTM	In-front of the Meter
GW	Gigawatt
GWh	Gigawatt-hour
HESS	Hybrid Energy Storage Systems
IDM	Intra-day Market
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IM	Imbalance Management
I-PHES	Integrated Pumped Heat Energy Storage
IRR	Internal Rate of Return

LFP	Lithium Iron Phosphate
LSM	Least Squares Monte Carlo
MBA	Master of Business Administration
MENR	Ministry of Energy And Natural Resources Of The Republic Of Turkey
MoEUCC	Ministry of Environment, Urbanization And Climate Change
MoIT	Ministry of Industry And Technology
MoTF	Ministry of Treasury And Finance
MS	Master of Science
MW	Megawatt
MWe	Megawatt Electric
MWh	Megawatt-hour
NEP	National Energy Plan
NPV	Net Present Value
NRECA	National Rural Electric Cooperative Association
PFC	Primary Frequency Control
PFM	Power Futures Market
PhD	Doctor of Philosophy
PV	Photovoltaic
RCSRES	Regulation on Certification and Support of Renewable Energy Resources
RSAEM	Regulation on Storage Activities in the Electricity Market
SFC	Secondary Frequency Control
SMS	Storage Management Systems
SoC	State of Charge
TEİAŞ	Türkiye Elektrik İletim Anonim Şirketi
YEKDEM	Renewable Energy Resources Support Mechanism

CHAPTER 1

INTRODUCTION

1.1. Main Background

The 2015 Paris Agreement on Climate Change calls for a sharp reduction in global fossil CO_2 emissions to keep the global average temperature rise in this century below 2°C compared to pre-industrial levels; for developed countries. Reaching such ambitious decarbonization targets, referred to as deep decarbonization, will require profound structural changes for regional and national energy systems (Borasio & Moret, 2022).

Decarbonization of power systems typically involves two strategies: i) improving the energy efficiency of the existing system, and ii) replacing carbon-intensive generation sources with low- or zero-carbon generation sources such as renewables, nuclear, and power plants with carbon capture and storage. The key challenge of integrating renewables into the power system, however, is to balance the supply and demand in the presence of variable power generation from renewables. Unlike with fuel-based power plants, where a controllable factor, i.e. the amount of fuel provided to the plant, dictates the electricity output, with renewable generation, variable factors like sunlight and wind speed determine the electricity generation (Jafari et al., 2022). This problem can be addressed with the utilization of energy storage systems to balance power supply and demand continuously (Zhang et al., 2021).

Energy storage systems (ESSs) absorb and then release power so it can be generated one time and used at another. There are four major benefits to ESSs: (i) smoothing the flow of power, (ii) providing the backup service, improving reliability, (iii) increasing the utilization of power generation by absorbing power that exceeds

current demand, and (iv) smoothing out the costs (D'Aprile et al., 2016). The availability of firm low-carbon resources is an important factor in containing the cost of power sector decarbonization and thus the overall cost of climate mitigation efforts (Sepulveda et al., 2018). Together with low-carbon flexible generation technologies and transmission network expansion, energy storage could serve as an effective source of flexibility to allow higher penetration of renewable generation (Jafari et al., 2022). Battery electric energy storage systems (BESSs), in particular, have gained a crucial role in the transition to low-emissions energy systems since their costs decreased sharply while improving their performance characteristics over the last decade (IEA, 2024).

In terms of application, ESSs that are integrated with a power plant (hybrid energy storage systems (HESS)), are gaining importance since they bring: (i) *energy value* coming from the production management, relying on a difference of prices within a period – electricity is stored in periods of excess production (low prices on the spot market), and produced during periods of high demand (high prices), (ii) *capacity value* coming from the ability to serve as a back-up plant, and (iii) *balancing value* coming from ancillary services they can offer such as frequency regulation, voltage regulation (Després et al., 2017). According to the International Energy Agency (IEA, 2024) data, the global market for battery storage doubled in 2023 and reached over 90 Gigawatt-hour (GWh). Growth came mostly from utility-scale systems with behind-the-meter battery storage accounting for 35% of the growth (IEA, 2024).

1.2. The Thesis in the Literature

A preliminary literature review shows that ESSs provide flexibility and efficiency when coupled with renewable energy resources and help achieve decarbonization targets. On the other hand, the deployment of ESSs depends on cost-effectiveness and efficiency.

The studies on the economics of ESSs can be grouped as follows:

- The studies on the role of ESSs for the decarbonization targets and integration of renewables indicate:

- EU’s emission reduction targets can be achieved by investing in a system that is mainly dominated by wind power which requires storage capacity building to temporally and spatially distribute electricity (Pleßmann & Blechinger, 2017).
- A lowering of carbon emissions intensity in the electricity sector will result from higher shares of renewables facilitated by different ESS technologies by 2050. The role of ESSs in decarbonizing the electricity system depends on several factors such as targeted decarbonization level, geographical location, capital investment cost of ESS, availability of other low-emission flexibility options, and the ESS technology (Jafari et al., 2022).
- The studies assessing the effectiveness of different ESS technologies for their role in decarbonization show that there are two main characteristics: duration and capital costs (Jafari et al., 2022).

- The studies on the profitability of ESSs suggest that;
  - While energy storage has obvious benefits, it also has key challenges in terms of achieving cost (capital, operating, and financing expenditures), scale (energy capacity and duration), and effectiveness (round-trip efficiency and technology readiness level) (Davies et al., 2019). The deployment of ESSs will remain limited until they achieve an attractive internal rate of return (IRR) (Bradbury et al., 2014).
  - The important factors affecting the profitability/net present value – and hence attractiveness for the firms - are revenue, charging costs, and round-trip efficiency (Walawalkar et al., 2007). Revenue tends to increase with round-trip efficiency but this also leads to an increase in the energy storage capacity (whose cost must be considered for the net profitability of the system) (Zhang et al., 2021).
  - Storage development also depends on the carbon price and the frequent surplus of renewable energy while the economic value of the ancillary services depends on the existence of an adequate market or special agreements (Després et al., 2017).
  - Effective policy changes and incentives will be key enablers to accessing the full potential of battery systems (Martins & Miles, 2021). Any policy to

promote renewable energy and efficient operation of existing generation resources needs to pay special attention to market design so that ESSs can participate and be fairly compensated for the flexibility and value they add to the systems in which they operate (Bradbury et al., 2014). Policies might be in the form of a specific tax regime or the possibility for prosumers to sell energy (Després et al., 2017).

- Electricity exchanges between consumers and prosumers are a promising growth area (Després et al., 2017).

The contribution of the thesis to the literature will be two-fold: (i) It will contribute to the studies on the profitability of ESS literature by determining the optimal investment strategy for a hybrid battery energy storage system that is integrated with a power plant and (ii) it will contribute through identifying factors affecting investment decisions and observing the perspectives of stakeholders.

1.3. Motivation and Objective

Energy storage systems (ESSs) are gaining more importance with the increase in demand for a change in the patterns of energy generation and consumption associated with decarbonization and energy independence concerns. A preliminary literature review shows that ESSs provide flexibility and efficiency when coupled with intermittent renewable energy resources and hence can help achieve these targets. Despite their usefulness especially for increasing the use of renewable energy sources, there are key challenges for effective deployment of ESSs in terms of cost/profitability and effectiveness (round-trip efficiency). The core objective of this thesis is to assess the economic potential of the ESSs from the perspective of key stakeholders while unfolding the factors affecting the economic value, investment appraisal, and broad deployment of these systems. To help understand the economic value of storage, the method of approach will be based on a combination of qualitative and quantitative analyses. This study aims to extend the previous literature by providing a detailed analysis of the economics of ESSs through

(1) taking a wide picture of the current state and gaining insights into barriers and opportunities for the deployment of energy storage,

(2) finding the factors affecting the economic value of energy storage systems for those actors,
(3) investigating the uncertainties and expectations from the viewpoint of experts,
(4) economic analysis of the investments in energy storage systems.

1.4. Relevance for Türkiye

In July 2021, Türkiye announced its "Green Deal Action Plan" which sets the targets and planned actions to achieve a more sustainable economy. On January 19, 2023, the Ministry of Energy and Natural Resources of the Republic of Turkey (MENR) published the National Energy Plan (NEP), which aims for Turkey's installed electricity capacity to reach approximately 190 Gigawatt (GW) by 2035. The plan targets that around 65% of this capacity—equivalent to 52.9 GW from solar energy and 29.6 GW from wind energy—will come from renewable sources.

Türkiye can decarbonize its economy to a large extent and approach the Net-Zero target by early 2050s if clear and measurable targets are set in the medium and long term with the following targets regarding renewable energy share in electricity power production: (i) the share of renewable energy in installed electricity capacity can be increased to 50 percent in 2030, (ii) to increase the installed capacity of renewable energy to approximately 35 GW by 2030, an average of 3 GW of solar and 2.5 GW of wind power capacity should be installed every year, and (iii) by 2030, we can aim to increase the ratio of electric vehicles among total passenger vehicles to at least 20% and to at least 10% among the vehicles used in public transportation and freight transport SHURA Energy Transition Center (SHURA Energy Transition Center, 2023).

The targeted expansion of renewables may create stability and reliability issues due to the intermittency of renewable power sources if not supported by flexibility solutions. In other words, failing to increase the deployment of storage in line with the increase in renewables would risk the clean energy transitions in the power sector. To increase the storage capacity accordingly, there is a need for policy actions that support the deployment of storage systems and minimize barriers (IEA, 2024).

To enhance the flexibility of the electricity system in response to the increasing variable renewable energy production, the NEP (Ministry of Energy and Natural Resources, 2023) aims to expand battery energy storage capacity to 7.5 GW by 2035. In addition, Türkiye implemented significant regulatory measures in recent years to promote further deployment of storage systems. The regulation, published on November 19, 2022, is particularly noteworthy as it mandates the deployment of energy storage systems for renewable power plants to participate in the Renewable Energy Resources Support Mechanism (YEKDEM). However, in spite of the measures taken by the regulatory authorities, there are no grid-scale battery energy storage (BESS) facilities constructed in Türkiye yet. This implies a lack of private investments in storage systems which might negatively affect the transition pace towards cleaner energy systems. This emphasizes the critical need to thoroughly examine the factors affecting the investment appraisal of these systems as well as the need for developing a realistic investment appraisal model.

1.5. Research Questions

Literature review shows that there are various potential reasons for the lack of investment in ESSs including the high investment costs, regulatory and market-related barriers, and uncertainty. These factors might be the reasons for investors to postpone investment decisions to wait for more favorable environments.

Research questions are formulated as follows:

- *RQ1. What are the opportunities and barriers to the deployment of ESSs in Türkiye?*
- *RQ2. What are the factors and sources of uncertainties affecting ESS investment decisions, and how do the investors evaluate ESS investments?*
- *RQ3. What is the optimal investment strategy under the conditions of uncertain future revenues and investment costs?*

1.6. Method and Data

For this thesis, the research will use a mixed method that combines qualitative and quantitative methods. The research design is summarized below:

Qualitative research will be in the form of an exploratory study. The primary research method for this part is qualitative data collected through semi-structured interviews and surveys with key experts in the field of energy storage. By interviewing different actors and trying to represent all the groups engaged in the ESSs landscape, this research will observe perceptions and positioning about ESSs from diverse angles and identify the factors driving energy storage investments. *More specifically, the qualitative method will be used to answer RQ1 and RQ2. The data collected in this part also will be used to validate/enhance the assumptions for the quantitative study.*

In the **quantitative research** part, a real options model will be developed to analyze the investment appraisal of ESSs. The real options approach, which is gaining popularity in energy literature, is a powerful tool to reflect managerial flexibility in projects with high uncertainty. The model developed in the thesis will help to analyze the economic viability of ESS investments under the conditions of uncertainties regarding future cost reductions due to the continuous developments in the technology. In this model, the value of an ESS investment will be assessed by taking the value of delaying the investment (option to wait to invest) when there is uncertainty in future revenues and investment cost. The q*uantitative method will be used to answer RQ3*.

1.7. Expected Contribution

The study will contribute to the real options literature on energy storage investments by combining qualitative research with the real options framework to effectively address uncertainties and design sensitivity analysis. By using this novel mixed approach, the study enhances the findings and provides a more country-specific understanding of the BESS investment appraisal.

The study is important for two major reasons. First, the qualitative analysis will provide a multidimensional perspective and produce rich-quality data regarding the perceptions, uncertainties, and expectations of the key Turkish actors from which quantitative models analyzing the economics of ESSs can benefit. Second, the

economics of ESS investments for Türkiye will be quantitatively assessed by considering actual country-specific factors provided by the qualitative study. To this end, a real options framework will be developed in the quantitative part based on the uncertainties and the related managerial flexibilities derived from the results of the qualitative research. Unlike the other real options models applied in the literature, the study will not use a priori or theory-led assumptions but will build the modeling framework upon the data compiled through a qualitative study which makes the results of the study especially relevant for practitioners and policymakers.

In this approach, qualitative and quantitative analysis parts will feed each other: The research question of "What is the optimal investment strategy?" to be answered in the quantitative part defines the scope of the qualitative analysis. More specifically, this research question gives rise to the research questions of "What are the opportunities and barriers for deployment of ESSs in Türkiye?" and "What are the factors and sources of uncertainties affecting ESS investment decisions, and how do the investors evaluate ESS investments?".

Thus, the design of the interview guide and the selection of interviewees were done based on the data needs of the quantitative model. In turn, quantitative analysis will use the data collected in the qualitative analysis as an input. Firstly, qualitative data will be used to confirm the theory-led and/or reveal country-specific sources of uncertainty (to specify the model assumptions) and the type of flexibilities that the decision-makers have (to decide the real options type) when appraising energy storage investments. Secondly, the research question in the quantitative part is refined to reflect the real-life decision problem of the investor in Türkiye by using the data collected in the early phase of the qualitative study.

CHAPTER 2

LITERATURE REVIEW ON ENERGY STORAGE INVESTMENTS AND VALUATION METHODS

2.1. Overview of Energy Storage Systems

According to the DOE/EPRI Electricity Storage Handbook, there are 18 services and applications for electric grid energy storage which can be represented under five umbrella groups (Akhil et al., 2015):

Bulk energy services: Electric energy time shift (arbitrage), electric supply capacity

- Ancillary services: Regulation, spinning/non-spinning/supplemental reserves, voltage support, black start, other related uses
- Transmission infrastructure services: Transmission upgrade deferral, transmission congestion relief
- Distribution infrastructure services: Distribution upgrade deferral, voltage support
- Customer energy management services: Power quality, power reliability, retail electric energy time-shift, demand charge management

The user with the corresponding application and service profiles are presented in Table 1.

ESS applications can be differentiated as “behind-the-meter (BTM)” and “in-front of the meter (FTM)” depending on whether they are deployed at the consumer level by the residential, commercial and industrial users or at the transmission/distribution level. BTM storage applications, also called small-scale storages, can be deployed by consumers, system operators, and mini-grids. According to International Renewable

Energy Agency (IRENA), BTM storage applications can be used to store the energy that is either produced by on-site power systems (e.g. rooftop photovoltaic systems) or drawn from the grid. Their primary aim is to reduce energy costs through providing increased self-consumption, back-up power, and demand charge reduction for consumers; frequency regulation, network investment deferral, and peak capacity investment deferral for system operation; and replacing diesel generations, back-up power, and smoothing of variable renewable energy for mini-grids (IRENA, 2019).

Table 1. Users, typical applications, and corresponding services

Users	**Typical Energy Storage Applications**	**Energy Storage Services**
Residential Users	time shifting, energy cost reduction, back-up power, carbon footprint reduction	customer energy management services, bulk energy services, ancillary services
Commercial & Industrial Users	frequency regulation, voltage support, reactive power balancing, demand balancing, investment deferral, arbitrage	customer energy management services, bulk energy services, ancillary services
Transmission & Distribution Providers	frequency regulation, voltage regulation, reactive support, time shifting, supply security, black start, load and demand balancing, investment deferral and the ability for the grid to efficiently utilize renewable energy	transmission infrastructure services, distribution infrastructure services, bulk energy services, ancillary services
Power Plants **- Solar and Wind Power Plants**	time shifting, energy cost reduction, supply security	bulk energy services, ancillary services

Table 1. (continued)

- Power Plants Using Fossil Fuels	frequency regulation, lower grid connection times, efficient integration of renewable energy	bulk energy services, ancillary services
Electrical Vehicles Charging Stations	time shifting, demand balancing, investment deferral	bulk energy services, ancillary services, customer energy management services

Source: Product guides of Inovat (Inovat Co., n.d.) and Aggreko (energy storage suppliers) (Aggreko Co, n.d.), DOE/EPRI Electricity Storage Handbook (Akhil et al., 2015).

FTM systems, on the other hand, are on the utility side of the meter and interconnected to the distribution or transmission networks (IRENA, 2019). They include large-scale energy generation and storage facilities such as power plants or large-scale energy storage systems. They provide applications such as renewable energy smoothing, ancillary or bulk energy services.

2.2. Landscape in Türkiye

2.2.1. Electricity Trade

There are various types of markets in Türkiye for electricity trading which can be grouped under two categories as physical electricity trade markets and financial electricity trade markets.

– Physical Electricity Trade Markets

1. **Organized Spot Markets:** Spot electricity markets consist of day-ahead and intra-day markets both of which are operated by Energy Markets Operations Joint Stock Company (EPİAŞ) which is responsible for managing and operating energy markets, including power, gas, and environmental commodities.

- **Day-ahead market (DAM):** This market serves as the main platform for the electricity trade. In this market, participants submit bids specifying the price and quantity for purchasing or selling electricity for each hour of the next day. The market clearing price (DAMP) and traded volumes are determined hourly by matching buyers' and sellers' bids. DAMP is accepted as the reference price for other markets (PwC Turkiye, 2023).

- **Intra-day market (IDM):** IDM allows the participants to trade after the closure of the DAM. IDM serves as an alternative platform for DAM and aims to reduce the possibility of imbalance and increase the liquidity in the markets. IDM is used for imbalance management and arbitrage purposes. In this market, hourly offers can be placed up to 60 minutes before the physical delivery (PwC Turkiye, 2023).

2. **Real-Time Organized Markets:** Real-time markets are operated by the Turkish Electricity Transmission Corporation (TEİAŞ) and consist of balancing power market and ancillary services market. These markets aim to balance the electricity supply and demand instantly. Transactions in these markets take place after the closure of the DAM and IDM.

- **Balancing power market (BPM):** BPM is responsible for ensuring reserve capacity to maintain real-time balance (PwC Turkiye, 2023). The tertiary frequency control market is operated under the BPM.
- **Ancillary services market:** This market provides frequency control for real-time grid imbalance management. The following services are provided under the ancillary services market:
    - Primary frequency control (PFC)
    - Secondary frequency control (SFC)
    - Spinning reserves
    - Instantaneous demand control
    - Reactive power control
    - Black start
    - Regional capacity leasing service

3. **Bilateral Agreements**: Under these markets, predetermined medium and long-term contracts enable suppliers and consumers to reach a prior agreement on electricity purchase prices to mitigate risks (PwC Turkiye, 2023). Two markets operated under the physical electricity markets are:
   - Over-the-counter market
   - Organized power futures market (PFM) (launched by EPİAŞ on June 1st, 2021).

– Financial Electricity Trade Markets: Derivatives on electricity commodity are traded under Borsa Istanbul (Istanbul stock exchange).

2.2.2. Regulatory Environment Regarding Battery Electricity Energy Storages

Various government bodies are involved in energy storage investments with a wide range of responsibilities. The Ministry of Energy and Natural Resources (MENR) is responsible for developing policy framework regarding the energy sector and energy storage. The Energy Market Regulatory Authority (EMRA) is responsible for regulating and managing the energy markets and licensing of energy storage systems. YEKDEM price scheme is determined by EMRA. The Ministry of Industry and Technology (MoIT) develops policies to increase the share of domestic production in energy storage systems. Ministry of Environment, Urbanization and Climate Change (MoEUCC) provides support for environmental-friendly projects. Ministry of Treasury and Finance (MoTF) defines financial and tax policies for energy and energy storage projects. Electricity storage in Türkiye is regulated by the Energy Regulatory Authority (EMRA) based on the "Regulation on Storage Activities in the Electricity Market (RSAEM)" dated May 9, 2021 (Official Gazette, 2021). After the RSAEM, which outlines the principles governing storage activities, subsequent legislative changes were made to expand the installations of energy storage facilities and promote the integration of storages in renewable energy projects.

The regulation timeline is presented in Figure 1 below. The latest amendment to the regulation the electricity storage was published on November 19, 2022. With this amendment, firms licensed to establish an electrical storage facility on their site are

permitted to build and operate a wind power plant (minimum 20 MW) or a solar power plant (minimum 10 MW, maximum 250 MW) with a capacity matching that of the storage facility under the scope of YEKDEM. Under this amendment, total storage capacity applications were almost nearly 300 GW for storage facilities that are integrated into renewable power plants (PwC Turkiye, 2023).

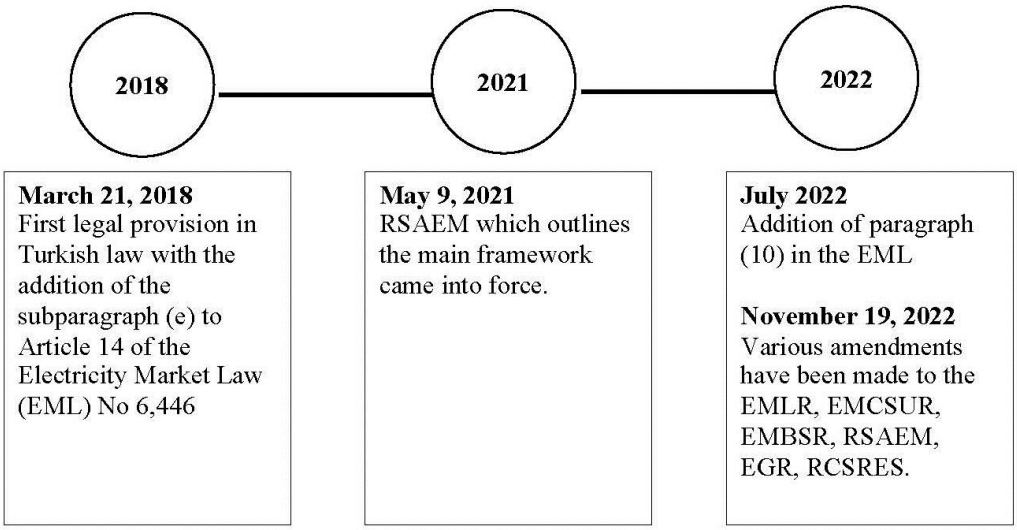


Figure 1. Regulation timeline

EMLR: Electricity Market License Regulation; EMCSU: The Electricity Market Connection and System Utilization Regulation; EMBSR: The Electricity Market Balancing and Settlement Regulation; RSAEM: Regulation on Storage Activities in the Electricity Market; EGR: The Electricity Grid Regulation; and RCSRES: Regulation on Certification and Support of Renewable Energy Resources.

According to the legislation, the following four different storage facilities can be installed (İzgi & Tezcan, 2024):

(1) Independent facilities can be established if it has a supply license, and its installed capacity is not less than two Megawatt (MW).

(2) Facilities integrated into a production plant (generation facility): Storage facilities can be installed by licensed electricity generation facilities with a maximum capacity not exceeding the installed capacity of that generation facility.

(3) Facilities integrated into a consumption facility: Consumers can install an electricity storage facility if (i) an appropriate connection opinion is provided by the relevant grid operator, (ii) installed capacity of the storage facility does not exceed the contractual capacity of the relevant consumption facility in the connection agreement, and (iii) it is located at the same measurement point.

(4) Facilities installed by a grid operator[1]: Distribution companies can install electricity storage facilities with the approval of the Board. For approval, they need to prove that installing electricity storage is more economical compared to new network investments.

Starting in November 2022, EMRA accepts pre-license applications for electricity storage facilities integrated with wind and solar power plants. According to the Article 14 of the EMLR, the following conditions are mandatory:

a) The ratio of the electrical installed capacity of the wind or solar energy-based electricity generation facility to the installed capacity of the committed electricity storage unit must not exceed 1 (referred to as 1:1 criteria).

b) Applications must have a minimum installed capacity of 20 MW for wind energy-based applications and a minimum installed capacity of 10 MW for solar energy-based applications, and the total installed capacity must not exceed 250 MW.

c) The ratio of the committed electricity storage capacity to the installed capacity of the electricity storage unit must be at least 1.

d) The committed electricity storage unit must be located within the boundaries of the proposed power plant site.

2.2.3. Energy Storage Developments

In July 2021, Türkiye announced its "Green Deal Action Plan" which sets the targets and planned actions to achieve a more sustainable economy. Based on that plan, the MENR published the NEP on January 19, 2023. The NEP targets to increase the share of renewables in electricity capacity from 52% in 2020 to 64.7% in 2035 which

[1] This type of electricity storage facility was included into RSAEM with the amendment of November 19, 2022.

is equivalent to a production of 52.9 GW from solar energy and 29.6 GW from wind energy (Figure 2) (Ministry of Energy and Natural Resources, 2023). In SHURA (2023)'s net zero 2053 scenario, the share of renewables in total energy generation is projected to be over 90% by 2055.

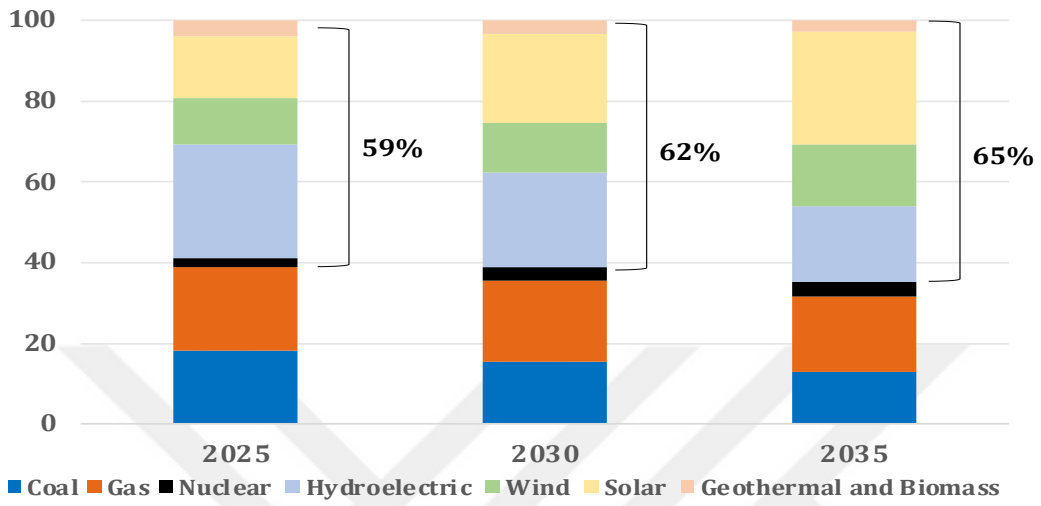


Figure 2. Projected shares in electricity capacity (%)

To enhance the flexibility of the electricity system in response to the increasing variable renewable energy production, the NEP aims to expand battery energy storage capacity to 7.5 GW (Figure 3) and electrolyzer capacity to 5 GW by 2035 (Ministry of Energy and Natural Resources, 2023). Electrolyzers can help reduce the need for batteries by converting excess energy from solar and wind power into e-fuels, offering long-term (seasonal) storage solutions. However, battery technologies will remain essential for addressing the grid's short-term (hourly) balancing requirements.

According to SHURA (2023)'s net zero 2053 scenario, the installed capacity of batteries will reach 30 GW/120GWh by 2053 to ensure system stability with 62% of the total investment required to achieve the net zero target being spent on new power plants and storage systems. This implies important investment opportunities for the private sector. To promote the deployment of ESSs in line with the increasing penetration of renewables, starting from November 2022, EMRA required the deployment of storage systems with the same capacity for new wind and solar power

plants to participate in the YEKDEM scheme. As of June 2024, applications for preliminary licenses for storage capacity have reached approximately 32 GW (Electricity Generation Pre-License Inquiry, n.d.). Although, there are no grid-scale battery energy storage facilities constructed under this legislation yet, the observed high demand suggests that Türkiye's storage capacity will increase through the deployment of hybrid storage systems which are integrated with renewable energy plants (SHURA, 2024).

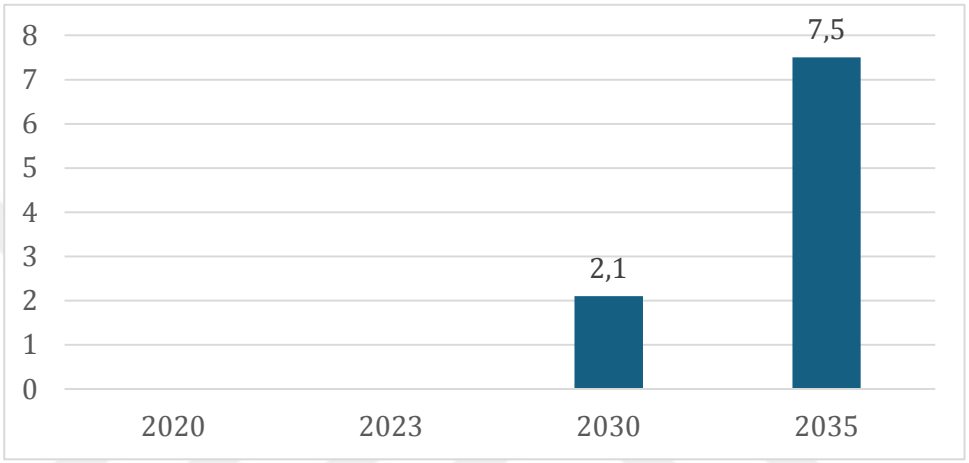


Figure 3. Projected battery capacity (GW)

2.3. Real Options Approach in the Energy Storage Literature

2.3.1. Real Options Frameworks

Conventionally, the investments are evaluated by using discounted cash flow (DCF) analysis, where cash flows are discounted to the current value and net present value (NPV) is the sum of the DCF over the life of the investment. In DCF analysis, the decision rule is that if the NPV of the investment project is greater than zero the investment project should be undertaken and if the NPV is less than zero the project should be deferred. This type of analysis, although simple to apply, makes two implicit assumptions that may not be valid for real-life investment decisions. Firstly, it assumes that the investment is reversible which means that an investment can be undone. The second assumption is that if an investment decision is not undertaken now, it will not be available in the future.

In other words, the DCF analysis ignores the management's flexibility to adapt its future actions and revise decisions in response to changing exogenous market conditions (Kulatilaka, 1993; Trigeorgis, 1993). Nearly all investments involve the option to undertake them when financing alternatives are more favorable (Ross, 1995). The importance of operating options becomes more important when there is high uncertainty and the technology is flexible (Kulatilaka, 1993). In an uncertain economy, nearly all investment projects have option right values, even including those projects with little or no uncertainty about their cash flows (Ingersoll & Ross, 1992).

Option theory provides a better analytical tool than the traditional DCF method based on NPV to analyze projects when investments are characterized by high risk and uncertainty (Fernandes et al., 2011) and when there exist options with future decisions being contingent on intermediate changes in an uncertain environment (Kumar, 2016).

2.3.1.1. Definition of Options

According to Black and Scholes (1973), "*An option is a security giving the right to buy or sell an asset, subject to certain conditions, within a specified period of time*". An option that gives the right to buy an asset at a pre-specified price (exercise price) in a specified period (time-to-maturity) is referred to as a "call option", while an option that gives right to sell the underlying asset at the exercise price in a specified period is referred to as "put option". The options can be either American or European. American options can be exercised at any time up to the maturity date, while European options can be exercised only on a certain date.

For an American option, the optimal strategy is to compare the immediate exercise price with the expected cash flow from continuing and exercising the option if the exercise value is positive and greater than or equal to the conditional expectation. At the final expiration date, exercise strategy is to exercise the option if it is in the money and to allow to expire if it is out of the money.

2.3.1.2. Real Options Framework

The term "real options" was first introduced by Myers in 1977 in his paper on the determinants of corporate borrowing. In this work, real options are defined as "*the opportunities to purchase real assets on possibly favorable terms"* (Myers, 1977). A technical definition for real options is given by Kogut and Kulatilaka (2001) as "*an investment decision that is characterized by uncertainty, the provision of future managerial discretion to exercise at the appropriate time, and irreversibility*".

In order to apply real options analysis, the underlying asset needs to feature flexibility, uncertainty, and irreversibility (Madlener & Stoverink, 2012). In other words, real options analysis enables to consider the value of waiting that is accrued by irreversibility, uncertainty, and management flexibility (Madlener & Stoverink, 2012). The higher the degree of uncertainty and the irreversibility of an investment has, the better the assessment of the investment's true value by the real options analysis compared to DCF analysis (Adner & Levinthal, 2004).

The most common real options include; option to invest/build, option to defer/wait, option to abandon, option to expand, contract, or extend the life of the facility, and option to switch (Trigeorgis, 1993) as defined below:

- option to invest/build: holder of the option decides whether to build or not a certain infrastructure (Locatelli et al., 2020);
- option to defer/wait: enables holder to wait before taking irreversible decisions (Locatelli et al., 2020). This means that, the holder has the option to invest now, or wait for more information or wait for the resolution of the uncertainty (Fernandes et al., 2011);
- option to abandon: holder has the possibility to abandon current projects permanently and realize the resale value of assets if market conditions decline severely (Trigeorgis, 1993);
- option to expand, contract, or extend the life of the facility: the holder can change the operation scale depending on the market conditions (Trigeorgis, 1993);

- option to switch: holder has possibility to change the output mix of the facility (product flexibility) or change the inputs to produce same outputs (process flexibility) or suspend the production depending on the price and demand conditions (Trigeorgis, 1993),
- option to prototype: enables holder to spend a fraction of actual system cost to invest in a prototype and receive valuable economic and technical information which reduces the investment risk (Lai & Locatelli, 2021).

Real options can be classified further based on their irreversibility as *timing options* and *switching options* where irreversibility means that although it is possible to undo, it would be too expensive or lengthy. A single investment opportunity is a timing option which includes the case of divestments. Swing options, which give option holder the right to buy a predetermined amount of energy at a predetermined price with some flexibility, are also timing options. Switching options, on the other hand, include reversible changes where reversibility means the ability to reverse the process at a reasonable cost or delay (Nadarajah & Secomandi, 2023).

Real options can be designed as single or multiple compound options. In compound case, uncertainties create multiple interacting options in which a subsequent option becomes available only after the prerequisite option is executed. For example, options to abandon or expansion only appear after the option to invest is executed. Proper modelling the subsequent options may change the investment decision and provide additional value to the investment (Ma et al., 2022).

Table 2. The analogy between a call option and project characteristics

Project Characteristics	**Call Option**
Present value of expected cash flows	Stock price
Present value of investment outlays	Exercise price
Length of deferral time	Time to maturity
Time value of money	Risk-free rate
Volatility of project's returns	Variance of stock returns

According to real options theory, an option to invest or defer is similar to a call option on stock price. The analogy is described in Table 2 (Fernandes et al., 2011).

2.3.2. Real Options Valuation

Real options method is applied to overcome the limitations of DCF method when there are valuable operating flexibilities due to the uncertainty regarding the underlying real asset. Although real options analysis is based on financial options theory, the underlying asset in this case is an investment project which is not traded in the market and thus does not have a market price unlike a financial asset. According to the market asset disclaimer hypothesis, proposed by Copeland and Antikarov (2001), assuming that the project itself is the underlying asset, the net present value of the cash flows of the project is the best non-biased estimator for the market value of the project.

Therefore, real options are defined with risks, decisions, and cash flows. There are different methodologies used in the literature to define risk measures and value the stream of cash flows in real options framework. Under risk-neutral valuation, the value of the cash flows equals to the expected risk-free discounted sum of risky cash flows under a probability distribution with the future price dynamics being a martingale. Alternatively, instead of adjusting probability distributions, discounted cash flow analysis uses modified discount rate to compute discounted cash flow to take the uncertainties into account (Nadarajah & Secomandi, 2023).

In any cases, the DCF`s question "whether or not to invest/invest if NPV is greater than zero" becomes "when to invest/invest if investment's NPV exceeds the value of the option to wait" in real options analysis (Locatelli et al., 2020) where the answer to that question depends on the comparison between the present value of the cash flows and the value of the operating options. For such a comparison, the following variables need to be estimated: (i) the value of the underlying asset at risk, (ii) the exercise price/value of the investment, (iii) the length/term of the option, (iv) the standard deviation/volatility of the risky underlying asset, and (v) the risk-free interest rate (Palma & Ibarra, 2020).

Real options valuation models can be either analytical which are based on exact equations such as the Black-Scholes formula or numerical which are based on approximation through computational simulations.

2.3.2.1. Numerical Models

There are three common numerical techniques used in the real options method to solve the investments` opportunity value which are lattice-based optimization (dynamic programming approach), least squares Monte Carlo (simulation approach), and the numerical partial differential equations (finite difference method).

2.3.2.1.1. Lattice-Based Optimization

Lattice-based methods are discrete-time models for valuing options. They use a lattice or a tree-like structure to illustrate the possible future states of the underlying asset. This approach uses dynamic programming techniques where the underlying asset's value is modeled by a tree with the branches showing the possible future values for the asset under plausible market scenarios.

Binomial tree models are commonly used lattice models, introduced by Cox, Ross, and Rubinstein (Cox et al., 1979), which allow for two states: The price of the asset either goes up or down in each interval. The diagram below (Figure 4), taken from Cox, Ross, and Rubinstein (1979), is a representation of a two-period binomial model for a financial asset whose price follows a multiplicative binomial process over time. It is assumed that starting from S (initial level of price), the price of the asset can have two possible values: The price of the asset can go up to uS with probability q, or it can go down to dS with probability (1-q) at the end of the first period. In the second period, there are three possible values assuming that probabilities are constant over time.

Unlike financial options where the underlying asset is traded at a market, there is usually no available market price in the case of real options. For these cases, the value of the underlying asset is estimated using the value of the investment project

which may be derived from non-option valuation approaches such as DCF. In the case of an investment project, for example, the lattice or the three would contain the full range of possible values that can be created during the project's lifetime from the beginning phase to the period upon completion. After estimating all the possible values of the option at different points, the value of the project today is calculated backward starting from the value at completion of the project (Copeland & Tufano, 2004).

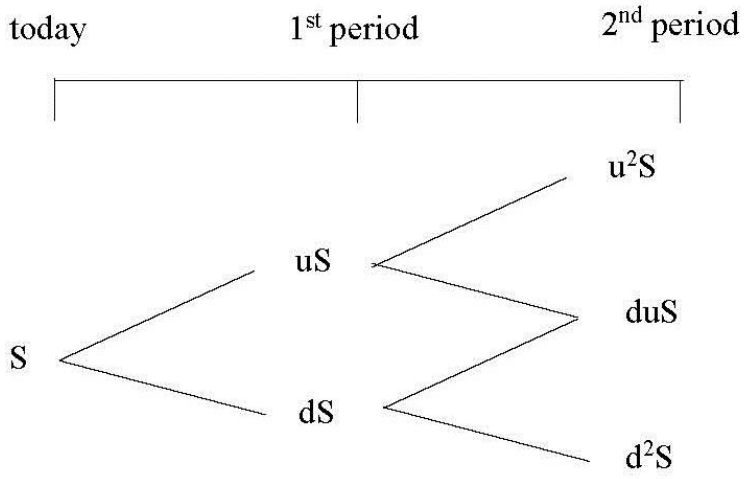


Figure 4. Binomial process for asset price with two periods remaining to maturity

2.3.2.1.2. Least squares Monte Carlo (LSM)

The main idea behind the Monte Carlo algorithm is by using repeated random sampling to approximate the probability of possible outcomes. The LSM algorithm, proposed by Longstaff and Schwartz (2001), aims to provide a path-wise approximation to the optimal stopping rule for *American options*, which gives its holder the right to exercise at multiple points in time. At each exercise point, the holder compares the immediate exercise value with the value from keeping the option alive. In the LSM approach, the conditional expected payoff from continuing to keep the option alive is estimated recursively from cross-sectional information. Thus, the algorithm can be defined as a hybrid approach that values American options by combining Monte Carlo simulation with least squares estimation of a conditional expected payoff function.

Following is a simple illustration of the algorithm as given in the Longstaff and Schwartz (2001). Assuming a complete probability space (Ω, $\mathcal{F}$, P) and finite time horizon [0, T], where the state space Ω is the set of all possible realizations of the stochastic economy between time 0 and T with w (sample path), $\mathcal{F}$ (sigma field of distinguishable events at time T), and P (probability measure defined on the elements of $\mathcal{F}$), the value of continuation for an American option that can only be exercised at K discrete times is as below:

$$F(w; t_k) = E_Q \left[\sum_{j=k+1}^{K} exp\left(- \int_{t_k}^{t_j} r(w, s)\, ds \right) C\left(w, t_j; t_k, T\right) \mid \mathcal{F}_{t_k} \right], \qquad (1)$$

In equation (1), $F(w; t_k)$ is the value of continuation at time t_k with k ε {1, K }equals to the expectation of the remaining cash flows $C\left(w, t_j; t_k, T\right)$ taken conditional on the information set $\mathcal{F}_{t_k}$ with respect to the risk-neutral pricing measure Q (an equivalent martingale measure for the economy) where $r(w, t)$ is the riskless discount rate. In this setting, the optimal stopping rule is to exercise the option as soon as the exercise value is greater or equal to the conditional expectation $F(w; t_k)$.

The LSM approach implements dynamic programming using least squares regressions to approximate expected conditional value of $C\left(w, t_j; t_k, T\right)$ at $t_{K-1}, t_{K-2}, \ldots, t_1$ on the current value of the state variables to estimate the optimal stopping time. The path of cash flows is defined recursively so the regressions are run recursively.

2.3.3. Benefits of Real Options Valuation Over Traditional Valuation Methods

Most of the studies on the profitability and the economic feasibility of energy storage systems use net present value (NPV) for analyzing the economic and financial viability of energy storage systems. Although it is the most commonly used approach, the deterministic discounted cash flow (DCF) analysis for evaluating energy storage projects does not consider the uncertainties arisen from electricity market liberalization and the investor's flexibility to deal with them.

- In deregulated electricity markets, the economic performance of the storage systems cannot be considered separate from the clearing market price of the market which causes the DCF approach to be insufficient to evaluate the market potential since it does not take operational flexibility into consideration.
- This disadvantage of the DCF approach is especially valid for large-scale investments like the energy supply sector.
- The increased uncertainty of the profits due to long project lifetimes, the irreversibility of the investments, and the opportunity to wait for more information make the NPV inadequate for energy sector investments.
- On the other hand, the **real options approach** is a powerful tool to reflect managerial flexibility in projects with high uncertainty.

2.3.4. The Use of Real Options Approach in the Energy Storage Systems Investment Literature: A Systematic Review

While energy storage has obvious benefits, it also has key challenges in terms of achieving cost (capital, operating, and financing expenditures), scale (energy capacity and duration), and effectiveness (round-trip efficiency and technology readiness level) (Davies et al., 2019). The deployment of ESSs will remain limited until they achieve an attractive IRR (Bradbury et al., 2014).

Most of the studies on the profitability and the economic feasibility of energy storage systems use NPV for analyzing the economic and financial viability of energy storage systems. Although it is the most commonly used approach, the deterministic DCF analysis for evaluating the energy storage projects does not consider the uncertainties arisen from electricity market liberalization and the investor's flexibility to deal with them. On the other hand, the real options approach is a powerful tool to reflect the managerial flexibility in projects with high uncertainty (Locatelli et al., 2016). In deregulated electricity markets, the economic performance of the storage systems cannot be considered separate from the clearing market price of the market which causes the DCF approach to be insufficient to evaluate the market potential since it does not take operational flexibility into consideration (Hu

et al., 2022). This disadvantage of the DCF approach is especially valid for large-scale investments like the energy supply sector. The increased uncertainty of the profits due to long project lifetimes, the irreversibility of the investments, and the opportunity to wait for more information make the NPV inadequate for energy sector investments. For such investments, the real options approach is a better choice (Kroniger & Madlener, 2014).

In this section, I reviewed a sub-set of real options literature that deals with the viability of ESS investments to understand the research focus, trends, and valuation models used. For identification of the relevant papers, the Scopus database and Google Scholar websites are used with the keywords "real options", "investment appraisal", "economic viability", and "energy storage systems". Screening of titles and abstracts resulted in 27 papers (as of July 2023). After screening the full text, one paper was excluded because its focus was not energy storage. Further screening process is carried out to exclude the papers on residential and microgrid energy storage applications. The delimitation process resulted in 18 eligible papers dealing with the economics of non-domestic ESS investments. Below is a summary of the systematic literature review for the selected sample of 18 papers regarding their main characteristics (Appendix A gives summaries for each paper).

Below is a systematic literature review for the selected sample of 18 papers regarding their main characteristics. I selected the following categories to review the chosen papers: (i) the research topic, (ii) publication year, (iii) geographical coverage, (iv) the type of energy storage, (v) the source of uncertainty, (vi) type of real options, and (vii) real options valuation model.

2.3.4.1. Research Topic

The literature on real options applications on energy storage can be divided into three groups according to their topics (i) determining the optimal investment decisions, (ii) valuation of renewables combined with storage, and (iii) policy and social welfare analysis:

***a. optimal investment decisions*:** Bakke et al. (2016) aims to value investments in lithium-ion battery banks and determine the optimal investment time under the conditions of uncertain revenue stream and investment cost using a real options framework. Kelly and Leahy (2020) also developed a real options model to find the optimal investment decisions. Both study shows that there is a "value of waiting" to observe capital costs before making an investment decision. Locatelli et al. (2016) assess the profitability of electric energy storage systems and provide monetary quantification of the investors' risks and flexibility during the decision-making process. The study concludes that due to the investment uncertainty, the real options approach evaluates the profitability of the project more positively compared to DCF.

Coronel et al. (2017) also illustrate that valuing the additional flexibility of the technology can make vanadium batteries more attractive compared to results from NPV analysis. In Hammann et al. (2017), the real options framework yields the same result as NPV analysis and shows that the Integrated Pumped Heat Energy Storage (I-PHES) applications are not profitable due to the high costs of the storage. Hu et al. (2022) find that current empirical battery wear cost from degradation prevents battery energy storage systems from being profitable for energy arbitrage in most of the European markets while they have a higher potential for frequency support services.

Muche (2009) shows that the NPV analysis, which does not consider the flexibility of power producers to change between different operation modes, leads to the misvaluation of investment. The real options approach, on the other hand, takes the future scope of actions into account and results in a risk-appropriate valuation of future cash flows. Lai and Locatelli (2021) introduces and tests an algorithm based on a real options approach to quantitatively assess the option to prototype in the energy sector and find that the cost of the prototype and the market size (number of identical systems to build) are the key parameters.

b. renewables combined with storage: Hedman and Sheblé (2006) analyzes whether energy storage can be an option for hedging against the uncertainty of wind power and compares it with a financial option. The study concludes that both hedging

method is financially competitive and future research is needed to determine if there is a preferred method.

Kroniger and Madlener (2014) studies the economic viability of hydrogen storage for wind power plants. The results show that a hydrogen storage plant with re-electrification is not economically viable. Schmitz et al. (2015) investigates the economic feasibility of kite-based wind energy power ships with Compressed Air Energy Storage (CAES) or hydrogen storage and shows that including a real option increases NPVs for all storage options analyzed.

c. policy and social welfare analysis*:* Reuter et al. (2012) compares the profitability of the wind technology combined with pumped storage with the standard wind farms and concludes that without substantial public subsidy, the wind technology combined with pumped storage is not profitable. Xiu and Li (2012) aims to evaluate the application of an electric energy storage system to improve wind power acceptance and finds that under the current cost level, li-on battery becomes profitable if social benefits are taken into account.

Li and Cao (2022) analyzes the optimal investment decision for Photovoltaic (PV)-ESS project considering the carbon emission trading market, auxiliary service market, and incentive policies. The study illustrates that incentive policies also can promote the development of photovoltaic-energy storage systems. Sun et al. (2023) establishes a sequential investment decision model considering policy, technological innovation, and market uncertainties. The study shows derives the flexibility value of sequential decisions more rigorously and quantifies the policy uncertainty as the frequency of policy adjustments and the magnitude of subsidy adjustment.

2.3.4.2. Publication Year

Figure 5 shows the yearly distribution for the paper sample illustrating that the application of the real options approach in energy storage investments is still scarce although there is an ongoing interest.

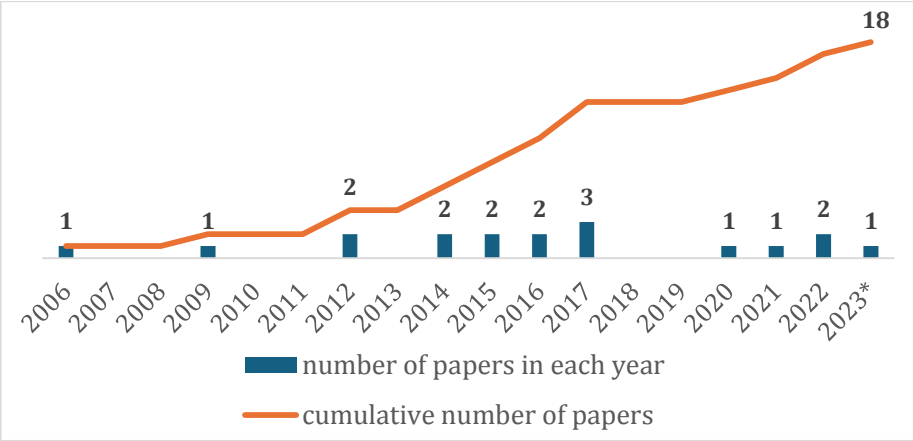


Figure 5. Annual scientific production (* as of July 2023)

2.3.4.3. Geographical Coverage

Country distribution in Figure 6 shows that most of the studies are on European countries with Germany and the United Kingdom being the most analyzed markets. Public data availability and decarbonization efforts of these countries can be accepted as the drivers behind this concentration (Lai & Locatelli, 2021). China is the third most analyzed country.

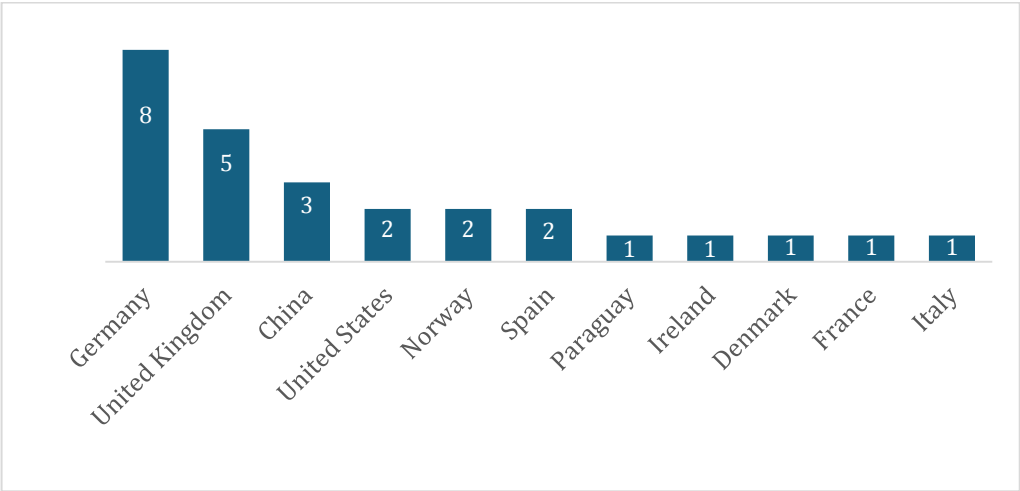


Figure 6. Number of papers by country

2.3.4.4. Type of ESS Analyzed

Regarding the energy storage type analyzed in the papers, the sample covers various types of energy storage. Among them, battery electric energy storage is the most

considered type of storage with six papers out of 18, which is followed by pumped hydro storage with four papers and compressed air energy storage with three papers as shown in Figure 7.

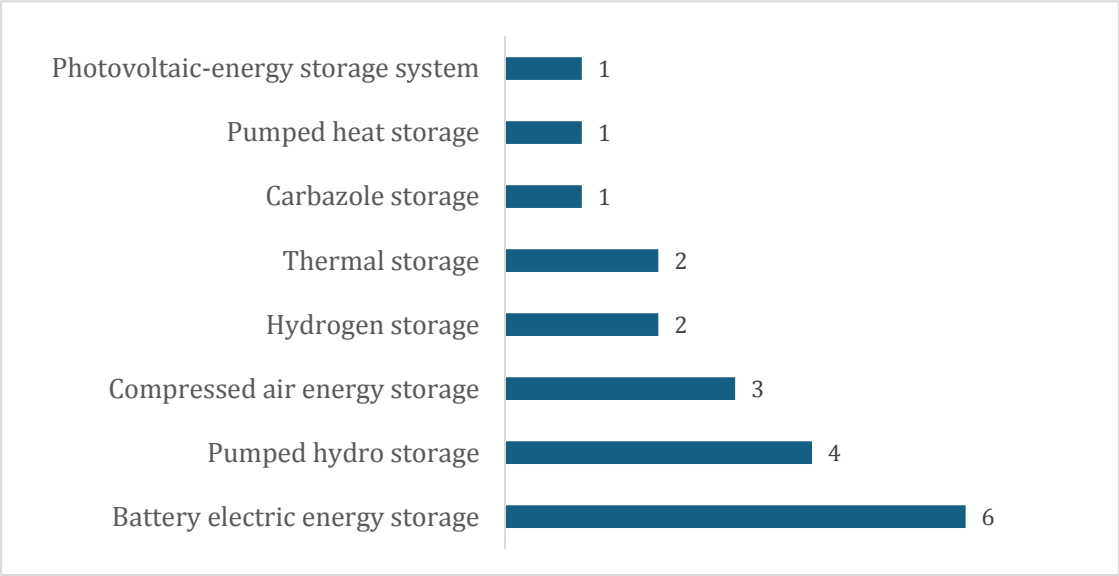


Figure 7. Number of papers by type of energy storage

2.3.4.5. Source of Uncertainty

As explained in the above discussion, the real options approach is more valuable for cases where there is uncertainty and managerial flexibility. The uncertainty in storage investments can stem from market conditions such as volatility of power prices in a deregulated market (economic uncertainties), characteristics of the storage such as uncertainty in future capital cost and efficiency level due to technical improvements (technological/innovation related uncertainties), policy-related issues such as frequency of regulation adjustments (regulatory uncertainties), or the characteristics of the power to be stored such as the fluctuations in wind speed (power source related uncertainties). Figure 8 presents the source of uncertainties that are analyzed in the paper sample. Economic and technological advances-related uncertainties are the leading categories in the sample. More specifically, fluctuations in power prices and uncertainty in the future cost of energy storage are the most considered source of the uncertainties with 12 and six papers, respectively. Intermittency of the renewables is the third most regarded source of uncertainty with three papers followed by policy and technological innovation-related uncertainties.

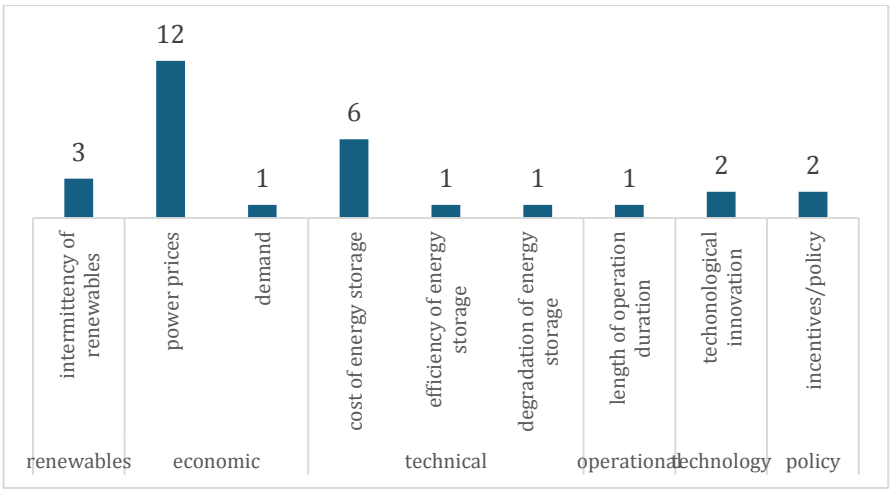


Figure 8. Number of papers by source of uncertainty

2.3.4.6. Real Options Type

Figure 9 below shows the real options types used to model managerial flexibility in the paper sample. The sample covers all six types of real options defined in the literature. Note that it is possible to consider more than one flexibility in one study by designing multiple options as is the case with five papers in the sample (see Table A.1). Figure 9 shows that the most common type of real options is the "option to defer/wait". It is used in nine out of 18 papers that stress the importance of management's flexibility to wait to invest for additional information in an uncertain environment. "Option to invest/build" is the second most used type with five papers. "Option to switch" is also a popular type which is used to represent management's ability to change the operational decisions based on the additional information. The least used option type is "option to prototype", it appears only in one paper.

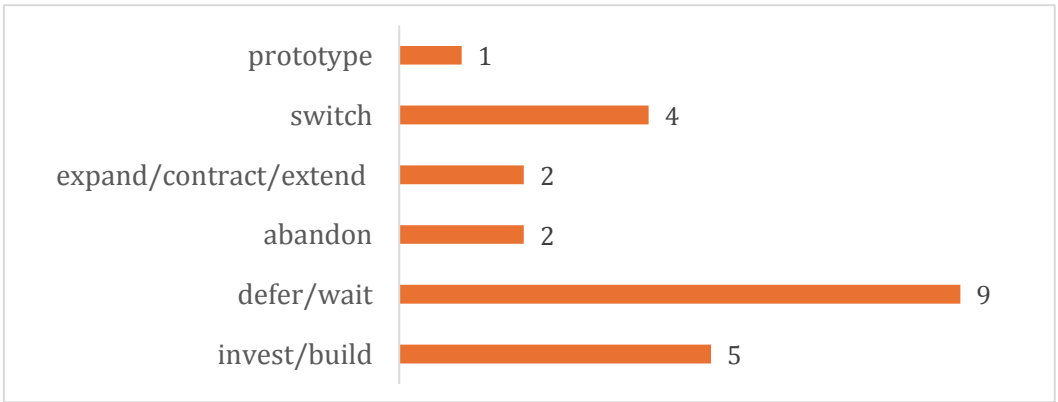


Figure 9. Number of papers by real options type

2.3.4.7. Valuation Model

The valuation models used in the papers are presented in Figure 10 It can be seen that numerical models outweigh the literature. Only one paper solves an analytical model while 14 papers use numerical models. Out of those 14 papers, eight papers use simulation-based models, five papers use dynamic programming, and one paper uses the differential equation method. Three papers classified as “other” use either a different numerical model that we could not classify or their solution method is not given explicitly.

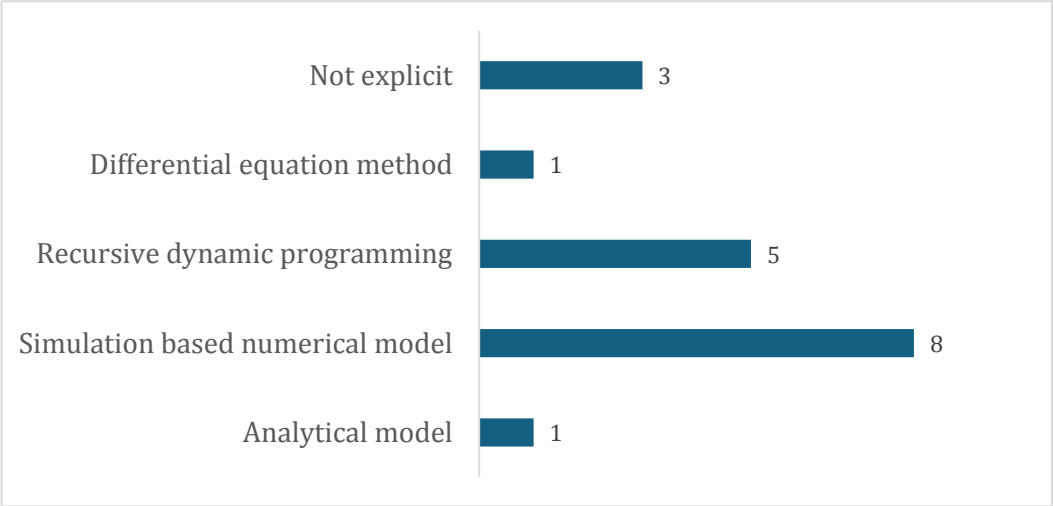


Figure 10. Number of papers by real options valuation models

CHAPTER 3

METHODS AND DATA

3.1. Introduction

This chapter aims to explain the data collection and analysis methods of this study. In this chapter, firstly the problem formulation process is explained. Then the research questions, objectives, and the foundations of the research process to answer the research questions are described. The research method used in this dissertation is a mixed method combining qualitative and quantitative methods.

In the first section, the preliminary analysis and the problem formulation process are explained. Then the foundations of the research method and the reasons to choose a mixed methodology are discussed. In this section, I also discuss how the two parts feed each other to answer the research questions. The following two sections describe the research process in qualitative and quantitative parts in detail. The stakeholder identification, design of the interview guide, and the procedures used to analyze data are presented for the qualitative part, while the model characteristics are given for the quantitative part.

3.2. Preliminary Analysis and Problem Formulation

3.2.1. Preliminary Analysis

A preliminary study is carried out to answer the question of "What should be the focus of the analysis for the economics of energy storage in Türkiye based on the current situation?." I used the preliminary analysis to narrow down the research question and specify the research method.

To this aim, I started the preliminary analysis with desk research using documentary data to reveal the current trends regarding energy storage in Türkiye.

For the documentary analysis, the foundation documents were "Turkey 2021 Energy Policy Review" by the International Energy Agency and "Turkey's Decarbonization Pathway Net Zero In 2050" by the Istanbul Policy Center. Both analyses suggested that with the increased share of renewables in the electricity sector, the ESSs will become more important for Türkiye to ensure flexibility in energy generation and transmission.

The second cluster of the documentary data was the legal framework documents about energy storage. Regulation on Storage Activities in the Electricity Market ("Storage Regulation"), which can be seen as a first step for a regulatory framework, is published by the EMRA in the Official Gazette dated May 9th, 2021. Prior to the announcement of legislation, Mustafa Yılmaz, head of EMRA, told Anadolu Agency that "… *regulations will enable investors to build electricity storage facilities to accommodate more power from intermittent renewable energy sources*". Together with the Storage Regulation, EMRA also announced various amendments to the other related regulations to add electricity storage in relevant legislations, including the Electricity Market Licensing Regulation, Electricity Market Balancing and Settlement Regulation, Electricity Market Grid Regulation, Electricity Market Connection and System Usage Regulation, and Regulation on Certification and Support of the Renewable Energy Resources. Through these legislations, EMRA provided clarity and guidance regarding the procedures and principles for investors which can be seen as an incentive policy that aims to promote the deployment of the electricity storage.

As an additional data source, I scanned the media covering the energy storage news to keep track of the latest sectoral developments. The media news showed that starting from 2021, there are new BESS investments in Türkiye undertaken by both national and multi-national private companies reflecting the interest of the private sector. I also used publicly available interviews of the top managers of the ESS companies to compile expert views on the subject. These interviews were selected by

purposeful sampling. The selection criterion was to select the experts from the companies that have recent storage investments. To this end, I utilized the video recordings and media articles based on the interviews given by the managers of the two companies which are Aggreko Microgrid Co. and Storage Solutions Co. and Inovat Co.. There were three relevant interviews from the years of 2019, 2021, and 2022[2]. The data collected from those interviews further added to the feedback obtained from the legal documents and official reports by revealing that (i) for increasing the level of penetration of renewables, ESSs are needed to smooth the generation profile of variable solar PV and wind generation, and (ii) although the installed storage capacity is low compared for a big industrial country, energy storage solutions in Türkiye is quite feasible because of the low cost, but also because of high-quality production and high-quality engineering, (iii) the current storage deployment projects can serve as use cases for other potential users, and (iv) the changes in the legislative environment (the rules announced by EMRA in 2021) are expected to speed up the markets pretty fast by which instead of investing itself, government is transferring the role to invest in ESSs to the private companies.

From the preliminary study it has been seen that given the target of increasing the penetration of variable renewable energy sources, it is important for Türkiye to facilitate the deployment of the ESSs as a flexibility option. It can be expected that with the growing renewable capacity, the need for new energy storage investments will emerge. Parallel to that need, the regulatory body is announcing new legislation to provide clarity and guidance regarding the procedures and principles for storage deployment and thus to facilitate investments in energy storage. From the expert opinions and statements of the officials, it is inferred that the regulatory changes can be accepted as an incentive to enable ESS investments. Expert opinions also reveal that the market participants expect the market to grow and they also think that the level of deployment is low compared to size of the country suggesting the existence of prospects for ESS investments. Building upon these findings, the focus of the study is chosen as the *economics of investment decisions in energy storage in Türkiye*.

[2] The views are collected from interviews conducted by Energy-Storage.news with Can Tokcan- managing partner at Turkish energy storage EPC Inovat in 2022 and with Karim Wazni - managing director of Aggreko Microgrid and Storage Solutions in 2019 and 2021.

3.2.2. Problem Formation

ESSs absorb and then release power so it can be generated one time and used at another. These systems allow the time of energy production and consumption to be differentiated. Thus, they can be used for various purposes, such as balancing supply and demand in the market, providing backup for possible energy outages, and ensuring network security. Thanks to these systems, it is possible to store it when the supply is greater than the demand and use it quickly when the supply is not sufficient. ESSs also support the widespread use of renewable resources like wind, solar, hydroelectric, etc, in energy production by increasing the predictability of the supply.

While energy storage has obvious benefits, key challenges affect the widespread deployment of these systems. These challenges could be economic (in terms of achieving cost), technological (in terms of scale and effectiveness), infrastructural, legislative, and firm/sector-specific.

The core objective of this thesis is to assess the economic potential of the ESSs from the perspective of key stakeholders while unfolding the factors affecting the economic value, investment appraisal, and broad deployment of these systems. The following questions are formulated to help understand the economic value of storage:

RQ1. What are the opportunities and barriers for deployment of ESSs in Türkiye?

RQ2. What are the factors and sources of uncertainties affecting ESS investment decisions, and how do the investors evaluate ESS investments?

RQ3. What is the optimal investment strategy under the conditions of uncertain future revenues and investment costs?

3.3. Research Strategy: Mixed Method

Türkiye has a target of increasing the penetration of renewables in electricity production. According to the National Energy Plan (NEP) 2022 (Ministry of Energy and Natural Resources, 2023), the share of renewable energy sources in electricity

installed capacity is expected to increase from 52% in 2020 to 64.7% in 2035. Due to the intermittent nature of renewables, however, the need for flexibility is going to grow with the increase in the share of renewables. In the NEP 2022, it is expected that the battery capacity will increase with the increased share of renewables (Ministry of Energy and Natural Resources, 2023). Parallel with the NEP 2022 targets, the regulatory authority announced new legislation together with issuing amendments to existing ones in order to facilitate private investments in energy storage and ensure flexibility.

Although there is a growing interest in the deployment of energy storage, the installed capacity is not still high in the country. This dissertation aims to investigate the economics of the ESS investments. Literature review shows that there are various potential reasons for the lack of investment in ESSs including the high investment costs, regulatory and market-related barriers, and uncertainty. These factors might be the reasons for investors to postpone the investment decision to wait for more favorable environments.

The real options approach, which considers the flexibilities held by the investors when there are uncertainties, is chosen as the model framework for the study. Unlike the other real options models applied in the literature, I did not use apriori or theory-led assumptions but built my modeling framework upon the data compiled through a qualitative study. Thus, this study uses an approach that integrates qualitative and quantitative methods to evaluate the investment appraisal of energy storage technologies. The deployment of energy storage is in its early face in Türkiye and, as all other investments, storage investments result from the active decisions of the key actors in the area. At this stage, communicating with key stakeholders and decision-makers is important to determining a model framework that fits the current situation in Türkiye. Built on this background, a mixed-method approach combining qualitative and quantitative research methods is chosen to answer the research questions.

In this approach, qualitative and quantitative analysis parts feed each other: The research question of "*What is the optimal investment strategy*?" to be answered in the

quantitative part defines the scope of the qualitative analysis. More specifically, this research question gave rise to the research questions of "*What are the barriers and enablers for the deployment of ESSs in Türkiye*?" and "*What are the factors and sources of uncertainties affecting ESS investment decisions, and how do the investors evaluate ESS investments*?". Thus, the design of the interview guide and the selection of interviewees were done based on the data needs of the quantitative model. To specify the model characteristics in the quantitative analysis, the data collected in the qualitative analysis is used as input. Firstly, qualitative data is used to confirm the theory-led and/or reveal country-specific sources of **uncertainty** (specifying model assumptions) and the **type of flexibilities** that the decision-makers have (deciding the real options type) when appraising energy storage investments. Secondly, the research question in the quantitative part is refined to reflect the real-life decision problem of the investor in Türkiye by using the data collected in the early phase of the qualitative study.

The dissertation contains two intertwined parts as represented in Figure 11 below:

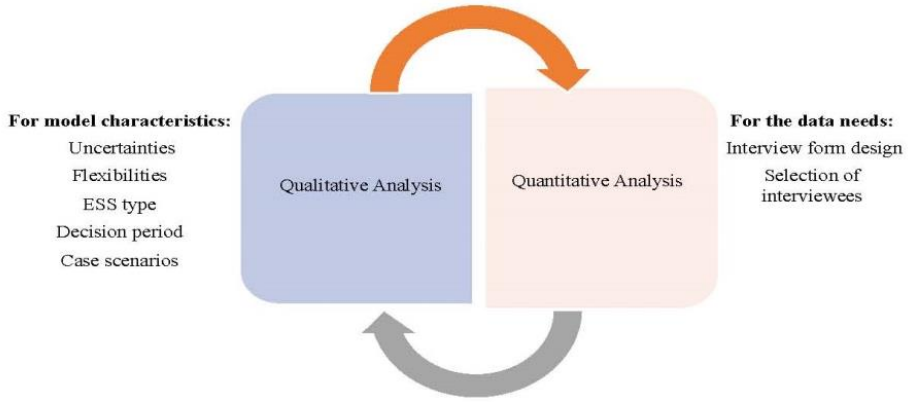


Figure 11. Building blocks of research methods in the dissertation

3.4. Qualitative Research

The qualitative part of the thesis will provide an overview of the perspectives on how energy storage investment decisions are taken and will help to answer *"RQ1. What are the enablers and barriers for deployment of ESSs in Türkiye?"* and *"RQ2. What are the factors and source of uncertainties affecting ESS investment decisions, and how do the investors evaluate ESS investments?"*.

In this section, I explain the research organization for the qualitative study. I began by introducing the research process. In the second sub-section, I discuss the research strategy and explain the data generation process. The next sub-section describes the interview guide design and presents the question group. In the last sub-section, the data analysis methods are given.

3.4.1. Research Process

The research process has four main stages which are literature study, empirical study, research analysis, and discussion and conclusion. The outline of the research process is given in Figure 12 below.

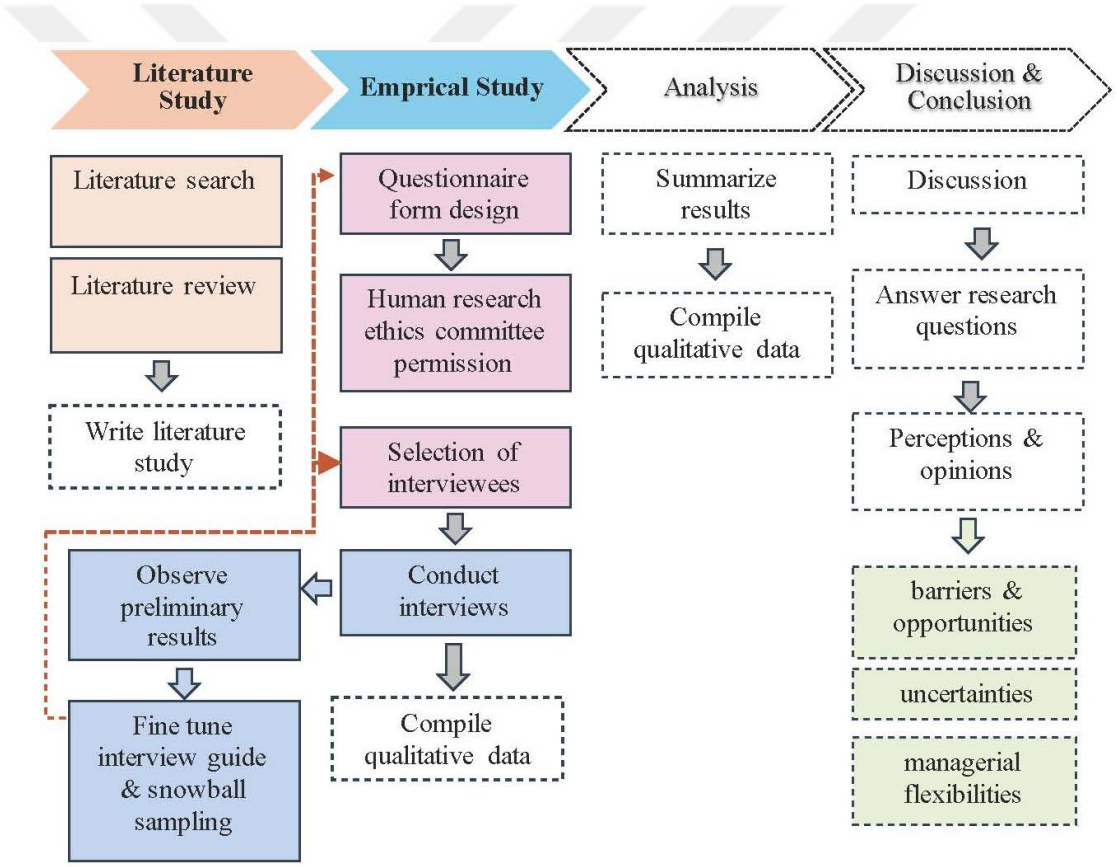


Figure 12. Outline of qualitative research process

The research process covers the following steps:

- **Literature Study**: A literature study on the economics of energy storage is carried out to design the questionnaire guide and specify the characteristics of the target sample.

- **Empirical Study:**
    - An interview guide is designed building on the studies reviewed in the literature study.
    - Human research ethics committee permission processes are completed (as of August 2023) (Appedix B).
    - A sampling strategy which is a combination of purposeful sampling and snowball sampling is followed.
    - All the participants received a personally addressed e-mail with a cover text with the questionnaire attached requesting participation in this study via an online interview. The e-mails were started to be sent in the first half of December 2023.
    - Preliminary results are obtained and the questionnaire guide is refined with the feedback from the first four interviewees.
- **Analysis:** The analytical framework approach is used to describe the data. In the analytical framework, the responses to the questions are organized question-by-question to describe the raw data.
- **Discussion & Conclusion:** The data compiled in the qualitative part uncovers the perceptions regarding the enablers and barriers for ESS deployment and uncertainties and expectations that drive energy storage investments. In addition to generating data to answer the RQ1 and RQ2, the qualitative study provides data for the quantitative study by using the feedback of the key actors.

3.4.2. Research Strategy and Data Generation Process

3.4.2.1. Why Qualitative Approach?

Storage investments result from the active decisions of the key actors in the area. The value they grant to investment is determined by their expectations for future revenues and costs, perception of risks and challenges, and predictions for changes in the regulatory environment which depend on their sector of activity, expertise, and subjective representations. Based on this starting point, the focus of the qualitative part of the thesis is to understand the perceptions of the key actors regarding the issues in the ESS area that might shape their investment decisions.

The research method for this study is based on the researchers' current knowledge and perception of reality. The focus of the study is to compile stakeholders` opinions on the further deployment of investment decisions for ESSs. Thus, primary data sources are the perspectives, expertise, approaches, and statements of professionals, academicians, non-profits, and think-tank organizations in the energy sector regarding the use, further deployment, and financing of ESSs. The qualitative data enabling such information can be collected via the interview method as stated in Patton (2002): "Open-ended questions yield in-depth responses about people's experiences, perceptions, opinions, feelings, and knowledge". For this purpose, the study uses semi-structured interviews to collect data. This interview method is helpful because it enables us to put all these experiences, perspectives and approaches into their cultural and social context and allows us to see the whole picture through the eyes of critical actors. In addition, this interview method is the most appropriate method among the four types of interviewing strategies suggested by Silverman (2006), which are structured interviews, semi-structured interviews, open-ended interviews and focus group study, for the study to reach the target audience.

Thus, in my field research, semi-structured interviews allow me to examine the topic in detail and from the eyes of experts. The process for gathering the perceptions of stakeholders in this study consisted of conducting semi-structured interviews with the key stakeholders in the energy sector. The analysis aims to explore the opinions of the key actors on drivers and barriers to the deployment of energy storage, risks and uncertainties of energy storage, as well as the current issues affecting the economics of energy storage investments.

3.4.2.2. Data Generation Process

The data generation process aims to, from the viewpoint of stakeholders working directly or indirectly in the field of energy storage;

(1) gain insights into barriers/challenges and drivers for the deployment of energy storage,
(2) investigate the factors driving energy storage investments,

(3) identify the uncertainties regarding energy storage investments and expectations,
(4) collect data on the capital budgeting practices of the energy sector companies, focusing on real options analysis.

Data collection is carried out by conducting semi-structured interviews with the key stakeholders in energy storage investments in Türkiye. In this way, stakeholder opinions are compiled regarding the factors and uncertainties affecting or supporting/limiting the ESS investments. Furthermore, the study collects data on the capital budgeting practices of the energy sector companies, focusing on their familiarity with real options analysis.

The fundamental research motivation of the qualitative study is to *find out the factors affecting ESS investments and help determine the appropriate model framework for the quantitative study*. The results of the data analysis are used to answer RQ1 and RQ2. In addition, the data is used to design the model framework in the quantitative study to (i) validate or enhance the theory-led assumptions based on the stakeholders' expectations for the future and perceptions regarding uncertainties, (ii) specify the real options type based on the flexibilities used by the investors, (iii) to choose the ESS type for optimal dispatch, (iv) to determine the decision period (time period in which model will be solved), and (v) to specify the scenarios for the sensitivity analysis (case studies).

3.4.3. Interview Guide

The design of the interview guide aims to explore different views and perspectives of the stakeholders on the same subject of the economic viability of ESS investments. To this end, a flexible interview guide is designed in which the wording of the questions could be modified while the principal meaning is preserved.

The resulting interview guide has five sections: (i) Introduction/warm-up, (ii) general descriptive assessment, (iii) drivers and barriers, (iv) uncertainties and expectations, and (v) investment decision and capital budgeting processes. There are 27 open-

ended and multiple-choice questions. I used the "Market and Policy Barriers to Energy Storage Deployment"(U.S. Department of Energy, Energy Storage Technology and Systems Department, n.d.), "The Use of Real Options Theory in Scandinavia's Largest Companies ", and "Management Views on Real Options in Capital Budgeting" (Baker et al., 2011) studies in the literature as a starting point to design the interview guide. To cover timely issues in the interview guide, I utilized current discussions on the subject. The guide is finalized after the first four interviews based on the feedback of the interviewees. The final interview guide in Turkish is given in Appendix C.

Introduction/warm-up section: This section aims to provide information that can be used to identify the group of stakeholders. This section starts with the questions about the respondents' background, including their education and expertise. Further, they are asked whether they hold a Master of Business Administration (MBA) or not to assess their answers regarding capital budgeting practices. Then the section asks the actor's area of the activity to identify which stakeholder group the interviewee belongs to. If the interviewee classifies his/her organization as a (potential) ESS user, producer, designer, or developer, then he/she is classified as a "beneficiary", while others are classified as "secondary stakeholders". The beneficiaries are further asked about the type of ESS they are involved in and whether they plan to invest in ESSs.

Second section (general descriptive assessment): This section aims to observe the stakeholder's views on the ESSs' role and explore whether it differs among and/or within the stakeholder groups and whether they coincide with the theory. To this end, this section starts with an open-ended question asking to assess the role of the ESSs in the energy sector. Then the interviewees are asked to order the potential use areas of the ESSs based on their significance.

Third section (drivers and barriers): ESSs can provide numerous benefits to the grid services that drive the ESS investments such as security, flexibility, and time shifting as well as cost reduction and furthering integration of renewables. There are also several factors (barriers) that restrict their further deployment. This section asks respondents to define the benefits (drivers) that support and barriers which restrict

the extensive deployment of storage systems from a multiple-choice list. These questions are followed by two open-ended questions asking them to discuss how these barriers could be removed and how the ESSs would develop if the barriers were removed.

Fourth section (uncertainties and expectations): Investors might face economic uncertainties such as volatility of power prices in a deregulated market (economic uncertainties), technological/innovation-related uncertainties stemming from characteristics of the storage such as uncertainty in future capital cost and efficiency level due to technical improvements, regulatory uncertainties arising from policy related issues such as frequency of regulation adjustments, or power source related uncertainties due to the characteristics of the power to be stored such as the fluctuations in wind speed. This section aims to collect data on the stakeholders' perceptions regarding the uncertainties that the investors might face. Then the interviewees are asked to elaborate on their expectations for future developments in the ESS area.

Fifth section (investment decision & capital budgeting processes): The first part of this section aims to reveal the factors considered when an investment decision is appraised, and the capital budgeting techniques used in this appraisal process. The second part of the section asks questions to observe the familiarity of the interviewees with the real options approach.

3.4.4. Data Sources and Data Collection: Stakeholder Approach and Interviewee Selection Criteria

The data is collected by the qualitative data generation method of semi-structured interviews. The sources are the stakeholders of the ESS investment decisions in Türkiye. This section gives the details of the interviewee selection criteria, the profile of the interviewees, and the sampling strategy.

The aim of the qualitative study is to explore and understand the factors affecting ESS investment decisions and formulate an appropriate model framework for an investor. Stakeholder analysis enables the researcher to develop an understanding of

how the decisions are taken in a particular subject (Brugha et al., 2000). The stakeholder approach is applied to identify targeted groups. The targeted interviewees are selected from the group of actors (i) involved in the energy sector with a focus on storage energy technologies and implications, (ii) engaged in activities related to ESSs, (iii) who are potential or current users of ESSs, (iv) member of energy storage-related associations, (v) researchers in the field of storage systems.

3.4.4.1. Stakeholder Identification

A stakeholder analysis starts with the identification of the stakeholders and the definition of stakeholder is adjusted for each specific research question (Ansorena et al., 2024). For this study, the stakeholder is defined as the "*actors who have interest and who are directly or indirectly affected by and/or has an effect on the further deployment and investment decisions of ESSs in Türkiye*". The time focus of the analysis is the *present* and the *future* of ESS in Türkiye.

Figure 13 illustrates the BESS eco-system. In this eco-system investors/users represent the demand side while the supply side provides goods and services. Due to the legislation, there are four types of facilities on the demand side which are independent facilities, consumption facilities, power plants, and grid operators. The supply side on the other hand covers both production and service-providing components. The producers and service providers are classified based on their functions in the production process of the BESS as represented in Figure 14 Regarding the investment decisions, demand and supply form the "Beneficiaries" which represent the group of actors that are directly taking investment decisions and the group of actors that are supplying the goods and services to meet the demand. The second group of actors interacts with the beneficiaries either in terms of consulting services or producing and increasing knowledge (academia), providing platforms to discuss the issues (non-profits such as think tanks and associations), or distributing the news on the latest developments (digital platforms). The government and regulator group affects the investment decisions of the investor by taking policy actions, determining the legal framework, and publishing regulations.

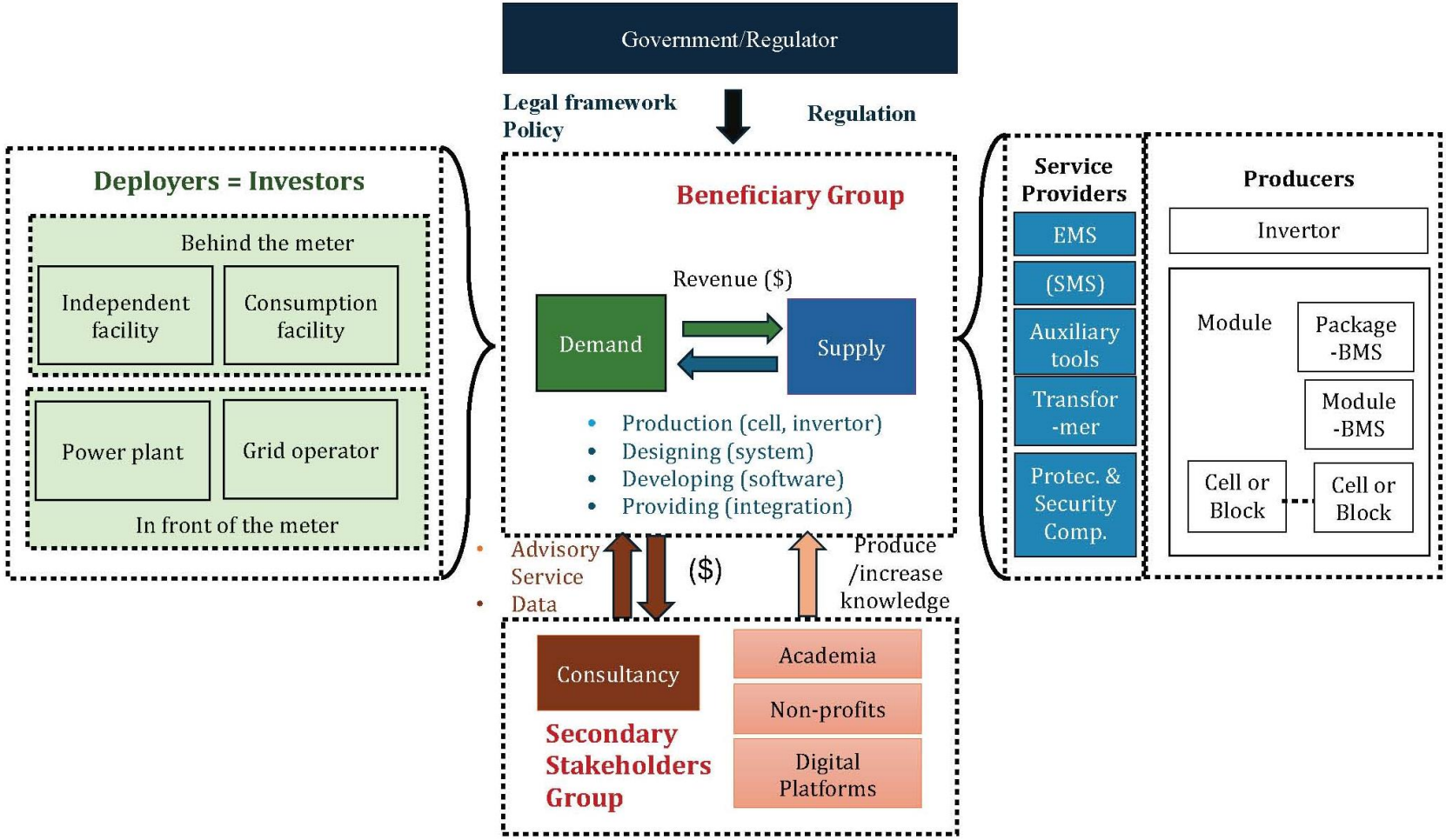


Figure 13. BESS eco-system: Stakeholders (EMS: Energy management systems, SMS: Storage management systems)

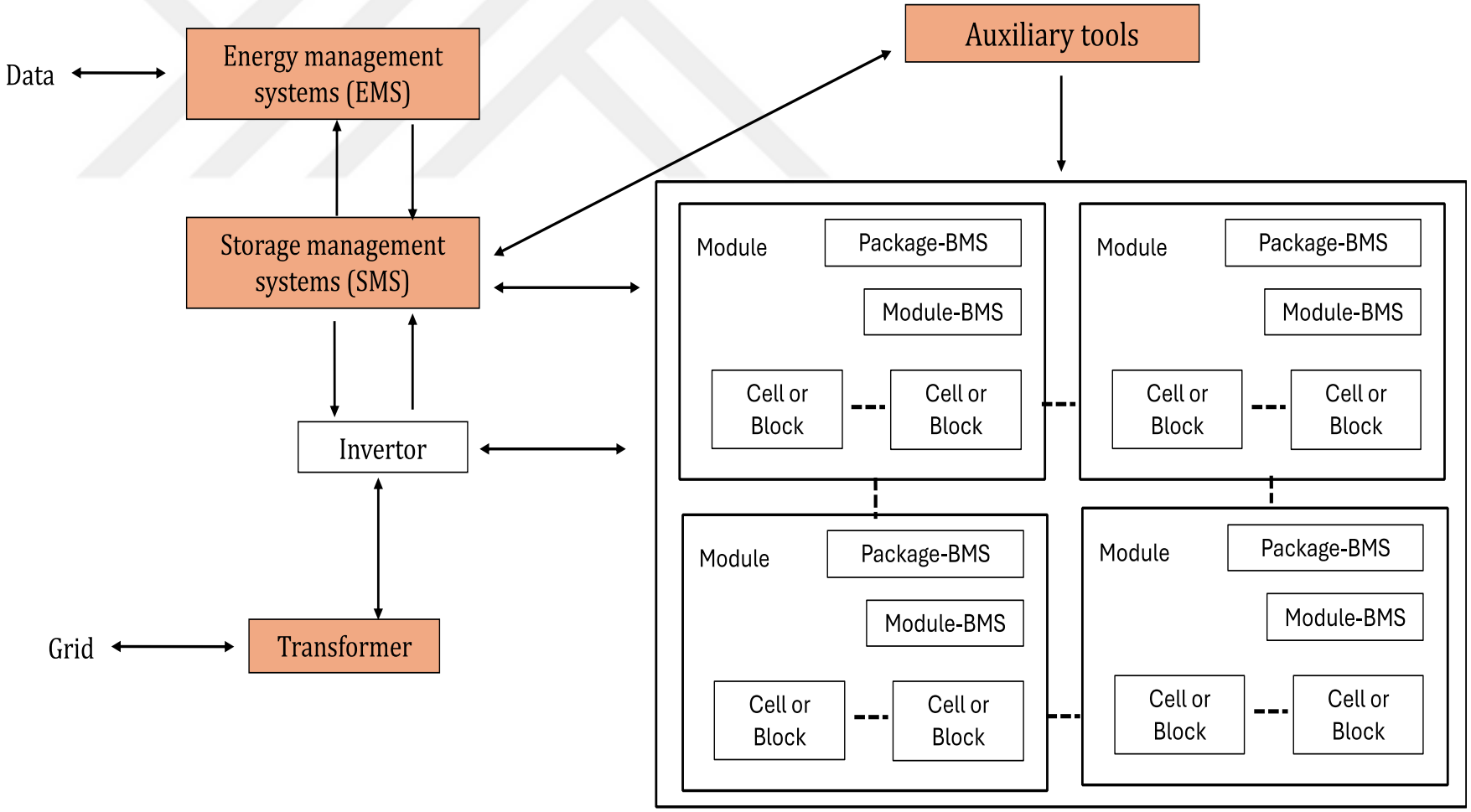


Figure 14. Working principle of cell-based BESSs (adapted from SHURA (2024))

In the sampling process, the starting point was to identify the actors who are actively involved in the discussions on the barriers and enablers/opportunities regarding the further deployment of ESSs in Türkiye through delivering presentations in seminars or conferences, publishing academic papers or review notes in journals as well as the professionals from the companies making ESS investments.

All the participants received a personally addressed e-mail via LinkedIn or company accounts with a cover text explaining the scope of the study with the questionnaire and human research ethics committee permission attached. Except for one all the interviews are conducted online and recorded. The questions on capital budgeting are directed to a senior financial officer in the company whenever the respondent does not possess adequate knowledge about the investment decision process of the organization.

3.4.4.2. Sampling Strategy

The stakeholder identification in this study was carried out using a sampling strategy that is a combination of purposeful sampling and snowball sampling following the steps below:

Step 1. An initial list of interviewees was selected using a purposeful sampling strategy from the experts who have recent public appearances (by making presentation in a seminar on ESSs or publishing ESS-related studies) and who are members of the energy storage-related associations. The initial list included 21 different stakeholders representing the actors involved in the energy sector with a focus on storage energy technologies and implications, activities related to ESSs, who are potential or current users of ESSs, who are members of energy storage-related associations, and researchers in the field of storage systems.

Step 2. Purposeful sampling strategy is also used to enlarge the initial list. For this aim, during the interview period, additional experts were identified from scanning the agendas of the conferences and seminars that were organized after the initial list was formed.

Step 3. Other potential stakeholders were identified based on the referrals of the interviewees, which is a technique called "snowball sampling". Step 2 and Step 3 increased the number of identified stakeholders from 21 to 104.

The data generation process started in December 2023 and ended in May 2024. Online interview lengths change between 11 minutes to 111 minutes. In addition to these interviews, I held in-depth technical meetings with three key experts. One of them was in the form of a follow-up meeting after the interview. The remaining two meetings were in the form of extended interviews in which in addition to the questions in the interview guide, I asked technical questions to better understand the concepts and define the scope of the study from the experts' perspective.

3.4.4.3. Interviewee Profile

The interviewees represent various types of organizations that are actively participating in the area of ESSs. During the field research, we conducted 24 interviews with 25 interviewees from 23 organizations representing beneficiary and other stakeholder groups. 16 of the organizations belong to the beneficiary group while 7 of them belong to the secondary stakeholders group. The classification was made based on the responses to the questions of the first section of the interview guide on the area of activity.

Beneficiary stakeholder groups include the "investors" and "suppliers" sub-groups. The investors sub-group represents the users and thus the demand side of the ESS market. This group covers the organizations that use grid-scale ESSs, hold pre-licenses for renewable power plants integrated with BESS, and operate in the electrical vehicle area. The suppliers, on the other hand, include producers (e.g. producing cells, inverters, etc.) and engineering firms (service providers) that provide technical and software solutions for the users to enable them to deploy these systems smoothly. The service providers category covers the organizations defining themselves as ESS designer, ESS developer, and ESS providers. The services they provide for their customers include developing battery and energy management

systems, system integration, mechanical and electronic system design, software development, optimization, and technical consultations.

The sample covers organizations that are both producing ESSs/providing ESS-related services to their customers and at the same time deploying these systems for their businesses. In those cases, the identification of the stakeholder group is done based on the relative importance of the activities for that specific company. The selection criterion was whether the organization operates (or holds a pre-license) grid/power plant (classified as investor) or uses the storage for their own energy needs (classified as supplier).

Secondary stakeholders are sub-grouped as "consultants" and "researchers". The organizations providing advisory services to both investors and suppliers for the actualization of projects but not engaging in ESS development and deployment phases are classified as "consultants". On the other hand, the organizations that engage in activities to increase the knowledge in the area of ESSs through research or organizing events and creating content are classified as "researchers". The selection criterion for sub-grouping is whether the organization provides advisory services for a fee or not.

Characteristics of the Interviewees in the Sample: Interviewees were mostly top managers or founders of the organization they represent. Seven out of 25 interviewees were founders, co-founders, or the board members of the organization, 13 of them were department heads, managers, or directors while the remaining interviewees held senior positions in their companies. The sample also covers one professor from academia.

The sample is dominated by engineers with 22 of them holding an engineering degree while two interviewees have a degree in social sciences. Among the engineers, seven of them hold a degree in electrical and electronic engineering, eight of them hold a degree in energy or power management programs, and two of them hold mechanical engineering degrees. The remaining holds degrees from various

engineering branches including construction engineering, soil mechanics, and aircraft and aerospace engineering.

3.4.5. Analyzing the Qualitative Data

In this dissertation analytical framework approach is used to describe the data. In the analytical framework, the responses to the questions are organized question-by-question to describe the raw data (Topal, 2016). The interview responses are analyzed using MAXQDA which is a qualitative data analysis software.

In the data generation process, semi-structured interviews were conducted with an interview guide. In the qualitative analysis section, the reporting of the raw data was based on the sections of the interview guide and the questions asked under these sections. Therefore, sections and sub-sections of the interview guide were used as the categories to represent the raw data. The responses were reported under the four stakeholder sub-groups which are investors, suppliers, consultants, and researchers to reflect the differences or similarities in the views of different stakeholders.

The first section in the interview guide was an introduction/warm-up section to collect data to identify the group of stakeholders. This section starts with the questions about the respondents' background, including their education and expertise followed by the questions on the organization's area of the activity. If the interviewee classifies his/her organization as a (potential) ESS investor, producer, designer, or developer, then he/she is classified as a "beneficiary", while others are classified as a "secondary stakeholder".

The general descriptive assessment section aims to observe the stakeholder's views on the ESSs' role and explore whether it differs among and/or within the stakeholder groups and whether they coincide with the theory. To this end, this section starts with an open-ended question asking to assess the role of the ESSs in the energy sector. Then the interviewees are asked to order the potential use areas of the ESSs based on their significance.

The third section, which is on the drivers and barriers**,** asks interviewees to define the benefits (drivers) which support and barriers that restrict the extensive deployment of storage systems from a multiple-choice list. These questions are followed by two open-ended questions asking them to discuss how these barriers could be removed and how the ESSs would develop if the barriers were removed.

The following section is on uncertainties and expectations including economic uncertainties, technological/innovation-related uncertainties, regulatory uncertainties, and power source-related uncertainties due to the characteristics of the power to be stored such as the fluctuations in wind speed. This section aims to collect data on the stakeholders' perceptions regarding the uncertainties that the investors might face. Then the interviewees are asked to elaborate on their expectations for future developments in the ESS area.

The last section is on investment decisions and capital budgeting processes. The first part of this section aims to reveal the factors considered when an investment decision is appraised, and capital budgeting techniques used in this appraisal process. The second part of the section asks questions to observe the familiarity of the interviewees with the real options approach.

3.5. Quantitative Research

The main driver behind the interest for the BESS in Türkiye is the latest amendment of November 2022. With the new legislation, firms licensed to establish an electrical storage facility on their site are permitted to build and operate a wind power plant (minimum 20 MW) or a solar power plant (minimum 10 MW, maximum 250 MW) with a capacity matching that of the storage facility under the scope of YEKDEM (PwC Turkiye, 2023). This legislation can be seen as an incentive policy that aims to promote the extensive deployment of electricity storage.

Following the legislation, the EMRA started to grant pre-licenses for electricity storage facilities that are integrated into renewable power plants with a total capacity of almost nearly 300 GW (PwC Turkiye, 2023). The qualitative part of this

dissertation also shows that all of the organizations classified as investors hold pre-licenses for BESS integrated into a power plant. Building upon this background, the quantitative research will help to answer "*RQ3. What is the optimal investment strategy for a pre-license holder under conditions of uncertain future revenues and investment cost*?".

3.5.1. Objective of the Study

The study aims to develop a model to analyze the economic viability of BESSs integrated into renewable power plant investments and determine the optimal decision under the conditions of uncertainty in future revenues and investment costs. In this model, the value of the investment will be assessed by taking into account the value of the flexibilities the investor holds as a real option.

3.5.2. Methodology

A real options model will be developed to analyze the investment appraisal of BESSs. Most of the studies on the profitability and the economic feasibility of energy storage systems use the NPV for analyzing the economic and financial viability of energy storage systems. Although it is the most commonly used approach, the deterministic DCF analysis for evaluating the energy storage projects does not consider the uncertainties arisen from electricity market liberalization and the investor's flexibility to deal with them.

- In deregulated electricity markets, the economic performance of the storage systems cannot be considered separate from the clearing market price of the market which causes the DCF approach to be insufficient to evaluate the market potential since it does not take operational flexibility into consideration.
- This disadvantage of the DCF approach is especially valid for large-scale investments like the energy supply sector.
- The increased uncertainty of the profits due to long project lifetimes, the irreversibility of the investments, and the opportunity to wait for more information make the NPV inadequate for energy sector investments.

- On the other hand, the **real options approach** is a powerful tool to reflect the managerial flexibility in projects with high uncertainty.

3.5.3. Research Process

The research process has four main stages which are literature study, modeling analysis, and discussion and conclusion. The outline of the research process is given in Figure 15 below.

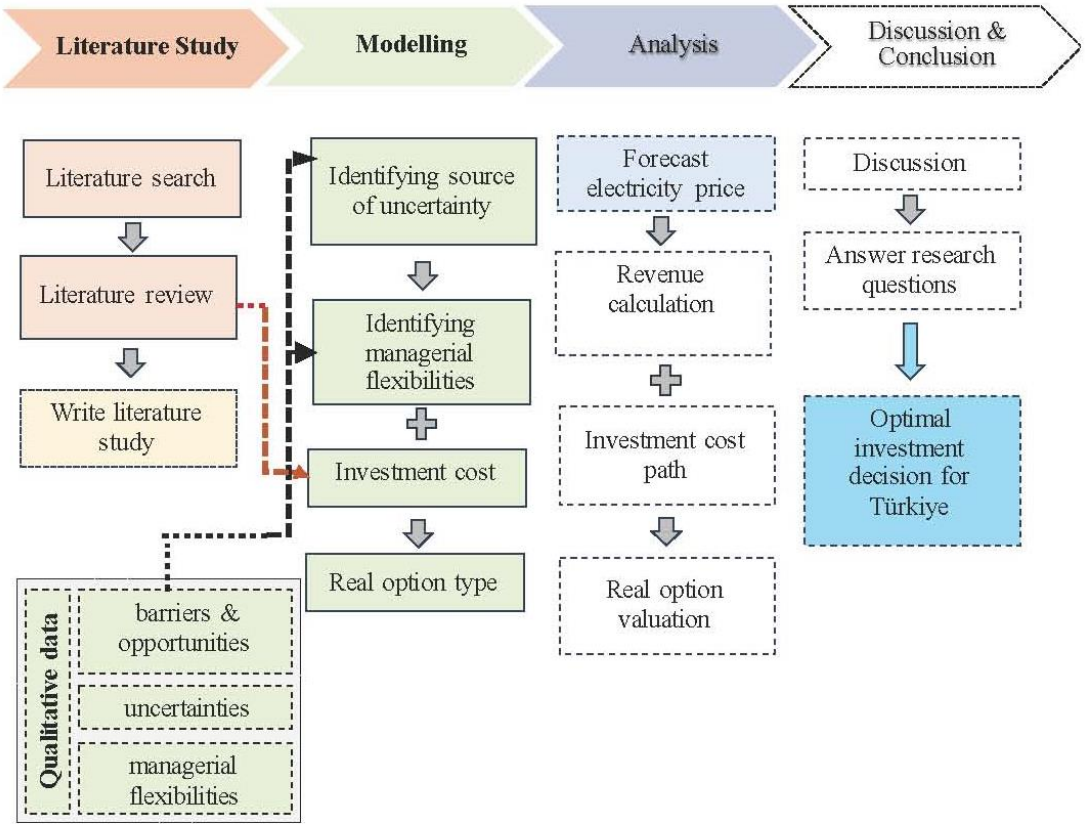


Figure 15. Outline of the quantitative research process

3.5.4. Previous Works- Meta-Analysis:

In this subsection, the studies using real options analysis for evaluating the economics of the energy storage systems are summarized in chronological order.

Muche (2009) aims to evaluate the investments in pump storage plants by taking into account the peculiarities of pump storage plants and the characteristics of liberalized

power markets. The study considers the strong power price volatility and the occurrence of price spikes as the main characteristics of power markets and proposes a model to value the real options arising from future price-based unit commitment planning. The results from real option valuation are then compared with the results from classical NPV analysis which takes expected power prices as a basis for valuation. The study concludes that due to a lack of consideration of the future scope of actions, NPV analysis leads to a mis-valuation of the investment.

Reuter et al. (2012) studies the profitability of wind technology combined with pumped storage when compared to the standard wind farms in a real options model. The study uses a real options approach to investigate the specific characteristics of renewables and their associated uncertainties considering the market effects of investment decisions to assess the level of incentives that would trigger the investment.

Kroniger and Madlener (2014) investigate the economic viability of hydrogen storage for wind power plants using real options analysis with the risks of fluctuating wind speed, fluctuating spot market electricity prices, and fluctuating call of minute reserve capacity. The study uses real options analysis to assess the flexibility of timing for the investor.

Moon (2014) develops a real options model to determine the optimal investment time for energy storage systems by considering the option of a firm to defer the investment and uncertainty of profits. The study analyzes the investment decision concerning several characteristics of the uncertainty of profits from arbitrage trade and the electric energy storage costs. The analyses show that classical NPV and real option approaches give significantly different results. More specifically, the NPV method underestimates the value of investing in electric energy storage systems and suggests an earlier time to invest than the optimal time.

Lai & Locatelli et al. (2021) proposes a model based on real options analysis to assess the profitability of electric energy storage systems and support investors' decision-making strategy. The study considers three types of real options which are

the option to wait to invest, the option to build, and the option to wait to build to appraise the value of waiting for capital cost reduction, the value of postponing the decision to build after the detailed design, and value of waiting to build after the detailed design, respectively. The results show that in all scenarios with a negative expected NPV, the option to wait for a decrease in capital costs results in the expected NPV to turn to positive. The second option further increases the expected NPV, while there is no additional value coming the from third option unless a halving of capital costs is observed.

Bakke et al. (2016) develops a real options approach to evaluate the viability of investing in a battery bank in Germany and the United Kingdom. In their model, the battery bank investment is characterized by a large sunk cost and a time interval during which the investment can be undertaken. The option to wait is designed as a Bermudan call option, an exotic option that allows the holder to exercise only once but gives the flexibility to choose the optimal exercise date between a number of given discrete times during the lifetime of option T. The results show that there is a "value of waiting" for a decrease in investment costs which cannot be captured by traditional NPV analysis.

In their study, aiming to find the optimal investment timing and size for battery energy storage systems, Kelly and Leahy (2020) illustrates that static NPV analysis does not capture the variety of dynamic decisions available in battery energy storage systems. On the other hand, study shows that real options analysis is a powerful tool to utilize these dynamics along with the uncertainty.

Hu et al. (2022) proposes an option-based general payoff model to analyze the potential utilization of battery energy storage systems considering the future cost reductions in the major European countries with a comparison of results in different regional markets. The model is composed of is set of spread options based on the price difference the service remuneration and the battery operating cost. The results show that the current empirical battery wear cost prevents battery energy storage systems from being profitable for energy arbitrage in most of the European markets while there is a heterogeneity in the potential profitability of these systems across the

countries analyzed. The results suggest that higher volatility in energy prices increases the potentially profitable utilization rate. For the frequency support services, the study shows that battery energy storage systems have a higher potential compared to energy arbitrage.

3.5.5. Modeling & Analysis

Optimal investment timing for ESS investments will be estimated using a real options approach. The study will be built on the studies "Investment in electric energy storage under uncertainty: A real options approach" (Bakke et al., 2016), "Investment and risk appraisal in Energy Storage Systems: a real options approach" (Locatelli et al., 2016), "Optimal investment timing and sizing for battery energy storage systems" (Kelly & Leahy, 2020), "Potential utilization of battery energy storage systems (BESS) in the major European electricity markets" (Hu et al., 2022). The structure of the approach will be similar to Bakke et al. (2016) as illustrated below (Figure 16):

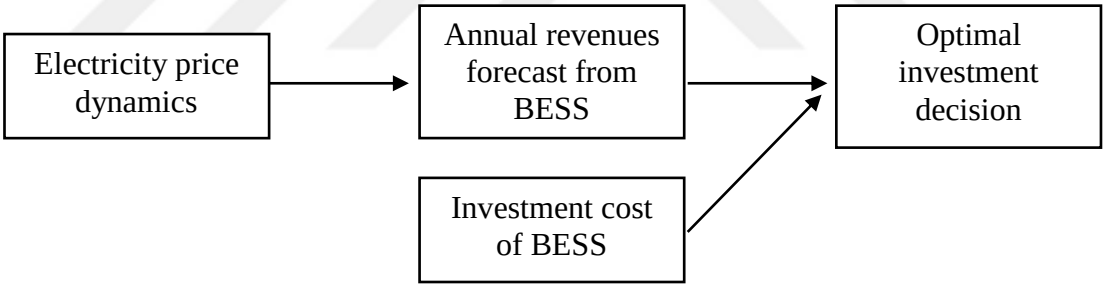


Figure 16. Model structure

According to this structure, the valuation of the ESS consists of the following steps:

(i) Revenue model for BESS integrated into a renewable power plant
   a. price dynamics: Electricity price dynamics will be modeled using scenario-based analysis.
   b. revenue generation: the battery is assumed to generate arbitrage revenue from the DAM market through charging in the low-price hours and discharging in high-price hours.

(ii) investment cost dynamics: The investment cost is generally accepted as fixed or deterministic. However, due to the rapid changes in energy storage technology, investment cost changes over time with the changes in the market.

(iii) real options valuation: The investment opportunity will be valued considering the management's flexibilities in response to uncertainties in the market.

The characteristics of the real options model in this thesis are specified as follows.

- ESS type: The study will analyze investments in BESS because of the rapid decrease in battery cost and its popularity which is also confirmed as the dominant type in Türkiye by the results from the qualitative study.
- Investor profile: Following the feedback obtained in the qualitative analysis, the study will solve the investment decision problem for a hybrid BESS investor.
- Country coverage: The geographic area of the study will be limited to Türkiye. Although the geographic area is limited to Türkiye, results are expected to be representative of other emerging economies as well and help to fill a gap in the literature in terms of location due to the high concentration of the related studies in Europe, the USA, and China (see section 2.3.4).
- Source of uncertainty: The study will consider three groups of uncertainties which are market-related (fluctuations in electricity prices-*as suggested by the literature),* technology-related uncertainties (uncertainty in the cost of investment *as confirmed in the qualitative part),* and policy-related uncertainties *(*frequency of regulatory changes-*as confirmed in the qualitative part)*
- Real options type: The optimal investment decision for BESSs will be determined by valuing the management's *option to wait to invest* until the cost of the storage becomes profitable. *The preliminary results of the qualitative research reveal that investors wait to invest because they expect costs to decline and changes in the regulations.*

Real options valuation model: Following the referred studies, a simulation-based numerical model will be used to value real options for investing in energy storage.

CHAPTER 4

QUALITATIVE ANALYSIS: OPPORTUNITIES AND BARRIERS TO FINANCIALIZATION OF THE ENERGY STORAGE INVESTMENTS IN TÜRKİYE

4.1. Introduction

Türkiye has a target of increasing the penetration of renewables in electricity production. According to the National Energy Plan (NEP) 2022 (Ministry of Energy and Natural Resources, 2023), the share of renewable energy sources in electricity installed capacity is expected to increase from 52% in 2020 to 64.7% in 2035. However, as the share of renewable energy sources grows, the need for flexibility will increase due to the intermittent nature of these resources. To enhance the flexibility of the electricity system in response to the increasing variable renewable energy production, the NEP aims to expand battery energy storage capacity to 7.5 GW by 2035. In addition, Türkiye implemented significant regulatory measures in recent years to promote further deployment of storage systems. Specifically, the regulation published on November 19, 2022 requires the deployment of energy storage systems for renewable power plants to participate in the Renewable Energy Resources Support Mechanism (YEKDEM).

Despite the increasing interest in energy storage deployment, the installed capacity in the country remains relatively low compared to the size of the country which implies a possible lack of private investments in storage systems. A low level of private investments might negatively affect the transition pace towards cleaner energy systems emphasizing the critical need to thoroughly examine the factors affecting the investment appraisal of these systems as well as the need for developing a realistic investment appraisal model.

This part of the thesis aims to investigate the economics of ESS investments by identifying factors affecting investment decisions and observing the perspectives of stakeholders. The qualitative part of the thesis will provide an overview of the perspectives on how energy storage investment decisions are taken and will help to answer *"RQ1. What are the enablers and barriers for deployment of ESSs in Türkiye?"* and *"RQ2. What are the factors and source of uncertainties affecting ESS investment decisions, and how do the investors evaluate ESS investments?"*.

The interview responses are analyzed using MAXQDA, a qualitative data analysis software. Based on the questions and answers, a codebook was prepared for use in the analysis (Appendix D).

I present the result of the empirical study in this chapter.

4.2. The Profile Study

The profile study aims to identify the stakeholders and categorize the interviewees. For this study, the stakeholder is defined as the "*actors who have interest and who are directly or indirectly affected by and/or have an effect on the further deployment and investment decisions of ESSs in Türkiye*". Two stakeholder groups are identified based on the scope of the study: (i) beneficiaries and (ii) secondary stakeholders. Beneficiary stakeholders group include the "investors" and "suppliers" sub-groups. Secondary stakeholders are sub-grouped as "consultants" and "researchers". The stakeholder groups are defined as below:

(i) **Beneficiary group**: This group represents the stakeholders who are either at the demand (user/investor) or supply (producer, designer, developer, provider) side of ESSs. The stakeholders are the ones who will be affected by and/or whose actions are likely to affect the investments and deployment decisions for the ESSs.

   a) **User/Investor**: For the scope of the study, the actors who make investment decisions (create demand) to deploy ESSs are defined as "investors". This group represents the demand side for the ESSs and

includes power plants, grid operators, and commercial and industrial facilities[3].

b) **Supplier**: This group of stakeholders includes ESS producers, designers, developers, and providers. These are the actors that produce storage systems, develop or design software for energy and battery management systems, and provide engineering solutions for storage deployment.

(ii) **Secondary stakeholders group:** This group represents the stakeholders, although not taking investment decisions directly or supplying ESSs to users, whose actions guide investment and deployment decisions for the ESSs.

a) **Consultancy:** Individuals in this group provide consultancy services to ESS investors in terms of feasibility analysis, technical analysis, and strategy and business development.

b) **Research**: Stakeholders in this group include academia, think tanks, and news platforms who engage in research activities related to ESSs, renewables, and energy transition; and organize conferences and seminars to increase the knowledge in the ESS area.

Given the aim of providing an overview of the perspectives on how energy storage investment decisions are taken, beneficiary group is the primary focus group in this study. Opinions of the secondary stakeholders group is also covered because they are interacting directly with the beneficiaries.

4.2.1. Profile of the Organization and Stakeholder Identification

In the field research, 24 interviews were conducted with 25 interviewees from 23 organizations. Regarding to area of business activity, almost all the firms engage in more than one activity related to ESSs (Table 3).

Based on the area of business activity, the organizations are distributed between beneficiary and secondary stakeholder groups. 16 of the organizations belonged to the beneficiary group with nine of them classified as suppliers while seven of them

[3] ESSs can also be used by residential users and electric vehicles which are not in the scope of study.

classified as investors. In the suppliers sub-group, eight organization defined their area of activity as “ESS designer”, “ESS developer”, “ESS provider” or a combination of these three definitions. In this group, one organization defined itself as an “ESS producer, user, designer, developer, and provider”. This organization is classified as a supplier, not an investor because it uses storage for their own energy needs, i.e. in their factories as a stand-alone storage and not as part of their area of activity. In the investors sub-group, there are two organizations whose area of activity overlaps with the supplier group.

Table 3. Area of business activity

	Profile	Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Area of Business Activity	Power Producer	0	0	0	6	6
	Power Plant	0	0	1	8	9
	Energy Storage Systems Producer	0	0	3	3	6
	Energy Storage Systems Designer	0	0	6	2	8
	Energy Storage Systems Developer	0	0	7	2	9
	Energy Storage Systems Provider	0	0	8	1	9
	Consultancy Firm	1	3	0	0	4
	Researcher	0	1	0	0	1
	Think-tank/Non-profit	1	0	0	0	1
	News Platform	3	0	0	0	3
	Research and Development	0	1	1	2	4

These organizations are classified under the investor sub-group because they hold a pre-license for renewable power plants integrated with BESSs as the remaining five organizations in this sub-group (Figure 17).

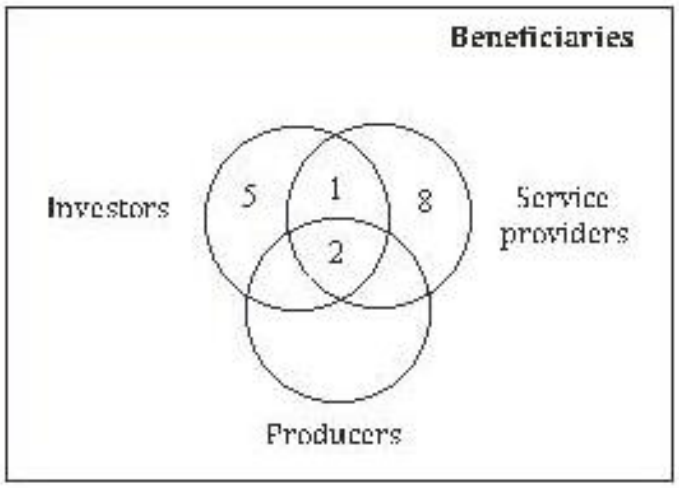


Figure 17. Distribution of beneficiaries according to their area of activity

(The number of organizations classified as beneficiary = 16; the number of interviews in this group = 17. Two separate interviews were conducted with the representatives of the same organization)

Seven interviews were conducted with the interviewees from the organizations in the secondary stakeholders group. Secondary stakeholders are sub-grouped as "consultants" and "researchers". The organizations providing advisory services to both investors and suppliers for the actualization of projects but not engaging in ESS development and deployment phases are classified as "consultants". On the other hand, the organizations that engage in activities to increase the knowledge in the area of ESSs through research or organizing events and creating content are classified as "researchers".

The selection criterion for sub-grouping is whether the organization provides advisory services for a fee or not. The organizations that provide techno-economic analysis, simulation studies, or research against a fee from their customers are classified as consultants while the organizations that engage in similar activities to increase the general knowledge in the area are classified as researchers. In the field research, we conducted interviews with four consulting firms that provide consultancy for their customers on strategy building and technical analysis regarding the deployment and development of ESSs. We conducted three interviews with the researchers. This sub-group includes both non-profits (think tanks and academia) and for-profits (news platforms).

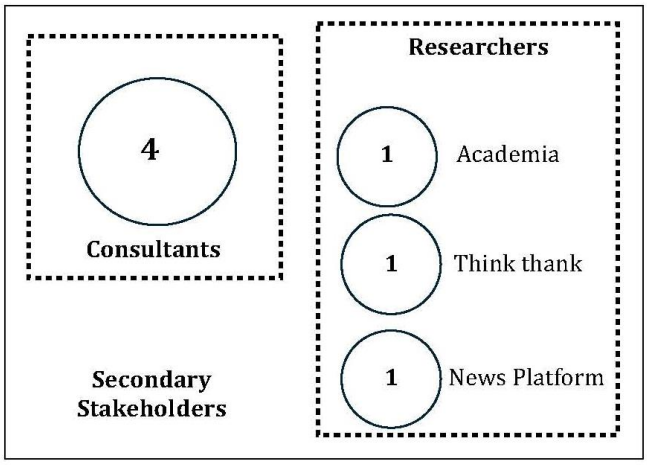


Figure 18. Distribution of secondary stakeholders according to their area of activity

The sample covers four consultancy firms that provide advisory services for deployers and the suppliers of the ESSs. Three organizations were classified under the researcher sub-group representing one organization for each of the academia, news platform, and think-tank institutions.

4.2.2. Profile of the Interviewees

Interviewees were mostly (top) managers or founders of the organization they represent. Seven out of 25 interviewees were either founders, co-founders, or the board members of their organization, 13 of them were department heads, managers, or directors while the remaining interviewees held senior positions in their companies. The sample also covers one professor from academia (see Table 4).

Table 4. Positions of the interviewees

Position	Consultant	Investor	Researcher	Supplier	Total
Digital content creator			1		1
Founder/Top Manager	3			4	7
Manager/Director	1	7	1	4	13
Professor			1		1
Senior Specialist/Analyst		1	1	1	3
Total	**4**	**8**	**4**	**9**	**25**

Most of the interviewees have an engineering degree while two interviewees have a degree from social sciences. Among the engineers, seven of them hold a degree in electrical and electronic engineering, eight of them hold a degree in energy or power management programs, and two of them hold mechanical engineering degrees. The remaining holds degrees from various engineering branches including construction engineering, soil mechanics, and aircraft and aerospace engineering. 16 of the interviewees have a graduate-level degree (seven Doctor of Philosophy -PhD-, nine Master of Science-MS-), nine of them hold a Bachelor of Science (BS) degree while one of them is a bachelor‘s student in the third grade (Table 5). Interviewees were also asked whether they have knowledge or formal education in finance. Two of the interviewees hold an MBA degree while three of the interviewees took finance or project management courses.

Table 5. Education level of the interviewees

Profile		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Education Level	BS	0	1	4	4	9
	BS (3rd degree)	1	0	0	0	1
	MS	0	4	4	1	9
	PhD	2	2	1	2	7
	MBA	0	0	2	0	2

4.2.3. Type of ESS involved

The majority of the organizations only use BESS technology while a few stated the use of other ESS technologies in addition to the BESSs. All the organizations work with the lithium-ion BESSs while five of them also work with hydrogen battery systems while thermal energy storage and renewable hydrogen energy storage systems were also mentioned (Table 6).

Table 6. ESS type

Profile		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Type of ESS Based on Technology	Battery Electric Energy Storage	1	2	4	11	18
	Renewable Hydrogen Energy Storage	0	0	0	1	1
	Thermal Energy Storage	0	0	0	1	1
	Hydrogen Energy Storage	0	0	2	3	5
	All	1	0	0	0	1

4.2.4. Scale of Deployment

Regarding the scale of deployment, the most common application is power plant-scale storage systems with 13 organizations which is followed by grid-scale storage systems with nine organizations (Table 7).

Table 7. The scale of deployment

Profile		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Scale of Deployment	Grid-scale	1	0	6	2	9
	Power Plant-scale	1	2	7	3	13
	Residential (Home-scale)	0	1	0	0	1
	Commercial and Industrial	0	1	2	0	3
	Electrical Vehicle Charing Station	0	1	1	1	3
	Island Mode	0	0	1	0	1

4.3. General Descriptive Assessment

This section aims to observe the stakeholder's views on the ESSs' role and explore whether it differs among and/or within the stakeholder groups and whether they coincide with the theory.

4.3.1. The Role of Storage in the Energy Market

This section starts with an open-ended question asking to assess the role of the ESSs in the energy sector. "Frequency control" is the most stated role of the ESSs among the stated functions. It is also mostly stated function in each stakeholder sub-group. The frequency control function was followed by the "integration of renewables" function with a frequency of 10 statements also being the second most stated role among all stakeholder sub-groups. Int. SP_1 stressed the complementary nature and fast response capacity of the storage systems together with the intermittency of renewables as the reasons behind their importance for the frequency control service and integration of renewables functions. He elaborated as:

> In the current energy market, the primary application for energy storage is as ancillary services, which is also the case in Europe. This is because storage is somewhat of a complementary technology. (…) The amount of this imbalance grows with the proportion of renewable energy on the grid, and you need to be able to respond to it quickly. Previously, when renewable energy levels were not so high, gas and coal plants could be instructed to handle this imbalance, but now they cannot keep up. **Storage facilities, however, can provide balancing responses almost instantaneously.**

"Demand balancing", "time shifting", "supply security", and "grid security" are the other important functions which are state 11, four, five, and five times respectively. Int. SP_8 argued that the current role of these systems is stabilization rather than storing energy. One of the least stated roles was "deferral of maintenance/repair investments" which was only defined by Int. IN_6 as indirect (see Table 8).

Table 8. The role of storage for the energy market by stakeholder sub-groups

	Role of ESS	Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Reliability and Stability Functions	Frequency control	3	2	3	6	14
	Grid security	0	1	1	3	5
	Supply security	2	1	1	1	5

Table 8. (continued)

Flexibility Functions	Integration of renewables	3	2	3	2	10
	Time shifting	0	1	1	2	4
	Demand balancing	1	2	5	3	11
	Self balancing	0	0	0	1	1
Economic Optimization Functions	Arbitrage	0	2	2	0	4
	Reduction of costs	0	1	1	0	2
	Ancillary services	1	0	3	1	5

4.3.2. The Relative Significance of the Functions

In this part, interviewees were asked to order the potential functions of the ESSs based on their significance. The grid security function was ordered eight times as the most important role while the integration of renewables and frequency control functions were stated as the most important five times each (Table 9).

Table 9. The role of storage for the energy market by their significance order

Significance		**Frequency of statement**				**Total**
		Secondary Stakeholder		**Beneficiary**		
		Researcher	**Consultant**	**Supplier**	**Investor**	
Most Important	Grid Security	2	3	0	3	8
	Supply Security	0	0	2	1	3
	Frequency Control	1	0	2	2	5
	Time Shifting	1	0	2	0	3
	Demand Balancing	0	0	1	0	1
	Integration of Renewables	1	1	1	2	5
	Reduction of Costs	0	0	0	2	2
	Other Ancillary Services	0	0	2	0	2
Second Important	Grid Security	0	1	2	1	4
	Supply Security	2	1	0	3	6
	Frequency Control	0	1	1	1	3
	Demand Balancing	0	0	2	1	3
	Integration of Renewables	0	1	3	1	5
	Other Ancillary Services	0	0	0	3	3

Table 9. (continued)

Third Important	Grid Security	0	0	1	0	1
	Supply Security	0	0	0	1	1
	Frequency Control	0	1	4	3	8
	Time Shifting	0	0	0	4	4
	Demand Balancing	0	0	1	2	3
	Integration of Renewables	1	1	1	0	3
	Reduction of Costs	0	0	1	0	1
	Other Ancillary Services	1	1	0	0	2
	Capacity Management	0	0	1	0	1

4.4. Drivers and Barriers

This section asks respondents to define the benefits (drivers) that support and barriers that restrict the extensive deployment of storage systems. These questions are followed by two open-ended questions asking them to discuss how these barriers could be removed and how the ESSs would develop if the barriers were removed.

4.4.1. The Drivers Behind the ESS Deployment

The drivers stated by the interviewees are allocated to three classes Technical Drivers, Economic Drivers, and Regulatory Drivers. Int. SP_7 explained the different kinds of motivation behind the deployment of storage systems as follows:

> Firstly, there is the commercial aspect, and secondly, the technical aspect. On the technical side, there are certain needs arising from regulating energy systems or addressing issues that arise. To meet these needs, some systems, including energy storage systems, can be established regardless of the financial model. On the commercial side, there are renewable energy investors in Türkiye. Some companies have wind turbines or solar panels. These companies may focus on aspects such as arbitrage or exploring ways to sell more electricity, which should also be considered from a commercial perspective.

He also further elaborated that storage systems are *not attractive for the investors* while the government's focus is on establishing energy storage systems to regulate the grid and commented that regulation that enables the BESS investor to get a license for the renewable energy power plant is the motivation behind the investors' interest. Int. SP_7 commented that "*ESSs haven't been very appealing to investors"*

which was supported by the Int. IN_4's comment "*ESS investments are not feasible financially due to the high costs*". Technical drivers stem from the functions that the ESSs serve such as flexibility- and grid stability-related drivers. Among this group, the most stated functions as the drivers are the integration of renewables, supply security, grid security, and demand balancing, respectively. For example, Int. IN_2 elaborated that "*storage is needed purely for supply security and it doesn't benefit the investors*". Under the Economic Drivers class, decrease in the cost of battery and revenue from the ancillary services are stated as important drivers. Five interviewees stated the latest regulation as the driver of BESS investments, and seven stated the importance of support mechanisms. Those two drivers are classified under the Regulatory and Policy Support class (Table 10).

Table 10. The drivers of ESSs

	Drivers	Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Grid Stability-related Drivers	Grid Security	0	0	1	2	3
	Supply Security	0	1	1	2	4
	Frequency Control	1	0	0	2	3
Flexibility-related Drivers	Integration of Renewables	0	3	2	4	9
	Time Shifting	0	0	2	1	3
	Demand Balancing	0	0	1	1	2
	Preventing Curtailment	2	0	0	0	2
Economic Drivers	Energy Arbitrage	0	0	0	1	1
	Revenue from Other Ancillary Services	0	0	3	0	3
	Deferral of Maintenance/repair Investments	0	1	0	0	1
	Reduction of Costs	1	1	2	0	4
	Profit	1	0	1	0	2
Technological Advancements	Decreases in the Battery Costs	0	0	0	1	1
Regulatory and Policy Support	Encouraging changes in Regulation	0	1	3	1	5
	Support Mechanisms	2	1	3	1	7

4.4.2. The Barriers Hindering the ESS Deployment

The barriers stated by the interviewees can be allocated into five classes: Technical, Economic, and Financial, Regulatory and Policy, Unpredictability, and Integration Challenges and Market Design. The two most frequently stated barrier classes are Economic and Regulatory. The most stated barrier in the Economic and Financial class is "high capital cost" which was stated 25 times (20 of which were stated by beneficiaries). "Barrier to accessing finance" is the second most stated economic barrier with five statements.

For the Regulatory barriers, the interviewees stated "insufficiency of regulations/lack of grid code", "frequency of changes in regulations", and "insufficiency of support mechanism" as the main regulatory barriers. In the Unpredictability class, "everchanging technology", "uncertainties regarding electricity prices", and "expectations that cost will decrease" are stated as barriers hindering the storage deployment.

In the Technical barriers class, "lack of sufficient information about techno-economic characteristics" was stated six times. Interviewees also perceive "low round-trip efficiency` and "degradation of the ESSs" as the technical limitations that pose challenges against extensive deployment of these systems.

Integration Challenges and Market Design class covers infrastructure and market structure-related barriers. "Inadequate infrastructure and connection capacity" was stated by one investor and one supplier (Table 11).

Table 11. The barriers to ESS deployment

	Barrier	Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		R	C	S	I	
Technical Limitations	Low Round-trip Efficiency	0	0	0	1	1
	Lack of Sufficient Information about Techno-economic Characteristics	1	0	5	0	6
	Degradation	1	0	0	0	1

Table 11. (continued)

Economic and Financial Constraints	High Capital Cost	3	2	9	11	25
	Insufficient Revenue from Ancillary Services	2	0	1	0	3
	Barrier to Accessing Finance	0	1	1	3	5
	Complicated Revenue Model	0	0	1	0	1
Regulatory and Policy	Frequency of Changes in Regulations	2	1	4	2	9
	Insufficiency of Regulations/Lack of Grid Code	1	3	4	3	11
	Complexity of the Regulations for Users	1	0	4	0	5
	Insufficiency of Support Mechanism	2	0	3	3	8
	Rigid Structures due to Regulations	0	1	0	0	1
Unpredictability	Expectations that costs will decrease	0	1	3	1	5
	Uncertainties regarding Electricity Prices	2	0	4	0	6
	Everchanging Technology	1	0	3	3	7
	Uncertainty of Life-cycle	0	0	1	1	2
	Uncertainty in the Technological Progress	0	1	1	2	4
	Uncertainty in the Supply Chain	0	0	1	1	2
	Dependence on Critical Materials	1	0	0	0	1
Integration Challenges and Market Design	Inadequate Infrastructure and Connection Capacity	0	0	0	1	1

R: researcher, C: Consultant, S: Supplier, I: Investor

4.4.3. Suggestions to Overcome the Barriers

Interviewees suggested several measures to overcome the barriers. The most stated suggestions include “regulatory support” with 11 statements, and “governmental monetary support” and “standardization in legislation” with five statements which are followed by “transparency in financial and political operations” with four statements (Table 12).

Table 12. Suggestions to overcome the barriers

Suggestion to Overcome	Frequency of statement				Total
	Secondary Stakeholder		Beneficiary		
	Researcher	Consultant	Supplier	Investor	
Participation of Non-Government Organizations	0	0	1	0	1
Creating a Discussion Environment with Various Actors	0	0	1	0	1
Standardization in Legislation	1	1	1	2	5
Transparency in Financial and Political Operations	2	1	1	0	4
Regulatory Support	2	1	4	4	11
Governmental Monetary Support	1	0	1	3	5
Public Participation to the Decision-Making Process	1	0	0	0	1
Increasing Awareness and Vision	1	0	1	0	2
Creating Sub-industry	0	0	0	1	1
Using More Efficient and Safer Technologies	0	0	0	1	1

4.4.4. Direction if the Barriers Were Removed

According to the interviewees, "investment appraisals would be easier" (five statements), "installed capacity of ESSs would increase" (four statements), and integration of renewables would increase" (three statements) if the barriers were removed (Table 13).

Table 13. Directions if barriers were removed

Direction if Removed	Frequency of statement				Total
	Secondary Stakeholder		Beneficiary		
	Researcher	Consultant	Supplier	Investor	
Increase in the Battery Quality/Longevity	1	1	0	0	2
Easiness in the Investment Decision	0	1	2	2	5

Table 13. (continued)

Increase in the Possibility of Integration	1	0	1	1	3
Increase in Installed Capacity	1	1	1	1	4
Establishing Huge Storage Systems for Ancillary Services	0	0	1	0	1
Finding Finance	0	0	0	1	1

4.5. Uncertainties and Expectations

In this section, with three open-ended questions, interviewees were asked to elaborate on their perceptions regarding uncertainties, the electricity markets that will be affected by the deployment of these systems, and expectations regarding the investment cost.

4.5.1. Source of Uncertainties for ESS Investments

The responses to the question *"What do you think are the sources of uncertainty in energy storage investments?"* are summarized in Table 14. The results show that the majority of the interviewees stated the "regulatory uncertainties" as the main source of the uncertainty. "Insufficiency of regulations/lack of grid code" was stated 16 times while "frequency of changes in regulation" was stated nine times as the main source of uncertainty for ESS investments. Int. SP_4 further elaborated that:

> (…) The frequent changes in the most important regulations are indeed an obstacle to the widespread adoption of ESSs. (…) One day, we might wake up and find out that the criteria of one-to-one (renewable/storage) have been changed to one-to-zero.

Regulatory uncertainties were followed by technological uncertainties. The interviewees stated that "lack of knowledge in technical characteristics of these systems", "longevity/lifecycle of batteries", and "technological advancements" create uncertainty. Int. IN_1 explained the issue as the following:

> Energy storage systems are still in the development stage, which can confuse investors (especially for manufacturing companies). Let's say you want to invest, you have the financial power, and you don't care too much about regulations, but which technology should you invest in? What if it becomes obsolete tomorrow?

Financing and market-related uncertainties were other frequently stated categories. Int. IN_5 stressed how the uncertainty in the electricity prices makes it difficult for investors to model the revenue for BESS investments. Three interviewees stated the "capital costs" as another source of uncertainty. Int. IN_1 commented that:

> First, we can't access financing. Second, costs are high. Third, they say costs will decrease, so we are waiting.

Dependency in the supply chain and the intermittent nature of the renewables were the other uncertainties mentioned by the interviewees.

Table 14. Sources of uncertainty

	Uncertainty	Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Technology-related Uncertainties	Technological Advancements	1	1	0	1	3
	Longevity/Life-cycle of Batteries	1	1	0	2	4
	Lack of Sufficient Information about Techno-economic Characteristics	0	1	2	6	9
Regulatory Uncertainties	Frequency of Changes in Regulations	2	0	4	3	9
	Insufficiency of Regulations/Lack of Grid Code	3	2	5	6	16
Market-related Uncertainties	Price of Electricity	1	0	2	3	6
	Revenue from Storage Services	0	0	1	2	3
	Expectations regarding Capital Cost Reductions	1	0	1	0	2

Table 14. (continued)

Financing Uncertainties	Capital Cost (Capex)	1	1	3	2	7
	Finance Cost	1	0	0	1	2
	Return on Investment	0	2	2	0	4
Supply Chain and Raw Material-related Uncertainties	Dependency in Supply Chain	0	0	1	1	2
	Price of Raw Materials	0	0	0	1	1

4.5.2. Expectations for Investment Cost

The question in this section asks the interviewees' expectations regarding the investment cost dynamics.

Although the majority of the interviewees expect a decrease in investment costs, their expectations differ both in terms of the magnitude of the decrease and the time window that the decrease will take place. Some of the interviewees pointed out the dependency of the BESS production to China as the reason for even an increase in the cost. Int. IN_2 explained that

> An increase in demand can even cause the costs to increase dramatically since there are no battery producers in the world besides China.

15 of the interviewees stated that they expected a further decrease in the cost of ESSs, two of which expected the decrease to be to a limited extent while two expected a decrease to a large extent.

On the other hand, some of the interviewees also stated that costs could increase especially in the short term. Two of the interviewees expected the costs to remain unchanged and another two expected that the investment costs could go either way depending on the demand and supply side developments (Table 15).

Table 15. Expectations for investment cost

Expectation		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Cost of Battery	Decrease	1	2	4	4	11
	Decrease (Limited Extend)	1	0	1	0	2
	Decrease (Large Extend)	1	1	0	0	2
	Increase (In Short Term)	0	0	1	2	3
	Not Change	0	1	0	1	2
	Can go either way	1	0	0	1	2

4.5.3. Electricity Markets to be Affected

The next question was "*From your perspective, what are the expectations for the electricity market that are likely to be affected by the energy storage investments?"*. The interviewees stated that the ancillary and intra-day markets would be affected mostly by the increasing deployment of ESSs while the day-ahead market would be also affected (Table 16).

Table 16. Electricity markets to be affected

Electricity Markets to be Affected	Frequency of statement				Total
	Secondary Stakeholder		Beneficiary		
	Researcher	Consultant	Supplier	Investor	
Ancillary Services	2	2	4	2	10
Day-ahead Market	1	4	2	2	9
Intra-day Market	1	4	2	3	10
Balancing Power Market	1	2	0	1	4
Curtailment Prevention	1	0	0	0	1
All	0	0	2	0	2

The interviewees also stated their expectations that the ancillary market will develop and there will be diversified services for ESSs in this market. Int SP_1 explained their expectation with the following words:

(…) the expectation is that the ancillary services market will introduce products specifically for storage. Currently, the market continues with two ancillary service products, primary frequency control (PFC) and secondary frequency control (SFC), which are provided by natural gas, coal, and hydroelectric power plants. However, these are not suitable for plants that need to respond within 15 minutes. We see specialized ancillary service products for storage in Europe, such as FFR (Fast Frequency Response) and dynamic containment products. We have expectations for these types of products, and they need to be defined in Türkiye as well. This is important both for differentiating storage returns and because, if storage systems are integrated into the existing PFC and SFC markets, natural gas and coal plants may face significant revenue losses.

4.6. Capital Budgeting

The last section of the interview asks questions on the capital budgeting practices of the organizations. The first part of this section aims to reveal the factors considered when an investment decision is appraised, and capital budgeting techniques used in this appraisal process. The second part of the section asks questions to observe whether the organizations are familiar with the real options approach, the types of real options used, and the reasons behind not using them.

4.6.1. Investment Decision Criteria

Interviewees were asked about the decision criteria they use when evaluating ESS investments. The responses show that the technical characteristics of the underlying asset (stated 35 times) along with the cost (stated 27 times) are the primary criteria for investment appraisal. On the other hand, environmental effects are stated only eight times (Table 17).

Table 17. Investment decision criteria

	Investment Decision Criteria	Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Technical	Round-trip Efficiency	2	2	5	3	12
	Longevity	2	3	8	6	19
	Quality	1	1	2	0	4

Table 17. (continued)

Economic	Cost of Energy Storage Systems	3	3	9	9	24
	Payback Expectation	0	0	1	0	1
	Taxes	1	0	1	0	2
Environmental	Effects on Environment	1	1	1	3	6
	Recycling Process	1	0	0	0	1
	Safety of the Technology	0	0	1	0	1

4.6.2. Financial Evaluation Technique

The question on the capital budgeting technique reveals that the organizations commonly use NPV, IRR, and payback period together for assessing the economic performance of the investment. Hurdle rate and multiple earning methods are also stated as one of the techniques used (Table 18).

Table 18. Financial evaluation technique

Capital Budgeting		**Frequency of statement**				**Total**
		Secondary Stakeholder		**Beneficiary**		
		Researcher	**Consultant**	**Supplier**	**Investor**	
Financial Evaluation Technique	Net Present Value (NPV)	1	3	9	5	18
	Internal Rate of Return (IRR)	1	2	4	7	14
	Minimum Acceptable Rate of Return (Hurdle Rate)	0	0	6	1	7
	Multiple-earnings Approach	0	0	2	0	2
	Payback Period	1	1	7	5	14
	Longevity/Degradation Calculation	0	0	1	0	1

4.6.3. Investment Evaluation Period

Regarding the question on the frequency of investment evaluation in their organizations, 13 of the interviewees stated that the investment appraisal is done on a continuous basis meaning they consider the investment opportunities immediately when they arrive (Table 19).

Table 19. Evaluation period

Capital Budgeting		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Evaluation Period	Once a year	0	0	1	0	1
	Twice a year	0	0	2	0	2
	Continously	0	1	5	7	13
	Quarterly	0	0	0	1	1

4.6.4. Real Options Approach

In this part of the capital budgeting section of the interview, the interviewees were asked questions regarding their familiarity and use of the real options framework as a capital budgeting technique. The majority of the interviewees were not familiar with the real options concept (15 statements) while only six interviewees were familiar with the technique (Table 20).

Table 20. Familiarity with real options approach

Capital Budgeting		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Familiarity with Real Options Approach	Yes	1	1	3	1	6
	No	1	3	6	5	15

Consistently, the majority of the organizations do not use a real options approach. Only four of the interviewees stated the use of the approach in their organizations (Table 21).

Table 21. Use of real options approach

Capital Budgeting		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Use of Real Options Approach	Yes	0	1	2	1	4
	No	2	3	7	4	16

Interviewees were also asked the reasons for not using the real options framework. The results show that the real options framework is not used mainly because it is seen as “too technical” and “too detailed for the company” (Table 22).

Table 22. Reason for not using real options approach

Capital Budgeting		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Reason for not using use of real options approach	Lack of support from senior management or stakeholders	0	0	2	0	2
	Too technical	0	1	1	1	3
	Encourages excessive risk-taking	0	0	1	0	1
	Too detailed for the company	0	0	1	2	3
	Using without realizing	1	0	0	0	1
	Lack of knowledge about the conditions of Türkiye	0	0	1	1	2
	Not suitable for the company	0	0	1	0	1
	Lack of flexibilities	0	0	0	2	2

The interviewees who stated the use of real options framework were asked a dependent question on the use case of the technique. Only two of four interviewees responded to this question and both stated that the real options approach is not used as the primary technique but rather is used to complement and support the results from other capital budgeting techniques (Table 23).

Table 23. Use types of real options

Capital Budgeting		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Use Type of Real Options Approach	To complement and support the results obtained from other methods	0	0	1	1	2

Regarding the use area, the real options framework is mainly used when a new investment decision is taken. The second use area is mergers and acquisitions (Table 24).

Table 24. Use areas of real options

Capital Budgeting		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Use Area of Real Options Approach	Deciding New Investment	0	1	1	1	3
	Mergers and Acquisitions	0	0	1	0	1

Regarding the real options type, the option to invest/build is stated three times while the option to wait and the option to expand are stated one time (Table 25).

Table 25. Real options type

Capital Budgeting		Frequency of statement				Total
		Secondary Stakeholder		Beneficiary		
		Researcher	Consultant	Supplier	Investor	
Type of Real Options Approach Used	Option to Invest/Build	0	1	1	1	3
	Option to Defer/Wait	0	0	0	1	1
	Option to Expand	0	0	1	0	1

4.7. Additional Takeaways

4.7.1. Real Options Type Used in Practice

Although the majority of the interviewees said that they were not familiar with the real options framework, I was able to deduce use cases for three types of real options in practice from their remarks as summarized below (Table 26).

- Option to wait: As expected, investors choose to wait until the uncertainties are resolved or because they wait for more favorable conditions in the future. Expectations for cost reductions and regulatory uncertainties were stated as the reasons behind why the investors delayed investments.
- Option to prototype: The interviewees talked about some small-scale projects as prototypes which investors make to learn more about the technical details of ESSs before making actual large-scale BESS investments. Regulatory uncertainties, lack of sufficient information about techno-economic characteristics, and the ever-changing nature of these systems were the stated reasons behind investing in prototypes.
- Option to invest/build: Investors also use the option not to build even though investments were completed if the investment became unprofitable due to a change in the regulatory environment.

Table 26. Real options type in use

Reason (Source of uncertainty)	Real options type	Comments of the interviewees
Expectations for cos reduction	**option to wait**	Int. IN_1: “First, we can't access financing. Second, costs are high. Third, they say costs will decrease, so we're waiting.”
Lack of regulatory grid-code/frequency of regulatory changes	**option to wait**	Int. IN_8: "If the existing data were clearer, I think investments would have already started. (…) The situation isn’t entirely clear, so everyone comes with questions. If the obstacles can be removed, I believe investments would start as soon as possible. They would have started much earlier. (…) Instead of waiting for costs to decrease, Turkish investors generally expect to receive support."
		Int. RE_3: "(…) for a 1 megawatt renewable energy installation, investors expect a battery with a capacity of a quarter of that, i.e., 0.25 megawatt-hours. These are the types of investor expectations we see."
	option to prototype	Int. SP_6 : "Because companies still have concerns—like, if we design and announce a project today and set it up as a 1-to-1 ratio, for example, what if tomorrow the requirement changes to 0.2 or 0.3? They are worried that they will have spent money unnecessarily to obtain the license. As a result, what we see in the sector right now is that energy companies are starting with pilot projects in the range of 2-4 megawatt-hours with a single container. They will conduct feasibility studies based on these initial setups."
	option to invest/build	Int. IN_6:: "We have applied for and obtained a license for battery storage investment, but as of today, we are still unsure whether we will proceed with the investment. We will make a decision in a few months."
Lack of sufficient information about techno-economic characteristics/techn ological developments	**option to prototype**	Int. IN_8: "Many of the projects you hear about—those saying ‘it’s done, it’s in progress, it’s being installed’—are actually on a smaller scale. For example, we recently installed a 4-megawatt battery for testing purposes at our Bandırma plant. However, the regulations you mentioned, like the 1-to-1 ratio, are more applicable to larger-scale projects, such as those in the range of 100 megawatts or 200 megawatts. We do have plans for these larger investments, but there is a specific timeline for them."
		Int. SP_5: "It looks like investments will start in 2025. The current investments we are making are all pilot projects for testing purposes."

4.7.2. Selected Assessments by Interviewees on the Latest Regulation

The latest amendment to the regulation on electricity storage was published in November 19, 2022. With this amendment, firms licensed to establish an electrical storage facility on their site are permitted to build and operate a wind power plant (minimum 20 MW) or a solar power plant (minimum 10 MW, maximum 250 MW) with a capacity matching that of the storage facility under the scope of YEKDEM (PwC Turkiye, 2023). Almost all of the interviewees commented on this regulation either as a driver for the BESS deployment or a barrier for extensive deployment of these systems.

Table 27 below summarizes three mostly stated topics related to the regulation which are: (i) one-to-one criteria (regulation requires deployment of storage with the same capacity as the capacity of the renewable power plant), (ii) the preliminary license granting process, and (iii) lack of a grid code that specifies technical requirements and operational procedures.

(i) From the statements of the interviewees, it is observed that "one-to-one criteria" is a mostly debated issue regarding the regulation. Interviewees expressed their expectations regarding a change in the criteria and pointed to this expectation as a reason for delaying the investments.

(ii) Starting in November 2022, EMRA started to accept pre-license applications for electricity storage facilities. As of June 2024, applications for preliminary licenses in the scope of this regulation for storage capacity have reached approximately 32 GW (Electricity Generation Pre-License Inquiry, n.d.). However, there are no plants built yet. The interviewees stated the view that, in addition to the uncertainties that cause pre-licenses to delay investment, some of the pre-license holders are not active in the energy field and possibly would not turn into investment.

(iii) Lack of a grid code for storage deployment was stated by almost all the interviewees. It is also one of the most important barriers and sources of uncertainty for storage investments.

Table 27. Policy assessments

Issue	Assessment
1:1 BESS deployment criteria in the regulation	• A battery with one-fourth of the capacity (0.25) of a 1-megawatt renewable energy installation would be a better option. (Int. RE_3) • If 1:1 is applied, they will store energy from the grid at night and sell it from YEKDEM (Renewable Energy Support Mechanism) during the day (the opposite of the intent of the regulation) (Int. CT_1)
Granted pre-licenses	• Investors who really want to do it say that they were unable to get the pre-license (blocking the real investors). (Int. RE_3) • Currently, the payback periods for storage systems are not short enough. Therefore, most of those who obtain these preliminary licenses will not make the investments. Only the ones which already have facilities, whether wind or solar, will find a way to secure long-term loans and make these investments. But the number of such companies is limited. (Int. CT_4) • Many licenses have been granted, but there are no storage systems that have been implemented yet. (Int. SP_9) • The pre-license holders are looking around to figure what to do. (Int. SP_6) • We only expect 10% realization. (Int. SP_4)
Lack of grid-code	• There is a need for a supplementary regulation similar to Supplementary-18 (Grid Connection Criteria for Wind Energy-Based Production Facilities) for renewables. (Int. CT_1)

4.8. Conclusion

Despite the significant regulatory measures taken in recent years to promote the further deployment of storage systems, there is a lack of investment, especially in large-scale ESSs. Given the importance of increasing the flexibility of the electricity system with the increased penetration of renewable power sources, it is critical to understand the factors affecting ESS investment decisions.

This part of the thesis aims to investigate the economics of ESS investments by identifying factors affecting investment decisions and observing the perspectives of stakeholders. To this end, qualitative research with semi-structured interviews is carried out to examine the topic in detail and from the eyes of experts. In the field research, 24 interviews were conducted with 25 interviewees from 23 organizations. Responds were analyzed using MAXQDA software.

The results show that flexibility- and grid stability-related functions of ESSs along with regulatory and policy support are perceived as the main drivers supporting the further deployment of those systems. Recent encouraging regulatory changes and support mechanisms are as important as the technical functions provided by the ESSs for investment decisions. Additionally, the reduction of investment costs in recent years and the revenue generation potential especially from ancillary services support ESS investments. On the other hand, despite the rapid decrease, high capital cost is still the main barrier against the expansion of those systems. In addition, regulatory constraints such as insufficiency of regulations/lack of grid code and frequency of changes in regulations are perceived as barriers hindering ESS investments. The unpredictability of the investment cost and technological advancements are other important barriers revealed from the interviews.

The study shows that unpredictability of the ESS investments mainly results from regulatory and technological uncertainties. Insufficiency of regulation and insufficient knowledge about the techno-economic characteristics of storage systems create uncertainty for investors. Additionally, the volatility of electricity prices and capital costs are also perceived as important sources of uncertainty affecting the

profitability of those investments. Interviewees expect that the decline in the investment costs will continue although there is no consensus on the magnitude of the decrease.

Regarding the investment appraisal techniques, the study shows that DCF analysis with NPV, IRR, and payback period calculations are used as expected. Although the majority of the interviewees were not familiar with the real options framework, the study revealed the use of the real options approach for evaluating storage investments in practice. Due to the perceived uncertainties, investors use the option to defer/wait, the option to invest/build, and the option to prototype.

CHAPTER 5

QUANTITATIVE ANALYSIS: INVESTMENT APPRAISAL FOR HYBRID BATTERY ENERGY STORAGE SYSTEMS (A REAL OPTIONS APPROACH)

5.1. Introduction

5.1.1. Background

Given the target of increasing the penetration of variable renewable energy sources, it is important for Türkiye to facilitate the deployment of the ESSs as a flexibility option. Although there are no grid-scale battery energy storage facilities in Türkiye yet, preliminary license applications for hybrid energy storage to capacity have reached approximately 32 GW (Electricity Generation Pre-License Inquiry, n.d.). This suggests that Türkiye's storage capacity will increase through the deployment of hybrid energy storage systems (HESS) which are integrated with renewable energy plants[i].

Thus, the legislation that requires the deployment of energy storage for renewable power plants to participate in the YEKDEM scheme can be seen as one of the main drivers for investment decisions. This is also supported by the results obtained in the qualitative part. According to interviewees, those encouraging changes in regulation along with the integration of the renewables are the main drivers for the private ESS investments in Türkiye (section 4.4).

This part of the thesis will develop a model to analyze the economic viability of BESS investments which are integrated into a renewable power plant and determine the optimal decision under the conditions of uncertainty in the future revenues and

investment cost. The developed framework will be used to answer "*RQ3. What is the optimal investment strategy under the conditions of uncertain future revenues and investment cost*?"

5.1.2. Literature Review

In line with the current developments in Türkiye, there is an increasing number of concept studies on optimal capacity selection and financial feasibility of HESS investments. Korkmaz (2024) proposes to build three batteries with different configurations that participate in different electricity markets simultaneously to overcome the limitation stemming from the minimum State of Charge (SoC) criteria. Given the minimum SoC criteria, a battery can only serve in one market at a certain point in time. By building three smaller batteries instead of a large battery, the investor will be able to diversify the revenue sources. Şensoy (2023), on the other hand, proposes a model that will optimize battery, wind and solar installation capacities simultaneously to maximize the utilization of renewable sources. The study shows that investments in BESSs are not economically feasible on their own and combining BESSs with multiple renewable energy sources rather than combining with only wind or solar power plants yields the highest revenue.

Studies show that combining BESS with a renewable power plant increases the revenue potential. Eyupoğlu and Akpınar (2024) shows that although the net present value for a wind tribune investment is greater than zero (financially viable), integrating the power plant with storage enhances the financial performance of the investment. The BESS provides enhanced management capacities which increases the net present value of the investment. On the other hand, investment's payback period and IRR worsen due to the higher capital investment. SHURA (2024) shows that a stand-alone BESS becomes economically feasible by 2034 while a HESS with one-fourth of the renewable capacity becomes feasible

Although integrating energy storage with a power plant increases the economic value, the studies agree that the storage capacity should not exceed the required level. Eyupoğlu and Akpınar (2024) and Şensoy (2023) take one-to-one ratio for energy

storage capacity as given and do not analyze different storage sizes. Korkmaz (2024) limits the total capacity of the three batteries to be not greater than the required level while leaving room for additional capacity depending on the statistics on the change in the frequency and the magnitude of Megawatt Electric (Mwe) stemming from wind profile. SHURA (2024), on the other hand, carries out a cost-benefit comparison for different-sized batteries integrated with solar power plants. The results show that a battery with the same capacity as the power plant becomes feasible one year later than the case with a battery with one-fourth of the renewable capacity. This analysis suggests that increasing the storage capacity beyond the required level will further deteriorate the economic feasibility due to high initial costs.

The primary revenue source is arbitrage in the day-ahead market, with Korkmaz (2024) being the only exception. Şensoy (2023) takes the degradation of the batteries into account while optimizing the mechanical capacity of the battery.

5.1.3. Contribution

The qualitative study showed that there are regulatory, economic, and technology-related uncertainties which are observed by the investors (section 4.5). In response to those uncertainties, investors exploit their managerial flexibilities such as delaying the investment decision (option to wait), building in a smaller-scale battery to observe the technical characteristics (option to proto-type), and choosing not to build even though investments were completed if the investment became unprofitable due to a change in the conditions (option to invest) (Table 26). However, the studies reviewed above, in particular, as well as those on the profitability and economic feasibility of energy storage systems in general, use net present value (NPV) to assess the economic and financial viability of these systems which do not consider the uncertainties or investor's flexibility to deal with them.

The study will develop a real options framework based on the real-life uncertainties and flexibilities for a hybrid BESS investment decision. The real options approach is chosen for two two key reasons. First, the results of the qualitative study highlight

the presence of uncertainties for ESS investments. Second, the qualitative analysis reveals that, albeit unknowingly, investors already apply real options in practice to deal with those uncertainties. Building on these observations, a real options framework would be better suited than traditional DCF analysis to analyze the optimal investment timing under the conditions of uncertain future revenues and investment costs.

Uncertainties and the related managerial flexibilities are derived from the qualitative part of the thesis. The option to wait will be considered as managerial flexibility in response to economic and policy uncertainties. Using the real options framework, optimal timing for investment will be analyzed and the value of the option to wait will be quantified. Effects of electricity price and cost dynamics uncertainties on optimal investment timing will be analyzed using a case study. In addition, policy uncertainty will be assessed in the sensitivity analysis.

The study will contribute to the real options literature on energy storage investments by combining qualitative research with the real options framework to effectively address uncertainties and design sensitivity analysis. By using this novel mixed approach, the study enhances the findings and provides a more country-specific understanding of the BESS investment appraisal. Additionally, the study uses scenario-based modeling to better capture the future dynamics of key variables. Table 28 below provides a benchmarking comparison of the study with the existing literature.

Table 28. Benchmarking table with the literature on real options

	This study	Bakke et al. (2016)	Locatelli et al. (2016)	Sun et al. (2023)
Country	Türkiye	Germany and United Kingdom	United Kingdom	China
Topics	Assessing economics of hybrid BESS investments under the conditions of uncertainty	Valuing investments in battery banks and determining the optimal investment time	Profitability of ESSs process	Establishing a sequential investment decision model considering uncertainties
Application type	Electricity sold in DAM	Electricity sold in spot and balancing market	Arbitrage and Short Term Operating Reserves	Peaking auxiliary services
ESS type	Battery Electric Energy Storage	Battery Electric Energy Storage	Pumped hydro storage and compressed air energy storage	Battery Electric Energy Storage
Initial ESS investment cost	Taken from literature/from qualitative study	Taken from literature	Taken from literature	Taken from literature
Source of uncertainty	Uncertainty in arbitrage price, investment cost, policy uncertainty	Uncertainty in the cost of battery banks and fluctuations in electricity prices	Uncertainty in capital costs and incentives, volatility of electricity prices	Uncertainty in technological innovation, price, and policy
Real options type	Option to wait to invest	Option to wait to invest	Option to wait to invest)	Options to wait
Real options valuation model	Simulation based numerical model	Simulation based numerical model	Simulation based numerical model	Differential equation method
Results obtained	Although there is "value of waiting", the option value is not significant enough to justify delaying wind power plant investment.	There is a “value of waiting” for a decrease in investment costs.	The real options approach evaluates more positively the profitability of the project compared to DCF	Technological innovation can offset the negative effect of policy uncertainty.

5.2. Model Description

In this study, the economic feasibility of a BESS investment which is integrated with a wind farm will be analyzed. Optimal investment timing for a hybrid BESS investment will be estimated using a real options approach. The study will be built on the studies "Investment in electric energy storage under uncertainty: A real options approach" (Bakke et al., 2016), "Investment and risk appraisal in Energy Storage Systems: a real options approach" (Locatelli et al., 2016), "Optimal investment timing and sizing for battery energy storage systems" (Kelly and Leahy, 2020), "Potential utilization of battery energy storage systems (BESS) in the major European electricity markets" (Hu et al., 2022).

In this study, BESS will be charged at the day-ahead market and will be discharged based on the market prices and maintenance costs. The structure of the approach will be as illustrated below (Figure 19):



Figure 19. Structure of the approach

5.2.1. Revenue Framework

Figure 20 below illustrates the basic framework for an integrated BESS including the stakeholders (investors, government, and grid companies), cash flows, and commodity flows. In this framework, investors can generate a revenue stream from selling the electricity generated to the grid at the YEKDEM price as well as the extra revenue obtained from stored energy in the BESS by proving frequency regulation in the ancillary market, earning arbitrage revenue, and also providing imbalance

management and balancing services. The government can subsidize the integrated BESS projects and can levy taxes on the revenue generated by them. In the current regulatory environment, instead of directly subsidizing the BESS investments, the government subsidizes renewable energy investments that are integrated with BESSs through including the power plant into the YEKDEM scheme.

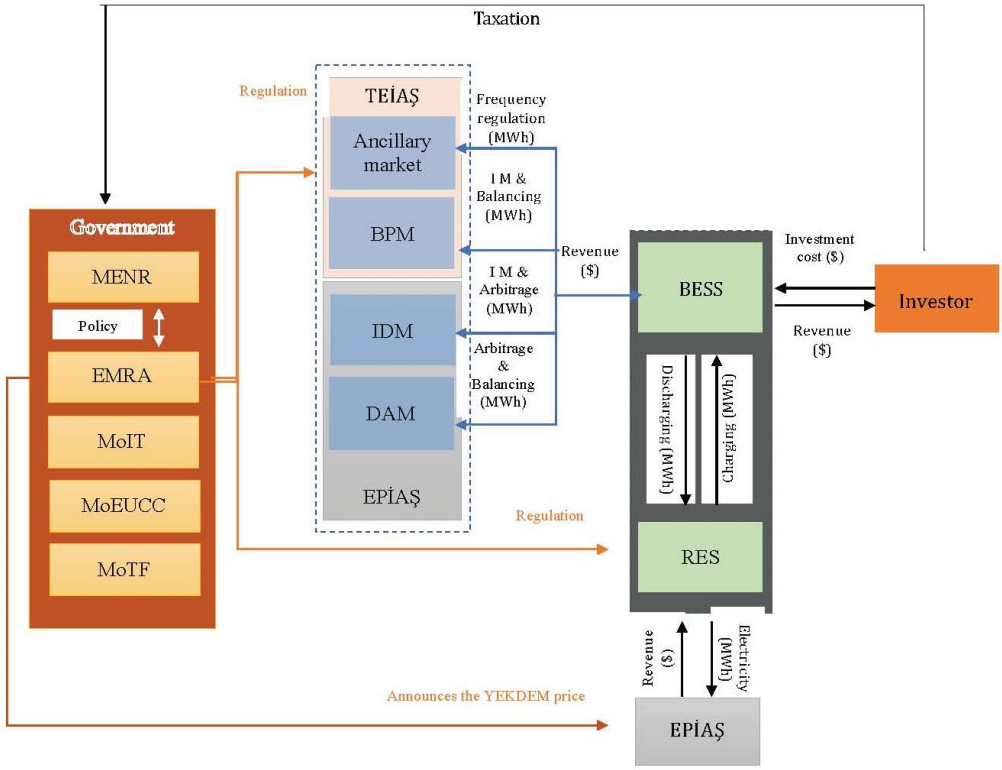


Figure 20: Basic revenue framework for a battery energy storage system (BESS) integrated with renewable energy sources (RES)

(DAM: Day-Ahead Market, IDM: Intra-Day Market, BPM: Balancing Power Market, I M: Imbalance management)

As illustrated in Figure 20, in addition to the YEKDEM scheme, there are four physical electricity markets in which integrated batteries can participate and potentially generate revenue which are DAM, IDM, BPM, and ancillary services market. While the YEKDEM price is determined by the EMRA, the prices in the spot (DAM, IDM) and real-time (BPM, ancillary) markets are determined by supply and demand conditions.

Table 29 shows the historical yearly average prices for those electricity markets.

Table 29. Historical electricity prices (yearly average, TL/Megawatt-hour (MWh))

	2019	2020	2021	2022	2023	2024
DAM Market Clearing Price	260	279	508	2,511	2,189	2,236
IDM Weighted Average Price	252	278	506	2,489	2,157	2,210
Primary Frequency Capacity Price	160	133	161	757	853	1,107
BPM System Marginal Price	253	272	499	2,549	2,161	2,179

DAMP is accepted as the reference price for electricity markets. Non-negative prices are not allowed in Turkish electricity markets. Historical values show that the correlation between DAM price and IDM and BPM prices are greater than 90%. Thus, in this study, DAM price will be used as a reference for the revenue potential of the battery. Batteries can participate in DAM and generate revenue by providing arbitrage and imbalance management services. Figure 21 and Figure 22 show the historical monthly averages for DAM price in USD/MWh and TL/MWh, respectively. It is observed that DAM prices in USD/MWh increased sharply in 2022 which was followed by a return to the levels slightly higher than that observed in the period before 2022.

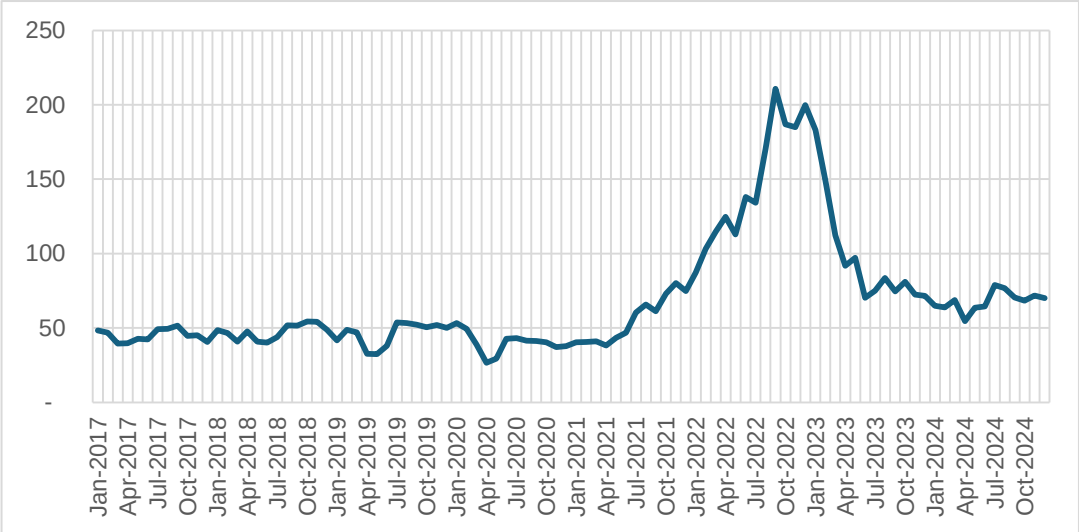


Figure 21. Day-ahead market price (monthly average, USD/MWh)
(Source: EPİAŞ Transparency Platform)

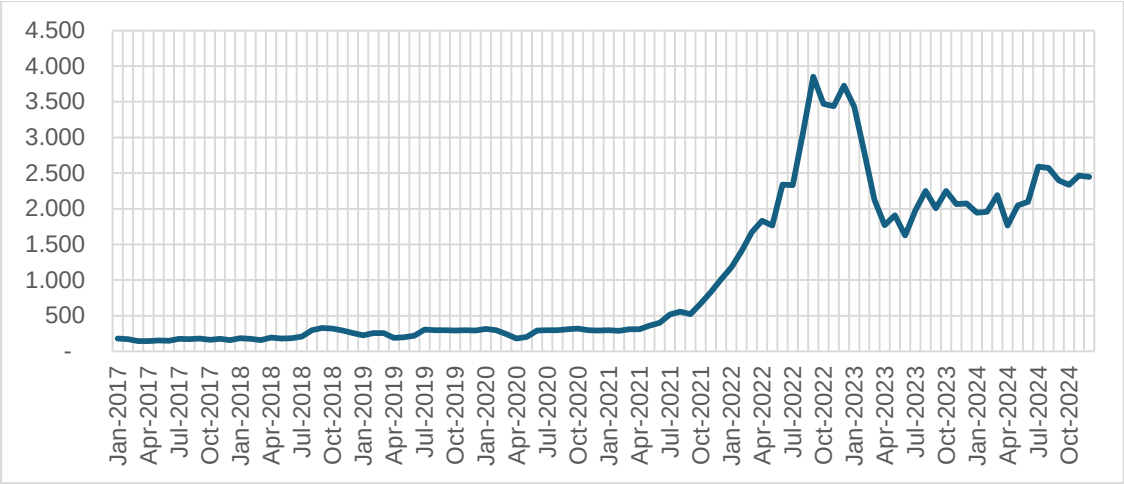


Figure 22. Day-ahead market price (monthly average, TL/MWh)
(Source: EPİAŞ Transparency Platform)

5.2.2. Investment Cost

The cost of lithium-ion batteries fell more than 90% from 1,400 USD/kWh in 2010 to 115 USD/kWh in 2024 (IEA, 2024). The cost decreased steadily each year with the only exception being the year 2022 (Figure 23). It is expected that the costs of lithium-ion batteries will decline by 40% by 2030 compared to 2023 (IEA, 2024).

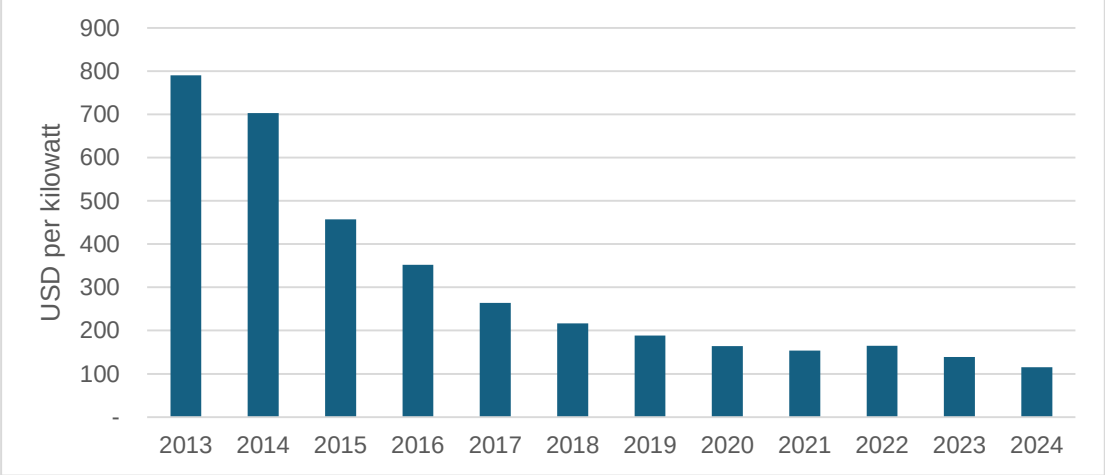


Figure 23. Lithium-ion battery prices, 2013-2024
(Sources: IEA (2024) and BNEF (2024))

Despite the observed sharp and continuous decline, the qualitative study showed that the high cost of storage systems is still a barrier against further deployment (see

section 4.4 in Chapter 4). Additionally, cost reduction expectations and the uncertainties regarding the cost dynamics stemming from the uncertainties in technological development cause investors to wait to invest in more favorable conditions (sections 4.5 and 4.7 in Chapter 4).

5.2.3. Real Options Model

In this study, investing in a hybrid BESS by a pre-license holder will be valued as an American call option where choosing to invest will be equivalent to exercising the option.

The investment opportunity for a pre-license holder is as follows:

- Option has a lifetime of T years
- At any time, t, the firm can choose to invest in the BESS
- Investment cost is I
- The discounted revenue stream from operating the battery storage is F
- Discount rate is r

The real option valuation will be solved using the LSM approach. In the LSM approach, at each exercise point, the holder compares the immediate exercise value with the value from keeping the option alive. Monte Carlo simulations for battery cost and arbitrage price are the inputs for the LSM approach. The approach decides the optimal investment timing by comparing the revenue from immediate exercise and the continuation value of keeping the option alive. The LSM algorithm only considers the in-the-money paths, meaning the paths in which the option value is greater than the strike price at the final exercise date.

The value of the option is given below:

$$V_{s,t} = \begin{cases} F_{s,t} - I_{s,t}, & if\ F_{s,t} - I_{s,t} > W_{s,t} \\ W_{s,t}, & if\ else \end{cases} \quad (2)$$

where for each path s at each time step t, $F_{s,t}$ is the simulated discounted revenue stream, $-I_{s,t}$ is the simulated investment cost (strike price), and $W_{s,t}$ is the continuation value. The option value is calculated by averaging all the payoff paths in time zero. If the option value is greater than zero, the value of investing in the BESS is positive while it is never profitable if the option value is negative (Bakke et al., 2016).

5.3. Case Study

This section will present a case study addressing the investment problem of a pre-license holder for a wind power plant that is integrated with a BESS with the same capacity. BESS participates in the DAM to generate arbitrage revenue. In this setup, the BESS charges from the grid when the prices are low and sells when the prices are high.

Figure 24 below, shows the annual hourly average price levels for the period between 2017 and 2024. Historically, the lowest price occurs at noon while the highest price occurs at 8 pm.

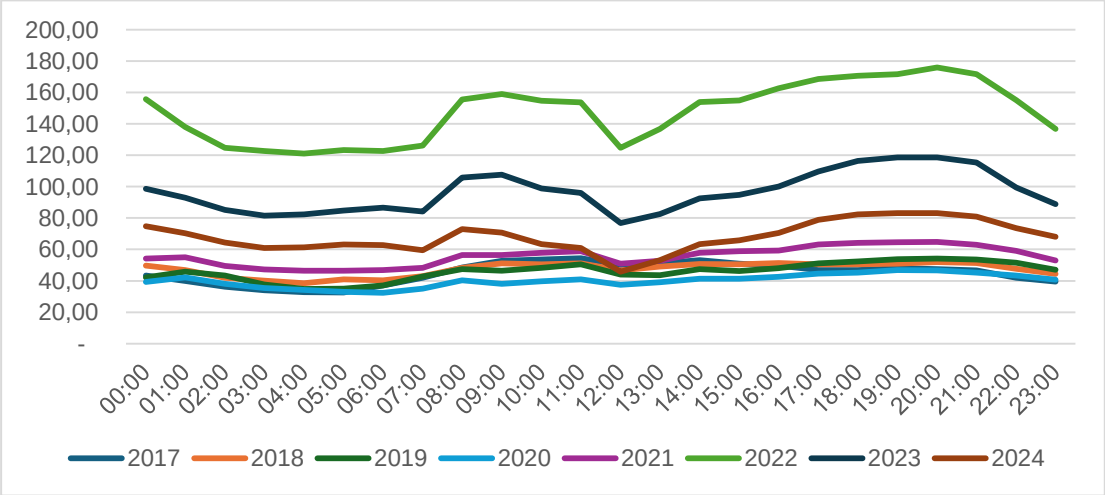


Figure 24. Annual hourly average DAM price($/MWh) 2017-2024
(Source: EPİAŞ Transparency Platform)

For the sake of simplicity, it will be assumed that the BESS will perform one charge-discharge cycle daily which is consistent with the price patterns with a clear

minimum and maximum point in a 24-hour time horizon. To maximize profit, the BESS will be charged at the minimum price and discharged at the maximum price of the day. The daily payoff function for the energy arbitrage is defined as follows:

$$\prod_d = max\left(P_{discharge,d}\theta_{discharge,d} - P_{charge,d}\theta_{charge,d} - O_d, 0\right) \quad (3)$$

$$\theta_{discharge,d} = \theta_{charge,d}\eta \quad (4)$$

$$O_d = \propto Capex/EFC \quad (5)$$

where $\prod_d$ is the payoff for day d, $O_d$is the operational cost for day d which is a fraction of capital cost (capex) divided by EFC (equivalent full cycle), $P_{discharge,d}$ and $P_{charge,d}$ are the maximum and minimum price levels for day t while $\theta_{discharge,d}$ and $\theta_{charge,d}$ are discharged and charged energy at day d, respectively. η represents the round-trip efficiency.

The annual payoff for energy arbitrage is calculated by summing the daily payoffs in a year.

$$Annual\ Payoff = \sum_{d=1}^{365} \prod_d \quad (6)$$

Following Bakke et al. (2016), it is assumed that annual payoffs throughout the lifetime of the battery bank are approximately the same. The NPV of the total payoff stream F, for a BESS with a lifetime of N years and the discount rate r, is calculated as follows:

$$F = \sum_{n=0}^{N} \frac{Annual\ Payoff}{(1+r)^n} \quad (7)$$

The case study is carried out for Lithium Iron Phosphate (LFP) BESS with a capacity of 1MW/1MWh as required by the legislation. As a benchmark study, a DCF analysis is carried out by using hourly DAM price data for the year 2024. The payoffs are calculated using daily maximum and minimum price levels. The figure

shows the daily payoffs for the year 2024. The payoffs fluctuate between 0 $/MWh and 72,8 $/MWh with the annual average being 35,30 $/MWh which is very close to the difference between the maximum annual average hourly price and minimum annual average hourly price.

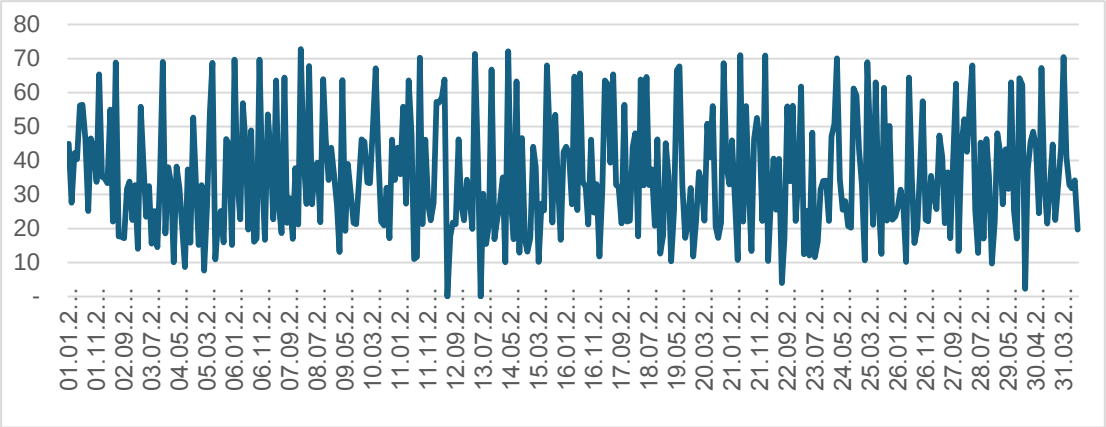


Figure 25. Daily payoffs from arbitrage in DAM ($/MWh)
(Source: EPİAŞ Transparency Platform)

Initial investment cost (capex) (285,000 $/MWh) and operational cost (opex) (capex*%2.5) and round-trip efficiency (0.88) figures are taken from SHURA (2024). The lifetime of the battery is assumed to be 10 years (first replacement time in Şensoy (2023). The discount rate is chosen as 7% from SHURA (2024). EFC is taken as 4000 as in Hu et al (2022). The results and parameter values are summarized in Table 30 below.

Table 30. Economic performance of BESS

	based on 2024 hourly prices
Battery capacity	1MW/1MWh
Investment Cost ($)	285,000
Lifetime in EFC	4000
Round-trip efficiency	0.88
Marginal Opex ($)	1.8
Lifetime in Years	10
Annual Arbitrage Revenue ($)	12,918

Table 30. (continued)

Discount rate (%)	7
Net Present Value ($)	**-187,918**
Payback Period (years)	22
Internal Rate of Return (%)	-13

In line with the literature, the results of the DCF analysis show a poor economic performance for the battery in the case of energy arbitrage with a negative net present value of 187,918 per MWh. The payback period is 22 years which is longer than the expected lifetime of the battery. A negative IRR also suggests that the investment is not feasible under current conditions.

However, as discussed earlier, the main driver behind the battery investment in the current legislative landscape is the right to construct a renewable power plant integrated with the battery. Thus, the investment appraisal should consider the revenue stream from the renewable power plant.

The revenue stream from a wind farm will depend on several factors such as wind speed data, wind power estimation, technical details of the wind tribune, as well as the cost of the wind tribune. Since these factors are beyond the scope of the thesis, NPV calculations for the wind power plant will be based on the results of Eyupoğlu and Akpınar (2024). The study calculates the NPV for a wind farm with 30MWe capacity. The study calculates an NPV of $429,517 per MW[4] which yields a positive NPV for the hybrid BESS investment even in the case of arbitrage case for battery.

Contrary to positive NPV for the hybrid BESSs, the qualitative analysis showed that investors wait for more favorable conditions due to uncertainties stemming from the volatility in electricity price (market-related uncertainties) and investment costs (financing uncertainties), frequent changes in legislation (regulatory uncertainties), and ever-changing nature of the battery technology (technology-related uncertainties). This study will develop a real options framework considering

[4]The study calculates a 422,516,000.7093 TL NPV for a 30 MW wind power plant based on 2022 prices. The US dollar equivalent is calculated using 2024 yearly average USD/TL exchange rate. Then NPV in 2024 US dollar values are divided by 30 to calibrate for a 1 MW case.

electricity price and investment cost uncertainties and quantify the option value of waiting. The effect of regulatory uncertainty will be assessed through a sensitivity analysis.

5.3.1. Case Study: Option to Invest with Uncertain Price and Investment Cost

In this subsection, the value of the option to wait to invest will be analyzed taking into account the investment cost and electricity price uncertainties. The expected value of the continuation will be solved by using Least Squares Monte Carlo (LSM) method proposed by Longstaff and Schwartz (2001). The method aims to provide a path-wise approximation to the optimal stopping rule for *American options*, which gives its holder the right to exercise at multiple points in time. At each exercise point, the holder compares the immediate exercise value with the value from keeping the option alive (a detailed description of the method is given in Section 2.3.2.1.2).

To apply the LSM method, the initial cost and electricity price will be simulated using a Monte Carlo approach. Each variable will be simulated 10,000 times based on its dynamics.

5.3.1.1. Modeling the Investment Cost

Based on the background developed in Section 5.2.4, this study will assume that the battery costs will continue to decline steadily as in the last decade. Following Bakke et al. (2016), investment cost dynamics will be modeled as a geometric Brownian motion with a negative growth rate.

$$dI = \propto Idt + \sigma Idz \tag{8}$$

where I represents battery cost, $\propto$ is the growth rate of the battery cost ($\propto < 0$), σ is the volatility ($\sigma > 0$), and dz is the increment of the Wiener process, which captures the randomness in the process.

The growth rate of the battery cost ($\propto$) will be estimated based on the expectations of IEA (2024) and BloombergNEF data (BNEF, 2024). Given the expectation of a decline of 40% by 2030 compared to 2023 and the fact that the cost of batteries declined by 17% between 2023 and 2024, it can be assumed that the cost of lithium-ion batteries will decline approximately by 27.71% over the six years from 2024 to 2030. This implies a growth rate of approximately a -5% annual growth rate for the period between 2025 and 2030 which is close to the BloombergNEF's 3% decrease for only battery packs in 2025 (BNEF, 2024). It also aligns with the expectations of the interviewees in the qualitative study, as most anticipate a decline in costs, but they also expect that the decrease will not be large (Section 4.5).

The volatility (annualized standard deviation of the log returns) of the battery prices between 2013 and 2024 is calculated as approximately 46.75% per year. The volatility between 2018 and 2024 is calculated as approximately 21.39% per year. This period excludes the years with large declines like 2015 but includes the pandemic period. Based on that background, the study will assume a yearly volatility of 20% for battery cost. Table 31 summarizes the investment cost dynamics.

Table 31. Parameters for investment cost dynamics for a 1 MW/ 1 MWh Battery

Parameter	**Value**
Initial Investment Cost ($/MWh)	285,000
Capacity (MWh)	1MW/1MWh
Growth Rate (%)	-5
Volatility (%)	20

For each year in the lifetime of the option, 10,000 paths will be simulated using a Monte Carlo approach. As a result, 10,000*T (including the initial year) number of cost values will be used as input in the LSM method with the price simulations. Figure 26 illustrates the results of simulated paths for 100 paths with the red tick line showing the average.

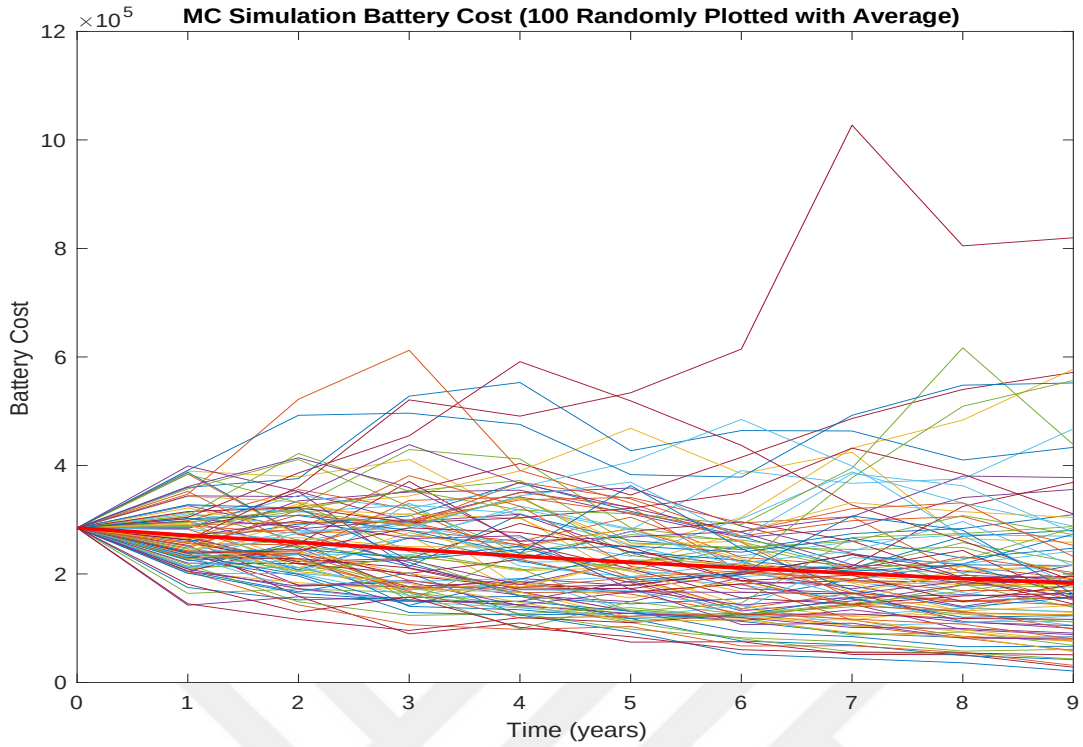


Figure 26. Monte Carlo Battery Cost Simulation for a 1 MW/1 MWh ($/MWh)

5.3.1.2. Modeling the Arbitrage Price

In this case study, the battery is assumed to generate arbitrage revenue from the DAM market through charging in the low-price hours and discharging in high-price hours. In this subsection, the arbitrage revenue will be calculated using annual hourly average price differences.

Figure 27 shows historical differences in nominal US dollars. The difference between maximum and minimum prices saw its peak in 2022 at 55 $/MWh which was followed by a gradual decline in the difference.

Since the arbitrage revenue stream depends on the difference between the maximum and minimum price in a day rather than the level of prices, it is chosen to simulate the price difference instead of simulating hourly DAM prices. Given the net zero emission target of Türkiye, it is expected that the shares of renewables will increase rapidly in the middle to long term. With the increase in renewable penetration,

electricity price levels are expected to decline especially for noon hours. Although the general price level is expected to decline, due to the intermittency of the renewables, the difference between the maximum and the minimum price is expected to increase which will increase the arbitrage revenue SHURA (2024).

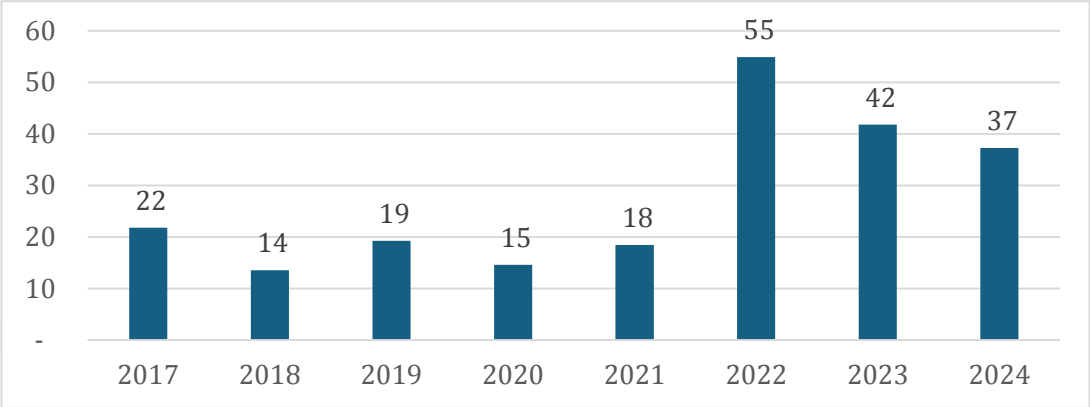


Figure 27. Annual differences between average hourly maximum and minimum in DAM ($/MWh)

(Source: EPİAŞ Transparency Platform)

There are various scenarios regarding the expected share of renewables towards achieving the net zero emission target. As of the end of 2023, the share of renewables in installed power capacity is 56,6%. The NEP released in 2023 projects an increase in the share of renewables to reach 59% in 2025, 62% in 2030, and 65% in 2035 (Ministry of Energy and Natural Resources, 2023). SHURA (2023) expects the share of renewables to exceed 90% by 2055. From SHURA (2024)'s hourly average price expectations figure, I roughly calculated the difference between maximum and minimum average price levels (arbitrage price) as 75 $/MWh in 2030 and 93 $/MWh in 2035 implying a linear increase in the arbitrage price in the case of increase in the share of renewables in line with the expectations.

Monte Carlo simulation for the difference between maximum and minimum average price levels (arbitrage price) will be based on a scenario analysis. Table 32 below summarizes the details of the scenario analysis.

Table 32. Arbitrage price scenarios

Probability	Scenarios	Explanation	Arbitrage Price Modelling
0.2	Advanced Renewables Scenario	Share of renewables exceeds 70% in 2035 and negative prices are allowed	Arbitrage price will move towards 120 $/MWh over time
0.5	NEP Scenario	Share of renewables reach to 65% in 2035	Arbitrage price will move towards 100 $/MWh over time
0.2	Moderate Renewables Scenario	Share of renewables remain below 60% in 2035	Arbitrage price will decline to 20 $/MWh over time
0.1	Volatility Scenario	Unexpected change in the natural gas price, drought, geopolitical risks	Arbitrage price will follow a random walk

Four scenarios are considered in the analyses. Each scenario is assigned a probability. The details of the scenarios are explained below:

- **NEP Scenario**: This scenario assumes that the share of renewables will increase as targeted at the NEP. Given the already achieved level of 56,6% share of renewables by the end of 2023, the probability assigned to this scenario is 50%. Arbitrage price is assumed to move in line with the estimates of SHURA (2024).
- **Advanced Renewables Scenario**: In this scenario, the share of renewables exceeds 70% which is over the targeted level in the NEP. Additionally, with the increase of volatility between hourly prices due to the intermittency of the renewables, it is assumed that negative price levels are allowed. Thus, this scenario assumes that the arbitrage price will be greater than the NEP scenario. A 20% probability is assigned to this scenario reflecting the fact that it is more challenging than the NEP case.
- **Moderate Renewables Scenario:** This scenario assumes that although the share of renewables will increase, it will remain close to its current level and not reach the targeted level in 2035. Thus, the arbitrage price is assumed to continue to fall to 20 $/MWh which is closer to the arbitrage price levels before 2022. A 20% probability is assigned to this scenario reflecting the fact it is more unlikely given the zero emission targets.
- **Volatility Scenario:** This scenario is included to cover the unexpected changes in the conditions that can affect the price levels. A 10% probability is assigned to this scenario.

In the first three scenarios, assuming the share of renewables will increase gradually in the next 10 years, price change is modeled as a linear interpolation from the initial price level. Arbitrage price increases by the yearly change which is calculated as below.

$$Yearly\ Change = \frac{Arbitrage\ Price_{target} - Initial\ Arbitrage\ Price}{Number\ of\ Years} \quad (9)$$

10,000 Monte Carlo simulations for 10 years (including the initial year) are generated based on the arbitrage prices modeled based on the scenarios. 2024 average arbitrage price of 37 $/MWh is used as the initial price. Figure 28 illustrates the results of simulated paths for 100 paths with red tick line showing the average.

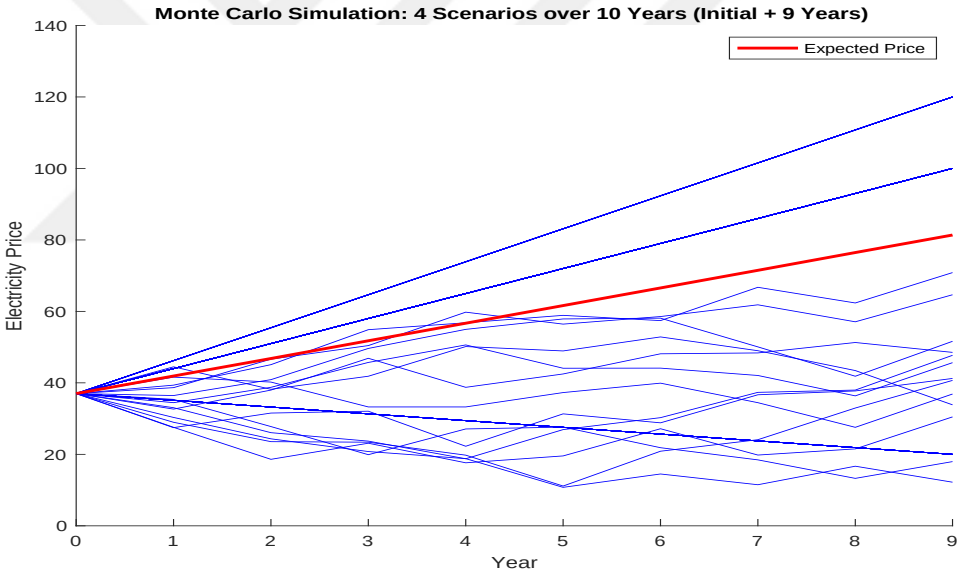


Figure 28. Monte Carlo Simulation for Arbitrage Price ($/MWh)

5.3.1.2. Real Option Valuation

The results for the real option valuation for an LPF battery investment with 1MW/1MWh capacity which generates arbitrage revenue in the DAM are summarized in Table 33 below. The daily marginal opex is assumed to be zero for the sake of simplicity. The results indicate that based on the simulated investment

costs and arbitrage prices, the best strategy is to wait for nine years before investing in the battery. The option has an estimated value of $1,763 per MW which represents the increase in the revenue (premium) by investing in year 9 instead of investing immediately.

Table 33. Results of the Real Option Valuation

Battery capacity	1MW/1MWh
Investment Cost ($)	285,000
Net Present Value ($)	-187,918
Option Life	10
Optimal Time to Invest	9
Option Value ($)	1,763

Although the option to wait has a positive premium, it is only 0.6% of the initial investment cost. In addition, the optimal time to invest is very long. This result suggests that given the large declines in the last decade and the increased penetration of renewables, the value of waiting for an increase in arbitrage price and/or a decline in investment costs is almost zero.

For a hybrid battery, on the other hand, waiting for 9 years to invest would mean forgoing the revenue potential of the wind farm for those years which should also be considered. The annual revenue of the wind farm in Eyupoğlu and Akpınar (2024) is calculated as $153,244 per MWh with 2024 US dollar/TL buying exchange rate. This implies that even in one year, the wind farm generates a revenue stream that is significantly higher than the option value of $1,763 per MWh.

5.3.2. Sensitivity Analysis: A Change in the Regulation

Although the qualitative study revealed that one of the main drivers for battery investment is the latest regulation, it is also one of the reasons causing investors to delay investment since there is an expectation for further supportive changes. More specifically, there is an expectation that the requirement of installing 1MW/1MWh battery for a 1MWh renewable power plant will be relaxed which will lower the initial investment cost (see Section 4.7.2).

A sensitivity analysis will be carried out to consider a new regulation that changes the requirement of 1MW/1MWh battery to 1MW/4MWh battery for a 1MWh power plant. Thus, DCF and real option analyses will be repeated for a battery with a capacity of 1MW/4MWh integrated with a 1MWh wind power plant and the results will be compared to analyze the effect of the change on NPV and the optimal time to invest.

5.3.2.1. Investment Cost Dynamics

In the sensitivity analysis, only the initial investment cost (capex) will be lower to 228,000 $/MW for an LFP battery with four hour (SHURA, 2024) which is 20% lower than the battery with one hour capacity. On the other hand, other parameters and model dynamics will remain the same as in the case study (Table 34).

Table 34. Parameters for investment cost dynamics for a 1 MW/4MWh battery

Parameter	Value
Initial Investment Cost ($/MWh)	228,000
Capacity (MWh)	1MW/1MWh
Growth Rate (%)	-5
Volatility (%)	20

Figure 29 shows the simulated cost paths for a 1 MW/4 MWh using equation (7) which results in a lower average level for battery cost.

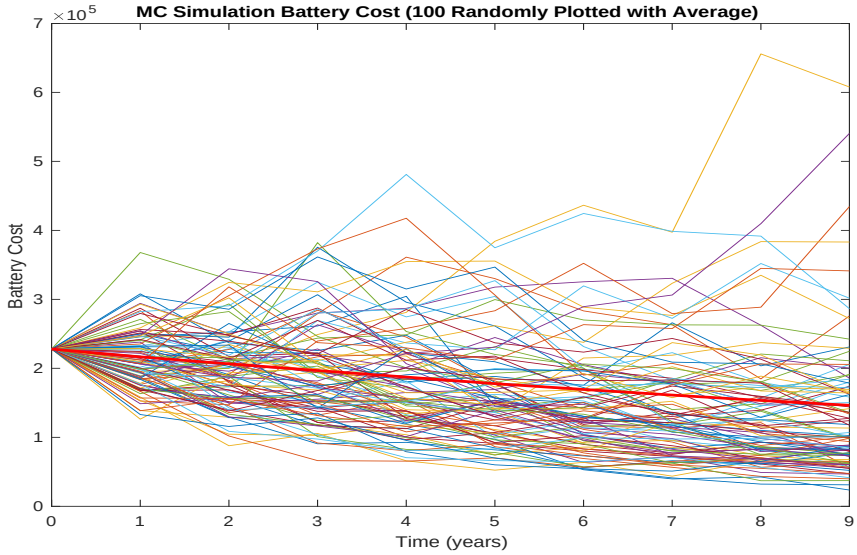


Figure 29. Monte Carlo Battery Cost Simulation for a 1 MW/4 MWh ($/MWh)

5.3.2.2. Arbitrage Price Dynamics

Arbitrage price dynamics will not be affected by the change in the legislation. Arbitrage price scenarios summarized in Table 35 will be used for modeling the arbitrage price uncertainty.

5.3.2.3. Net Present Value

As in the case study, the battery is assumed to generate arbitrage revenue from the DAM market through charging in the low-price hours and discharging in high-price hours. The BESS charges from the grid when the prices are low and sells when the prices are high. Using equations (2) to (6), annual arbitrage revenue, NPV, payback period, and IRR is calculated for a 1MW/4MWh battery. The results are summarized in Table 35 below.

Table 35. Comparison of economic performance

	based on 2024 hourly prices	
Battery capacity	1MW/1MWh	1MW/4MWh
Investment Cost ($)	285,000	228,000
Lifetime in EFC	4000	3000
Round-trip efficiency	0.88	0.88
Marginal Opex ($)	1.8	1.4
Lifetime in Years	10	10
Annual Arbitrage Revenue ($)	12,918	13,048
Discount rate (%)	7	7
Net Present Value ($)	**-187,918**	**-129,943**
Payback Period (years)	22	18
Internal Rate of Return (%)	-13	-9

The results show that, as expected, the reduction in the capex improves the economic performance compared to the battery in the case study. However, the reduction in the capex is not sufficient to yield a positive NPV for a battery generating only arbitrage revenue. The payback period for a 1 MW/4 MWh battery, on the other hand, is

lowered by four years compared to a 1 MW/1 MWh battery although it is still longer than the lifetime of the battery.

5.3.2.4. Real Option Valuation

The results for the real option valuation for an LPF battery investment with 1 MW/4 MWh capacity which generates arbitrage revenue in the DAM are summarized in Table 36 below. The results indicate that based on the simulated investment costs and arbitrage prices, the best strategy is to wait for 9 years before investing in the battery which is the same as the 1 MW/1 MWh battery. The option has an estimated value of $4,341 per MW which represents the increase in the revenue (premium) by investing in year 9 instead of investing immediately (Table 36).

Table 36. Comparison of option value

Battery capacity	1MW/1MWh	1MW/4MWh
Investment Cost ($)	285,000	228,000
Net Present Value ($)	-187,918	-129,943
Option Life	10	10
Optimal Time to Invest	9	9
Option Value ($)	1,763	4,341
Number of in-the-money paths	1,085	2,188

Although there are no changes in the cost and arbitrage price dynamics, a 20% reduction of the initial capital cost resulted in an increase in the option value (for a decrease in the investment cost or an increase in the revenue stream) from $1,763 per MW to $4,341 per MW indicating a 250% increase. Additionally, the results show that the number of in-the-money paths[5] increased from 1,085 to 2,188. Although the option value for delaying the investment decision for more favorable conditions increased significantly for a 1 MW/4 MWh battery, the optimal time to invest is still year nine.

Thus, waiting for a more favorable regulatory environment does not increase the NPV enough to invest earlier. In this case, the value of the option to wait for a

[5] Option is in-the-money if at the final exercise date, the option value is greater than the strike price. In the case of an American option, the option is exercised if it is in the money.

regulatory change relaxing the requirement of 1MW/1MWh battery to 1MW/4MWh battery should be calculated as the increase in the NPV from -$87,918 to -$129,943 per MWh which is earned from delaying the investment. To decide whether to use the option to wait for a more favorable regulatory environment, the option value should be compared with the foregone revenue from not building the wind power plant immediately. The comparison shows that the premium earned from waiting for a more supportive regulatory environment is negative (Table 37) suggesting that even in one year the wind farm generates a revenue stream which is significantly higher than the premium earned.

Table 37. Option value for waiting for a regulatory change

Increase in the NPV (option value) ($/MWh)	57,975
Annual revenue from wind power plant ($/MWh)	153,244
The premium earned from waiting for a change in the regulation ($/MWh)	**-95,269**

This result indicates that the best strategy for the pre-license holder is still to invest immediately (exercise the option immediately) and not wait for a more supportive regulatory environment. In other words, the results of the real option analysis is robust to the mostly anticipated regulatory change.

5.4. Conclusion

Given the net zero emission target and increasing penetration of renewable energy sources, it is important for Türkiye to facilitate the deployment of the ESSs as a flexibility option. However, under current conditions regarding the initial battery cost and electricity price levels, storage investments are not economically feasible yet. On the other hand, recent encouraging regulatory changes, which are perceived as one of the main drivers for energy storage investments, created an investment opportunity for hybrid BESSs which are integrated with renewable power plants.

Contrary to positive NPV for the hybrid BESSs, the qualitative analysis showed that investors wait for more favorable conditions due to uncertainties stemming from the

volatility in electricity price (market-related uncertainties) and investment costs (financing uncertainties), frequent changes in legislation (regulatory uncertainties), and ever-changing nature of the battery technology (technology-related uncertainties). Based on that background, the study developed a real options framework considering electricity price and investment cost uncertainties. The effect of regulatory uncertainty is assessed through a sensitivity analysis.

A simple case study is used to solve the investment problem of a pre-license holder for a hybrid BESS integrated with a wind power plant with the same capacity considering the option to wait. In the case study, the battery is assumed to generate revenue solely from arbitrage in DAM. Initial investment cost dynamics are modeled using a geometric Brownian motion with the parameters taken from data while the price differences between high- and low-price hours are modeled by using a scenario-based simulation.

Real option valuation results show that for a BESS generating arbitrage revenue in DAM, the best strategy is to wait nine years before investing with a positive option value of $1,763 per MW. However, delaying the battery investment for 9 years is equivalent to losing the right to establish a wind power plant within the scope of YEKDEM. Thus, the premium earned from keeping the option alive for nine years should be compared to the revenue potential of the integrated wind power plant. Given the low level of the option value, the revenue potential of the wind power plant far exceeds the value of waiting. The result suggests that under the current conditions, the best strategy for a pre-license holder is to invest immediately (immediate exercise of the option). Additionally, sensitivity analysis shows that the results are robust to the most anticipated regulation change (relaxing the 1 MW/1MWh battery criteria).

CHAPTER 6

CONCLUSION

Given the net zero emission target and increasing penetration of renewable energy sources, it is important for Türkiye to facilitate the deployment of the ESSs as a flexibility option. However, under current conditions regarding the initial battery cost and electricity price levels, storage investments are not economically feasible yet. On the other hand, recent encouraging regulatory changes, which are perceived as one of the main drivers for energy storage investments, created an investment opportunity for hybrid BESSs which are integrated with renewable power plants.

Despite those regulatory measures taken in recent years to promote further deployment of storage systems, there is a lack of investment especially in large-scale ESSs which might negatively affect the transition pace towards cleaner energy systems. Given the importance of increasing the flexibility of the electricity system with the increased penetration of renewable power sources, it is critical to understand the factors affecting investment decisions and develop a realistic investment appraisal model. To meet both needs, this study adopted an integrated approach by mixing qualitative and quantitative methods to evaluate the investment appraisal of energy storage technologies.

The novelty of the study comes from the way of integrating qualitative and quantitative analysis. In this approach, the qualitative and quantitative parts fed each other: The research question of “What is the optimal investment decision?” to be answered in the quantitative part defined the scope of the qualitative analysis. More specifically, this research question gave rise to the research questions of “What are the opportunities and barriers for deployment of ESSs in Türkiye?” and “What are the factors and sources of uncertainties affecting ESS investment decisions, and how

do the investors evaluate ESS investments?". Thus, the design of the interview guide and the selection of interviewees were done based on the data needs of the quantitative model.

The model characteristics in the quantitative analysis were specified in accordance with the data collected in the qualitative analysis. Firstly, qualitative data is used to confirm the theory-led and/or reveal country-specific sources of uncertainty (specifying model assumptions) and the type of flexibilities that the decision-makers have (deciding the real options type) when appraising energy storage investments. Secondly, the research question in the quantitative part is refined to reflect the real-life decision problem of the investor in Türkiye by using the data collected in the early phase of the qualitative study.

Based on the uncertainties and the related managerial flexibilities derived from the results of the qualitative research, a real options framework is developed in the quantitative part. The real options approach is chosen for two main reasons. Firstly, the results of the qualitative research indicate the presence of uncertainties for ESS investments. Secondly, the qualitative analysis also revealed that, albeit unknowingly, investors use real options in practice to deal with those uncertainties. Building on these observations, a real options framework would be better suited than traditional DCF analysis to analyze the optimal investment timing under the conditions of uncertain future revenues and investment costs.

The study's findings should be especially relevant for practitioners and policymakers because unlike the other real options models applied in the literature, the study did not use a priori or theory-led assumptions but built the modeling framework upon the data compiled through a qualitative study. The option to wait is considered as the managerial flexibility in response to economic and policy uncertainties. Using the real options framework, optimal timing for investment is analyzed and the value of the option to wait is quantified. The dissertation used a case study to analyze the effects of electricity price and cost dynamics uncertainties on optimal investment timing. In addition, policy uncertainty is assessed through a sensitivity analysis.

This chapter concludes the dissertation, summarizes and interprets the main findings from qualitative and quantitative analyses, lists the policy implications, and outlines possible future research opportunities.

6.1. Summary of the Main Findings

The global market for battery storage doubled in 2023 and reached over 90 GWh where the growth came mostly from utility-scale systems with the behind-the-meter battery storage (IEA, 2024). Table 38 below shows that, in line with the global energy trends, there is a clear dominance of BESSs among the ESS types while hydrogen energy storage is the second most stated technology. The results also show that most of the interviewees plan to invest in power plant-scale storage systems reflecting the effect of the recent regulation, which sets the deployment of energy storage as a prerequisite for renewable power plants to participate in the YEKDEM scheme, on the investment decisions. The next application area is the grid-scale ESSs which are followed by commercial and industrial applications and electrical vehicle charging stations.

Table 38. ESS technology and scale of deployment

ESS Technology	**Frequency of statements**	**Scale of Deployment**	**Frequency of statements**
BESS	18	Power Plant-scale	13
Hydrogen Energy Storage	5	Grid-scale	9
Renewable Hydrogen Energy Storage	1	Commercial and Industrial	3
Thermal Energy Storage	1	Electrical Vehicle Charging Station	3
		Residential (Home-scale)	1
		Island Mode	1

There are four major benefits to ESSs: (i) smoothing the flow of power, (ii) providing the backup service, improving reliability, (iii) increasing the utilization of

power generation by absorbing power that exceeds current demand, and (iv) smoothing out the costs (D'Aprile et al., 2016). They can prevent renewable energy curtailment by storing excess electricity generated by renewable power plants and reducing reliance on fossil-fuel power plants in the ancillary services market (Shura, 2024). In line with the literature, the results showed that interviewees expect ESSs to play diverse roles in energy markets due to their ability to provide reliability and stability-related functions, flexibility functions, and economic optimization functions. It is observed that interviewees perceive frequency control, demand balancing, and integration of renewables as the main roles of the ESSs in Turkish electricity markets. Next are the stability-related functions such as grid and supply security which are followed by economic functions such as ancillary services and arbitrage. When it comes to the relative significance of the roles, grid security is the most frequently stated role, followed by integration of renewables and frequency control. Economic roles, on the other hand, such as reduction of costs and revenue potential from ancillary services are each mentioned only twice as the most important (Table 39).

Table 39. Main roles and their significance

Main Roles	**Frequency of statements**	**Most Important Role**	**Frequency of statements**
Frequency control	14	Grid security	8
Demand balancing	11	Integration of renewables	5
Integration of renewables	10	Frequency control	5
Grid security	5	Supply security	3
Supply security	5	Time shifting	3
Ancillary services	5	Reduction of costs	2
Arbitrage	4	Other ancillary services	2
Time shifting	4	Demand balancing	1

Table 40 below summarizes the main drivers and barriers. The results show that flexibility- and grid stability-related functions of ESSs along with regulatory and policy support are perceived as the main drivers supporting the further deployment of those systems. Recent encouraging regulatory changes and support mechanisms are as important as the technical functions provided by the ESSs for investment

decisions. Additionally, the reduction of investment costs in recent years and the revenue generation potential especially from ancillary services support ESS investments.

Though ESSs can provide numerous grid services, several barriers restrict their current deployment which can be categorized into regulatory barriers, market (economic) barriers, utility and developer business model barriers, and technology barriers (Sandia, 2013). The responses of the interviewees show that, despite the significant decreases in recent years, high capital cost is still the main barrier against the further deployment of those systems. In addition, regulatory barriers such as insufficiency of regulations/lack of grid code, frequency of changes in regulations, and complexity of the regulations for users together with the unpredictability of the investment cost and technological advancements are also hindering the ESS investments. Furthermore, several other economic barriers exist which are barriers to accessing finance and insufficient revenue potential of these systems from ancillary services. Additionally, unpredictability regarding the investment costs and electricity prices restricts ESS investments.

Table 40. Main drivers and barriers

Main Drivers	**Frequency of statements**	**Main Barriers**	**Frequency of statements**
Integration of renewables	9	High capital cost	25
Support mechanisms	7	Insufficiency of regulations/lack of grid code	11
Encouraging changes in regulation	5	Frequency of changes in regulations	9
Supply security	4	Insufficiency of support mechanism	8
Reduction of Costs	4	Everchanging technology	7
Frequency control	3	Lack of sufficient information about techno-economic characteristics	6
Revenue from other ancillary services	3	Uncertainties regarding electricity prices	6
Time shifting	3	Barrier to accessing finance	5

Table 40. (continued)

	Complexity of the regulations for users	5
	Expectations that costs will decrease	5
	Uncertainty in the technological progress	4
	Insufficient revenue from ancillary services	3

The study shows that unpredictability of the ESS investments mainly stems from regulatory and technological uncertainties. More specifically, insufficiency of regulation and insufficient knowledge about the techno-economic characteristics of storage systems create uncertainty for investors. Additionally, volatility of electricity prices and capital costs are also perceived as important sources of uncertainty affecting the profitability of those investments. Most of the interviewees expect that the decline in the investment costs will continue although there is no consensus on the magnitude of the decrease. Regarding the electricity markets, ancillary services and intra-day markets along with the day-ahead market are anticipated to be most affected by an increase in ESS deployment (Table 41).

Table 41. Uncertainties and expectations

Source of Uncertainty	**Frequency of statements**	**Investment Cost Expectation**	**Frequency of statements**	**Electricity Markets to be Affected**	**Frequency of statements**
Insufficiency of regulations/lack of grid code	16	Decrease	11	Ancillary services	10
Frequency of changes in regulations	9	Increase (in short term)	3	Intra-day market	10
Lack of sufficient information about techno-economic characteristics	9	Decrease (limited extend)	2	Day-ahead market	9
Capital cost (capex)	7	Decrease (large extend)	2	Balancing power market	4

Table 41. (continued)

Price of electricity	6	Not change	2	Curtailment prevention	1
Longevity/life-cycle of batteries	4	Can go either way	2	All	2
Return on investment	4				
Technological advancements	3				
Revenue from storage services	3				

The importance of the operating options becomes more important when there is high uncertainty and the technology is flexible (Kulatilaka, 1993). Table 42 summarizes the capital budgeting methods used for ESS investment appraisal and whether the organizations use the real options approach. The results show that although there are various types of uncertainty in ESS investment decisions, the organizations use DCF analysis with NPV, IRR, and payback period calculations as their capital budgeting methods. Only four interviewees stated the use of the real options approach.

Table 42. Capital budgeting methods

Capital Budgeting Method	**Frequency of statements**	**Use of Real Options Approach**	**Frequency of statements**
Net present value (NPV)	18	Yes	4
Payback period	14	No	16
Internal rate of return (IRR)	14		
Minimum acceptable rate of return (hurdle rate)	7		
Multiple-earnings approach	2		
Longevity/degradation calculation	1		

Although the majority of the interviewees stated that they were not familiar with the real options framework, that study revealed that managerial flexibilities are not ignored in practice. Unknowingly, investors utilize real options in response to the perceived uncertainties. From the responses of the interviewees, it is observed that

investors use the option to wait in response to uncertainties regarding the investment cost; the option to wait, the option to prototype, and the option to invest/build in response to regulatory uncertainties; and the option to prototype in response to technological uncertainties (Table 43).

Table 43. Real options types

Reason (source of uncertainty)	**Real options type**	**Frequency of statements**
Expectations for cost reduction	option to wait	1
Lack of regulatory grid-code/frequency of regulatory changes	option to wait	2
	option to prototype	1
	option to invest/build	1
Lack of sufficient information about techno-economic characteristics/technological developments	option to prototype	2

In summary, the qualitative analysis showed that in the current landscape, the leading ESS type is BESS with the leading application area being storage systems integrated with renewable power plants (hybrid BESS). The results also reveal that although the flexibility and stability-related functions of ESSs along with the encouraging regulatory changes support the deployment of these systems, the economic, regulatory, and technological barriers together with the uncertainties hinder extensive deployment of these systems. The interviewees expect the initial investment costs to decline further and the regulatory environment to change in a more favorable direction. In response to those uncertainties, investors either postpone their investment decisions (use the option to wait) for more favorable conditions or build smaller-scale storage systems (use the option to prototype) for testing purposes. Either case results in a delay in large-scale investment decisions. Drawing from the assessments gathered in the qualitative analysis, a real options framework is developed in the quantitative part to analyze optimal investment strategy and to quantify the value of postponing the investment. The effect of regulatory uncertainty on the optimal investment strategy is analyzed through a sensitivity analysis.

Based on that background, a case study is used to solve the investment problem of a pre-license holder for a hybrid BESS which is integrated with a wind power plant considering the option to wait. In the case study, the battery is assumed to generate revenue solely from arbitrage in DAM. Initial investment cost dynamics are modeled using a geometric Brownian motion with the parameters taken from data and literature while the price differences between high- and low-price hours (arbitrage price) are modeled by using a scenario-based simulation. Investment cost dynamics are estimated based on the expectations of IEA (IEA, 2024) and BloombergNEF data (BNEF, 2024) which are in line with the expectations of the interviewees in the qualitative study, as most anticipate a decline in costs, but they also expect that the magnitude of the decrease will not to be large. To model arbitrage price dynamics, on the other hand, four scenarios are designed which are (i) the NEP scenario which assumes that the share of renewables will increase as targeted at the NEP, (ii) the advanced renewables scenario which assumes that the share of renewables exceeds the target level of NEP, (iii) moderate renewables scenario in which the increase in the share of renewables will lose pace, and (iv) volatility scenario which covers the unexpected changes in the conditions that can affect the energy price levels.

The results show that although investing in BESS is not profitable due to high capital costs and low arbitrage price levels, the NPV of the hybrid BESS is positive. Thus, integrating the BESS with a renewable power plant increases the economic value of storage. However, qualitative analysis reveals that, in the current landscape, investors postpone large-scale investments and wait for more favorable conditions. To analyze optimal investment time and the value of waiting, investing in a hybrid BESS by a pre-license holder is designed as an American call option. In this setup, choosing to invest is equivalent to exercising the option. Real option valuation results show that for a pre-license holder of a hybrid BESS, the revenue potential of the wind power plant far exceeds the value of waiting for a decrease in the initial BESS investment cost or an increase in the arbitrage price. The result suggests that under the current conditions, the best strategy for a pre-license holder is to invest immediately (exercise the option immediately) and not wait for a decrease in investment costs or an increase in the revenue stream.

The qualitative research revealed that in addition to the uncertainties in investment cost and revenue streams, the expectation for further supportive regulatory changes also causes investors to delay their investment decisions. More specifically, there is an expectation that the requirement of installing 1MW/1MWh battery for a 1MWh renewable power plant will be relaxed which will lower the initial investment cost. A sensitivity analysis is designed to consider the effect of this regulatory uncertainty on the results of real options analysis. The results show that, as expected, the reduction in the initial capital cost improves the economic performance compared to the more expensive battery considered in the case study. It also increases the value of waiting for further reduction in capital costs and an increase in arbitrage price. However, annual revenue from the integrated wind power plant outweighs the increase in the NPV earned from postponing the investment decision for a more supportive regulatory change. This result indicates that the best strategy for the pre-license holder is still to invest immediately (exercise the option immediately) and do not wait for a decrease in investment costs, an increase in the revenue stream, or a more supportive regulatory environment. Hence, the results of the real option valuation, which only considers the cost and revenue uncertainties, are robust to the regulatory uncertainties.

The overall summary of the conclusions derived from the integrated analysis are:

- The main drivers behind the storage investments are flexibility- and grid stability-related functions of ESSs along with the regulatory and policy support. Additionally, the reduction of investment costs in recent years and the revenue generation potential especially from ancillary services support ESS investments.
- Regulatory constraints such as insufficiency of regulations/lack of grid code and frequency of changes in regulations are perceived as barriers hindering ESS investments. The unpredictability of the investment cost and technological advancements are other important barriers revealed from the interviews.
- The unpredictability of the ESS investments mainly results from regulatory and technological uncertainties. Additionally, volatility of electricity prices

and capital costs are also perceived as important sources of uncertainty affecting the profitability of those investments.

- Based on this background, this study establishes a real options framework to assess whether the option to wait to invest is optimal. The effect of regulatory uncertainty is assessed through a sensitivity analysis. The model is solved for the worst-case scenario for the BESS (generating only arbitrage revenue).
- The results show that investing in a BESS alone is not economically feasible yet. It becomes feasible in 9 years given the expectations for electricity prices and investment costs. On the other hand, delaying the battery investment for 9 years is equivalent to losing the right to establish a wind power plant within the scope of YEKDEM.
- Investing in a BESS integrated with a RES (hybrid BESS) which is eligible to participate in the feed-in mechanism is economically feasible. Although there is a value of waiting, the optimal investing strategy for hybrid BESS is not to postpone the investment for cost decrease and/or revenue increase. The investment would be profitable anyway. The results are also robust to the most anticipated change in legislation.

6.2. Policy Implications

The policy implications are assessed by leveraging on the suggestions expressed by interviewees to overcome the barriers that challenge further deployment of ESSs. The barriers stated by the interviewees can be allocated into five classes Economic and Financial, Regulatory and Policy, Technical, Unpredictability, and Integration Challenges and Market Design. This sub-section represents the suggestions with the related barrier categories.

Economic and Financial Barriers: The most stated barrier in the Economic and Financial class is “high capital cost” which was stated 25 times (20 of which were stated by beneficiaries). The NPV analysis in the quantitative part supported this observation by showing that BESS is not economically feasible on its own. Additionally, the real options analysis showed that the best strategy is to wait for nine years before investing in the battery which is very long and not compatible with

Türkiye's target of increasing the storage capacity. To overcome this barrier, the government announced legislation that mandates the deployment of energy storage systems for renewable power plants to participate in the YEKDEM scheme. The NPV analysis showed that integrating the BESS with a renewable power plant, as required by the latest regulation, is increasing the economic value of these systems and making the BESS investments economically feasible due to the high revenue potential of the renewable power plant. Real options analysis also showed that the optimal investment strategy is not to wait and invest immediately which is in line with the country's target of increasing storage capacity as a flexibility solution.

Although requiring the renewable power plant investors to integrate BESS to participate in the YEKDEM scheme created an incentive for BESS investments, the interviewees anticipate that only a few pre-licenses held by investors which already have renewable power plant facilities will translate into actual investments due to the "barriers to accessing finance". To overcome this barrier, the respondents suggest government *provide monetary support to the BESS investor* in addition to the existing regulatory supports.

Regulatory and Policy Barriers: Regarding the Regulatory barriers, the interviewees stated "insufficiency of regulations/lack of grid code", "frequency of changes in regulations", and "insufficiency of support mechanism" as the main regulatory barriers. It is observed that the "lack of grid code" together with "frequent changes in regulations" cause investors to postpone their investment decisions to wait for a more favorable regulatory environment. To overcome the insufficiency of regulations/lack of grid code barrier, the respondents expressed the need for *standardization in legislation* and suggested the *release of supplementary regulations* as in the case of renewables. More specifically, one of the interviewees stated that a supplementary regulation similar to Supplementary-18 (Grid Connection Criteria for Wind Energy-Based Production Facilities) would be very useful for investors.

To solve the barriers stemming from frequent changes in regulations, the respondents suggest several measures mostly stated being the *ensuring transparency in financial and political operations*. Respondents also think that *public participation in the*

decision-making process, the *discussion environment open to various actors*, and *the participation of non-governmental organizations* could help to overcome these limitations. To overcome the barriers resulting from the insufficiency of support mechanisms, on the other hand, the suggestions are *providing additional regulatory and monetary support.*

Technical Barriers: In the Technical barriers class, "lack of sufficient information about techno-economic characteristics" was stated six times. Interviewees also perceive "low round-trip efficiency` and "degradation of the ESSs" as the technical limitations that pose challenges against extensive deployment of these systems. Interviewees think that *using more efficient and safer technologies by investors* would help overcome these technical limitations. But they also express the need for *increasing awareness and vision* in technical characteristics of storage systems and *the need for a sub-industry* to facilitate access to the necessary equipment and technical support which might require policy actions such as supporting academic studies on storage systems and designing incentives that accelerates the sub-industry creation.

6.3. Future Research Opportunities

In conclusion, the key findings of this research demonstrate that despite the existence of barriers and uncertainties, investing in a BESS integrated with a RES (hybrid BESS) which is eligible to participate in the feed-in mechanism is economically feasible. Results also show that the optimal investing strategy for hybrid BESS is to invest immediately and not postpone the investment for a cost decrease and/or a revenue increase since the investment would be profitable anyway.

Despite its contributions, the study has limitations due modeling framework for future cost and revenue dynamics. By taking this thesis as a starting point, future research can develop a more comprehensive modeling framework by examining the following dynamics.

- Revenue framework: For the sake of simplicity, the study assumed that the BESS performs one charge-discharge cycle daily and only participates in

DAM. A more realistic revenue model can be developed by optimally dispatching the BESS charge-discharge behavior and allowing the BESS to participate in different electricity markets such as ancillary and balancing power markets.

- Electricity price dynamics: The study considered the effect of the penetration level of renewables on electricity price dynamics but did not analyze the impact of increasing the deployment of storage. Due to their intermittent nature, an increased penetration level of renewables is expected to increase the difference between the maximum and the minimum price levels which increases the future revenue potential and value of waiting before investing. On the other hand, increased deployment of ESSs is expected to lower the price difference by increasing the minimum price (through storing the excess energy when the supply is greater than demand) and lowering the maximum price (through releasing the stored energy when the demand is greater than the supply). By allowing the price dynamics to consider the interaction between the increasing level of renewables and the increasing deployment of storage systems, future research could provide additional insights regarding the optimal investment timing and the benefits of early investments.
- Arrival of new technology: The research revealed that technological advancements create uncertainty and hinder the further deployment of storage systems. However, the approach taken in this study assumed that the technological advancements would only decrease the investment cost but did not examine the potential of new technology arrivals. Modeling the technological uncertainty and capturing the effect of the arrival of new technology on investment decisions could bring meaningful contributions to the discussion.
- Degradation and recyclability issues: This study relied on a simple assumption that the efficiency of the battery does not change during its lifetime and there are no recyclability issues. Considering both issues could be of value.

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APPENDICES

A. REVIEW OF REAL OPTIONS LITERATURE ON ENERGY STORAGE INVESTMENTS

Paper	**Country**	**ESS type**	**Source of uncertainty**	**Real options type**	**Real options valuation model**	**Results obtained**
Hedman and Sheblé (2006)	United States	Pumped hydro storage	wind power	Option to invest	Simulation based numerical model	Hedging with both financial options and storage are financially competitive.
Muche (2009)	Germany	Pumped hydro storage	Volatility and spikes in electricity prices	Option to switch between turbine and pump mode based on the maximization of contribution margin (revenues in turbine mode minus costs in pump mode)	Simulation based numerical model	Real options approach takes the future scope of actions into account and results in a risk appropriate valuation of future cash flows.

Reuter et al. (2012)	Germany and Norway	Pumped hydro storage	Volatility in wind speed and electricity prices	Option to invest (whether wind or wind+storage), option to wait to invest (when)	Recursive dynamic programming	Without substantial public subsidy, the wind technology combined with pumped storage is not profitable.
Xiu and Li (2012)	China	Battery Electric Energy Storage	Not explicit	Option to invest	Recursive dynamic programming	Under the current cost level, li-on battery becomes profitable if social benefits are taken into account.
Kroniger and Madlener (2014)	Germany	Hydrogen storage	Fluctuations in wind speed, electricity prices, and call of minute reserve capacity	Option to wait to invest, option to switch	Simulation based numerical model	A hydrogen storage plant with re-electrification is not economically viable while electricity-to fuel plant (direct trading of hydrogen) can be profitable depending on the level of cost-effectiveness of the devise and variations in the hydrogen price.

Moon (2014)	United States	Not explicit	Characteristics of energy storage systems which are cost, efficiency level (round-trip efficiency, depth of discharge, and loss of energy), and length of operation duration	Option to wait to invest	Analytical model	The more uncertain the profits, the longer the investor needs to wait.
Kitapbayev et al. (2015)	United Kingdom	Thermal storage	Gas price, electricity price	Option to switch	Simulation based numerical model	Resuts exemplify the proposed approach and shows that thermal storage can be significant for flexibility.
Schmitz et al. (2015)	Germany	Compressed air energy storage, carbazole storage, and hydrogen storage	Investment cost, hydrogen price, hydrogen storage cost, uncertainties of R&D projects	Option to abandon	Recursive dynamic programming	Insertion of a real option increases NPVs for all storage options analyzed with different magnitudes for each storage solution.

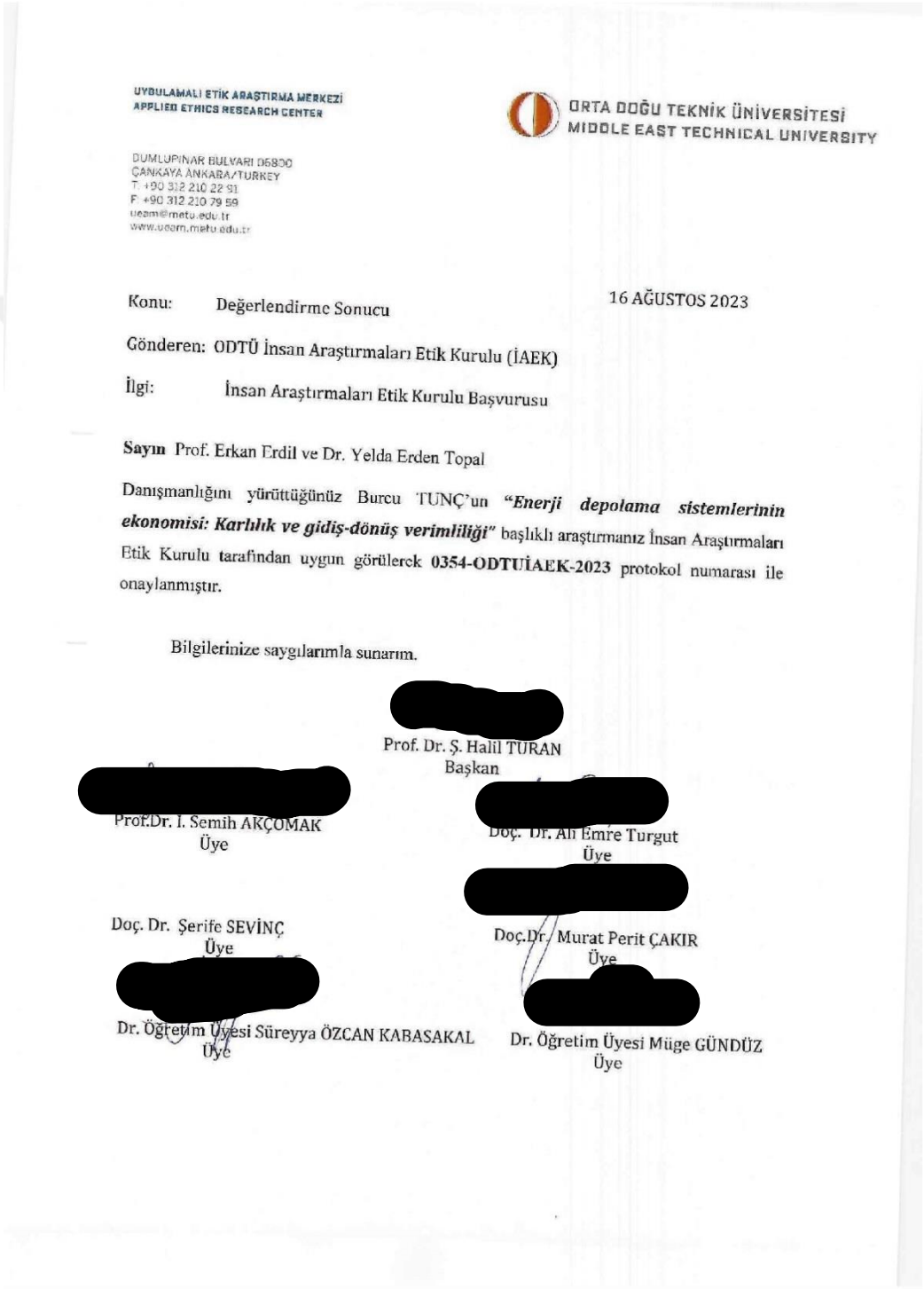
Bakke et al. (2016)	Germany and United Kingdom	Battery Electric Energy Storage	Uncertainty in the cost of battery banks and fluctuations in electricity prices	Option to wait to invest	Simulation based numerical model	There is a “value of waiting” for a decrease in investment costs and battery banks are profitable only if they operate both in spot and balancing market.
Locatelli et al. (2016)	United Kingdom	Pumped hydro storage and compressed air energy storage	Uncertainty in capital costs and value of incentives, and volatility of electricity prices	Option to wait to invest (for a reduction in capital costs), the option to build (postponing the decision to build after the detailed design) and the option to wait to build (waiting to build after detailed design)	Simulation based numerical model	Due to the investment uncertainty, the real options approach evaluates more positively the profitability of the project compared to DCF

Coronel et al. (2017)	Paraguay	Vanadium redox battery	Electricity market (demand, price fluactuations of fuel)	None	None	If the additional flexibility of the technology can be valued, vanadium batteries could be more attractive compared to results from NPV analysis
Hammann et al. (2017)	Germany	Compressed air energy storage	Demand rate for minute reserve, electricity and natural gas spot prices	Option to wait	Recursive dynamic programming	There is a "value of waiting" to gain additional information and NPV underestimates the project value due to the presence of high degrees of uncertainty.
Risthaus and Madlener (2017)	Germany and Spain	Integrated pumped-heat-electricity storage	Fuel price, solar power	Option to invest	Recursive dynamic programming	NPV and real options analysis gives the same results: Under the current market situations. I-PHES applications are not profitable due to the high costs of the storage.

Kelly and Leahy (2020)	Ireland	Battery Electric Energy Storage	Uncertainty in the cost of battery banks, fluctuations in electricity prices, and battery degradation	Timing option (option to wait to invest), swing option (choosing the size)	Deterministic Policy Gradient Algorithm	There is a "value of waiting" to observe capital costs before making the decision on the sizing of the storage capacity.
Lai and Locatelli (2021)	United Kingdom	Wind -driven Thermal Pumping System	Generator capital cost	Option to prototype	Simulation based numerical model	The cost of the prototype and the market size (number of identical systems to build) are the key parameters.
Hu et al. (2022)	Denmark, France, Germany, United Kingdom, Italy, Norway, and Spain	Battery Electric Energy Storage	Fluctuations in electricity prices	Option to switch (where the operational expenses are taken as strike price and the storage option would be exercised when the revenue is higher than the strike price)	Not explicit	Current empirical battery wear cost from degradation prevents battery energy storage systems from being profitable for energy arbitrage in most of the European markets while they have a higher potential for the frequency support services.

Li and Cao (2022)	China	Photovoltaic-energy storage system (PV-ESS)	Electricity price and carbon dioxide price	Compound options (options to wait/abondon in the investment stage and options to wait/expand in the operational stage)	Simulation based numerical model	Both the carbon emission trading market and the auxiliary service market have a positive impact on investment in the PV-ESS projects. Incentive policies also can promote the development of PV-ESSs.
Sun et al. (2023)	China	Battery Electric Energy Storage	Uncertainty in technological innovation, volatility and the expected growth rate of the peak and off-peak power price difference, policy uncertainty	Options to wait	Differential equation method	Policy uncertainty has an impact on the value of energy storage investments while technological innovation can offset that negative effect.

B. APPROVAL OF THE METU HUMAN SUBJECTS ETHICS COMMITTEE



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MIDDLE EAST TECHNICAL UNIVERSITY

Konu: Değerlendirme Sonucu

16 AĞUSTOS 2023

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi: İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Prof. Erkan Erdil ve Dr. Yelda Erden Topal

Danışmanlığını yürüttüğünüz Burcu TUNÇ'un ***"Enerji depolama sistemlerinin ekonomisi: Karlılık ve gidiş-dönüş verimliliği"*** başlıklı araştırmanız İnsan Araştırmaları Etik Kurulu tarafından uygun görülerek **0354-ODTUİAEK-2023** protokol numarası ile onaylanmıştır.

Bilgilerinize saygılarımla sunarım.

[redacted]
Prof. Dr. Ş. Halil TURAN
Başkan

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C. INTERVIEW GUIDE (IN TURKISH))

ENERJİ DEPOLAMA SİSTEMLERİ - NİTELİKSEL SORU FORMU

AÇIKLAMA YAZILACAK – En fazla 1 Paragraf.
(İtalik olanlar: soru formuna girmeyecek. Onlar soruların soranlar için ipucu niteliğinde)

BÖLÜM 1: PROFİL BİLGİSİ:

1. Sizi/ kurumunuzu aşağıdaki seçeneklerden hangisi en doğru tanımlamaktadır? ((Uygun olan tüm seçenekleri işaretleyiniz)

- ☐ Enerji Depolama Sistemleri Üreticisi
- ☐ Enerji Depolama Sistemleri Tasarımcısı
- ☐ Enerji Depolama Sistemleri Geliştiricisi
- ☐ Enerji Depolama Sistemleri Sağlayıcısı
- ☐ Enerji Üreticisi
- ☐ Enerji Dağıtımcısı
- ☐ Perakende Enerji Satıcısı
- ☐ Enerji Ticaret Şirketi
- ☐ Yenilenebilir Enerji Üreticisi
- ☐ Enerji Tüketicisi (Endüstriyel)
- ☐ Enerji Tüketicisi (Ticari)
- ☐ Düzenleyici Kuruluş
- ☐ Entegrasyon Hizmetleri Sağlayıcısı
- ☐ Bakım ve Yönetim Hizmetleri Sağlayıcısı
- ☐ Mühendislik, Tedarik ve İnşaat Hizmetleri (EPC)
- ☐ Araştırma ve Geliştirme Faaliyetleri
- ☐ Sivil Toplum Kuruluşu
- ☐ Akademik ve Araştırma Kurumu
- ☐ Danışman
- ☐ Akademisyen
- ☐ Fon Sağlayan Kuruluş
- ☐ Ticari Banka
- ☐ Yatırımcı
- ☐ Ticari Kuruluş
- ☐ Hukukçu/Hukuk Firması
- ☐ Other (Lütfen belirtiniz)

2. Öğrenim seviyeniz nedir? (Uygun olan tüm seçenekleri işaretleyiniz)

- ☐ Lisans Mezunu
- ☐ Yüksek Lisans (MBA)
- ☐ Yüksek Lisans (İktisat)
- ☐ Yüksek Lisans (MBA ve İktisat dışındaki alanlar)
- ☐ Doktora
- ☐ Diğer *(Sertifika programı vb.)*

BÖLÜM 1.1. Enerji depolama sistemi üreticileri/geliştiricileri/sağlayıcılarına yönelik sorular

3. Hangi tür depolama sistemi alanında faaliyet gösteriyorsunuz? (Pil depolama sistemleri, pompalanabilir Hidroelektrik Depolama (PHES), Yenilenebilir Hidrojen Depolama, Kinetik Enerji Depolama Sistemleri)

4. Pil depolama sistemi alanında faaliyet gösteriyorsanız, türü nedir? (Lityum-iyon piller, kurşun-asit piller, sodyum-sülfür piller ve diğer türler)

BÖLÜM 1.2. Enerji depolama sistemi (potansiyel) kullanıcılarına yönelik sorular (aynı katılımcı hem üreten hem kullanan olabilir)

5. Enerji depolama sistemlerini kullanıyor musunuz?

Bu soruya Evet yanıtını verdiyesiniz 6-8 arasındaki soruları yanıtlayınız, Hayır yanıtını verdiyseniz 9.soruya geçiniz.

6. Hangi tür depolama sistemini kullanıyorsunuz? (Pil depolama sistemleri, pompalanabilir Hidroelektrik Depolama (PHES), Yenilenebilir Hidrojen Depolama, Kinetik Enerji Depolama Sistemleri)

7. Pil depolama sistemi kullanıyorsanız, hangi tür pil kullanıyorsunuz? (Lityum-iyon piller, kurşun-asit piller, sodyum-sülfür piller ve diğer türler)

8. Depolama sistemini hangi amaçla kullanıyorsunuz? (Şebeke Tipi Batarya Enerji Depolama Sistemi, Santral Tipi Batarya Enerji Depolama Sistemi)

9. Enerji depolama sistemlerine yatırım yapmayı planlıyor musunuz?

BÖLÜM 2: ENERJİ DEPOLAMA SİSTEMLERİ GENEL – BETIMSEL DEĞELENDİRME

10. Sizce enerji depolama sistemlerinin, enerji piyasasındaki rolü nedir? (customer energy management services, bulk energy services, ancillary services) (

11. Enerji depolanmanın fayda sağladığı aşaıdaki alanları önemine göre sıralayınız? İlk 10 (en Önemli 10, en az önemli 1)-

☐ Şebeke güvenliği
☐ Arz güvenliği
☐ Frekans regülasyonu
☐ Voltaj desteği
☐ Voltaj regülasyonu
☐ Zaman kaydırması
☐ Talep dengelemesi
☐ Bakım/onarım yatırımlarını ötelemesi
☐ Yenilebilir enerjinin entegrasyonu
☐ Maliyetleri azaltması
☐ Gelir getirici yan hizmetler (ancillary services)

BÖLÜM 3: –DESTEKLER VE ENGELLER

12. Sizce enerji depolama sistemlerinin yaygınlaşmasına destek veren avantajları nelerdir?

☐ Şebeke güvenliği
☐ Arz güvenliği
☐ Frekans regülasyonu
☐ Voltaj desteği
☐ Voltaj regülasyonu
☐ Zaman kaydırması
☐ Talep dengelemesi
☐ Bakım/onarım yatırımlarını ötelemesi
☐ Yenilebilir enerjinin entegrasyonu
☐ Maliyetleri azaltması
☐ Gelir getirici yan hizmetler (ancillary services)
☐ Diğer (Lütfen açıklayınız

13. Sizce enerji depolama sistemlerinin yaygınlaşmasının önündeki engeller nelerdir?

☐ Maliyetin yüksek olması

☐ Düşük çevrim verimliliği

☐ Yardımcı hizmetlerden (ancilliary services) yeterince gelir sağlanmaması

☐ Tekno-ekonomik özellikler hakkında yeterince bilgi sahibi olunmaması

☐ Düzenlemelerin kullanıcılar açısından karmaşık olması

☐ Düzenlemelerin sık değişmesi

☐ Desteklerin yetersiz olması

☐ Destekler hakkında yeterince bilgi sahibi olunmaması

☐ Enerji depolama sistemlerinin hala gelişim aşamasında olması

☐ Maliyetin düşeceği yönündeki beklentiler

☐ Elektrik fiyatlarına ilişkin belirsizlikler

☐ Düşük karbon salınımına yönelik politikaların yarattığı belirsizlikler

☐ Diğer (Lütfen açıklayınız)

14. Sizce bu engelleri ortadan kaldırmak için neler yapılabilir?

15. Bu engellerin tamamı ortadan kalkmış olsaydı, sizce depolama sistemleri nasıl ve hangi yönde gelişmiş olurdu?

BÖLÜM 4: BEKLENTİLER VE BELİRSİZLİKLER

16. Sizce enerji depolama yatırımlarındaki belirsizlik kaynakları nelerdir?

17. Enerji depolama yatırımları maliyetlerine ilişkin beklentileriniz nelerdir? Neden? (Yorumlarınız…)

18. Sizce Enerji depolama yatırımlarını en çok etkilemesi beklenen elektrik piyasasına ilişkin beklentiler nelerdir?

19. Varsa öngördüğünüz diğer belirsizlik kaynakları nelerdir?

BÖLÜM 5: YATIRIM KARARI VE SERMAYE BÜTÇELEMESİ:

20. Enerji depolama sistemlerine yatırım kararını verirken hangi değişkenleridikkate alınmaktadır?

☐ Maliyet

☐ Çevrim Verimliliği

☐ Dayanıklılık (uzun ömür)

☐ Çevreye etkisi

☐ Diğer (Lütfen açıklayınız)

21. Şirketinizde yatırımları ya da projeleri değerlendirirken reel opsiyon analiz yaklaşımını kullanılıyor mu?

☐ Evet

☐ Hayır

22. Şirketinizde sermaye bütçelemesi tekniklerinden hangisi ya da hangileri kullanılmaktadır? (Uygun olan tüm seçenekleri işaretleyiniz)

☐ Net şimdiki değer (NPV)

☐ İç verim oranı (IRR)

☐. Kabul edilebilir en düşük getiri oranı (hurdle rate)

☐. Çoklu kazanç yaklaşımı

☐. Geri ödeme süresi

☐. Diğer (Lütfen açıklayınız)

23. Şirketinizde yatırımlar ya da projeler hangi sıklıkta değerlendirilir?

BÖLÜM 5.1: Reel opsiyon analiz yaklaşımını kullanmayan şirketlere yönelik sorular

24. Reel opsiyon analiz yönteminin çalışma prensipleri ve teknikleri hakkında bilginiz var mı?

☐ Evet

☐ Hayır

25. Şirketiniz reel opsiyon analize yöntemini kullanmama sebebiniz nedir?

☐ Üst yönetim ya da ortakların desteklememesi

☐ Fazla teknik olması

☐ Fazla risk alımını teşvik etmesi

☐. Diğer (Lütfen açıklayınız)

BÖLÜM 5.2: Reel opsiyon analiz yaklaşımını kullanan şirketlere yönelik sorular

26. Şirketiniz reel opsiyon analiz yaklaşımını nasıl kullanmaktadır?

☐. Birincil sermaye bütçeleme tekniği

☐. Birkaç teknikten biri olarak

☐. Diğer yöntemlerden elde edilen sonuçları tamamlamak ve desteklemek amacıyla

☐. Diğer (Lütfen açıklayınız)

27. Şirketiniz hangi kararlar için reel opsiyon analizini kullanmaktadır? (Uygun olan tüm seçenekleri işaretleyiniz)

☐. Yeni ürün tanıtımı

☐. Yeni yatırım kararı

☐. Araştırma ve geliştirme

☐. Birleşmeler veya satın almalar

☐. Yabancı yatırım

☐. Diğer (Lütfen açıklayınız)

28. Şirketinizi hangi reel opsiyon analizinde hangi opsiyon türünü değerlendirmektedir? (Uygun olan tüm seçenekleri işaretleyiniz)

☐. Yatırım/inşa etme opsiyonu

☐ Erteleme/bekleme opsiyonu

☐ Terk etme opsiyonu

☐ Genişletme opsiyonu

☐ Değiştirme opsiyonu

29. Bir yatırım kararı verildikten sonra şirketiniz reel opsiyon analizini kullanmaya devam ediyor mu?

☐ Evet

☐ Hayır

D. CODEBOOK

Code System	Frequency
Code System	923
Capital budgeting	0
9_ Continuing to use real options approach after decision taking	0
9_2 No	2
9_1 Yes	1
8_ Type of real options approach used	0
8_3 Option to expand	1
8_2 Option to defer/wait	1
8_1 Option to invest/built	3
7_ Use area of real options approach	0
7_2 Mergers and Acquisitions	1
7_1 Deciding new investment	3
6_ Use type of real options approach	0
6_1 To complement and support the results obtained from other methods	2
5_ Reason for not using use of real options approach	0
5_8 Lack of flexibilities	2
5_7 Not suitable for the company	1
5_6 Lack of knowledge about the conditions of Türkiye	2
5_5 Using without realizing	1
5_4 Too detailed for the company	3
5_3 Encourages excessive risk-taking	1
5_2 Too technical	3
5_1 Lack of support from senior management or stakeholders	2
4_ Use of real options approach	0
4_2 No	16
4_1 Yes	4
3_ Familiarity with real options approach	0
3_2 No	15
3_1 Yes	6
2_ Evaluation period	0
2_4 Quarterly	1
2_3 Continously	13
2_2 Twice a year	2
2_1 Once a year	1
1_ Fincancial evaluation technique	0

1_6 Longevity/degradation calculation	1
1_5 Payback period	14
1_4 Multiple-earnings approach	2
1_3 Minimum acceptable rate of return (hurdle rate)	7
1_2 Internal Rate of Return (IRR)	14
1_1 Net Present Value (NPV)	18
Investment Decision Criteria	0
3_ Environmental	0
3_3 Safety of the technology	1
3_2 recycling processes	1
3_1 Effects on environment	6
2_ Economic	0
2_3 Taxes	2
2_2 Payback expectation	1
2_1 Cost of energy storage systems	24
1_ Technical	0
1_3 Quality	4
1_2 Longevity	19
1_1 Round-trip efficiency	12
Expectation	0
2_ Electricity markets to be affected	0
2_6 All	2
2_5 Curtailment Prevention	1
2_4 Balancing Power Market	4
2_3 Intra-Day Market	10
2_2 Day-Ahead Market	9
2_1 Ancillary Services	10
1_ Cost of Battery	0
1_6 Can go either way	2
1_5 Not Change	2
1_4 Increase (in short term)	3
1_3 Decrease (large extent)	2
1_2 Decrease (limited extent)	2
1_1 Decrease	11
Uncertainty	0
5_ Supply chain and raw material-related uncertainties	0
5_2 Price of raw materials	1
5_1 Dependency in supply chain	2
4_ Financing uncertainties	0
4_3 Return on investment	4
4_2 Finance cots	2
4_1 Capital cost (capex)	7
3_Market-related uncertainities	0

3_3 Expectations regarding capital cost reductions	2
3_2 Revenue from storage services	3
3_1 Price of electricity	6
2_ Regulatory uncertainties	0
2_2 Insufficiency of regulations/lack of grid code	16
2_1 Frequency of changes in regulations	9
1_ Technology-related uncertainties	0
1_3 Lack of sufficient information about techno-economic characteristics	9
1_2 Longevity/life cycle of batteries	4
1_1 Technological advancements	3
Barrier	0
7_ Direction if removed	0
7_6 Finding Finance	1
7_5 EstablishingHugeStorageSytemsforAncillaryServices	1
7_4 Increase in installed capacity	4
7_3 Increase in the possibility of integration	3
7_2 Easiness in the investment decision	5
7_1 Increase in the battery quality/longevity	2
6_ Suggestion to overcome	0
6_11 Using more efficient and safer technologies	1
6_10 Division of labor	1
6_9 Creating Sub-Industry	1
6_8 Increasing awareness and vision	2
6_7 Public participation to the decision-making process	1
6_6 Governmental monetary support	5
6_5 Regulatory support	11
6_4 Transparency in financial and political operations	4
6_3 Standardization in legislation	5
6_2 Creating a discussion environment with various actors	1
6_1 Participation of NGOs	1
5_Integration challenges and market design	0
5_1 Inadequate infrastructure and connection capacity	1
4_Unpredictability	0
4_7 Dependence on critical materials	1
4_6 Uncertainty in the supply chain	2
4_5 Uncertainty in the technological progress	4
4_4 Uncertainty of life-cycle	2
4_3 Everchanging technology	7
4_2 Uncertainties regarding electricity prices	6
4_1 Expectations that costs will decrease	5
3_Regulatory and policy	0
3_5 Rigid structures due to regulations	1

3_4 Insufficiency of support mechanism	8
3_3 Complexity of the regulations for users	5
3_2 Insufficiency of regulations/lack of grid code	11
3_1 Frequency of changes in regulations	9
2_ Economic and financial constraints	0
2_4 Complicated revenue model	1
2_3 Barrier to accessing finance	5
2_2 Insufficient revenue from ancillary services	3
2_1 High capital cost	25
1_Technical limitations	0
1_3 Degradation	1
1_2 Lack of sufficient information about techno-economic characteristics	6
1_1 Low round-trip efficiency	1
Driver	0
5_ Regulatory and policy support	0
5_2 Support mechanisms	7
5_1 Encouraging changes in regulation	5
4_ Technological advancements	0
4_1 Decreases in the battery costs	1
3_ Economic drivers	0
3_5 Profit	2
3_4 Reduction of costs	4
3_3 Deferral of maintenance/repair investments	1
3_2 Revenue from other ancillary services	3
3_1 Energy arbitrage	1
2_ Flexibility-related drivers	0
2_4 preventing curtailment	2
2_3 Demand balancing	2
2_2 Time shifting	3
2_1 Integration of renewables	9
1_ Grid stability-related drivers	0
1_3 Frequency control	3
1_2 Supply security	4
1_1 Grid security	3
Significance	0
3_ Third important	0
3_9 Capacity management	1
3_8 Other ancillary services is third important	2
3_7 Reduction of costs is third important	1
3_6 Integration of renewables is third important	3
3_5 Demand balancing is third important	3
3_4 Time shifting is third important	4

3_3 Frequency control is third important	8
3_2 Supply security is third important	1
3_1 Grid security is third important	1
2_ Second important	0
2_6 Other ancillary services is second important	3
2_5 Integration of renewables is second important	5
2_4 Demand balancing is second important	3
2_3 Frequency control is second important	3
2_2 Supply security is second important	6
2_1 Grid security is second important	4
1_Most important	0
1_8 Other ancillary services is most important	2
1_7 Reduction of costs is most important	2
1_6 Integration of renewables is most important	5
1_5 Demand balancing is most important	1
1_4 Time shifting is most important	3
1_3 Frequency control is most important	5
1_2 Supply security is most important	3
1_1 Grid security is most important	8
Role of ESS	0
3_Economic optimization functions	0
3_3 Ancillary Services	5
3_2 Reduction of costs	2
3_1 Arbitrage	4
2_Flexibility functions	0
2_4 Self balancing	1
2_3 Demand balancing	11
2_2 Time shifting	4
2_1 Integration of renewables	10
1_Reliability and stability functions	0
1_3 Supply security	5
1_2 Grid security	5
1_1 Frequency control	14
Profile	0
7_Planning to invest	0
7_2 no	7
7_1 yes	11
6_Scale of deployment	0
6_6 Island mode	1
6_5 electrical vehicle charing station	3
6_4 commercial and industrial	3
6_3 residential (home-scale)	1
6_2 power plant-scale	13

6_1 grid-scale	9
5_ Type of BESS based on technology	0
5_5 LPF	2
5_4 Lead-Acid Batteries	2
5_3 Flow Batteries	2
5_2 Sodium-Sulfur (NaS) Batteries	2
5_1 Lithium-Ion (Li-ion) Battery Energy Storage Systems	21
4_Type of ESS based on technology	0
4_5 All	1
4_4 Hydrogen Energy Storage	5
4_3 Thermal Energy Storage	1
4_2 Renewable Hydrogen Energy Storage	1
4_1 Battery Electric Energy Storage	18
3_Field of ESS activity	0
3_14 developer	3
3_13 organizing seminars	1
3_12 research	2
3_11 re-use and recycling	2
3_10 system design	1
3_9 technical specification	1
3_8 software	3
3_7 feasibility	1
3_6 consultancy	4
3_5 producer	4
3_4 designer	5
3_3 provider	4
3_2 potential user	3
3_1 user	6
2_Education level	0
2_5 MBA	2
2_4 PhD	7
2_3 MS	9
2_2 BS (3rd degree)	1
2_1 BS	9
1_Area of business activity	0
1_10 research and development	4
1_9 news platform	3
1_9 think-thank/non-profit	1
1_8 researcher	1
1_7 consultancy firm	4
1_6 energy storage systems provider	9
1_5 energy storage systems developer	9
1_4 energy storage systems designer	8

1_3 energy storage systems producer	6
1_2 power plant	9
1_1 power producer	6

E. MATLAB CODES

In this appendix, Matlab codes used for cost dynamics, arbitrage price dynamics, and LSM algorithm analyses are given.

- **Battery Cost Simulation (1MW/1MWh)**

```
% Parameters
I0 = 285000;        % initial battery cost
alpha = -0.05;      % drift coefficient
sigma = 0.2;        % volatility coefficient
T = 9;              % total simulation time (year 0 to year 9 equals 10 years)
dt = 1;             % time step in years
N = T/dt + 1;       % number of time steps (10 steps: 0 through 9)
time = 0:dt:T;      % time vector

% Number of simulation paths
numPaths = 10000;

% Preallocate matrix for the paths
I = zeros(numPaths, N);
I(:,1) = I0;

% Monte Carlo simulation of GBM paths
for t = 2:N
    dW = sqrt(dt) * randn(numPaths, 1);  % Brownian increments
    I(:,t) = I(:,t-1) .* exp((alpha - 0.5 * sigma^2)*dt + sigma * dW);
end

% Compute average cost across all simulation paths
avgCost = mean(I, 1);

% Randomly select 100 simulation paths for plotting
plotIndices = randperm(numPaths, 100);

% Plot the randomly selected paths and the average cost curve
figure;
plot(time, I(plotIndices, :)', 'LineWidth', 0.5); hold on;
plot(time, avgCost, 'r', 'LineWidth', 2);  % average cost plotted in red
xlabel('Time (years)');
ylabel('Battery Cost');
title('MC Simulation Battery Cost (100 Randomly Plotted with Average)');
grid on;

% Export simulation results to Excel
```

```
outputMatrix = [time' I'];
filename = 'battery_cost_simulation_1mwh_final.xlsx';
writematrix(outputMatrix, filename);
fprintf('Simulation results have been exported to %s\n', filename);
```

- **Battery Cost Simulation (1MW/4MWh)**

```
% Parameters
I0 = 228000;        % initial battery cost
alpha = -0.05;      % drift coefficient
sigma = 0.2;        % volatility coefficient
T = 9;              % total simulation time (year 0 to year 9 equals 10 years)
dt = 1;             % time step in years
N = T/dt + 1;       % number of time steps (10 steps: 0 through 9)
time = 0:dt:T;      % time vector

% Number of simulation paths
numPaths = 10000;

% Preallocate matrix for the paths
I = zeros(numPaths, N);
I(:,1) = I0;

% Monte Carlo simulation of GBM paths
for t = 2:N
    dW = sqrt(dt) * randn(numPaths, 1);  % Brownian increments
    I(:,t) = I(:,t-1) .* exp((alpha - 0.5 * sigma^2)*dt + sigma * dW);
end

% Compute average cost across all simulation paths
avgCost = mean(I, 1);

% Randomly select 100 simulation paths for plotting
plotIndices = randperm(numPaths, 100);

% Plot the randomly selected paths and the average cost curve
figure;
plot(time, I(plotIndices, :)', 'LineWidth', 0.5); hold on;
plot(time, avgCost, 'r', 'LineWidth', 2);  % average cost plotted in red
xlabel('Time (years)');
ylabel('Battery Cost');
title('MC Simulation Battery Cost (100 Randomly Plotted with Average)');
grid on;

% Export simulation results to Excel
outputMatrix = [time' I'];
filename = 'battery_cost_simulation_4mwh_final.xlsx';
```

```
writematrix(outputMatrix, filename);
fprintf('Simulation results have been exported to %s\n', filename);
```

- **Arbitrage Price Dynamics**

```
%% Monte Carlo Simulation for 4 Scenarios over 10 Years (P_low = 20)
clc; clear; close all;

% Parameters
P0 = 37;            % Initial price level
P_high = 120;       % Target price for Scenario 1
P_mid = 100;        % Target price for Scenario 2
P_low = 20;         % Target price for Scenario 3 (changed from 30 to 20)
p1 = 0.20;          % Probability for Scenario 1 (20%)
p2 = 0.50;          % Probability for Scenario 2 (50%)
p3 = 0.20;          % Probability for Scenario 3 (20%)
p4 = 0.10;          % Probability for Scenario 4 (10%)
years = 10;         % Time horizon (years, including year 0)
num_simulations = 10000;  % Number of Monte Carlo simulations

% Calculate yearly increments for the deterministic scenarios:
increment1 = (P_high - P0) / years;  % Scenario 1 increment
increment2 = (P_mid - P0) / years;     % Scenario 2 increment
increment3 = (P_low - P0) / years;     % Scenario 3 increment (negative value since
P_low < P0)

% Preallocate matrix to store simulation results (each row = one simulation)
price_paths = zeros(num_simulations, years + 1);  % Columns: Year 0 to Year 10

% Run Monte Carlo simulation
for i = 1:num_simulations
   price_paths(i,1) = P0;  % Set initial price at Year 0
   r = rand();  % Draw a random number to choose the scenario for this simulation

   if r < p1
      % Scenario 1: Linear growth to 120
      for t = 2:years+1
         price_paths(i,t) = price_paths(i,t-1) + increment1;
      end
   elseif r < p1 + p2
      % Scenario 2: Linear growth to 100
      for t = 2:years+1
         price_paths(i,t) = price_paths(i,t-1) + increment2;
      end
   elseif r < p1 + p2 + p3
      % Scenario 3: Linear decline to 20
      for t = 2:years+1
```

```
            price_paths(i,t) = price_paths(i,t-1) + increment3;
        end
    else
        % Scenario 4: Random walk
        % Each year, the price change is drawn from a uniform distribution between -10
and 10.
        for t = 2:years+1
            delta = -10 + (10 - (-10)) * rand(); % Uniform random step in [-10,10]
            price_paths(i,t) = price_paths(i,t-1) + delta;
        end
    end
end

% Compute expected price path (mean across simulations) for each year
expected_price = mean(price_paths, 1);

% Plot a subset (e.g., 100 paths) and the expected price path
figure;
hold on;
num_to_plot = min(100, num_simulations);  % For clarity, plot only 100 sample
paths
for i = 1:num_to_plot
    plot(0:years, price_paths(i,:), 'b', 'LineWidth', 0.5, 'HandleVisibility','off');
end
plot(0:years, expected_price, 'r', 'LineWidth', 2, 'DisplayName', 'Expected Price');
xlabel('Year');
ylabel('Electricity Price');
title('Monte Carlo Simulation: 4 Scenarios over 10 Years (P_{low} = 20)');
legend;
grid on;
hold off;

% Export the results to an Excel file
filename = 'MC_Scenarios.xlsx';
Years = (0:years)'; % Column vector of years

% Create table for expected price per year
T_expected = table(Years, expected_price', 'VariableNames', {'Year',
'Expected_Price'});
writetable(T_expected, filename, 'Sheet', 'ExpectedPrice');

% Create table for all simulation paths
colNames = strcat('Year_', string(0:years));
T_paths = array2table(price_paths, 'VariableNames', colNames);
writetable(T_paths, filename, 'Sheet', 'SimulationPaths');

disp(['Monte Carlo simulation results saved to ', filename]);
```

- **LSM Algorithm**

```
%% LSMC for Storage Investment Real Option Valuation with Overall Optimal
Exercise Time
% Assumptions:
% - 1 MW storage unit with 0.88 roundtrip efficiency.
% - Annual energy throughput = 365 * 0.88 MWh.
% - Simulated price data in "prices_data_4scenario.xlsx" (nPaths x 10 years).
% - Simulated cost data in "battery_cost_1mwh_final" (nPaths x 10 years).
% - Discount rate is 7% per year.

clear; clc;

%% Parameters
r = 0.07;                    % Discount rate (7%)
efficiency = 0.88;               % Roundtrip efficiency
annualEnergy = 365 * efficiency;   % Annual energy throughput (MWh)
T = 10;                      % Time horizon in years
priceFile = 'prices_data_4scenario.xlsx';    % Excel file for simulated prices ($/MWh)
costFile  = 'battery_cost_1mwh_final.xlsx';      % Excel file for simulated investment
costs

%% Load Data
% Each Excel file is assumed to have dimensions [nPaths x T] without headers.
price_data = readmatrix(priceFile);  % Simulated prices, size: [nPaths x T]
cost_data  = readmatrix(costFile);   % Simulated costs, size: [nPaths x T]
[nPaths, nYears] = size(price_data);
if nYears ~= T
   error('Price data must have %d columns corresponding to %d years.', T, T);
end

%% Calculate Annual Revenue
% revenue(i,t) = price(i,t) * (365 * efficiency)
revenue = price_data * annualEnergy;  % [nPaths x T]

%% Compute Present Value (PV) of Future Revenues
% PV_revenue(i,t) = sum_{k=t}^{T} [revenue(i,k) / (1+r)^k]
PV_revenue = zeros(nPaths, T);
for i = 1:nPaths
   for t = 1:T
      discountFactors = (1+r).^(t:T);
      PV_revenue(i,t) = sum( revenue(i,t:T) ./ discountFactors );
   end
end

%% Compute Discounted Investment Cost (Strike Price)
% Discounted cost if investing in year t: cost(i,t)/(1+r)^t.
discountedCost = zeros(nPaths, T);
for t = 1:T
```

```
    discountedCost(:,t) = cost_data(:,t) / ((1+r)^t);
end

%% Compute Immediate Exercise Payoff
% immediatePayoff(i,t) = PV_revenue(i,t) - discountedCost(i,t)
immediatePayoff = PV_revenue - discountedCost;

%% LSMC Backward Induction with Centering & Scaling
% V(i,t) will hold the option value (from time 0 perspective) for each simulation path
at time t.
V = zeros(nPaths, T);

% At maturity (year T), the option value equals the immediate payoff if positive.
V(:,T) = max(immediatePayoff(:,T), 0);

% Loop backwards from t = T-1 down to 1.
for t = T-1:-1:1
    % Identify in-the-money paths at time t (i.e. immediate payoff > 0).
    inTheMoney = immediatePayoff(:,t) > 0;

    % For these paths, regress V(:,t+1)/(1+r) on price_data(:,t).
    X = price_data(inTheMoney,t);
    Y = V(inTheMoney,t+1) / (1+r);

    if ~isempty(X)
        % Center and scale X.
        X_mean = mean(X);
        X_std = std(X);
        if X_std == 0
            X_std = 1; % Avoid division by zero if all X values are identical.
        end
        X_scaled = (X - X_mean) / X_std;

        % Fit a first degree polynomial (linear fit): Y = beta0 + beta1*X_scaled.
        coeffs = polyfit(X_scaled, Y, 1);

        % Evaluate the estimated continuation value on all paths at time t.
        continuation_est = polyval(coeffs, (price_data(:,t) - X_mean) / X_std);
    else
        continuation_est = zeros(nPaths, 1);
    end

    % Compute the continuation value by discounting the next period's option value.
    contValue = V(:,t+1) / (1+r);

    % Exercise decision: if the immediate payoff exceeds the estimated continuation
value, exercise.
    exercise_now = immediatePayoff(:,t) > continuation_est;
```

```
    % Set option value at time t:
    % If exercise is optimal, use immediate payoff; otherwise, use the continuation
value.
    V(:,t) = contValue;
    V(exercise_now,t) = immediatePayoff(exercise_now,t);
end

%% Determine Optimal Exercise Time for Each Simulation Path
% For each simulation, the optimal exercise time is approximated as the first time
% when the option value equals (within a small tolerance) the immediate exercise
payoff.
optimalExerciseTime = zeros(nPaths, 1);
tol = 1e-6;
for i = 1:nPaths
    % Find the earliest time where V equals immediate payoff.
    exerciseIdx = find(abs(V(i,:) - immediatePayoff(i,:)) < tol, 1, 'first');
    if isempty(exerciseIdx)
        % If no exercise occurs, assume exercise at T.
        optimalExerciseTime(i) = T;
    else
        optimalExerciseTime(i) = exerciseIdx;
    end
end

%% Determine One Overall Optimal Time to Invest
% One approach is to aggregate the individual optimal times.
% Here, we take the mean and round to the nearest whole year.
overallOptimalTime = round(mean(optimalExerciseTime));
fprintf('The overall optimal time to invest is: %d years\n', overallOptimalTime);

%% Compute the Overall Option Value
% The option value at time 0 is the average of V(:,1) over all simulation paths.
optionValue = mean(V(:,1));
fprintf('The estimated option value is: %f\n', optionValue);

%% Export Results to Excel
% Create a table that includes:
%   - Simulation number,
%   - Option value at time 0 for that simulation,
%   - Optimal exercise time for that simulation.
simIndex = (1:nPaths)';
resultsTable = table(simIndex, V(:,1), optimalExerciseTime, ...
    'VariableNames', {'Simulation', 'OptionValue_Time0', 'OptimalExerciseTime'});
writetable(resultsTable, 'LSMC_results_1mwh_scenario_firstdegree.xlsx');

% Additionally, write the overall optimal time and option value into a separate file or
sheet.
summaryTable = table(overallOptimalTime, optionValue, ...
    'VariableNames', {'OverallOptimalTime', 'OverallOptionValue'});
```

```
writetable(summaryTable, 'LSMC_summary_1mwh_scenario_ firstdegree.xlsx');

fprintf('Individual simulation results have been exported to
LSMC_results_1mwh_scenario_ firstdegree.xlsx\n');
fprintf('Overall summary results have been exported to
LSMC_summary_1mwh_scenario_ firstdegree.xlsx\n');
```

F. CURRICULUM VITAE

PERSONAL INFORMATION

Surname, Name: Tunç, Burcu

EDUCATION

Degree	Institution	Year of Graduation
MA	Boston University, Economic Policy	2010
BS	Hacettepe Unıversity, Economics (English)	2002

WORK EXPERIENCE

Year	Place	Enrollment
May 2024-Present	Central Bank of the Republic of Türkiye, Data Governance and Statistics Department, Monetary and Financial Data Division	Director
July 2023-May 2024	Central Bank of the Republic of Türkiye, Data Governance and Statistics Department, Monetary and Financial Data Division	Senior Specialist
June – September 2016	The Bank for International Settlements, Irving Fisher Committee on Central Bank Statistics	Visiting Statistician
April 2005 -July 2023	Central Bank of the Republic of Türkiye, Statistics Department, Monetary and Financial Data Division	Specialist
February 2004 – March 2005	Ziraat Bank, Credit Analysis Department	Assistant Specialist

LANGUAGES

English (writing, reading, and verbal proficiency), Turkish (Native)

PAPERS AND PROCEEDINGS

Methodological Studies

- "The fintech market in Turkey: statistical implications", A case study in the *IFC Report*, no 12, pp. 43-46, 2020.
- "Using financial accounts: A central banking perspective" (with B. Tissot, B. Çakmak and C. Gökçe Zeybek), *Statistical Journal of the IAOS*, vol. 36, no. 4, pp. 1223-1237, 2020.
- "Exchange Rate Effect on Monetary Aggregates: How Do We Adjust?" (with A. Tarman Topkaya, C. Gökçe Zeybek), *CBRT Blog*, March 2019.
- "Measuring the foreign exchange position for the corporate sector: CBRT's experience" (with A. Aslan), paper submitted for the *Eighth IFC Conference*, Basel, 8-9 September 2016 (presented by co-author).

Conference Proceedings

- "Using financial accounts" (with B. Tissot, B. Çakmak and C. Gökçe Zeybek), *IFC Bulletin*, No 51, 2020.
- "Statistical implications of the new financial landscape" (with B. Tissot), *IFC Bulletin*, No 43, 2017.
- "Assessing international capital flows after the crisis" (with B. Tissot), *IFC Bulletin*, No 42, 2017.

G. TURKISH SUMMARY / TÜRKÇE ÖZET

2015 Paris İklim Anlaşması, küresel ortalama sıcaklık artışını sanayi öncesi seviyelere kıyasla bu yüzyılda 2°C'nin altında tutmak için küresel fosil CO2 emisyonlarında keskin bir azalma çağrısında bulunmuştur; bu hedef gelişmiş ülkeler için geçerlidir. Derin dekarbonizasyon olarak adlandırılan bu tür iddialı dekarbonizasyon hedeflerine ulaşmak, bölgesel ve ulusal enerji sistemlerinde köklü yapısal değişiklikler gerektirecektir (Borasio & Moret, 2022).

Elektrik sistemlerinin dekarbonizasyonu tipik olarak iki strateji içerir: i) mevcut sistemin enerji verimliliğini artırmak, ii) karbon yoğunluğu yüksek üretim kaynaklarını yenilenebilir enerji, nükleer enerji ve karbon yakalama ve depolama teknolojisine sahip santraller gibi düşük veya sıfır karbonlu üretim kaynaklarıyla değiştirmek. Ancak, yenilenebilir enerjilerin elektrik sistemine entegrasyonunun temel zorluğu, yenilenebilirlerden elde edilen değişken enerji üretimiyle arz ve talep dengesini sağlamaktır. Yakıtla çalışan santrallerde, kontrol edilebilir bir faktör, yani santrale sağlanan yakıt miktarı, elektrik üretimini belirlerken, yenilenebilir enerji üretiminde, güneş ışığı ve rüzgar hızı gibi değişken faktörler elektrik üretimini belirler (Jafari et al., 2022). Bu sorun, enerji depolama sistemlerinin kullanımıyla, enerji arz ve talebini sürekli olarak dengeleyerek çözülebilir (Zhang et al., 2021).

Enerji depolama sistemleri (EDS'ler), enerjiyi emip ardından serbest bırakarak, enerjinin bir kez üretilip başka bir zaman kullanılmasını sağlar. EDS'lerin dört temel faydası vardır: (i) güç akışını düzleştirme, (ii) yedekleme hizmeti sağlama, güvenilirliği artırma, (iii) mevcut talebi aşan gücü emerek enerji üretiminin kullanımını artırma ve (iv) maliyetleri azaltma (D'Aprile et al., 2016). Düşük karbonlu kaynakların mevcudiyeti, enerji sektörü dekarbonizasyonunun maliyetini ve dolayısıyla iklim değişikliğiyle mücadele çabalarının toplam maliyetini kontrol altında tutmak açısından önemli bir faktördür (Sepulveda et al., 2018). Düşük karbonlu esnek üretim teknolojileri ve iletim ağı genişlemesiyle birlikte, enerji depolama, yenilenebilir enerji üretiminin daha yüksek penetrasyonunu sağlamak için

etkili bir esneklik kaynağı olarak hizmet edebilir (Jafari et al., 2022). Özellikle batarya elektrikli enerji depolama sistemleri (BEDS'ler), son on yılda maliyetlerinin keskin bir şekilde düşmesi ve performans özelliklerinin iyileşmesi sayesinde düşük emisyonlu enerji sistemlerine geçişte kritik bir rol kazanmıştır (IEA, 2024).

Uygulama açısından, enerji santraliyle entegre edilen EDS'ler (hibrit enerji depolama sistemleri (HEDS)), şu faydaları sağladığı için önem kazanmaktadır: (i) üretim yönetiminden gelen enerji değeri, zaman içinde fiyat farklarına dayanarak – elektrik, aşırı üretim dönemlerinde (spot piyasada düşük fiyatlar) depolanır ve yüksek talep dönemlerinde (yüksek fiyatlar) üretilir, (ii) yedek santral olarak hizmet verme yeteneğinden gelen kapasite değeri ve (iii) frekans düzenlemesi, voltaj düzenlemesi gibi sunabilecekleri yardımcı hizmetlerden gelen dengeleme değeri (Després et al., 2017).

Uluslararası Enerji Ajansı (IEA, 2024) verilerine göre, 2023'te batarya depolama küresel pazarı iki katına çıkarak 90 Gigawatt-saat (GWs) seviyesini geçti. Büyüme, büyük ölçüde şebeke ölçeğindeki sistemlerden gelirken ve sayaç arkası depolama, büyümenin %35'ini oluşturmuştur (IEA, 2024).

EDS'ler, karbon salınımının azaltılması ve enerji bağımsızlığı endişeleri ile ilişkili olarak enerji üretim ve tüketim desenlerinde bir değişim talebinin artmasıyla daha fazla önem kazanmaktadır. Yapılan ön literatür taraması, EDS'lerin, aralıklı yenilenebilir enerji kaynaklarıyla birleştiğinde esneklik ve verimlilik sağladığını ve bu nedenle bu hedeflere ulaşılmasına yardımcı olabileceğini göstermektedir. Yenilenebilir enerji kullanımının artırılmasında özellikle faydalı olmalarına rağmen, EDS'lerin etkin bir şekilde yaygınlaştırılmasına yönelik maliyet/karlılık ve verimlilik (çevrim verimliliği) gibi önemli zorluklar bulunmaktadır.

Bu tezdeki ana hedef, EDS'lerin ekonomik potansiyelini, anahtar paydaşların perspektifinden değerlendirirken, bu sistemlerin ekonomik değerini, yatırım değerlendirmesini ve geniş çapta yayılmasını etkileyen faktörleri ortaya koymaktır. Depolamanın ekonomik değerini anlamaya yardımcı olmak için, bu çalışma nitel ve nicel analizlerin birleşimini içeren bir yaklaşım kullanacaktır.

Bu araştırma, ESS'lerin ekonomisi üzerine mevcut literatürü şu şekilde genişletmeyi amaçlamaktadır:

- Mevcut durumu geniş bir perspektiften inceleyerek, enerji depolama yayılımı için engelleri ve fırsatları anlamak,
- Enerji depolama sistemlerinin ekonomik değerini etkileyen faktörleri bulmak,
- Uzmanların bakış açısına göre belirsizlikleri ve beklentileri araştırmak,
- Enerji depolama sistemlerine yapılan yatırımların ekonomik analizini yapmak.

Temmuz 2021'de Türkiye, Yeşil Mutabakat Eylem Planını açıklayarak daha sürdürülebilir bir ekonomi için hedefleri ve planlanan eylemleri belirlemiştir. 19 Ocak 2023 tarihinde, Türkiye Cumhuriyeti Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), Ulusal Enerji Planı (NEP)'nı yayımlayarak, Türkiye'nin kurulu elektrik kapasitesinin 2035 yılına kadar yaklaşık 190 GW'a ulaşmasını hedeflemiştir. Plan, bu kapasitenin yaklaşık %65'inin—52,9 GW'ının güneş enerjisinden ve 29,6 GW'ının rüzgar enerjisinden—yenilenebilir kaynaklardan sağlanmasını öngörmektedir.

Türkiye'nin ekonomisini büyük ölçüde karbon salınımından arındırması ve Net-Sıfır hedefine 2050'lerin başında yaklaşması mümkündür, ancak bunun için orta ve uzun vadeli açık ve ölçülebilir hedeflerin belirlenmesi gerekmektedir. Elektrik üretiminde yenilenebilir enerji payı ile ilgili olarak belirlenen hedefler şunlardır:

- 2030 yılına kadar kurulu elektrik kapasitesinde yenilenebilir enerjinin payı %50'ye çıkarılabilir,
- 2030 yılına kadar 35 GW yenilenebilir enerji kapasitesine ulaşmak için her yıl 3 GW güneş ve 2,5 GW rüzgar enerjisi kapasitesi kurulumları yapılmalıdır,
- 2030 yılına kadar toplam yolcu taşıma araçlarında en az %20 elektrikli araç oranı ve kamu taşımacılığı ile yük taşımacılığında en az %10 elektrikli araç oranı hedeflenebilir (SHURA Enerji Dönüşüm Merkezi, 2023).

Yenilenebilir enerji kaynaklarının hızla genişlemesi, eğer esneklik çözümleri ile desteklenmezse, kararsızlık nedeniyle istikrar ve güvenilirlik sorunları yaratabilir.

Diğer bir deyişle, yenilenebilir enerjilerin artışı ile paralel olarak enerji depolama sistemlerinin yaygınlaştırılmaması, temiz enerji geçişini tehdit edebilir. Bu sorunu çözmek için enerji depolama sistemlerinin dağıtımını destekleyecek politika önlemleri gereklidir (IEA, 2024).

Artan değişken yenilenebilir enerji üretimi karşısında elektrik sisteminin esnekliğini artırmak amacıyla, NEP (2023), 2035 yılına kadar 7,5 GW batarya enerji depolama kapasitesinin artırılmasını hedeflemektedir. Ayrıca, Türkiye son yıllarda depolama sistemlerinin daha fazla yaygınlaştırılmasını teşvik etmek amacıyla önemli düzenleyici önlemler almıştır. 19 Kasım 2022'de yayımlanan düzenleme, özellikle yenilenebilir enerji santrallerinin, Yenilenebilir Enerji Kaynakları Destekleme Mekanizması (YEKDEM)'ine katılım için enerji depolama sistemlerinin kurulmasını zorunlu kılmaktadır.

Ancak, düzenleyici otoriteler tarafından alınan önlemlere rağmen, Türkiye'de henüz herhangi bir şebeke ölçeğinde batarya enerji depolama (BEDS) tesisi kurulmamıştır. Bu durum, özellikle özel sektörde enerji depolama sistemlerine yapılan yatırımların eksik olduğunu ve bu durumun daha temiz enerji sistemlerine geçiş hızını olumsuz etkileyebileceğini göstermektedir. Bu bulgu, bu sistemlerin yatırım değerlendirmesini etkileyen faktörleri kapsamlı bir şekilde incelemenin ve gerçekçi bir yatırım değerlendirme modeli geliştirmenin kritik bir ihtiyaç olduğunu vurgulamaktadır.

Tezde araştırma soruları şu şekilde formüle edilmiştir:

4. Türkiye'de EDS'lerin yaygınlaşması için fırsatlar ve engeller nelerdir?
5. EDS yatırım kararlarını etkileyen faktörler ve belirsizlik kaynakları nelerdir ve yatırımcılar ESS yatırımlarını nasıl değerlendirir?
6. Gelecekteki belirsiz gelir ve yatırım maliyetleri koşullarında optimal yatırım stratejisi nedir?

Araştırma sorularını yanıtlamak için bu tezde, nitel ve nicel yöntemlerin birleşimini içeren bir karma yöntem kullanılmaktadır. Araştırma tasarımı şu şekilde özetlenebilir:

- Nitel araştırmanın birincil araştırma yöntemi, enerji depolama alanındaki kilit uzmanlarla yapılan yarı yapılandırılmış görüşmeler ve anketler ile toplanan nitel verilerdir. Farklı aktörlerle yapılan görüşmeler aracılığıyla EDS'ler hakkında farklı açılardan algıları ve konumlanmaları gözlemleyerek, enerji depolama yatırımlarını yönlendiren faktörleri tanımlamaya çalışacaktır. Daha spesifik olarak, nitel yöntem 1. ve 2. araştırma sorularına cevap vermek için kullanılmaktadır. Bu kısımdan elde edilen veriler, nicel çalışmanın varsayımlarını doğrulamak ve geliştirmek için de kullanılmaktadır.
- Nicel araştırma kısmında, EDS yatırımlarının ekonomik değerlendirmesini analiz etmek için bir reel opsiyon modeli geliştirilmektedir. Enerji literatüründe giderek daha fazla popülerlik kazanan gerçek seçenekler yaklaşımı, yüksek belirsizlik içeren projelerde yönetsel esnekliği yansıtmak için güçlü bir araçtır. Tezde geliştirilen model, teknolojideki sürekli gelişmeler nedeniyle gelecekteki maliyet düşüşleri konusunda belirsizlikler altındaki EDS yatırımlarının ekonomik geçerliliğini analiz etmeye yardımcı olacaktır. Bu modelde, EDS yatırımının değeri, gelecekteki gelirler ve yatırım maliyetlerindeki belirsizlik olduğunda yatırım kararını erteleme (yatırımı bekleme opsiyonu) değeri dikkate alınarak değerlendirilmektedir. Nicel yöntem, 3. araştırma sorusuna cevap vermek için kullanılmaktadır.

Çalışma, nitel araştırma ile reel opsiyon yaklaşımını birleştirerek literatüre katkı sağlamaktadır. Bu yaklaşım, belirsizlikleri etkili bir şekilde ele almayı ve duyarlılık analizleri tasarlamayı amaçlamaktadır. Bu yenilikçi karma yaklaşımı kullanarak, çalışma bulguları güçlendirmekte ve BEDS yatırım değerlendirmesi için ülkeye özgü bir model sunmaktadır.

Çalışma, iki ana sebepten ötürü önemlidir. İlk olarak, nitel analiz, enerji depolama alanındaki kilit aktörlerin belirsizlik algıları ve beklentileri hakkında çok boyutlu bir bakış açısı sağlamakta ve EDS'leri ekonomik yönden analiz eden nicel modellerin faydalanabileceği zengin veriler üretmektedir. İkinci olarak, Türkiye için EDS yatırımlarının ekonomik analizi, nitel araştırmadan elde edilen ülkeye özgü faktörler dikkate alınarak nicel olarak değerlendirilmektedir. Bu amaçla, nicel kısımda, nitel araştırma sonuçlarından elde edilen belirsizlikler ile bu belirsizlikler karşısında

yönetimin sahip olduğu esneklikler üzerine bir reel opsiyon çerçevesi geliştirilmektedir. Literatürdeki diğer reel opsiyon modellerinden farklı olarak, bu çalışma model çerçevesini önceden belirlenmiş veya teoriye dayalı varsayımlar yerine, nitel çalışmada derlenen veriler üzerine inşa etmektedir. Bu nedenle, çalışmanın sonuçları özellikle uygulayıcılar ve politika yapıcılar için önemlidir.

Bu yaklaşımda, nitel ve nicel analiz bölümleri birbirini beslemektedir: Nicel bölümde cevaplanacak olan "Optimal yatırım stratejisi nedir?" araştırma sorusu, nitel analizinin kapsamını tanımlamaktadır. Daha spesifik olarak, bu araştırma sorusu, "Türkiye'de EDS'lerin devreye alınması için fırsatlar ve engeller nelerdir?" ve "EDS yatırımlarını etkileyen belirsizlikler ve kaynaklar nelerdir, ve yatırımcılar EDS yatırımlarını nasıl değerlendirir?" araştırma sorularını doğurur. Bu nedenle, mülakat kılavuzunun tasarımı ve görüşme yapılacak kişilerin seçimi, nicel modelin veri ihtiyaçlarına göre yapılmıştır. Karşılığında, nicel analiz, nitel analizde toplanan verileri bir girdi olarak kullanmaktadır. İlk olarak, nitel veriler, teorik modelin uygunluğunu teyit etmek ve/veya ülkeye özgü belirsizlik kaynaklarını (model varsayımlarını belirlemek) ve yatırımcıların sahip olduğu esneklik türlerini (gerçek seçenek türünü belirlemek) ortaya koymak için kullanılmaktadır. İkinci olarak, nicel bölümdeki araştırma sorusu, Türkiye'deki yatırımcının gerçek hayat karar problemiyle uyumlu hale getirilmek için nitel araştırmanın ilk aşamasında toplanan verilerle rafine edilmektedir.

Depolama yatırımları, bu alandaki kilit aktörlerin aktif kararlarının bir sonucudur. Bir yatırıma verdikleri değer; gelecekteki gelir ve maliyet beklentileri, risk ve zorluk algıları ile düzenleyici ortamda meydana gelebilecek değişimlere dair öngörüleri doğrultusunda şekillenir. Bu beklenti ve öngörüler ise faaliyet gösterdikleri sektör, uzmanlık alanları ve öznel değerlendirmelerine bağlıdır. Bu noktadan hareketle, tezin nitel bölümünün odak noktası, EDS alanındaki konulara ilişkin kilit aktörlerin algılarını anlamak ve bu algıların yatırım kararlarını nasıl etkileyebileceğini incelemektir.

Bu çalışmanın araştırma yöntemi, araştırmacının mevcut bilgi birikimi ve gerçeklik algısına dayanır. Çalışmanın temel amacı, EDS yatırımlarının daha fazla

yaygınlaştırılmasına ilişkin paydaşların görüşlerini derlemektir. Bu nedenle, birincil veri kaynakları; enerji sektöründeki profesyonellerin, akademisyenlerin, sivil toplum kuruluşlarının ve düşünce kuruluşlarının EDS'lerin kullanımı, yaygınlaştırılması ve finansmanı hakkındaki bakış açıları, uzmanlıkları, yaklaşımları ve görüşleridir. Bu tür bilgilere erişim sağlayacak nitel veriler, Patton (2002) tarafından belirtildiği gibi, "Açık uçlu sorular, bireylerin deneyimleri, algıları, görüşleri, duyguları ve bilgileri hakkında derinlemesine yanıtlar alınmasını sağlar" ilkesi doğrultusunda, mülakat yöntemi ile toplanabilir. Bu amaçla çalışma, veri toplamak için yarı yapılandırılmış mülakatları kullanmaktadır. Bu mülakat yöntemi, tüm bu deneyimlerin, bakış açılarının ve yaklaşımların kültürel ve sosyal bağlamı içinde ele alınmasını sağladığı için faydalıdır ve kilit aktörlerin gözünden bütün resmi görmeye olanak tanır. Ayrıca, Silverman (2006) tarafından önerilen dört mülakat stratejisi—yapılandırılmış mülakatlar, yarı yapılandırılmış mülakatlar, açık uçlu mülakatlar ve odak grup çalışmaları—arasında, çalışmanın hedef kitleye ulaşması için en uygun yöntem yarı yapılandırılmış mülakat yöntemidir.

Bu nedenle, saha araştırmamda yarı yapılandırılmış mülakatlar, konuyu detaylı bir şekilde ve uzmanların bakış açısıyla inceleme fırsatı sunmaktadır. Bu çalışmada paydaşların algılarının toplanması süreci, enerji sektöründeki kilit paydaşlarla yapılan yarı yapılandırılmış mülakatlardan oluşmaktadır. Analiz, enerji depolamanın yaygınlaştırılmasına yönelik itici güçler ve engeller, enerji depolamanın riskleri ve belirsizlikleri ile enerji depolama yatırımlarının ekonomisini etkileyen güncel konular hakkında kilit aktörlerin görüşlerini ortaya koymayı amaçlamaktadır.

Veri üretim süreci, enerji depolama alanında doğrudan veya dolaylı olarak çalışan paydaşların bakış açısından;

- Enerji depolamanın yaygınlaştırılmasına yönelik engeller/zorluklar ve itici güçler hakkında içgörü kazanmayı,
- Enerji depolama yatırımlarını yönlendiren faktörleri araştırmayı,
- Enerji depolama yatırımlarıyla ilgili belirsizlikleri ve beklentileri belirlemeyi,
- Reel opsiyon analizi üzerine odaklanarak enerji sektörü şirketlerinin sermaye bütçeleme uygulamaları hakkında veri toplamayı amaçlamaktadır.

Veri toplama süreci, Türkiye'deki enerji depolama yatırımlarının kilit paydaşlarıyla gerçekleştirilen yarı yapılandırılmış mülakatlar yoluyla yürütülmektedir. Bu sayede, EDS yatırımlarını etkileyen veya destekleyen/sınırlayan faktörler ve belirsizlikler hakkında paydaş görüşleri derlenmektedir. Ayrıca, çalışma, enerji sektörü şirketlerinin sermaye bütçeleme uygulamaları hakkında veri toplayarak, özellikle gerçek opsiyon analizine aşinalıklarını incelemektedir.

Nitel çalışmanın temel araştırma motivasyonu, EDS yatırımlarını etkileyen faktörleri belirlemek ve nicel çalışma için uygun model çerçevesinin oluşturulmasına yardımcı olmaktır. Veri analizinin sonuçları 1. ve 2. araştırma sorularına yanıt vermek için kullanılmaktadır. Buna ek olarak, nicel çalışmadaki model çerçevesinin tasarlanmasında şu amaçlarla kullanılmaktadır:

i) Paydaşların gelecek beklentilerine ve belirsizlik algılarına dayalı olarak teori odaklı varsayımları doğrulamak veya geliştirmek,

ii) Yatırımcılar tarafından kullanılan esnekliklere bağlı olarak gerçek opsiyon türünü belirlemek,

iii) Optimum kullanım için EDS türünü seçmek,

iv) Karar dönemini (modelin çözüleceği zaman dilimini) belirlemek,

v) Hassasiyet analizi (vaka çalışmaları) için senaryoları oluşturmak.

Mülakat rehberinin tasarımı, ESS yatırımlarının ekonomik fizibilitesi konusunda paydaşların farklı görüş ve bakış açılarını keşfetmeyi amaçlamaktadır. Bu doğrultuda, ana anlam korunurken soruların kelime yapısının değiştirilebileceği esnek bir mülakat rehberi hazırlanmıştır.

Ortaya çıkan mülakat rehberi beş bölümden oluşmaktadır: (i) Giriş/ısınma, (ii) genel tanımlayıcı değerlendirme, (iii) destekleyici güçler ve engeller, (iv) belirsizlikler ve beklentiler ve (v) yatırım kararı ve sermaye bütçeleme süreçleri. Rehberde toplam 27 açık uçlu ve çoktan seçmeli soru bulunmaktadır. Mülakat rehberini tasarlarken literatürdeki "Market and Policy Barriers to Energy Storage Deployment" (ABD Enerji Bakanlığı, Enerji Depolama Teknolojileri ve Sistemleri Departmanı), "The Use of Real Options Theory in Scandinavia's Largest Companies" ve "Management Views on Real Options in Capital Budgeting" (Baker ve diğerleri, 2011)

çalışmalarını başlangıç noktası olarak kullandım. Güncel konuların mülakat rehberine dahil edilmesi amacıyla konuya ilişkin mevcut tartışmalardan da yararlandım. İlk dört mülakattan elde edilen geri bildirimler doğrultusunda rehber nihai haline getirilmiş olup, Türkçe versiyonu Ek C'de sunulmaktadır.

Giriş/Isınma Bölümü: Bu bölüm, paydaş grubunun belirlenmesine yardımcı olabilecek bilgileri toplamayı amaçlamaktadır. İlk olarak, katılımcının eğitim durumu ve uzmanlık alanı gibi geçmişine dair sorular yer almaktadır. Ardından, sermaye bütçeleme uygulamalarına ilişkin sorularına verilen yanıtları değerlendirebilmek adına katılımcılara bir İşletme Yüksek Lisansı (MBA) derecesine sahip olup olmadıkları sorulmaktadır. Daha sonra, görüşülen kişinin faaliyet alanı sorgulanarak hangi paydaş grubuna ait olduğu belirlenmektedir. Eğer katılımcı, çalıştığı kurumu bir (potansiyel) EDS kullanıcısı, üreticisi, tasarımcısı veya geliştiricisi olarak tanımlarsa, "kullanıcı/yatırımcı" olarak sınıflandırılmakta, diğerleri ise "ikincil paydaşlar" olarak kabul edilmektedir. Yatırımcılar ayrıca hangi tür EDS ile ilgilendikleri ve EDS yatırım planlarının olup olmadığı sorulmaktadır.

İkinci Bölüm (Genel Tanımlayıcı Değerlendirme): Bu bölüm, EDS'lerin rolüne ilişkin paydaşların görüşlerini gözlemlemeyi ve bu görüşlerin paydaş grupları arasında ve/veya içinde farklılık gösterip göstermediğini ve teorik çerçeveyle örtüşüp örtüşmediğini incelemeyi amaçlamaktadır. Bu doğrultuda, bölüm, EDS'lerin enerji sektöründeki rolünü değerlendirmelerini isteyen açık uçlu bir soruyla başlamaktadır. Ardından, katılımcılardan EDS'lerin potansiyel kullanım alanlarını önem sırasına göre sıralamaları istenmektedir.

Üçüncü Bölüm (İtici Güçler ve Engeller): EDS'ler, şebeke hizmetleri açısından güvenlik, esneklik, zaman kaydırma, maliyet azaltma ve yenilenebilir enerji entegrasyonunu artırma gibi birçok fayda sağlayarak EDS yatırımlarını teşvik edebilir. Bunun yanı sıra, EDS'lerin yaygınlaştırılmasını sınırlayan çeşitli faktörler (engeller) de bulunmaktadır. Bu bölümde, katılımcılardan EDS'lerin geniş çaplı yayılımını destekleyen faydaları (destekleyici güçleri) ve kısıtlayan engelleri bir çoktan seçmeli listeden tanımlamaları istenmektedir. Ardından, katılımcılara bu

engellerin nasıl ortadan kaldırılabileceği ve engellerin ortadan kalkması durumunda EDS'lerin nasıl gelişeceği konusunda açık uçlu iki soru yöneltilmektedir.

Dördüncü Bölüm (Belirsizlikler ve Beklentiler): Yatırımcılar, serbest piyasa koşullarında elektrik fiyatlarındaki oynaklık (ekonomik belirsizlikler), depolama teknolojisinin özelliklerinden kaynaklanan sermaye maliyeti ve verimlilik seviyesi gibi teknik gelişmelere bağlı belirsizlikler (teknolojik/yenilik belirsizlikleri), düzenleyici çerçevedeki değişim sıklığı (düzenleyici belirsizlikler) veya depolanacak enerji kaynağının değişkenliği (örneğin rüzgar hızındaki dalgalanmalar) gibi belirsizliklerle karşı karşıya kalabilirler. Bu bölüm, yatırımcıların karşılaşabileceği belirsizlikler hakkında paydaşların algılarını toplamayı amaçlamaktadır. Daha sonra, katılımcılardan EDS alanındaki gelecekteki gelişmelere dair beklentilerini detaylandırmaları istenmektedir.

Beşinci Bölüm (Yatırım Kararı & Sermaye Bütçeleme Süreçleri): Bu bölümün ilk kısmı, bir yatırım kararının değerlendirilmesi sırasında dikkate alınan faktörleri ve bu değerlendirme sürecinde kullanılan sermaye bütçeleme tekniklerini ortaya çıkarmayı amaçlamaktadır. İkinci kısımda ise katılımcılara reel opsiyon yaklaşımına aşinalıklarını gözlemlemeye yönelik sorular yöneltilmektedir.

Nitel çalışmada, hedef grupları belirlemek için paydaş yaklaşımı uygulanmıştır. Paydaş analizi, belirli bir konuda kararların nasıl alındığını anlamak için araştırmacıya yardımcı olur (Brugha ve diğerleri, 2000).

Hedeflenen görüşmeciler, aşağıdaki gruplardan seçilmiştir:

(i) Enerji sektöründe faaliyet gösteren ve enerji depolama teknolojilerine ve bunların etkilerine odaklanan aktörler,
(ii) EDS ile ilgili faaliyetlerde bulunanlar,
(iii) EDS'lerin potansiyel veya mevcut kullanıcıları,
(iv) Enerji depolama ile ilgili derneklerin üyeleri,
(v) Depolama sistemleri alanında araştırmalar yapan akademisyenler.

Bu çalışmada paydaşların belirlenmesi, amaçlı örnekleme ve kartopu (snowball) örnekleme stratejilerinin bir kombinasyonu kullanılarak aşağıdaki adımları izleyerek gerçekleştirilmiştir:

Adım 1: İlk görüşmeci listesi, amaçlı örnekleme stratejisi kullanılarak oluşturulmuştur. Bu kapsamda, yakın zamanda kamuoyunda görünürlüğü olan (ESS'ler ile ilgili bir seminerde sunum yapan veya ESS ile ilgili bir çalışma yayımlayan) uzmanlar ve enerji depolama ile ilgili derneklerin üyeleri seçilmiştir. İlk liste, enerji sektöründe faaliyet gösteren ve enerji depolama teknolojilerine ve etkilerine odaklanan aktörleri, ESS ile ilgili faaliyetlerde bulunanları, ESS'leri potansiyel veya mevcut olarak kullananları, enerji depolama ile ilgili derneklerin üyelerini ve depolama sistemleri alanında araştırmalar yapan akademisyenleri temsil eden 21 farklı paydaşı içermektedir.

Adım 2: İlk listeyi genişletmek için yine amaçlı örnekleme stratejisi kullanılmıştır. Bu doğrultuda, görüşme süreci boyunca, ilk liste oluşturulduktan sonra düzenlenen konferans ve seminerlerin gündemleri taranarak ek uzmanlar belirlenmiştir.

Adım 3: Kartopu (snowball) örnekleme tekniği kullanılarak, görüşmecilerin yönlendirmeleri doğrultusunda diğer potansiyel paydaşlar belirlenmiştir. Adım 2 ve Adım 3 sayesinde belirlenen paydaş sayısı 21'den 104'e çıkarılmıştır.

Veri oluşturma süreci Aralık 2023'te başlamış ve Mayıs 2024'te tamamlanmıştır. Çevrimiçi görüşmelerin süresi 11 dakika ile 111 dakika arasında değişmektedir. Bu görüşmelere ek olarak, üç kilit uzmanla derinlemesine teknik toplantılar gerçekleştirilmiştir. Bu toplantılardan biri, görüşme sonrası yapılan bir takip toplantısı niteliğinde olup, diğer iki toplantı ise genişletilmiş görüşmeler şeklinde gerçekleştirilmiştir. Bu genişletilmiş görüşmelerde, görüşme rehberindeki sorulara ek olarak, kavramları daha iyi anlamak ve çalışmanın kapsamını uzmanların bakış açısından netleştirmek amacıyla teknik sorular da yöneltilmiştir.

Görüşmeciler, ESS alanında aktif olarak yer alan çeşitli türdeki kuruluşları temsil etmektedir. Saha araştırması sırasında, faydalanıcı ve diğer paydaş gruplarını temsil

eden 23 kuruluştan toplam 25 görüşmeci ile 24 görüşme gerçekleştirilmiştir. Bu kuruluşların 16'sı faydalanıcı gruba, 7'si ise ikincil paydaşlar grubuna aittir. Sınıflandırma, görüşme rehberinin ilk bölümünde yer alan faaliyet alanı ile ilgili sorulara verilen yanıtlar doğrultusunda yapılmıştır.

Faydalanıcı paydaşlar grubu, "yatırımcılar" ve "tedarikçiler" olmak üzere iki alt gruba ayrılmaktadır. Yatırımcılar alt grubu, EDS pazarının kullanıcılarını ve dolayısıyla talep tarafını temsil etmektedir. Bu grup, şebeke ölçekli EDS kullanan, BEDS ile entegre yenilenebilir enerji santrali için ön lisansa sahip olan ve elektrikli araç alanında faaliyet gösteren kuruluşları kapsamaktadır. Tedarikçiler ise üreticiler (örneğin, hücre, invertör vb. üretenler) ve kullanıcıların bu sistemleri sorunsuz bir şekilde devreye almasını sağlayan teknik ve yazılım çözümleri sunan mühendislik firmalarından oluşmaktadır. Hizmet sağlayıcılar kategorisi, kendilerini EDS tasarımcısı, geliştiricisi veya sağlayıcısı olarak tanımlayan kuruluşları içermektedir. Bu kuruluşların müşterilerine sunduğu hizmetler arasında batarya ve enerji yönetim sistemlerinin geliştirilmesi, sistem entegrasyonu, mekanik ve elektronik sistem tasarımı, yazılım geliştirme, optimizasyon ve teknik danışmanlık bulunmaktadır.

Örneklemde, hem EDS üreten/EDS ile ilgili hizmetler sunan hem de bu sistemleri kendi iş süreçlerinde kullanan kuruluşlar yer almaktadır. Bu gibi durumlarda, paydaş grubunun belirlenmesi, ilgili kuruluş için faaliyetlerin göreceli önemi dikkate alınarak yapılmıştır. Seçim kriteri, kuruluşun bir şebeke/santral işletmesi (veya ön lisansa sahip olması) durumunda "yatırımcı", depolamayı yalnızca kendi enerji ihtiyacı için kullanması durumunda ise "tedarikçi" olarak sınıflandırılmasıdır.

İkincil paydaşlar, "danışmanlar" ve "araştırmacılar" olarak iki alt gruba ayrılmıştır. Danışmanlar, yatırımcılar ve tedarikçilere projelerin hayata geçirilmesi için danışmanlık hizmeti sağlayan ancak EDS geliştirme ve uygulama aşamalarına doğrudan katılmayan kuruluşları içermektedir. Araştırmacılar ise, EDS alanındaki bilgi birikimini artırmaya yönelik araştırmalar yapan, etkinlikler düzenleyen veya içerik üreten kuruluşlardan oluşmaktadır. Alt gruplara ayırma kriteri, kuruluşun danışmanlık hizmetini ücretli olarak sunup sunmamasına dayanmaktadır.

Görüşmecilerin çoğu, temsil ettikleri kuruluşların üst düzey yöneticileri veya kurucularından oluşmaktadır. 25 görüşmeciden yedisi kuruluşun kurucusu, ortak kurucusu veya yönetim kurulu üyesiyken, 13'ü departman başkanı, yönetici veya direktör pozisyonunda bulunmaktadır. Geriye kalan görüşmeciler ise şirketlerinde kıdemli pozisyonlarda görev yapmaktadır. Örneklemde ayrıca akademiden bir profesör de yer almaktadır.

Örneklem ağırlıklı olarak mühendislerden oluşmaktadır; 25 görüşmeciden 22'si mühendislik diplomasına sahipken, ikisi sosyal bilimler alanında eğitim almıştır. Mühendisler arasında yedisi elektrik ve elektronik mühendisliği, sekizi enerji veya güç yönetimi programlarından mezun olurken, ikisi makine mühendisliği diplomasına sahiptir. Geriye kalanlar ise inşaat mühendisliği, zemin mekaniği, uçak ve uzay mühendisliği gibi çeşitli mühendislik dallarından mezundur.

Bu tezde, verileri tanımlamak için analitik çerçeve yaklaşımı kullanılmaktadır. Analitik çerçevede, sorulara verilen yanıtlar ham veriyi tanımlamak amacıyla soru bazında düzenlenir (Topal, 2016). Görüşme yanıtları, nitel veri analizi yazılımı olan MAXQDA kullanılarak analiz edilmiştir.

Veri oluşturma sürecinde, yarı yapılandırılmış görüşmeler, bir görüşme rehberi kullanılarak gerçekleştirilmiştir. Nitel analiz bölümünde, ham verinin raporlanması, görüşme rehberinin bölümlerine ve bu bölümlerde yer alan sorulara dayandırılmıştır. Bu nedenle, görüşme rehberinin ana ve alt bölümleri, ham veriyi temsil eden kategoriler olarak kullanılmıştır. Yanıtlar, farklı paydaş gruplarının görüşlerindeki benzerlikleri veya farklılıkları yansıtmak amacıyla dört paydaş alt grubuna (yatırımcılar, tedarikçiler, danışmanlar ve araştırmacılar) göre raporlanmıştır.

Nicel bölümün amacı ise yenilenebilir enerji santrali yatırımlarına entegre edilen BEDS'lerin ekonomik fizibilitesini analiz eden bir model geliştirmek ve gelecekteki gelirler ile yatırım maliyetlerindeki belirsizlikler altında optimal kararı belirlemektir. Bu modelde, yatırımın değeri, yatırımcının sahip olduğu esneklikleri reel opsiyon olarak analiz etmektedir.

Enerji depolama sistemlerinin kârlılığı ve ekonomik fizibilitesi üzerine yapılan çoğu çalışma, enerji depolama sistemlerinin ekonomik ve finansal uygulanabilirliğini analiz etmek için net bugünkü değer (NPV) yöntemini kullanmaktadır. En yaygın kullanılan yaklaşım olmasına rağmen, enerji depolama projelerini değerlendirmek için yapılan deterministik iskonto edilmiş nakit akışı (DCF) analizi, elektrik piyasası serbestleşmesinden kaynaklanan belirsizlikleri ve yatırımcının bunlarla başa çıkma esnekliğini göz önünde bulundurmaz.

- Serbestleştirilmiş elektrik piyasalarında, depolama sistemlerinin ekonomik performansı, piyasa fiyatından ayrı düşünülemez, bu da DCF yaklaşımının operasyonel esnekliği dikkate almadığı için piyasa potansiyelini değerlendirmede yetersiz olmasına neden olur.
- DCF yaklaşımının bu dezavantajı, özellikle enerji tedarik sektörü gibi büyük ölçekli yatırımlar için geçerlidir.
- Uzun proje ömrü, yatırımların geri dönüşsüzlüğü ve daha fazla bilgi edinme fırsatının artması nedeniyle kazançlardaki belirsizliğin artması, NPV'nin enerji sektörü yatırımları için yetersiz olmasına neden olur.
- Diğer taraftan, reel opsiyonlar yaklaşımı, yüksek belirsizlik içeren projelerde yönetsel esnekliği yansıtmak için güçlü bir araçtır.

Çalışmada, ESS yatırımları için optimal yatırım zamanlaması reel opsiyon yaklaşımı kullanılarak tahmin edilmektedir Çalışma, “Investment in electric energy storage under uncertainty: A real options approach” (Bakke et al., 2016), “Investment and risk appraisal in Energy Storage Systems: a real options approach” (Locatelli et al., 2016), “Optimal investment timing and sizing for battery energy storage systems” (Kelly & Leahy, 2020), “Potential utilization of battery energy storage systems (BESS) in the major European electricity markets” (Hu et al., 2022) çalışmalarına dayanmaktadır. Model yapısı, Bakke et al. (2016) çalışmasına benzer olacaktır.

Bu yapıya göre, ESS'nin değerlendirilmesi aşağıdaki adımlardan oluşmaktadır:
(i) Yenilenebilir enerji santraline entegre edilmiş BESS için gelir modeli

a. Fiyat dinamikleri: Elektrik fiyatı dinamikleri senaryo bazlı analiz kullanılarak modellenecektir.

b. Gelir: Batarayanın düşük fiyatlı saatlerde şarj edilip yüksek fiyatlı saatlerde deşarj edilerek gün içi piyasası pazarından arbitraj geliri elde ettiği varsayılmaktadır.

(ii) Yatırım maliyeti dinamikleri: Yatırım maliyeti genellikle sabit veya stokastik olarak kabul edilir. Ancak, enerji depolama teknolojisindeki hızlı değişim nedeniyle, yatırım maliyeti zamanla piyasa değişimlerine bağlı olarak değişmektedir.

(iii) Reel opsiyon değerlendirmesi: Yatırım fırsatı, piyasa belirsizliklerine karşı yatırımcının esnekliklerini dikkate alarak değerlendirilecektir.

Bu tezdeki reel opsiyon modelinin özellikleri şu şekilde belirtilmiştir:

- EDS türü: Çalışma, batarya maliyetlerinin hızlı bir şekilde düşmesi ve popülerliğinin artması nedeniyle BESS yatırımlarını analiz edecektir; bu, nitel araştırmanın sonuçlarıyla Türkiye'deki baskın tür olarak da doğrulanmıştır.
- Yatırımcı profili: Nitel analizden elde edilen geri bildirimlere dayanarak, çalışma, hibrit bir BEDS yatırımcısı için yatırım kararını çözümleyecektir.
- Ülke kapsamı: Çalışmanın coğrafi alanı Türkiye ile sınırlıdır. Coğrafi alan Türkiye ile sınırlı olsa da, sonuçların diğer gelişmekte olan ekonomiler için de temsil edici olması ve literatürdeki boşluğu doldurmaya yardımcı olması beklenmektedir; çünkü literatürdeki mevcut çalışmaların büyük bir kısmı Avrupa, ABD ve Çin'de yoğunlaşmıştır.
- Belirsizlik kaynağı: Çalışma, üç belirsizlik grubunu dikkate alacaktır: piyasa ile ilgili belirsizlikler (elektrik fiyatlarındaki dalgalanmalar-literatür tarafından önerilen), teknoloji ile ilgili belirsizlikler (yatırım maliyetindeki belirsizlik-nitel araştırma kısmında doğrulanan) ve politika ile ilgili belirsizlikler.
- Reel opsiyon türü: BESS için optimal yatırım kararı, depolama maliyetinin karlı hale gelene kadar yatırım yapmama esnekliğini değerlendiren yönetim opsiyonu üzerinden belirlenecektir. Nitel araştırmanın ön sonuçları, yatırımcıların maliyetlerin düşmesini ve düzenlemelerdeki değişiklikleri bekleyerek yatırım yapmayı erteleddiklerini göstermektedir.

- Reel opsiyon değerlendirme modeli: Bahsedilen çalışmalara dayanarak, enerji depolamaya yatırım yapmak için gerçek opsiyonları değerlendirecek simülasyon tabanlı sayısal model kullanılmaktadır.

Tezde elde edilen sonuçlar aşağıda özetlenmektedir.

2023 yılında batarya depolama küresel pazarı iki katına çıkarak 90 GWh'nin üzerinde bir değere ulaşmış olup, büyüme büyük ölçüde şebeke ölçeğindeki sistemlerden ve sayaç arkası batarya depolama sistemlerinden (behind-the-meter) kaynaklanmıştır (IEA, 2024). Analiz sonuçları, küresel enerji trendleriyle paralel olarak, Türkiye'de EDS türleri arasında BEDS'lerin belirgin bir şekilde baskın olduğunu ve hidrojen enerji depolamanın ikinci en fazla ifade edilen teknoloji olduğunu göstermektedir. Sonuçlar ayrıca, çoğu katılımcının, enerji depolamanın yenilenebilir enerji santrallerinin YEKDEM programına katılabilmesi için bir ön koşul olarak belirlenmesinin yatırım kararları üzerindeki etkisini yansıtarak, yenilebilir enerjiye bütünleşik depolama sistemlerine yatırım yapmayı planladığını göstermektedir. Sonraki en çok kullanılan uygulama alanı ise şebeke ölçeğindeki EDS'ler olup, bunu ticari ve endüstriyel uygulamalar ve elektrikli araç şarj istasyonları takip etmektedir.

ESS'lerin dört ana faydası vardır: (i) güç akışını düzeltmek, (ii) yedek hizmet sağlayarak güvenilirliği artırmak, (iii) mevcut talebi aşan gücü emerek enerji üretiminin kullanımını artırmak ve (iv) maliyetleri azaltmak (D'Aprile et al., 2016). Yenilenebilir enerji santrallerinden üretilen fazla elektriği depolayarak yenilenebilir enerji kesintilerini engelleyebilir ve yardımcı hizmetler pazarında fosil yakıtlı santrallere olan bağımlılığı azaltabilirler (Shura, 2024). Literatürle uyumlu olarak, sonuçlar, katılımcıların EDS'lerin güvenilirlik ve istikrarla ilgili işlevler, esneklik işlevleri ve ekonomik optimizasyon işlevleri sağlama kabiliyetleri nedeniyle enerji piyasalarında çeşitli roller üstlenmesini beklediklerini göstermektedir. Katılımcıların, Türk elektrik piyasalarında EDS'lerin ana rollerinin frekans kontrolü, talep dengeleme ve yenilenebilir enerjilerin entegrasyonu olarak gördükleri gözlemlenmiştir. Sonraki roller ise şebeke ve tedarik güvenliği gibi istikrarla ilgili işlevler olup, bunları yardımcı hizmetler ve arbitraj gibi ekonomik işlevler takip etmektedir. Roller arasındaki göreceli önem sırasına bakıldığında, şebeke güvenliği

en sık ifade edilen rol olup, onu yenilenebilir enerjilerin entegrasyonu ve frekans kontrolü takip etmektedir. Diğer taraftan, maliyetlerin azaltılması ve yardımcı hizmetlerden elde edilecek gelir potansiyeli gibi ekonomik roller her biri sadece iki kez en önemli olarak belirtilmiştir.

Sonuçlar, EDS'lerin esneklik ve şebeke istikrarıyla ilgili işlevlerinin yanı sıra düzenleyici ve politik desteklerin, bu sistemlerin daha fazla yaygınlaşmasını destekleyen başlıca itici güçler olarak görüldüğünü göstermektedir. Son zamanlarda yapılan teşvik edici düzenleyici değişiklikler ve destek mekanizmaların, ESD'lerin sağladığı teknik işlevler kadar yatırım kararları için önemli olduğu görülmektedir. Ayrıca, son yıllarda yatırım maliyetlerindeki azalma ve özellikle yardımcı hizmetlerden elde edilecek gelir potansiyeli, EDS yatırımlarını destekleyici bir rol oynamaktadır.

EDS'ler birçok şebeke hizmeti sunabilse de, yaygın kullanımlarını kısıtlayan bir dizi engel bulunmaktadır. Bu engeller, düzenleyici engeller, piyasa (ekonomik) engeller, kamu hizmeti ve geliştirici iş modeli engelleri ve teknoloji engelleri olarak kategorize edilebilir (Sandia, 2013). Katılımcıların yanıtları, son yıllarda önemli azalmalar olmasına rağmen, yüksek sermaye maliyetinin hala bu sistemlerin daha fazla yaygınlaşmasının önündeki ana engel olduğunu göstermektedir. Ayrıca, düzenlemelerin yetersizliği/şebeke kodunun eksikliği, düzenlemelerdeki değişiklik sıklığı ve kullanıcılar için düzenlemelerin karmaşıklığı gibi düzenleyici engeller ile yatırım maliyetlerinin öngörülemezliği ve teknolojik ilerlemeler de EDS yatırımlarını engellemektedir. Dahası, finansmana erişim engeli ve bu sistemlerin yardımcı hizmetlerden elde edilen gelir potansiyelinin yetersizliği gibi ekonomik engeller de mevcuttur. Ayrıca, yatırım maliyetleri ve elektrik fiyatlarıyla ilgili belirsizlikler de EDS yatırımlarını kısıtlamaktadır.

Çalışma, EDS yatırımlarının öngörülemezliğinin çoğunlukla düzenleyici ve teknolojik belirsizliklerden kaynaklandığını göstermektedir. Daha spesifik olarak, düzenlemelerin yetersizliği ve depolama sistemlerinin teknoloji-ekonomik özellikleri hakkında yetersiz bilgi, yatırımcılar için belirsizlik yaratmaktadır. Ayrıca, elektrik fiyatları ve sermaye maliyetlerindeki volatilite de bu yatırımların kârlılığını etkileyen

önemli belirsizlik kaynakları olarak görülmektedir. Katılımcıların çoğu, yatırım maliyetlerindeki düşüşün devam edeceğini beklemektedir, ancak düşüşün büyüklüğü konusunda bir fikir birliği bulunmamaktadır. Elektrik piyasalarıyla ilgili olarak, yardımcı hizmetler, günlük içi piyasalar ve gün öncesi piyasası EDS'lerin yaygınlaşmasındaki artıştan en çok etkilenen alanlar olarak öngörülmektedir.

EDS yatırım değerlendirmesi için kullanılan sermaye bütçeleme yöntemlerini ve organizasyonların reel opsiyon yaklaşımını kullanıp kullanmadıklarını soran bölümdeki sonuçlar, EDS yatırım kararlarında çeşitli belirsizlik türleri bulunmasına rağmen, organizasyonların sermaye bütçeleme yöntemleri olarak DCF analizi, NPV, iç verim oranı ve geri ödeme süresi hesaplamalarını kullandıklarını göstermektedir. Yalnızca dört katılımcı, reel opsiyonlar yaklaşımını kullandığını belirtmiştir.

Çoğunlukla, katılımcıların reel opsiyon çerçevesine aşina olmadıklarını belirtmiş olmalarına rağmen, bu çalışma, yönetsel esnekliklerin pratikte tamamen göz ardı edilmediğini ortaya koymuştur. Farkında olmadan, yatırımcılar algılanan belirsizliklere yanıt olarak reel opsiyon yöntemini kullanmaktadırlar. Katılımcıların yanıtlarından, yatırımcıların yatırım maliyetine ilişkin belirsizliklere karşı bekleme opsiyonunu; düzenleyici belirsizliklere karşı bekleme opsiyonunu, prototip yapma opsiyonunu ve yatırım/yapılandırma opsiyonunu; teknolojik belirsizliklere karşı ise prototip yapma opsiyonunu kullandıkları gözlemlenmiştir.

Özetle, nitel analiz, mevcut ortamda önde gelen EDS türünün BEDS olduğunu ve önde gelen uygulama alanının yenilenebilir enerji santraliyle entegre edilmiş depolama sistemleri (hibrit BESS) olduğunu göstermektedir. Sonuçlar ayrıca, EDS'lerin esneklik ve stabilite ile ilgili işlevlerinin yanı sıra cesaretlendirici düzenleyici değişikliklerin bu sistemlerin dağıtımını desteklediğini, ancak ekonomik, düzenleyici ve teknolojik engellerin ve belirsizliklerin bu sistemlerin yaygın dağıtımını engellediğini ortaya koymaktadır. Katılımcılar, ilk yatırım maliyetlerinin daha da düşmesini ve düzenleyici ortamın daha elverişli bir yönde değişmesini beklemektedirler. Bu belirsizliklere yanıt olarak, yatırımcılar ya daha elverişli koşullar için yatırım kararlarını ertelemekte (bekleme opsiyonu) ya da test amaçlı daha küçük ölçekli depolama sistemleri inşa etmekte (prototip yapma opsiyonu)

kullanmakta olup her iki durumda da büyük ölçekli yatırım kararlarında gecikme yaşanmaktadır. Nitel analizde elde edilen değerlendirmelerden faydalanarak, yatırım ertelenme opsiyonunun değerini ve optimal yatırım stratejisini analiz etmek için nicel bölümde bir reel opsiyon çerçevesi geliştirilmiştir. Politika belirsizliğinin optimal yatırım stratejisi üzerindeki etkisi duyarlılık analizi ile incelenmiştir.

Bu bağlamda, bir ön lisans sahibi için hibrit BESS yatırımı ile ilgili yatırım sorununu çözmek amacıyla bir vaka çalışması yapılmıştır. Vaka çalışmasında, bataryanın yalnızca gün öncesi piyasada arbitraj yaparak gelir elde ettiği varsayılmaktadır. Başlangıç yatırım maliyetinin dinamiği, veri ve literatürden alınan parametrelerle geometrik Brownian hareketi kullanılarak modellenmiş, yüksek ve düşük fiyat saatleri arasındaki fiyat farkları (arbitraj fiyatı) ise senaryo tabanlı simülasyon ile modellenmiştir. Yatırım maliyeti dinamikleri, IEA (IEA, 2024) ve BloombergNEF verileri (BNEF, 2024) baz alınarak tahmin edilmiştir ve bu tahminler, nitel çalışmada elde edilen bulgularla uyumludur, çünkü çoğu katılımcı maliyetlerin düşmesini beklerken, düşüşün büyük olmayacağını öngörmektedirler. Arbitraj fiyatı dinamiklerini modellemek için dört senaryo tasarlanmıştır: (i) NEP senaryosu)yenilenebilir enerji payının NEP'teki hedeflere göre artacağı varsayımı), (ii) ileri düzey yenilenebilirler senaryosu (yenilenebilirlerin payının NEP hedef seviyesini aşacağı varsayımı), (iii) orta düzey yenilenebilirler senaryosu (yenilenebilirlerin payındaki artışın hız kaybedeceği varsayımı) ve (iv) volatilite senaryosu (enerji fiyat seviyelerini etkileyebilecek beklenmedik değişiklikleri kapsar).

Sonuçlar, yüksek sermaye maliyetleri ve düşük arbitraj fiyat seviyeleri nedeniyle BEDS yatırımlarının karlı olmadığını gösterse de, hibrit BEDS'nin NPV'sinin pozitif olduğunu ortaya koymaktadır. Bu nedenle, BEDS'nin yenilenebilir enerji santrali ile entegrasyonu, depolamanın ekonomik değerini artırmaktadır. Ancak nitel analiz, mevcut ortamda yatırımcıların büyük ölçekli yatırımları ertelediklerini ve daha elverişli koşullar beklediklerini ortaya koymaktadır. Optimal yatırım zamanı ve beklemenin değerini analiz etmek için, bir ön lisans sahibinin hibrit BESS yatırımı, Amerikan alım opsiyonu olarak tasarlanmıştır. Bu düzenlemede, yatırım yapmayı seçmek, opsiyonun kullanılmasına eşdeğerdir. Reel opsiyon değerlendirme sonuçları, hibrit BEDS rüzgar enerjisi santralinin gelir potansiyelinin, bekleme opsiyonunun

değerinin çok üzerinde olduğunu göstermektedir. Sonuç, mevcut koşullar altında ön lisans sahibi bir yatırımcı için en iyi stratejinin hemen yatırım yapmak (opsiyonu hemen kullanmak) diğer bir ifade ile yatırım maliyetlerinde bir azalma veya gelir akışında bir artış için yatırım kararının ertelememek olduğunu göstermektedir.

Nitel araştırma, yatırım maliyetleri ve gelir akışlarındaki belirsizliklerin yanı sıra, daha fazla destekleyici düzenleyici değişiklik beklentilerinin de yatırımcıların yatırım kararlarını ertelemesine neden olduğunu ortaya koymuştur. Daha spesifik olarak, 1MWs'lik bir yenilenebilir enerji santrali için 1MW/1MWs batarya kurma gerekliliğinin gevşetilmesi ve bu değişikliğin başlangıç yatırım maliyetini düşürmesi beklenmektedir. Bu düzenleyici belirsizliğin reel opsiyon analizi sonuçları üzerindeki etkisini değerlendirmek için bir duyarlılık analizi tasarlanmıştır. Sonuçlar, beklendiği gibi, başlangıç sermayesi maliyetindeki azalmaların, vaka çalışmasında ele alınan daha pahalı batarya ile karşılaştırıldığında ekonomik performansı iyileştirdiğini ve ayrıca sermaye maliyetlerindeki daha fazla azalma ve arbitraj fiyatındaki artış için beklemenin değerini artırdığını göstermektedir. Ancak, bütünleşik rüzgar enerjisi santralinden elde edilen yıllık gelir, yatırım kararının ertelenmesiyle elde edilen NPV artışını aşmaktadır. Bu sonuç, ön lisans sahibinin en iyi stratejisinin hala hemen yatırım yapmak (opsiyonu hemen kullanmak) olduğunu ve yatırım maliyetlerinde bir azalma, gelir akışında bir artış veya daha destekleyici bir düzenleyici ortam için beklememek olduğunu göstermektedir. Buna göre, çalışmadan elde edilen reel opsiyon değerlendirmesinin sonuçları, düzenleyici belirsizliklere karşı sağlamdır.

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