THE IMPACT OF LARGE-SCALE BATTERY ENERGY STORAGE SYSTEMS ON GREENHOUSE GAS EMISSIONS IN THE ENERGY MARKET OF TURKEY

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THE IMPACT OF LARGE-SCALE BATTERY ENERGY STORAGE SYSTEMS ON GREENHOUSE GAS EMISSIONS IN THE ENERGY MARKET OF TURKEY

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This thesis was read by us, quality and content as a Master's thesis has been seen and accepted as sufficient.

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ABSTRACT

THE IMPACT OF LARGE-SCALE BATTERY ENERGY STORAGE SYSTEMS ON GREENHOUSE GAS EMISSIONS IN THE ENERGY MARKET OF TURKEY

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Master's Program in Master of Administration
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As a result of increased energy demand and global warming issues, there is no doubt that innovative renewable energy solutions are needed to create a more sustainable world for our future. Wind and solar farms and such power plants are the results of this state of art step. Even though these plants are the key point for the future, power fluctuations resulting from renewable energy sources must be balanced to protect the grid. At this point, power plants with storage systems allow system operators to cope with these power oscillations. It is an undeniable fact that renewable energy plants will become widespread due to the benefit storage systems have provided to system operators. However, within the scope of the 2050 targets against global warming, the real contribution of the construction of battery storage systems and their use in the market is a question mark. In this study, due to this expectation, it has been examined whether the use of storage systems can reduce gas emissions in a way that supports these promises.

In order to make this calculation, four different scenarios with real market data were used from the beginning of 2018 to the end of 2021. In the first scenario, the battery storage system was operated only by arbitrage. It was designed to according to the changes in price levels during the day and the carbon emission effect was calculated accordingly. In the second scenario, the battery system, which took on the task of balance management of a wind farm, worked in such a way that the energy stored during the hours when the wind farm was over-producing was returned to the system during the hours when the power plant was under-production. For both two scenarios, BSS had negative impact in terms of CO_2 emissions.

In the third scenario, the battery system, which was included in the hybrid structure consisting of wind and solar power plant, was operated in such a way that in case of production above the maximum power that can be supplied to the grid, the excess generated energy was stored and returned to the market at the first appropriate hour. At the end, after four- and half-year BSS had achieved net zero target. In the fourth and final scenario, the battery system was operated with the logic of the third scenario, this time included in the hybrid power plant consisting of a hydroelectric power plant with a dam and floating solar panels. After ten years, the BSS was able to eliminate the amount of CO2 released during its manufacture.

At the end of the calculation, it was seen that the use of battery storage systems could not positively affect carbon emission in the first two scenarios. In the long run, it may be beneficial by leading the expansion of renewable power plants, as it will enable the demand to be met by more renewable energy.

Key Words: Energy Storage, Renewable Energy, Greenhouse Gas Emissions

ÖZ

TÜRKİYE ENERJİ PİYASALARINDA BÜYÜK ÖLÇEKLİ ENERJİ DEPOLAMA SİSTEMLERİNİN SERA GAZI EMİSYONLARINA ETKİSİ

Bolak, Orhan Vedat
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Dünya genelinde enerji talebinin ve küresel iklim ısınmasına dair endişelerin birlikte artmasından dolayı, geleneksel elektrik üretim metotlarının dışına çıkılması ve daha yenilikçi yenilebilir enerji çözümlerinin ortaya konması gerekmektedir. Fakat, yenilenebilir enerji santrallerinin kullanımları arttıkça, elektrik şebekesinde sebep oldukları gerilim dalgalanmalarının etkisi de artmakta ve sistem operatörlerinin işini zorlaştırmaktadır. Bundan dolayı, enerji depolama sistemine sahip santrallerin kullanılmasının yaygınlaşması enerji verimliliği ve sistem güvenliğinin sağlanması açısından elzemdir. Avrupa'da karbon emisyonlarının düşürülmesine dair verilen sözler neticesinde yenilenebilir enerji kaynaklarının elektrik üretimindeki payının artacağı ve buna bağlı olarak da batarya depolama santrallerinin yaygınlaşacağı beklentisi bulunmaktadır. Bu beklenti neticesinde bu çalışmada, batarya depolama sistemine sahip santrallerin, verilen sözleri destekleyici şekilde karbon salımlarını düşürüp düşüremeyeceği 2018 yılı başından 2021 yılı sonuna kadar gerçek piyasa verileri ile dört farklı kullanım metodu incelenerek hesaplanmıştır. Birinci senaryoda batarya depolama sistemi sadece arbitraj yapacak şekilde çalıştırılmıştır. Gün içerisinde fiyat seviyelerindeki değişimlere göre çalışma kararı verilmiş ve buna göre karbon emisyon etkisi hesaplanmıştır. İkinci senaryoda, bir rüzgar çiftliğinin denge yönetimi görevini üstlenen batarya sistemi, rüzgar santralinin yükümlülüğünden fazla üretim yaptığı saatlerde depolanan enerjinin, yükümlülüğünün altında üretim yaptığı saatlerinde sisteme geri verecek şekilde çalışma profili oluşturuldu. Üçüncü senaryoda, rüzgar ve güneş santralinden oluşan hibrit yapıya dahil edilen bataryalı

depolama sistemi, şebekeye verilebilecek maksimum güç olan lisans gücünün üzerinde üretim yapılması durumunda, üretilen fazla enerji depolanmış ve uygun olan ilk saatte sisteme verilmiştir. Dördüncü ve son senaryoda batarya sistemi üçüncü senaryo mantığı ile aynı şekilde çalıştırılmış, fakat bu sefer barajlı hidroelektrik santrali ve yüzer güneş panellerinden oluşan hibrit santrale dahil edilmiştir.
Hesaplama sonunda ilk iki senaryoda pil depolama sistemlerinin kullanılmasının karbon salınımını olumlu yönde etkilemediği görülmüştür. Uzun vadede, talebin daha fazla yenilenebilir enerji ile karşılanmasını sağlayacağı için yenilenebilir enerji santrallerinin yaygınlaşmasına öncülük ederek faydalı olabilir.

Anahtar Kelimeler: Enerji Depolama, Yenilenebilir Enerji, Sera Gazı Emisyonu

For my my beloved wife Ayça my son Rüzgar Efe and my dear parents, who were with me throughout the whole process.

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LIST OF ABBREVIATIONS

ANL	Argonne National Laboratory
API-2	Rotterdam Coal Futures
BC	Bilateral Contracts
BESS	Battery Energy Storage Systems
BPM	Balancing Power Market
CAL	Climate Auction Law
CAP	Climate Action Plan
CCAP	Climate Change Action Plan
CCGT	Combined Cycle Gas Turbine
DAM	Day Ahead Market
EU	European Union
EV	Electrical Vehicle
GES	Grid Energy Storage
GHG	Greenhouse Gas
HEV	Hybrid Electrical Vehicle
HPP	Hydroelectric Power Plant
IDM	Intraday Market
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
Li-Ion	Lithium Ion
MCP	Market Clearing Price
NaS	Sodium-Sulfur
NiCd	Nickel-cadmium hydride
NiMH	Nickel-metal hydride
NREL	National Renewable Energy Laboratory
OECD	The Organization for Economic Co-operation and Development
PFC	Primer Frequency Control
PHS	Pumped Hydro Storage

R&D	Research and Development
REA	Renewable Energy Act
SFC	Seconder Frequency Control
TTF	Dutch Gas Futures
VRE	Variable Renewable Energy

Chapter 1

Introduction

Since the beginning of the industrial revolution, energy generation is one of the most crucial topics for the increased daily demands. Several natural resources have been used for centuries to provide the energy amount for factories' production lines and houses, such as wind, solar, water reservoirs, coal, and natural gas. Due to the stable generation capability, the most preferred ones were generally resources from fossil fuels. Figure 1[1] shows that fossil fuels standouts in the energy mix with the lead of coal which has the most significant effect on GHG emissions as shown in Figure2[2].

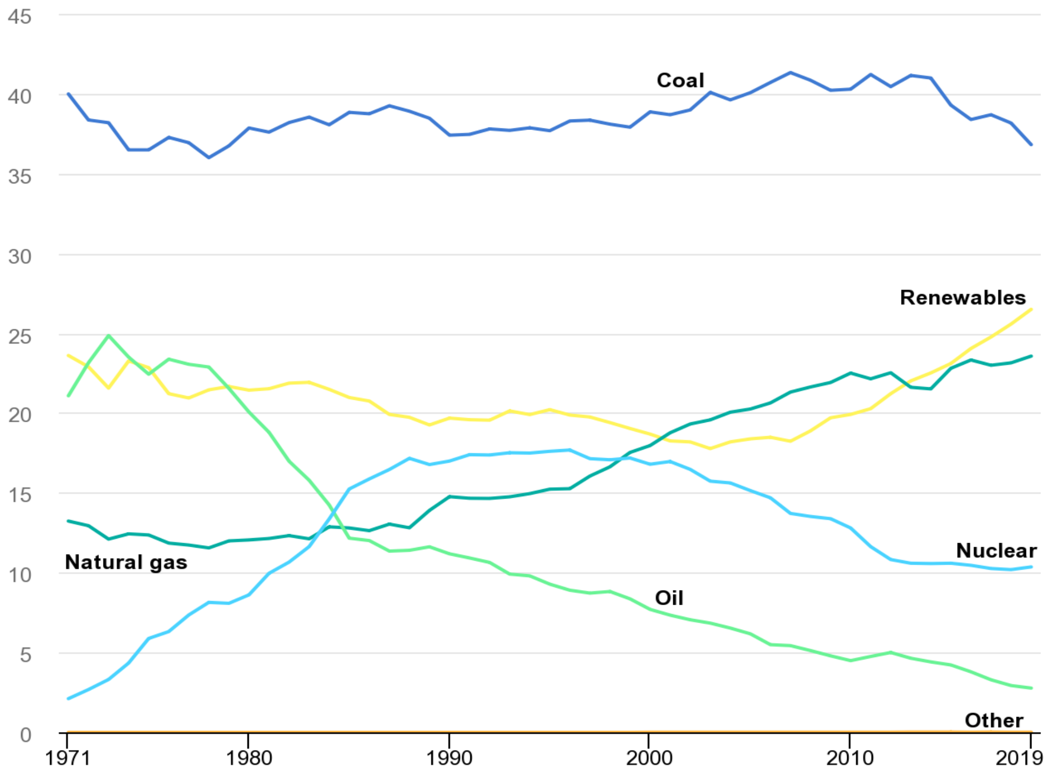

Figure 1 World electricity generation by source

[1] IEA, World electricity generation mix by fuel, 1971-2019, IEA, Paris https://www.iea.org/data-and-statistics/charts/world-electricity-generation-mix-by-fuel-1971-2019

[2] IEA, CO2 emissions from electricity and heat production by fuel, and share by fuel, 2000-2021, IEA, Paris https://www.iea.org/data-and-statistics/charts/co2-emissions-from-electricity-and-heat-production-by-fuel-and-share-by-fuel-2000-2021

However, exhaust gases of power plants that burn fossil fuels to generate electricity cause an increased carbon dioxide ratio in the atmosphere compared to before the industrial revolution which is shown in Figure 3[3]. According to the latest studies, the earth has warmed about 1°C since 1880. Although 1°C could be seen as unimportant, there is no doubt that it plays a vital role in global warming.

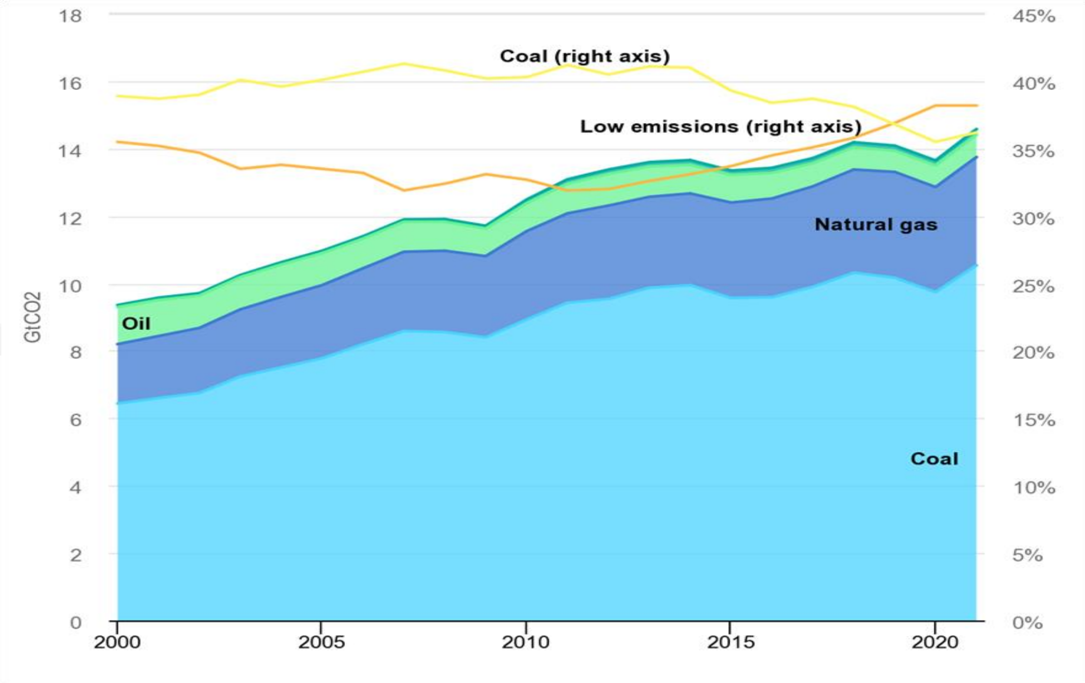

Figure 2 CO2 emissions from electricity and heat production by fuel, and share by fuel, 2000-2021

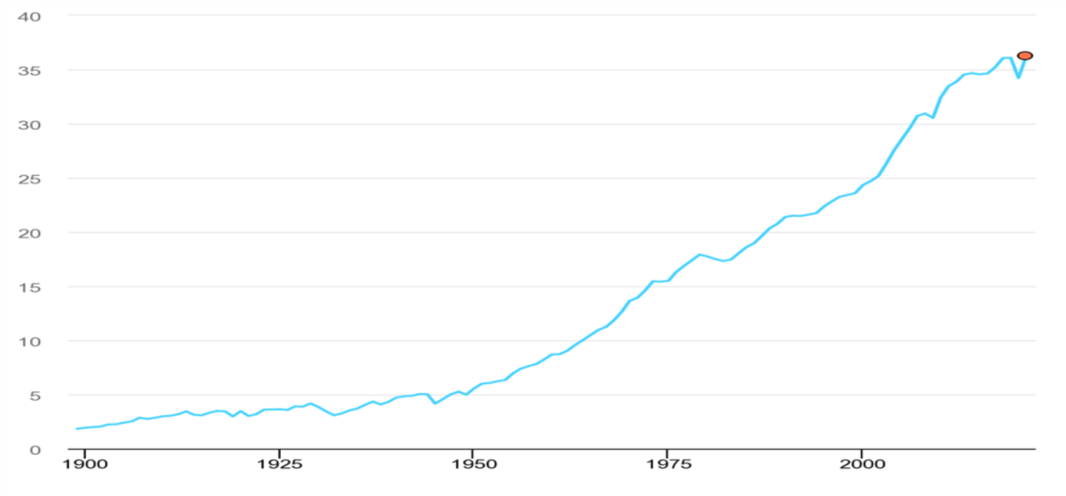

Figure 3 Gt CO2 emissions from energy combustion and industrial processes, 1900-2021

[3] IEA, CO2 emissions from energy combustion and industrial processes, 1900-2021, IEA, Paris https://www.iea.org/data-and-statistics/charts/co2-emissions-from-energy-combustion-and-industrial-processes-1900-2021

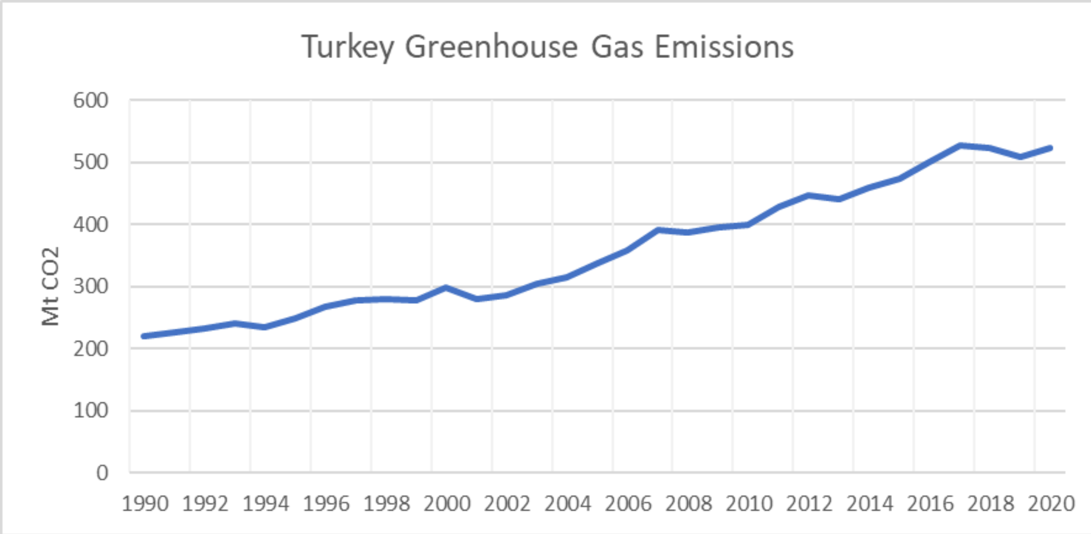

Figure 4[4] CO2 emissions of Turkey, 1990-2020

Thereby, rule-makers decided that it is time to change habits and explore renewable energy sources' opportunities instead of burning fossil fuels. Thanks to this view of point, governments worldwide signed the KYOTO Protocol and Paris Agreement to decrease carbon emissions by VRE investments. Progress was painfully and improved very slowly. According to the (Energy Agency, 2020), the OECD total generating capacity has increased at an average rate of 2,5%, while the most significant increase rate belongs to the wind by 24,2% between 2000 and 2010. Furthermore, between 2010 and 2018, 91% of increased capacity belongs to the wind and solar. Although these improvements are a hope for the future, it is clear that it is not enough to control global warming under 2°C. The current policies have decreased the carbon emissions only by 23% today, and it is expected that this ratio could be just 60% by 2050. For that reason, the EU decided to publish the green deal, which is the road map for its members to take action against global warming by giving targets for 2030 and 2050. As stated in the green deal, the ultimate goal is to achieve net-zero carbon emissions by 2050; this means having approximately 80% -95% fewer carbon emissions than in 1990. The interim target for 2030 is to have 50% -55% fewer carbon emissions than in 1990.

Among the EU members, Germany takes attention because of its energy transformation policies to be more environmentally friendly during the last years. Germany understands the importance of the situation, and they had made regulations

[4] Referred from TÜİK. *Sera Gazı Emisyon İstatistikleri, 1990-2020. https://data.tuik.gov.tr/Bulten/Index?p=Sera-Gazi-Emisyon-Istatistikleri-1990-2020-45862*

to drop GHG by VRE penetration over the previous 30 years. For that purpose, they launched their first renewable energy act twenty years ago.

With the declaration, they prepared CAL, CAP and updated the REA to show their determination about the issue. Climate Action Plan 2050 that the German government prepared based on Green Deal is pivotal for 2030 and 2050 to achieve carbon neutrality. All the innovative Germany's strategies and regulations are shaped around this plan. According to CAP, Germany goals to drop carbon emissions by at least 55% by 2030. Some key points of this plan are given below;

• The tax break for users or companies who reduce their emission ratios,

• Research and development incentives for green technology and energy efficiency studies,

• Closing all coal-fired power plants until 2038,

• 1 billion Euro worth battery cell investment,

• Provide fund programs

Sectoral reduction targets of Germany are shared in Table 1;

Area of action	1990 (in million tonnes of CO_2 equivalent)	2014 (in million tonnes of CO_2 equivalent)	2030 (in million tonnes of CO_2 equivalent)	2030 (reduction in % compared with 1990)
Energy sector	466	358	175 – 183	62 – 61 %
Buildings	209	119	70 – 72	67 – 66 %
Transport	163	160	95 – 98	42 – 40 %
Industry	283	181	140 – 143	51 – 49 %
Agriculture	88	72	58 – 61	34 – 31 %
Subtotal	**1,209**	**890**	**538 – 557**	**56 – 54 %**
Other	39	12	5	87 %
Total	**1,248**	**902**	**543 – 562**	**56 – 55 %**

Table 1 Emission targets of Germany based on sectors

At this point, Turkey has declared its desire to increase the share of VRE in the energy generation mix every ten years development program since 1985.Even though at the beginning the main purpose of this declaration was to reduce the share of imported energy sources, it turns into a GHG reduction strategy too with the declaration of the CCAP[5]. The important headlines of these plans are given below ;

[5] Referred from Türkiye Cumhuriyeti Çevre, Şehircilik ve İklim Değişikliği Bakanlığı. (2011). *Türkiye Cumhuriyeti İklim Değişikliği Eylem Planı 2011-2023.* https://iklim.csb.gov.tr/eylem-planlari-i-306

• Increasing the energy efficiency via some action plans

• Built pumped hydroelectricity power plants

• Increase the share of solar and wind power plants

• Research and development activities to use the biofuels in current coal power plants

• Increase the share of energy storage Technologies

In addition, Turkey is also one of the countries that agree on the KYOTO Protocol and Paris Agreement. However, it is crucial to indicate that, on the contrary developed countries Turkey is a developing country. For that reason, Turkey has declared a target to reduce the expected increase by 18,4% at the end of 2030 [8].

All of these measures indicate the importance of renewables penetration to the grid to have a cleaner and more liveable environment in the future for the next generation. Even though Green Deal was born among the EU members for carbon neutrality of Europe, this deal can trigger the rest of the world to take a step on the environment and change their energy mix such as Turkey.

In Germany thanks to feed-in tariffs which come with REA, generation from renewable energy sources have increased enormously. To show the development, the best way is to compare the generation from renewable energy between 1990 and 2020. In 1990, renewables' participation was just %5; during 2020, this ratio was %46,3, which can be seen in Figure 5[6].

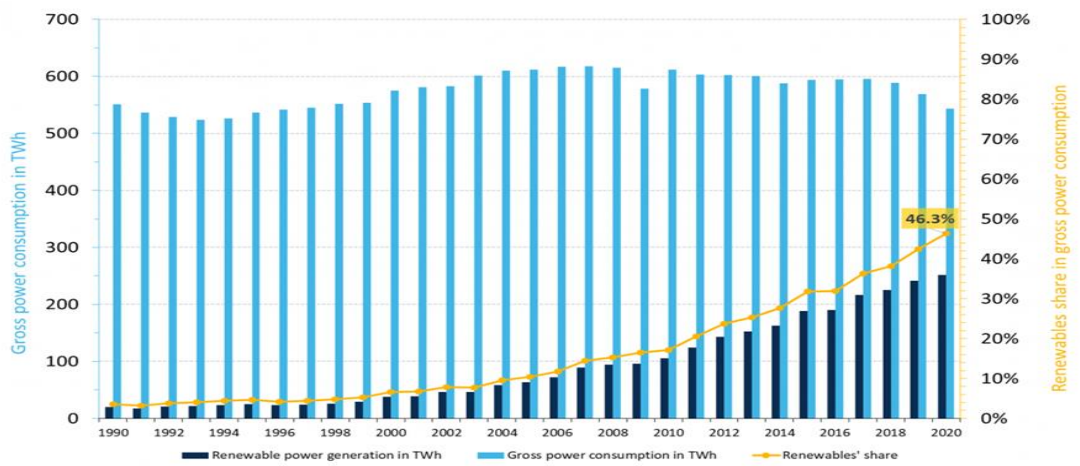

Figure 5 Renewable energy generation of Germany

[6] Referred from Kerstine AppunnYannick HaasJulian Wettengel (2021, February). *Germany's energy consumption and power mix in charts. https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts*

When the installed power capacity and GHG emissions are compared, the effect of growing renewable energy penetration on Germany's energy mix can be seen easily. As shown in Figure 6[7] and Figure 7[8], Germany decided to install renewables instead of fossil fuel power plants, and they did drop emission rates by 35,7% as a reward.

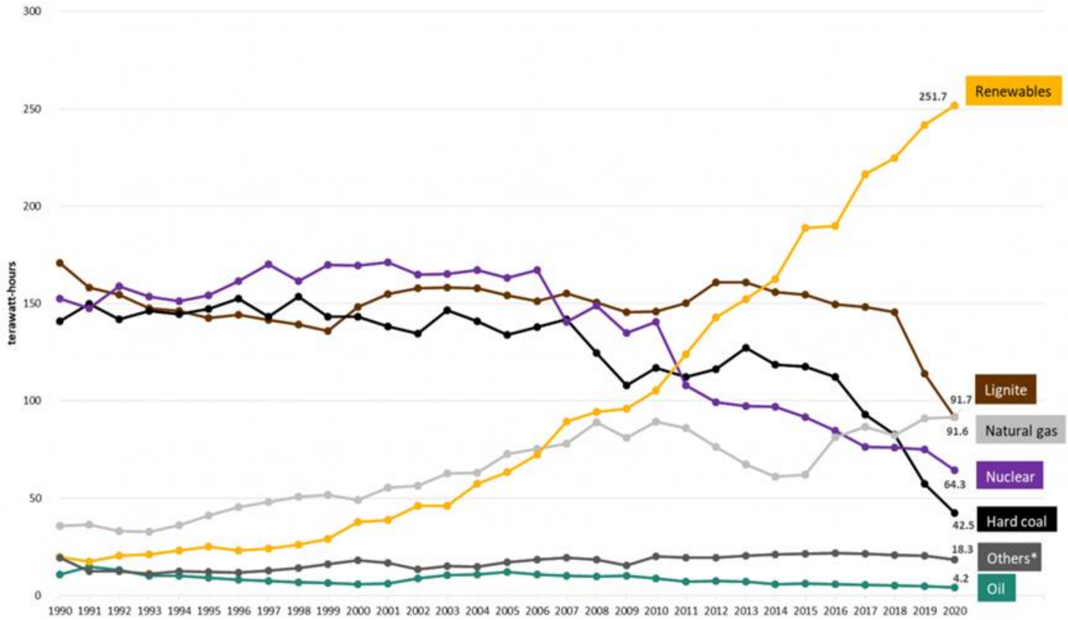

Figure 6 Power generation of Germany in TWh

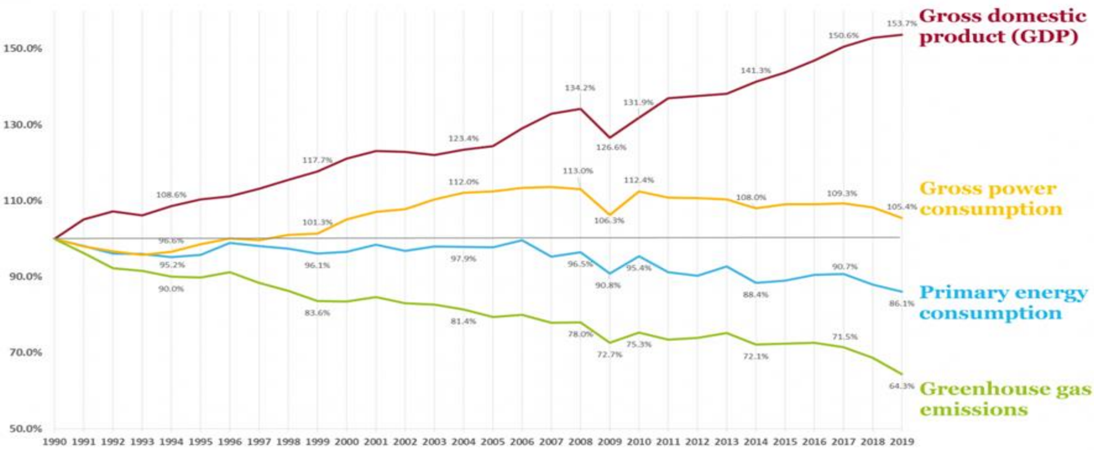

Figure 7 GHG of Germany

[7] Referred from Kerstine AppunnYannick HaasJulian Wettengel (2021, February). *Germany's energy consumption and power mix in charts. https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts*

[8] Referred from Kerstine AppunnYannick HaasJulian Wettengel (2021, February). *Germany's energy consumption and power mix in charts. https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mix-charts*

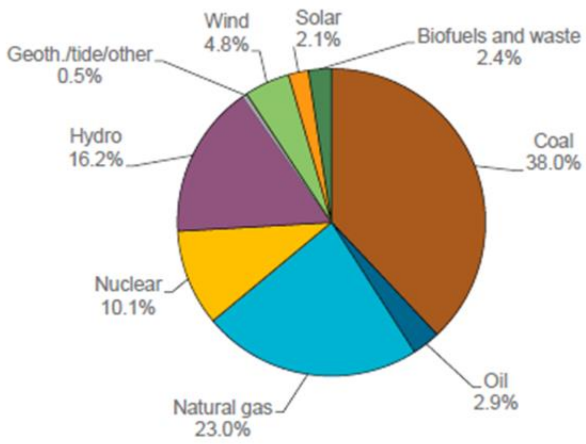

Figure 8 Share of energy sources

As of 2018, coal was the most popular resource to generate electricity, while VRE were %25, as shown in Figure 8 (Energy Agency, 2020). On the other hand, according to recent analyses by the IRENA made, the expectations about the electricity generation by VRE is 86% for 2050 when they include the deployment of low-carbon technologies to limits the rise in global temperature to below 2°C above pre-industrial levels, as can be analysed in Figure 9 (Renewable Energy Agency, 2020).

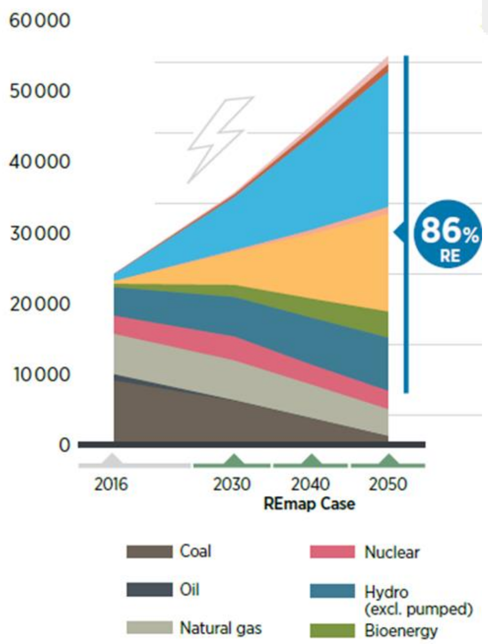

Figure 9 Electricity generation estimation (TWh/year)

Also, according to its climate action plan, Germany aims to reduce its energy sector's GHG emissions by 62-61% before 2030. Because the energy sector has the most negative impact on the released carbon with a share of 70%, understand the importance of renewable energy penetration becomes more critical now.

In conclusion, undoubtedly, increased renewables share will create some technical issues on the grid unless nobody draws a clear road map to achieve carbon zero aim by considering the electricity networks' technical constraints. One of the most vital constraints is the stability of electricity generation. Because of the nature of the electricity demand of factories and household customers, electricity generation should be predictable before the delivery period. Most power markets use the hourly settlement structure, while some have a 30 min period to the settlement period to make more accurate dispatch of the plants. Once predictability is a concern, the most preferred plant types until today are thermic power plants and dam-type hydroelectric plants, unlike wind and solar power plants. Another critical issue for grid constraint is voltage fluctuations because of the generation-level changes on the electricity network. Rapid voltage variations can cause fatal damage to machines that crucial for daily life and production lines of factories. For this purpose, system operators make great efforts to keep the system in balance by targeting the supply and demand relationship.

The balance between supply and demand only can be happened with the help of dispatchable power plants like thermic and dam-type hydroelectric power plants. These types of plants can respond to frequency changes by their rapid rump up and down specialties.

Although thermic power plants offer great flexibility for system operators to manage the network, the environmental effect of these power plants, especially coal power plants, are not acceptable for 2030 and 2050 carbon zero targets. The necessity of creating a more environmentally friendly solution with giving the desired predictability and dispatch ability to system operators is apparent. Electricity storage systems shine out as one of the most accurate solutions thanks to their flexible solution range. With the help of these systems, renewable power plants can offer system operators a more predictable generation profile that is critical to grid balance. Once one of the most vital issues of renewables for the grid is solved, and generation from these power plants will be more stabilized, BESS could be beneficial to reduce the GHG emissions of energy generation sector.

1.1 Energy Storage Systems

Integration of renewable energy systems is crucial for energy transition strategies to reduce toxic gas emissions. As mentioned before, when the installed power of environment-friendly power plants increased, technical constraints about the grid security increased also. Storage systems are excellent solutions to address these problems. There are five main systems services that storage systems can provide to help the grid operators (Renewable Energy Agency, 2020);

1. Provision of Inertia
2. Fast Frequency Response
3. Operational Reserves
4. Load Following and Time Shifting
5. Long-Duration Storage

Each system service requires a different energy storage method because of the technical limits, as shown in Figure 10 (Renewable Energy Agency, 2020).

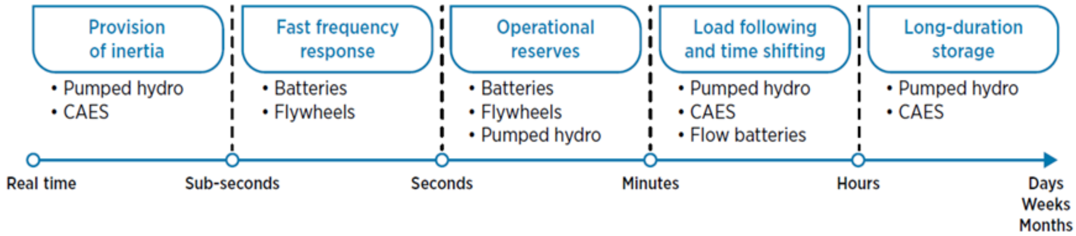

Figure 10 System services that storage systems can provide based on different timescales

Energy storage services show variations according to the technology they use. There are four different storage service types;

1. Electro-Chemical
   a. Battery Energy Storage Systems (BESS)
2. Electro-Mechanical Chemical
   a. Compressed Air Storage
3. Pumped Hydro Storage (PHS)
   a. Closed and Open Loop Pumped Hydroelectricity Storage
4. Thermal Storage
   a. Heat Thermal Storage

As of today, the most popular usage type of storage system is the pumped hydro storage, thanks to its advantages over other methods. These advantages can be explained as a longer life span, higher energy-to-power ratio, and lower initial investment costs (Renewable Energy Agency, 2020). These types of systems basically use the potential energy of water repeatedly with the help of a pump. Figure 11 shows the working principle of the system (Renewable Energy Agency, 2017).

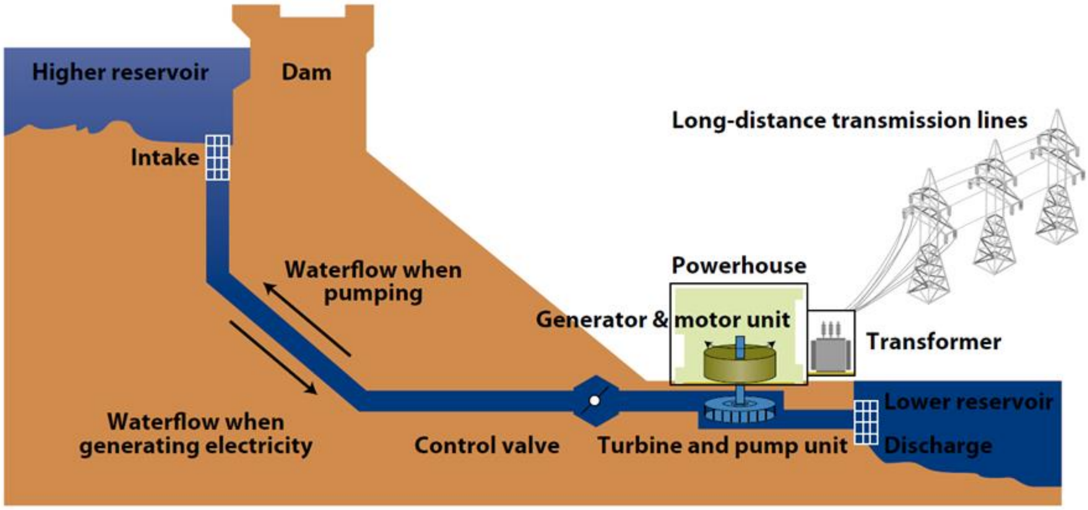

Figure 11 The Working principle of pumped hydro storage

Based on the information given by (Renewable Energy Agency, 2017), the pumped hydro's global operational energy storage capacity was approximately 170 GW in the middle of 2017. 75% of total pumped hydro storage systems belong to only the ten countries shown in Figure 12 (Renewable Energy Agency, 2017). Among these countries, China leads with a 19% share of installed power all over the world as shown in Figure 13 (Renewable Energy Agency, 2017).

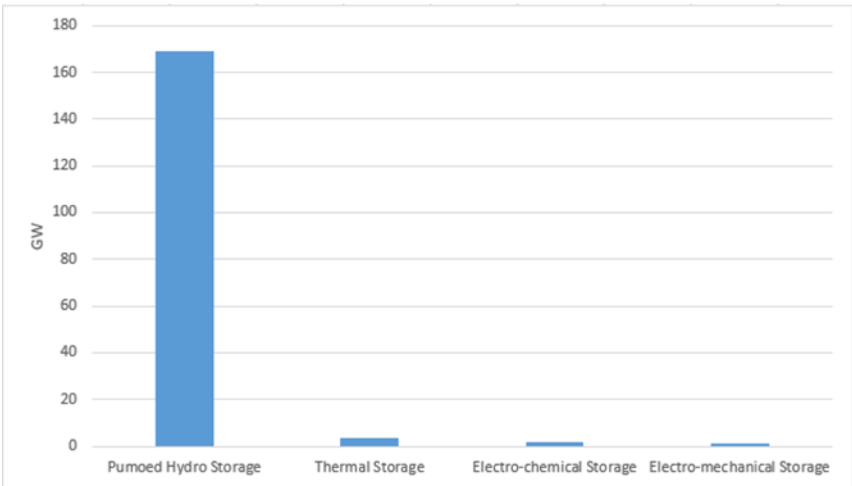

Figure 12 Global operational energy storage capacity by technology

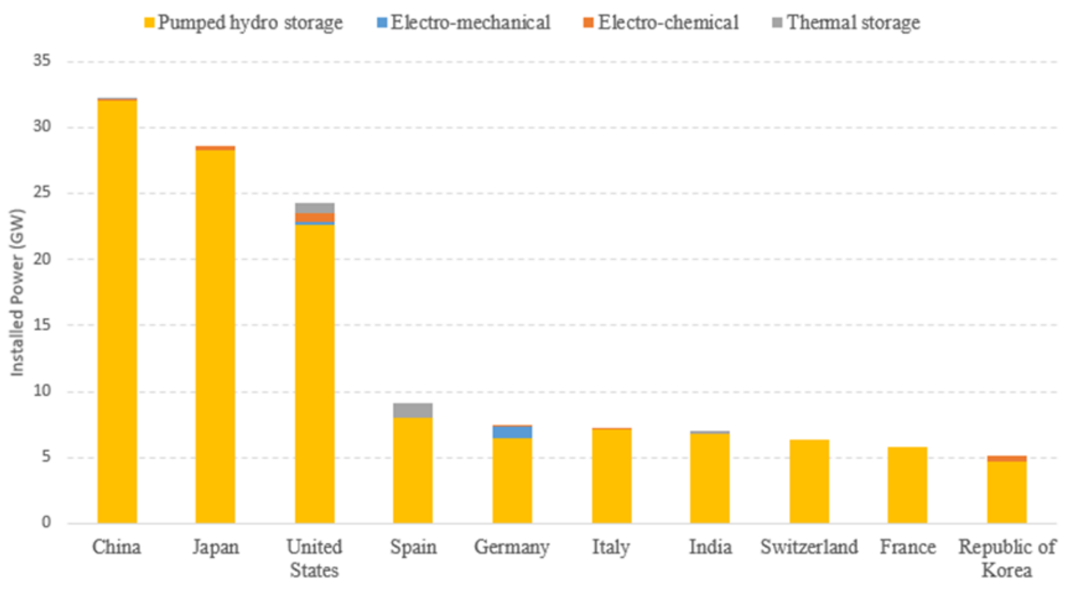

Figure 13 Top ten countries that use storage systems

Another critical and popular energy storage system for decarbonizing policies is the system in stationary applications that belongs to electro-chemical type storage systems. Historical background of the batteries back to the 1800s when Alessandro Volta developed the first battery. The principle behind the BESS based on the potential difference between two dissimilar metals (anode and cathode) in an electrolyte where the potential difference creates current flow. Figure 14 visualizes the working principle of BESS.

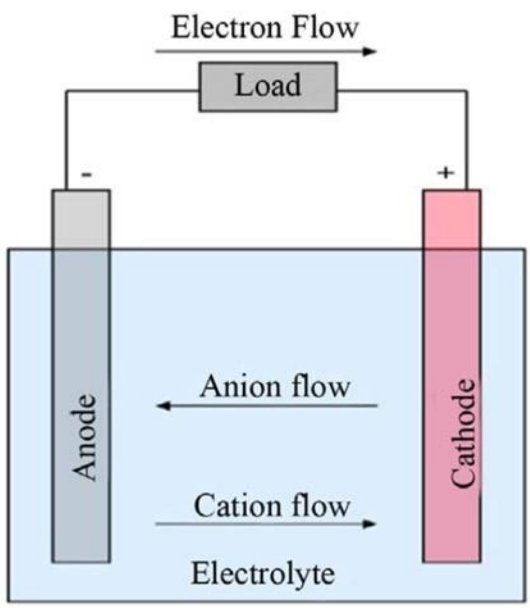

Figure 14 Working principle of batteries

Even though the working principle is not changing, there are several types of batteries based on the metal types used. These types of batteries are given below;

1. Lead Acid
2. Li-Ion
3. NiCd/NiMH
4. NaS
5. Flow Batteries

Lead Acid Batteries: These types of battery cells consist of spongy lead as the negative active material, immersed in a diluted sulfuric acid electrolyte, with lead as the current collector (Vazquez, Lukic, Galvan, Franquelo, & Carrasco, 2010). The common usage area for these battery types is rechargeable applications such as automotive engine starting[9].

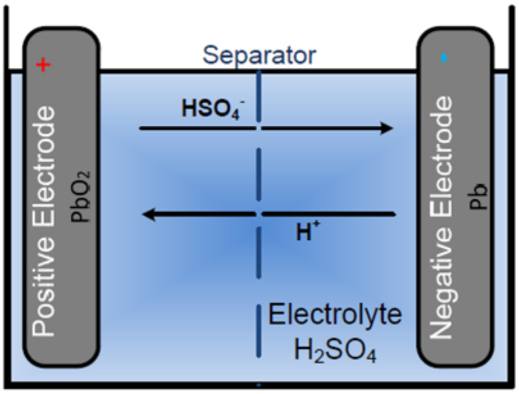

Figure 15 Working principle of lead-acid batteries (Sauer, Fuchs, & Leuthold, 2012)

Li-Ion Batteries: These types of batteries are a member of the rechargeable batteries' family. Li-Ion batteries use lithium ions to charge or discharge by moving between the negative and positive electrodes. They are one of the most common battery types in portable electronic products such as laptops, mobile phones, electric vehicles, thanks to their energy-to-weight advantage[10].

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[9] Referred from *Lead Acid Batteries* https://www.pveducation.org/pvcdrom/batteries/lead-acid-batteries

[10] Referred from *Lithium Ion Battery* https://www.sciencedirect.com/topics/chemistry/lithium-ion-battery

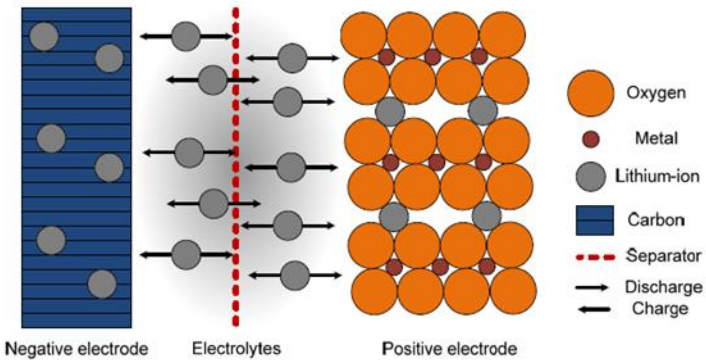

Figure 16 Working principle of li-ion battery (Sauer et al., 2012)

NiCd/NiMH Batteries: NiCd batteries use nickel oxide hydroxide and metallic cadmium as the anode and cathode to create electricity flow in the cell. Because of the toxicity issues, metal-hydride was started to use for the negative electrode, and NiCd batteries were replaced with NiMH-type batteries by transferring many distinct specialties[11]. The most apparent difference between the two batteries is that NiMH has almost twice the capacity of NiCd batteries. Both batteries are part of the rechargeable type of battery family. NiMH batteries had been preferred for EV and HEV until Li-Ion becomes more accessible because of decreased prices.

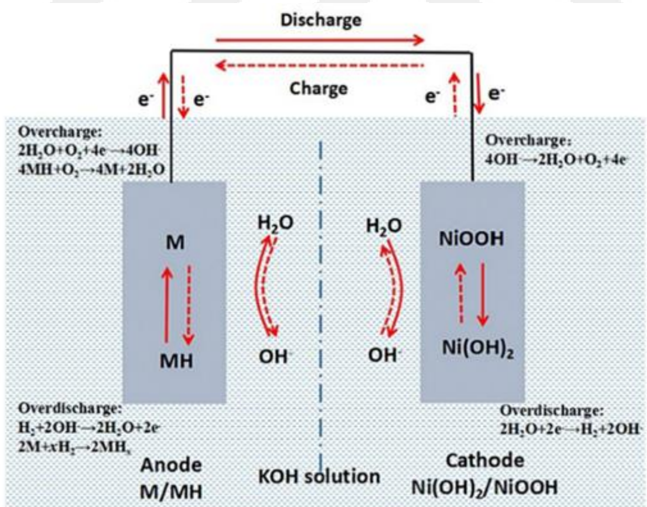

Figure 17 Working principle of NiCd/NiMH batteries (Fan et al., 2020)

NaS Batteries: Molten sulfur and molten sodium are the materials used as positive and negative electrodes separated by sodium alumina in this type of battery. The round-trip efficiency of NaS batteries is almost 89% while operating temperature should be between 300°C and 350°C, which is the most significant disadvantage of

[11] Referred from *Nickel-Based Batteries* https://batteryuniversity.com/article/bu-203-nickel-based-batteries

the battery[12]. After a Japanese firm bought this technology from Ford, who initially invested NaS batteries, 190 different projects preferred to use the NaS batteries.

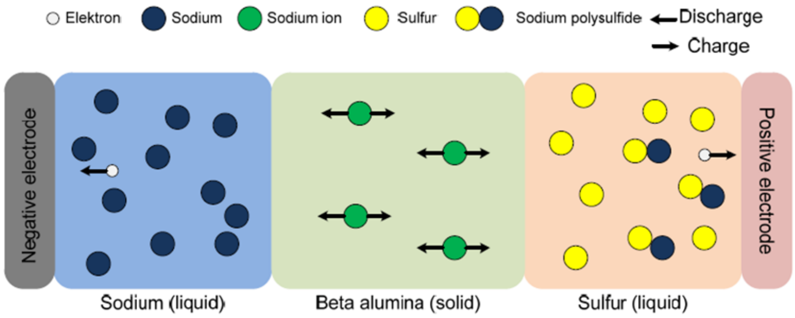

Figure 18 Working principle of NaS batteries (Sauer et al., 2012)

Flow Batteries: Flow batteries store energy in electrolyte solutions and contain two redox couples lowing through a power battery/reactor with the involvement of reversible chemical reactions (Fan et al., 2020). The significant difference from other types of batteries is that anode and cathode are separated from each other. Thanks to used electrolyte tanks which directly affect the energy capacity, it is expected that stored energy will be decoupled, and flow batteries will service with a higher amount of power. Also, this battery technology has three subgroups that vary according to electrode metals and electrolyte solution;

1. Zinc-Bromine Flow Batteries
2. Vanadium Redox Batteries
3. Polysulfide Bromide Batteries

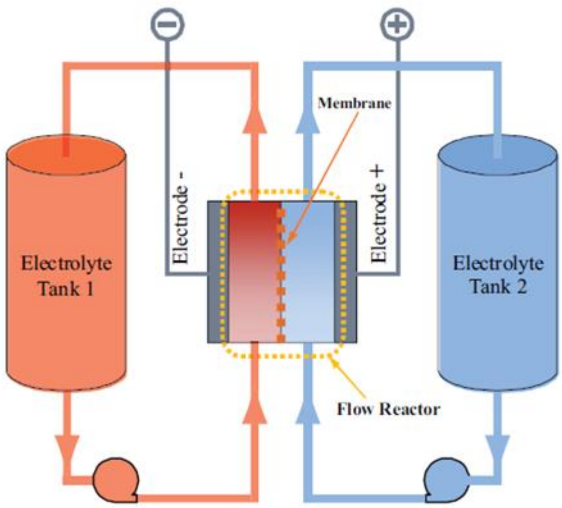

Figure 19 Working principle of flow batteries (Vazquez et al., 2010)

[12] Referred from *Sodium Sulfur Batteries* https://energystorage.org/why-energy-storage/technologies/sodium-sulfur-nas-batteries/

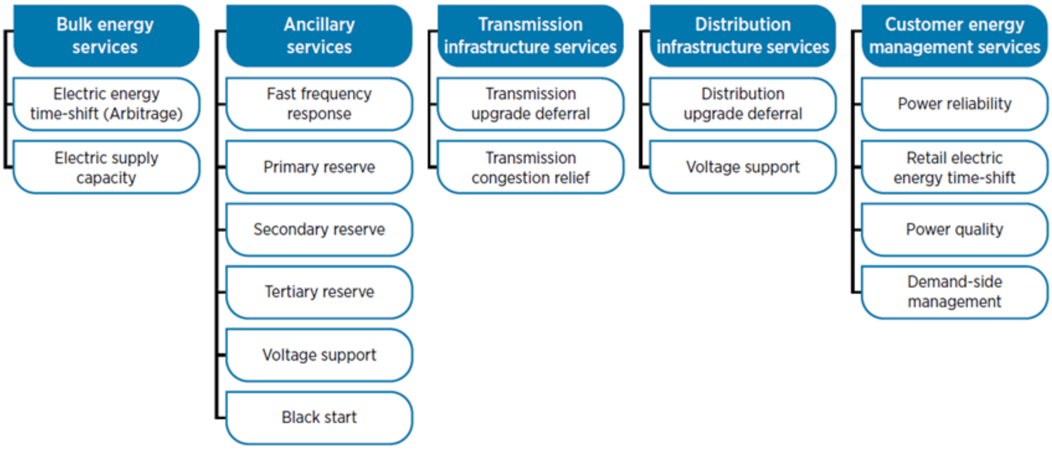

Figure 20 Application fields of energy storage systems

Apart from the system service capabilities and different technologies of energy storage systems, these systems can also be beneficial in terms of creating additional value to the energy value chain thanks to their specialties. To illustrate, PHS can be used to arbitrage between different price zones. Another example is the capacity firming method of systems to give additional power to the grid when the wind flow is lower. These application fields of energy storage systems are presented in Figure 20 (Renewable Energy Agency, 2020).

The most usage types of systems in worldwide in economic perspective can be detailed below;

1. Price Arbitrage

   The main purpose of this strategy is making profit by taking advantage from the price differences between different time zones of the day.

2. Imbalance Management

   Battery systems charge or discharge when the generation varies from Day Ahead of obligation. In this way, the imbalance cost will be lower than without a scenario.

3. Capacity Utilization Benefit

   The ultimate goal is to increase the production hours of the plant with additional resources. For example, wind and solar power plants can be converted into hybrid power plants. When more than one of the resources is produced, it can be stored and used later.

4. Ancillary Services

   It is basically a service to help the grid operator to balance the frequency fluctuations. On the other hand, it is most profitable usage type for the owners, thanks to their fast response times (*2020 Performance Review UQ's 1.1 MW Battery Project*, n.d.)

Even though systems seem green technology in paper, the effect of these systems on net zero targets will be analysed by using three different usage types: Price Arbitrage, Imbalance Management and Capacity Utilization benefit. According to results, there will be further recommendations.

Chapter 2

Literature Review

Energy storage technologies can be considered a relatively new concept for energy markets. Although it was a topic that was talked about and researched 15 years ago, it has recently started to gain popularity in order to achieve the greenhouse gas emission targets determined by the governments as a result of the agreements that shape carbon emission policies such as the Paris and Green Deal. On the other hand, not many studies have been conducted on the positive or negative impact of battery storage systems on the determined carbon emission targets.

The aim of this thesis is to examine the effect of usage types of battery storage systems on carbon emissions. In the literature research conducted for this purpose, the following articles and reports came to the fore. In summary, these articles provide a good perspective on the carbon emissions created during the manufacture and use of batteries.

2.1 Study of Hans Eric Melin, Analysis of the Climate Impact of Lithium-Ion Batteries and How to Measure It

In this study, the effect of the production stage of the battery and its materials on carbon emissions with the cradle to gate approach was examined. Therefore, it was stated that the size of the battery or the number of cycles had no effect on the result.

The biggest difficulty encountered during the study was the lack of a reference study using primary data, that is, data obtained from a source with a direct carbon emission effect. All the studies researched revealed the results by referring to the models they developed or the results of previous studies, so quite different values were obtained from each other. It was believed that the closest result to the truth was the study conducted by ANL since the primary data usage rate was the highest. During its research, ANL conducted studies in a cell manufacturing factory in China and three mines in the Republic of Congo for the value chain for cobalt. Therefore, the research was mostly based on ANL's study.

The process is divided into three parts the production of the cell, battery management system, and pack. Among these three components, Cell production came to the fore with a 75% energy requirement for the battery production process. Although the mining process and the subsequent transformation stage of the materials are important in cell production, it has been stated that the main effect of cell production occurs during the production of the cathode by 20% energy requirements of the entire production.

As a result of the research, it was stated that the entire production process of the battery was calculated as 73kg CO2e/kWh. However, it was also emphasized that this result may vary depending on the energy mix of the country. There will be a difference between production in China, which meets most of its energy needs from coal, and in Europe, where the proportion of renewable energy sources is higher.

During the studies for this thesis, 73kg of CO2e/kWh is taken as a base value.

2.2 Study of Solar 3W, Solar PV Potential for Coal Mining Fields in Turkey

In this study, battery storage technology and solar power plant were combined, and a hybrid power plant was created. As stated in the later parts of the thesis, one of the used methods by which battery storage systems can be beneficial in terms of carbon emissions is the creation of an energy mix where all the demand is met from renewable energy plants. When such an energy mix is built, the extra energy produced can be stored and given to the system when needed. Solar 3GW's work also takes this perspective. Accordingly, in the study, which aims to meet this production with solar power plants instead of lignite coal plants in Turkey, battery storage technology is also included in the study with the possibility of 4-hour and 16-hour storage. Although the simulated solar power plant does not fully meet the production of the coal plants it replaces, it stands out as an important perspective in terms of reducing carbon emissions.

2.3 Study of Trevor S.Hale, Kell Weeks, Coleman Tucker, Carbon Footprint Reductions via Grid Energy Storage Systems

This study was carried out by considering the American market and the effect of the efficiency and working hours of the battery on carbon emissions was examined. As an effect of efficiency, it has been stated that the battery can meet less of the demand it creates while being discharged, and therefore there will be more fossil-sourced generation. In addition, it is stated that the effect may vary depending on the share of renewable energy plants in production during the charging and discharging hours of the battery. Whether this effect exists for the Turkish market was calculated during the thesis process, but it was observed that there was no off-peak to peak change in domestic coal generation. Their generation level had not changed throughout the day. Therefore, this effect was not considered valid for Turkey.

2.4 Report of IRENA, Storage Valuation 2020

In this report, energy storage systems are discussed in detail. The benefits they will provide to the network and the types of services they can be used are explained. It is very clearly explained what kind of services they can perform according to their usage types. But what the report underlines, rather than technical specifications, is how energy storage systems can help increase the number of renewable power plants. For this, economic opportunities in peak shaving and ancillary services markets, especially arbitrage, are explained. Concluding that the increase in energy storage systems will lead to an increase in renewable energy plants, they stated that they expect a decrease in carbon emissions, therefore they find the existence of these systems very critical. The findings of this report are very important because the work of the international and highly prestigious IRENA is extremely detailed and guiding. This report is the most comprehensive report available on the technical and economic features of BSS and its impact on the energy market.

Chapter 3

Methodology

In this thesis study GHG emission effect of systems were analysed by considering Turkish electricity markets inputs. For that reason, it is necessary to understand the specifications of Turkish electricity market variables firstly. There are four connected market except ancillary service market, BC, DAM, BPM, and IDM. As it can be seen in Figure 21[13], the most volumed market is BC and DAM. Since MCP of the DAM is an indicator for each other market, in this study MCP was used.

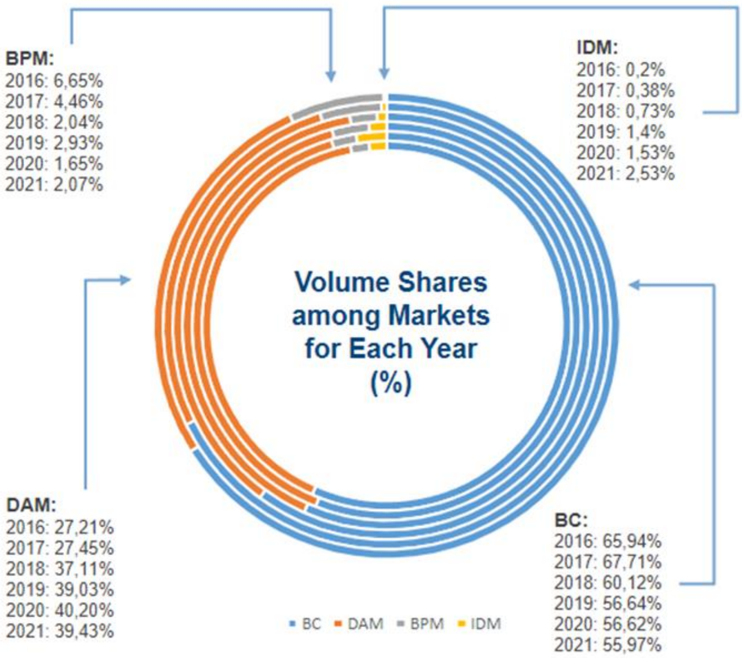

Figure 21 Turkish market volumes

The main concept for the DAM is matching the supply and demand one day ago from the delivery time. It is pivotal to balancing the system for each market participants. While grid operators care about the system security in terms of frequency and voltage, plant operators try to avoid from imbalancing for their profitability. For this purpose, there are four different offer types in the market;

[13] Referred from https://seffaflik.epias.com.tr/transparency/

1. Price Independent Block Offer
2. Price Depended Block Offer
3. Hourly Offer
4. Flexible Offer

In the price determination process, the market's optimization program first calculates the total demand for the relevant hour by taking the sum of the buying offers for each hour. It then removes price-independent blocks from this demand amount and starts accepting price-dependent block offers. However, while accepting each block, it also checks at what price hourly offers and demand meet and finds the optimum price. To illustrate, Figure 22[14] shows the matching point of demand and supply for 01.01.2018 00:00.

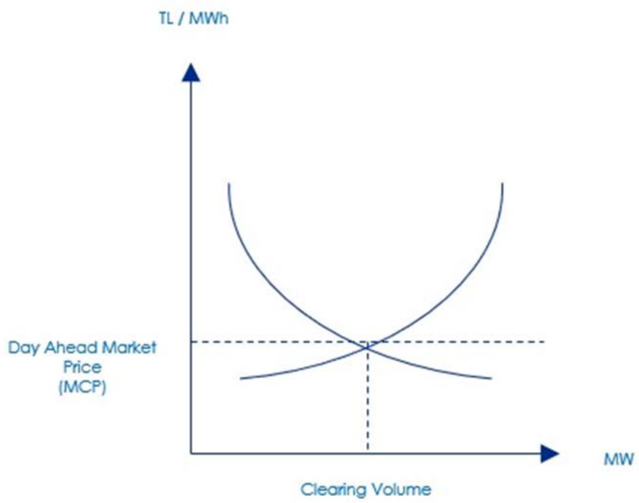

Figure 22 Demand – Supply curve

This sorting system, which includes of all type power plants' bid and ask offers, is called merit order. In merit order, renewable type power plants can make offer with price independent block because of their low operational cost unlike coal or natural gas power plants that heavily depended on commodity prices. Due to their commitment to commodity prices, these type of power plants, which have to be the power plant that determines the price in the merit order, are considered as marginal power plants due to these features. Which type of plant has a higher cost then that will

[14] Referred from Gama Energy

be the marginal source. Figure 23[15] shows the change of marginal source according to demand level.

Dark blue, yellow and blue dots represent the demand for three different days. Please note that on the right-side Dam Hydro has to be more costly than thermic power plants due to the fact that these power plants are classified as strategic resources. In this figure, three different sources are illustrated as a marginal source for separate three days. As it can be seen, when the demand rises generated electricity amount from thermic plants increase also.

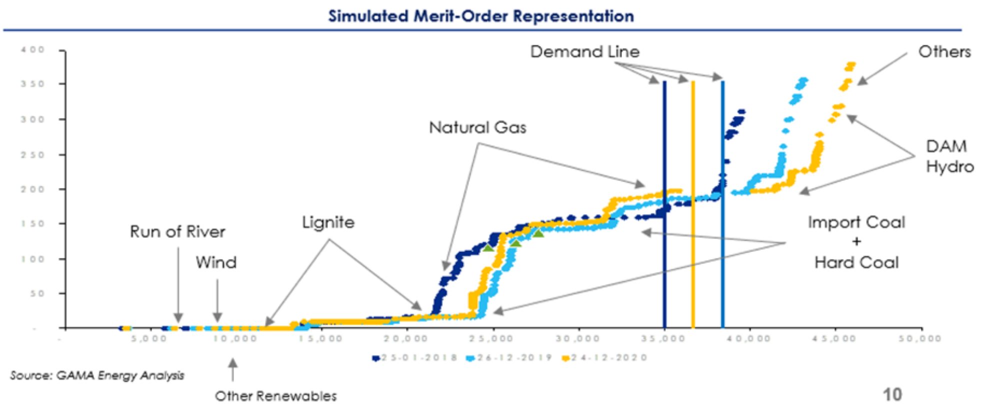

Figure 23 Merit-Order representation

At that point, it would be beneficial to understand that these marginal sources can switch with each other based on commodity price levels which are the main cost for these power plants. MCP is a clear result of commodity prices (API2 and TTF are the most important spot markets for coal and natural gas futures). Following Figures 23-26[16] explains the generation share of each source in the Turkish Electricity Market from the beginning of 2018 to end of the 2021. During this time period, many situations have happened that changed the generation mix for the market such as a wet year in 2019, Covid-19 Pandemic in 2020, and an energy crisis in 2021. High income of water (Renewable Hydro Generation) eliminated the thermic sources from March to July in the year 2019. Covid-19 was a real shock for the demand so, thermic power plants responded that demand decreased again during the Q2 of 2020. In 2021, there was a transition from coal to natural gas power plants as a result of the energy crisis.

[15] Referred from Gama Energy
[16] Referred from https://seffaflik.epias.com.tr/transparency/

As a result, when these four years are examined in detail, it is obvious that thermal power plants are the first ones to react to changes in demand and cost.

2018

Month	Natural Gas	Imported Coal	Lignite	DAM Hydro	Wind	Solar
1	34%	21%	14%	12%	7%	1%
2	32%	22%	15%	10%	8%	2%
3	25%	18%	16%	15%	9%	2%
4	27%	16%	16%	17%	5%	4%
5	23%	19%	16%	17%	5%	3%
6	25%	21%	16%	16%	6%	4%
7	36%	18%	14%	17%	5%	3%
8	27%	21%	14%	17%	9%	4%
9	34%	21%	15%	12%	7%	4%
10	33%	24%	17%	8%	7%	3%
11	28%	24%	16%	13%	9%	2%
12	26%	22%	16%	16%	7%	1%

Figure 24 2018 Monthly energy mix

2019

Month	Natural Gas	Imported Coal	Lignite	DAM Hydro	Wind	Solar
1	20%	20%	14%	22%	9%	1%
2	14%	23%	15%	23%	9%	2%
3	16%	18%	15%	22%	9%	4%
4	12%	13%	15%	29%	7%	4%
5	10%	11%	15%	33%	5%	4%
6	11%	15%	15%	32%	8%	4%
7	20%	20%	16%	23%	7%	4%
8	18%	21%	16%	23%	10%	4%
9	19%	23%	17%	20%	8%	4%
10	19%	25%	18%	19%	6%	4%
11	22%	25%	18%	17%	6%	3%
12	23%	23%	18%	17%	8%	2%

Figure 25 2019 Monthly energy mix

2020

Month	Natural Gas	Imported Coal	Lignite	DAM Hydro	Wind	Solar
1	27%	23%	12%	17%	9%	2%
2	18%	21%	12%	22%	10%	2%
3	8%	19%	12%	28%	9%	4%
4	6%	12%	12%	31%	10%	5%
5	6%	15%	13%	28%	8%	6%
6	14%	23%	16%	20%	6%	5%
7	22%	21%	13%	20%	10%	5%
8	25%	21%	12%	21%	9%	5%
9	29%	21%	12%	19%	8%	4%
10	32%	21%	15%	16%	5%	4%
11	32%	22%	15%	11%	10%	3%
12	32%	22%	14%	13%	10%	2%

Figure 26 2020 Monthly energy mix

				2021		
Month	Natural Gas	Imported Coal	Lignite	DAM Hydro	Wind	Solar
1	30%	20%	13%	14%	12%	2%
2	26%	22%	13%	13%	11%	4%
3	28%	16%	13%	17%	10%	4%
4	20%	13%	14%	21%	10%	5%
5	26%	13%	14%	16%	9%	6%
6	36%	14%	14%	13%	6%	6%
7	35%	15%	12%	14%	10%	5%
8	38%	16%	12%	13%	9%	5%
9	38%	15%	14%	8%	11%	5%
10	40%	10%	14%	10%	11%	5%
11	32%	20%	15%	10%	11%	3%
12	31%	20%	14%	10%	13%	2%

Figure 27 2021 Monthly energy mix

So, it is obvious that there should be more renewable generation to meet the demand to decrease GHG emissions. For this purpose, four separate scenarios are evaluated in this thesis study to calculate how much additional capacity is necessary by using the actual demand, total installed renewable power, and the realized capacity utilization ratio for each source for the period from the beginning of 2018 to the end of 2021. Please note that, while the total installed power of VRE increased by 36% from 38 GW to 52 GW in this four-year period, there was no significant increase in the rate of meeting the demand. At the end of the calculation, these scenarios also will serve as the reference for systems' GHG emission effect calculation methodology. These scenarios are given below;

1. Capacity addition for all type VRE
2. Capacity addition for only wind and solar power plants
3. Wind and Solar hybrid systems
4. Hydro and Solar hybrid systems

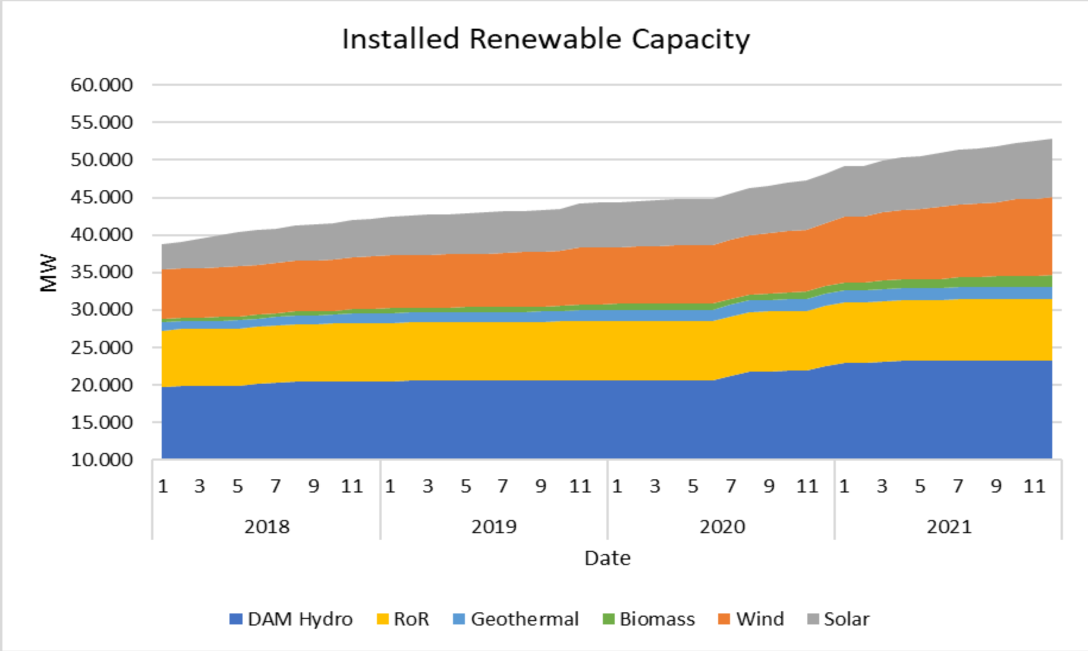

Figure 28 Installed renewable capacity[17]

Scenario 1 represents situations where all renewable energy source types meet demand without hybrid or solutions. In order to create a situation where all demand can be met only from VRE, the initial installed capacity in 2018 had to be at least 64% more. Even in this case, it could only meet this in April and May in 2019, which were rainy, and in 2020, when the Covid-19 pandemic hit. Therefore, it is not a very effective solution to consider meeting Turkey's demand permanently only with renewable energy sources.

	1	2	3	4	5	6	7	8	9	10	11	12	
2018	0	0	0	0	0	0	0	0	0	0	0	0	
2019	0	0	8	47	156	178	0	0	0	0	0	0	All Renewable Sources
2020	0	0	52	461	300	0	0	0	0	0	0	0	
2021	0	0	0	4	8	0	0	0	0	0	0	0	

Figure 29 Number of hours for scenario 1

Similarly, in scenario 2, the situation of meeting the demand with only wind and solar power plants was examined. Just like in scenario 1, the result here is far from being applicable. At least 250% capacity increase should have been achieved so that demand could be met by wind and solar resources at some hours in 2021.

	1	2	3	4	5	6	7	8	9	10	11	12	
2018	0	0	0	2	0	0	0	0	0	0	0	0	
2019	0	0	4	0	0	4	0	14	6	0	0	0	Wind + Solar
2020	0	4	0	33	34	2	4	4	0	0	7	0	
2021	8	28	0	17	52	0	34	13	19	31	16	20	

Figure 30 Number of hours for scenario 2

[17] EPDK. (2022). *Elektrik Piyasası Aylık Sektör Raporu.* https://www.epdk.gov.tr/Detay/Icerik/3-0-23/elektrikaylik-sektor-raporlar

However, when we make a calculation taking into account the hybrid power plant legislation in Turkey, the 250% wind and solar capacity increase in scenario 2 will result in an average installed power increase of 64% and above when these two sources are hybridized, that is, they are used together rather than separately. It is possible to say that there will be effective results.

	1	2	3	4	5	6	7	8	9	10	11	12	
2018	0	11	38	8	0	3	10	65	29	5	4	0	
2019	5	7	33	5	3	25	21	53	27	0	4	2	Wind + Solar (Hybrid)
2020	4	12	2	12	15	11	50	36	21	4	15	9	
2021	18	34	18	13	29	0	55	31	33	9	10	9	

Figure 31 Number of hours for scenario 3

Finally, the solar hybrid system built with the wind in scenario 3 was calculated in scenario 4, together with hydroelectric power plants. As a result, it was possible to obtain hours that could meet the demand in the years when the amount of water is high, such as 2019 and 2020, rather than the dry 2021 year.

	1	2	3	4	5	6	7	8	9	10	11	12	
2018	0	0	1	2	0	0	20	50	4	0	0	0	
2019	0	6	18	27	73	106	119	86	31	0	0	0	Hydro + Solar (Hybrid)
2020	0	4	13	28	30	6	82	109	40	0	0	0	
2021	0	0	2	3	0	5	14	28	0	0	0	0	

Figure 32 Number of hours for scenario 4

When all these results are examined, it seems that the best solution for the use of systems is the hybrid use method of wind and solar power plants. Therefore, in the next stage of the thesis, the effects of systems on carbon emissions with the following usage types were investigate;

1. Arbitrage
2. Imbalance Management
3. Wind-Solar Hybrid
4. HPP-Floating Solar Hybrid

The reason why 2018 was chosen as the starting year of the calculations, although not included in the calculations in this thesis, is that an important change in the regulation of the ancillary services market was made on this date. Even though, the Ancillary Service market especially PFC market, for batteries is one of the most profitable markets for batteries, it is not included in the calculations due to the lack of sufficient transparency about the market.

The realized MCP for the four years was used. Also, for the hybrid power plant calculation, a Wind farm with an installed power of 27 MW and a Solar farm with a power of 8 MW which not in operation yet were used.

While the realized generation values of the wind power plant were taken for the calculation, PVsyst simulation was used as location specific for solar power plant generation estimation. The summary of calculation inputs is shown below;

Rated Power (MW)	5
Storage Capacity (MWh)	20
Charge-Discharge Hour	4
Efficiency (%)	85
Instant Power (MW)	20
Coal CO2 (tonnes/MWh)	0,98
NG Co2 (tonnes/MWh)	0,34
Wind Installed Power (MWh)	27,5
Solar Installed Power (MWh)	8
CCGT Efficiency (%)	58
Coal Efficiency (%)	40

Figure 33 Calculation inputs

To determine another important concept marginal power plant type, the cost calculation was made with the BOTAS tariff price for natural gas and API-2 contract prices for coal power plants for each month. The result is given in Figure 34. As it can be seen, the marginal energy source is mostly natural gas except for some periods such as the summer of 2021. The effect of the marginal energy source switch can be also examined in Figure 26. Lastly, for the GHG calculation of these power plants per MWh, the GHG data announced in the national inventory report[18] and the generation values announced in EPİAS Transparency were included.

Understanding the marginal power plant concept is important in calculating the GHG impact of BESS usage types. As shown in Figure 35(Hale, Weeks, & Tucker, 2011), while the BESS purchases from the electricity grid will increase the demand, its supply of energy to the grid will cause a decrease in the supply where the demand is met. The first source that will respond when the demand increases, or decreases will be the marginal energy source. The effect of the four different usage styles calculated will be different for certain reasons. These reasons will be explained in detail.

[18] Referred from United Nations. (2021). *Turkey. 2021 National Inventory Report* https://web.archive.org/web/20210414114920/https://unfccc.int/documents/271544

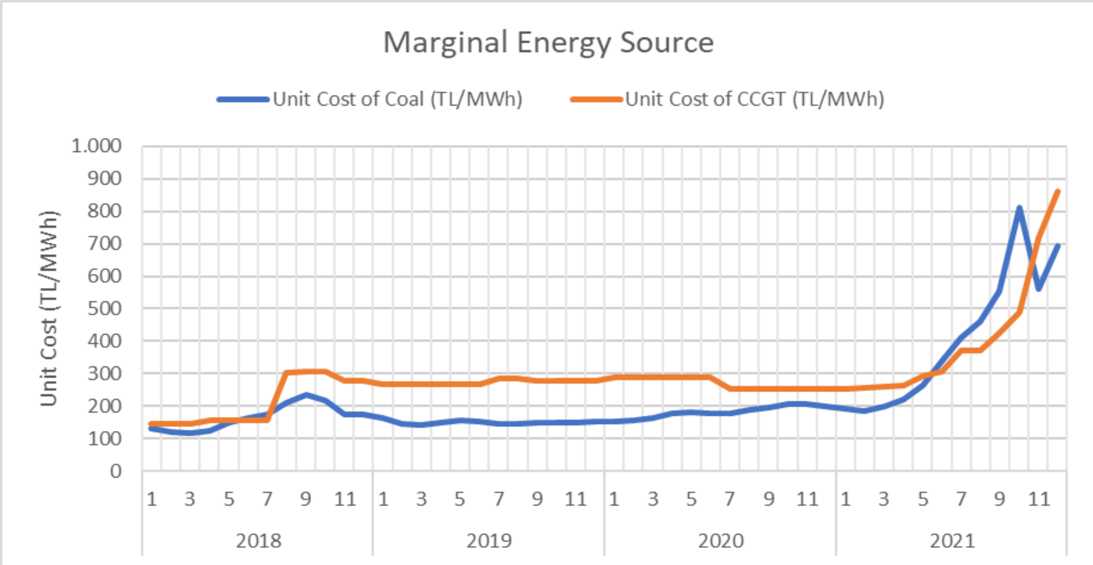

Figure 34 Marginal energy source monthly

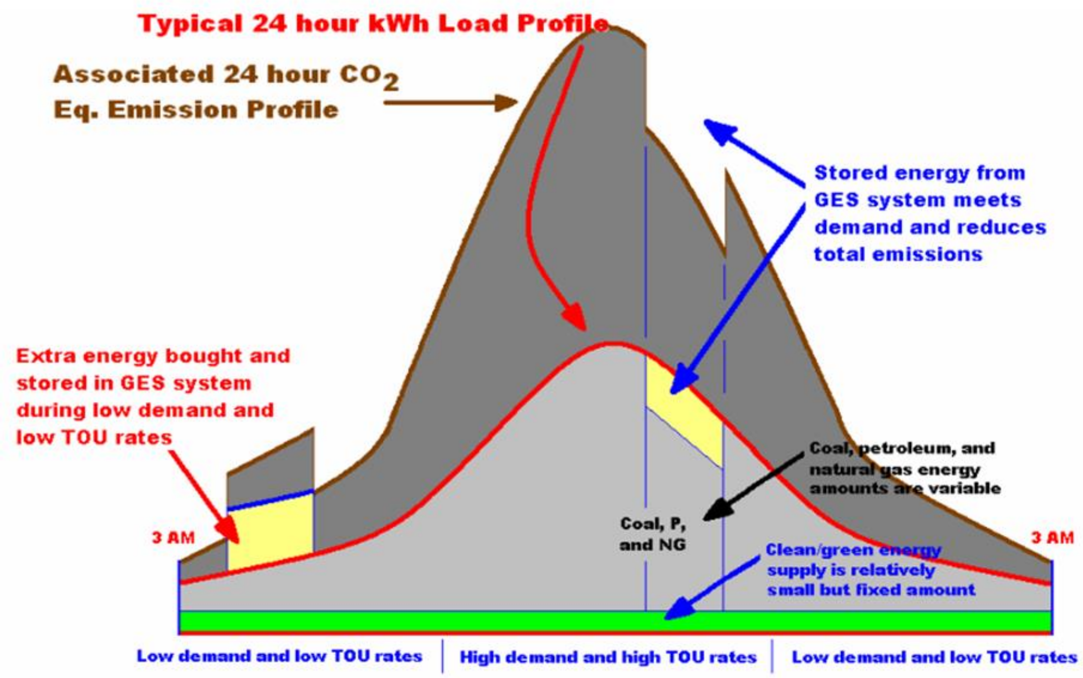

Figure 35 Generation switch between sources

3.1 Arbitrage for Battery Energy Storage

A day has completely different energy demand values for each hour. Demand is low during night hours when people are sleeping and factory production is decreasing, and demand is high during daytime hours when the workload is high. Figure 36[19] shows the hourly average demands for the related years. The purpose of arbitrage is to make a profit by buying low and selling high at varying price levels due to demand.

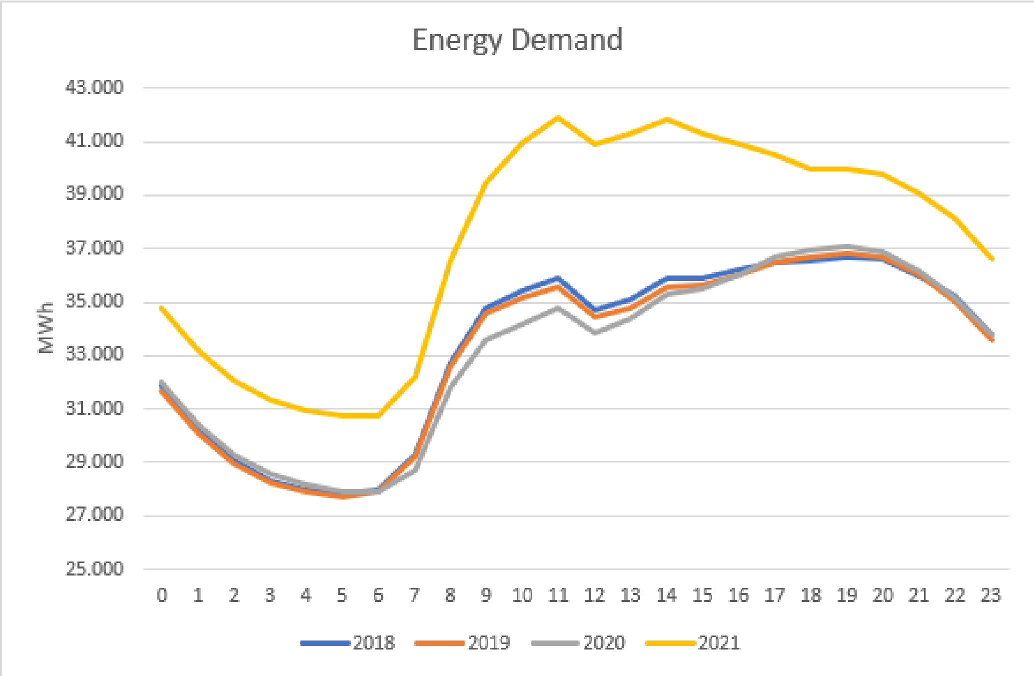

Figure 36 Energy demand curve

As shown in Figure 33, the BESS used in this study has 5 MW rated power and the total charge/discharge time is four hours. However, no degradation curve was used for this BESS. Since the battery has a total charge/discharge capacity of four hours, a model was developed that aims to buy in the lowest four hours of the day and sell in the highest four hours. Although there is not a homogeneous charge/discharge distribution in the daily sense due to the distribution of the relevant hours during the day and the instantaneous level of the battery, a balanced charge/discharge number has been achieved on an annual basis.

[19] Referred from https://seffaflik.epias.com.tr/transparency/

At the end of the four-year period, the average price spread has happened as 20 USD/MWh and the total revenue has realized as 395,110 USD which is not a sufficient result when it is considered with approximately 200,000 USD/MWh[20] system cost.

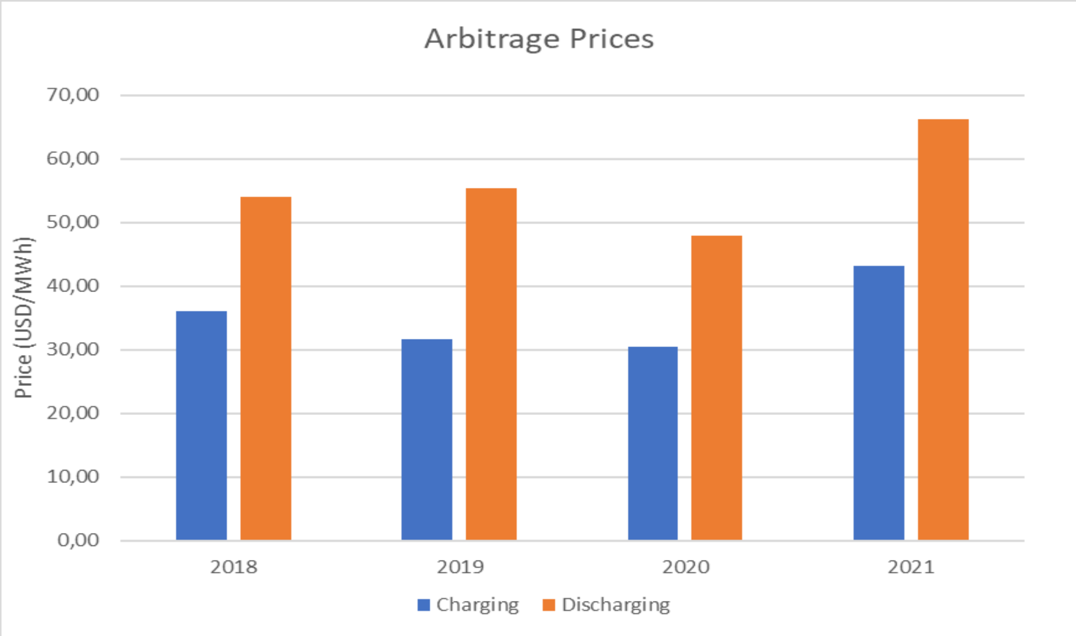

Figure 37 Average prices for arbitrage case

As mentioned earlier, the BESS creates a demand in the electricity grid when it is charged and reduces the need for supply when it is charged. However, since the BESS do not work 100% efficiently, the benefit it provides on the supply side has to be lower than the demand it creates. Therefore, it is not possible for a BESS used only for arbitrage purposes to meet the entire amount of GHG caused by the marginal power plant, which is trying to meet the extra demand created, by giving the energy it has stored to the system. In a conclusion, arbitrage caused additional 2,092.4 tCO2 as shown Figure 38.

[20] Referred from Solar 3GW. (2022). *Batarya Depolamalı GES Duyarlılık Analizi*. https://www.solar3gw.org/

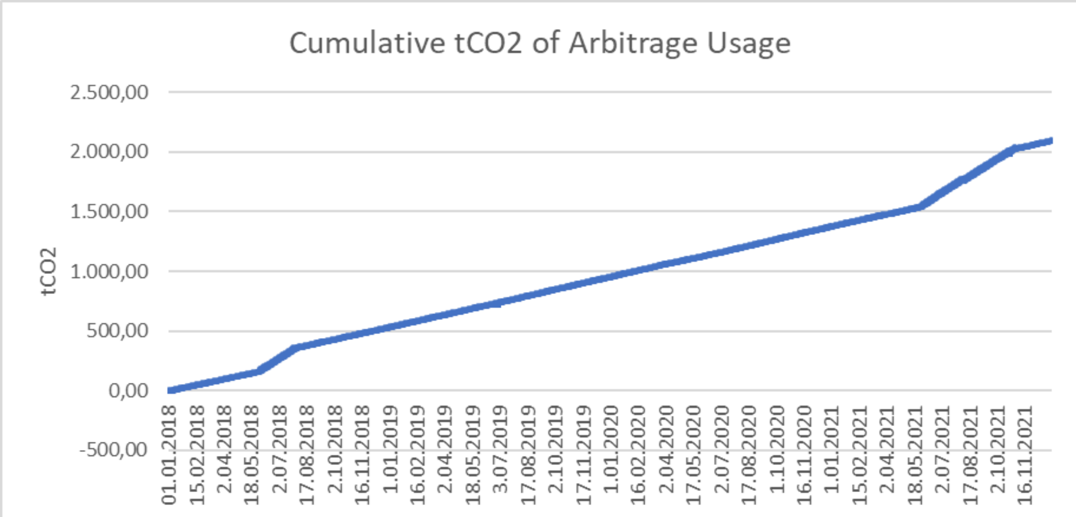

Figure 38 Cumulative tCO2 of arbitrage usage

3.2 Imbalance Management

This usage style, which is also very beneficial for the system operator, aims to reduce the opportunity cost incurred by reducing the imbalance volumes made by the power plant. While wind and solar power plants stand out as the most prone to an imbalance among all VRE, due to their complete dependence on weather conditions, the deviation in the estimations of solar power plants is lower than wind power plants. To support with numbers, the average deviation of generation from obligation in wind farms across Turkey is about 7%, while this rate is 0.2% in solar power plants..

Therefore, as mentioned before, a wind farm with an installed capacity of 27 MW is included in this calculation. The sales made by this power plant in the Day-Ahead Market and the actual generation values were compared, and accordingly, the battery was charged in case of overgeneration and discharged in case of under generation. In the end, total benefit for reducing the imbalance amount was only 169,140 USD.

Although the amount of energy supplied to the electricity grid by the battery is entirely generated from VRE, the marginal power plant will still have to cover the difference, since more renewable generation is not given to the grid on time. There is an inverse correlation between the generation of VRE and thermal power plants. Wind or if the solar power plants generate more than they sell in Day-Ahead Market the operator who wants to balance the grid will instruct the thermal power plants to reduce their generation. If this excess generation is not given to the grid, the thermal power plants will not be instructed to reduce their generation either. As a result, BESS used only for balancing management will not be beneficial in reducing GHG emissions. In this case, systems caused additional 1,407.74 tCO2 which more positive result when it considered with arbitrage usage.

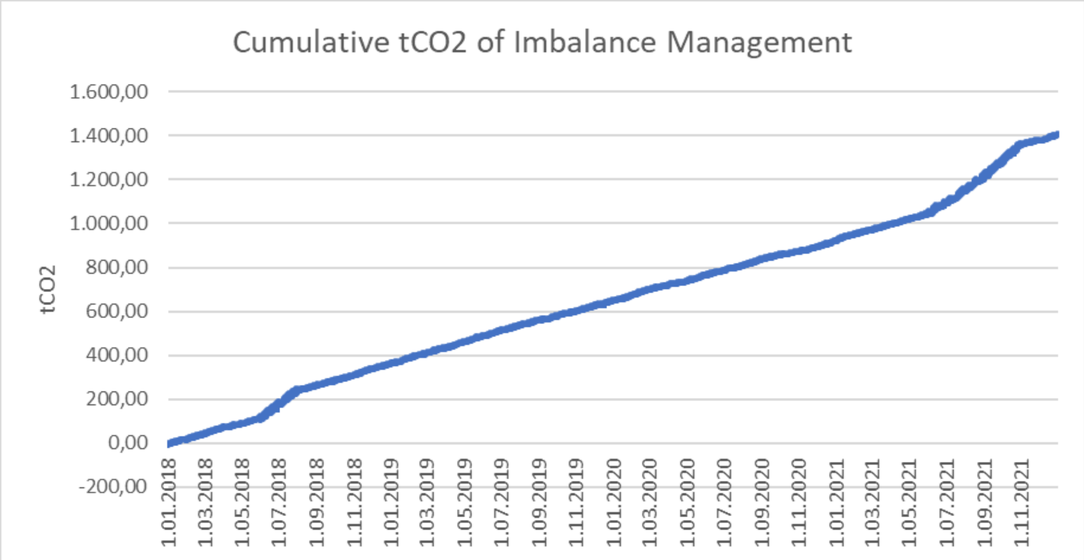

Figure 39 Cumulative tCO2 of imbalance management

3.3 Wind-Solar Hybrid Solution

In this calculation, the effect of BESS in a scenario where hybrid wind and solar power plants are used was calculated. The main purpose of this usage style is to increase the capacity utilization rate of the relevant power plant by combining two different generation sources. Figure 40[21] illustrates this very nicely. At noon, when the capacity utilization rates of solar power plants increase, the rate of wind power plants decreases, and in the opposite way, while the capacity usage of wind power plants increases, that of solar power plants decreases during night hours. When these two resource types are combined, they complete each other's deficiencies.

[21] Referred from https://seffaflik.epias.com.tr/transparency/

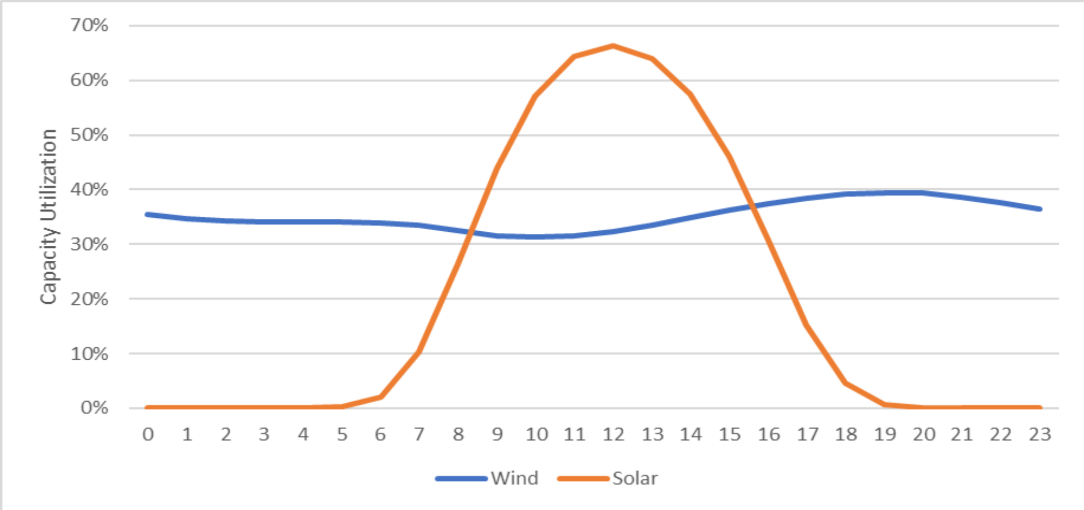

Figure 40 Capacity utilization for wind and solar power plants

In this study, besides the wind power plant with an installed power of 27 MW, which was used in the previous calculations, a solar power plant project with an installed power of 8 MW was used. Please note that while the wind farm is a real power plant in operation, the solar power plant is only at the project stage. In order to make the results as realistic as possible, the findings obtained in the PVsyst simulation program that use historical satellite data were used because a location-based production value was preferred. Since the electrical power supplied to the grid from the hybrid power plants must not exceed the licensed power of the main power plant in accordance with the legislation in Turkey, the battery is charged when the total generation of the wind and solar power plants exceeds 27 MW, and the battery is discharged when the generation of the wind farm is below the expected level.

Therefore, this type of use will have a positive effect on GHG emissions during operation, since energy that could not be supplied to the system under normal conditions is given by a system and this energy is provided entirely from VRE. Total GHG emission benefit of this usage type was 1,303.05 tCO2.

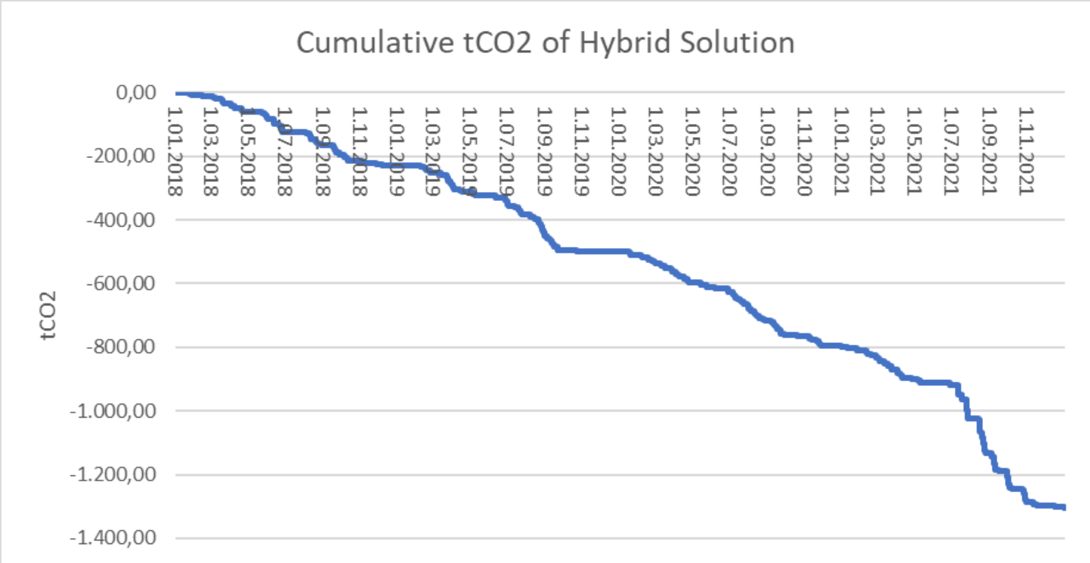

Figure 41 Cumulative tco2 of hybrid solution

	1	2	3	4	5	6	7	8	9	10	11	12	
2018	24	20	50	43	36	31	0	99	72	42	36	8	
2019	5	55	88	38	15	62	62	132	103	16	1	0	Hybrid Solution
2020	25	48	76	125	28	34	179	64	114	13	56	10	
2021	37	51	68	38	43	2	58	65	64	64	30	15	

Figure 42 Number of hours of hybrid solution

3.4 Hydro-Floating Solar Hybrid Solution

Finally, the effect of the hybrid operation of a floating solar power plant, which is a relatively new technology, and a dam hydroelectric power plant was investigated. Although the effects of floating solar power plant technology on underwater life have not been fully investigated and there are legal issues in its applications in Turkey, it was thought that it would be useful to examine the effect of such use. In order not to differ from other calculations, the technical characteristics of the battery and solar panel are considered the same. Since there is no simulation study specific to the selected hydroelectric power plant, the production and capacity utilization rates of two separate solar power plants in the region were examined and the average of the capacity utilization rates was used. The hydroelectric power plant used is in a cascade structure with another hydroelectric power plant used for the irrigation need in the region and is in a structure that works for the level control of the relevant power plant. During the summer period, the necessary generation capacity that is capacity utilization is higher because of the irrigation need as Figure 43 shows.

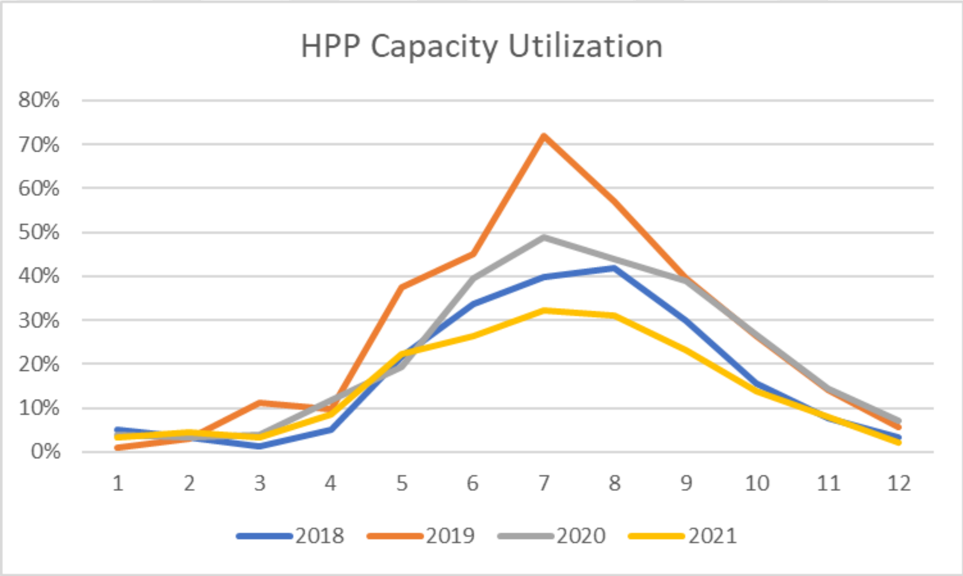

Figure 43 HPP Capacity Utilization

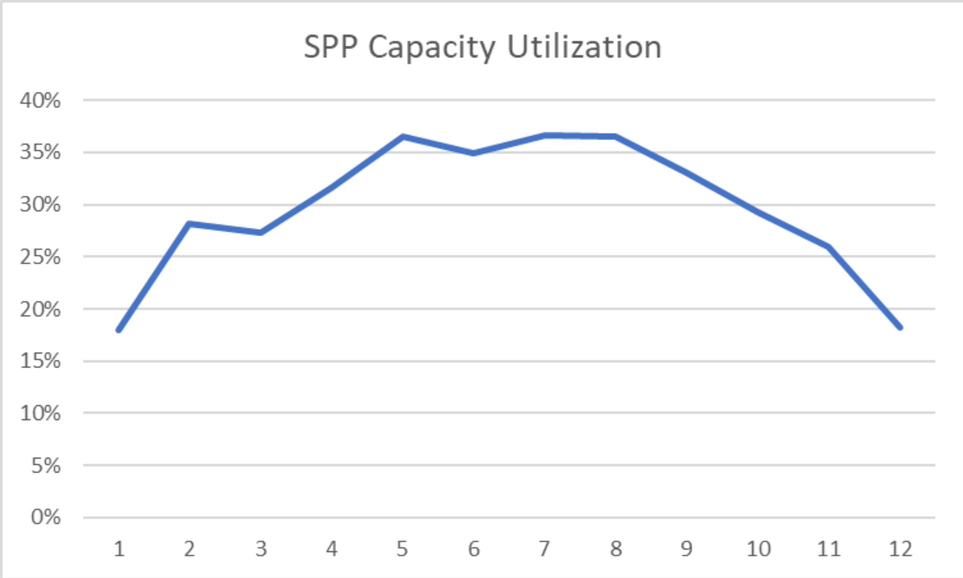

Figure 44 SPP Capacity Utilization

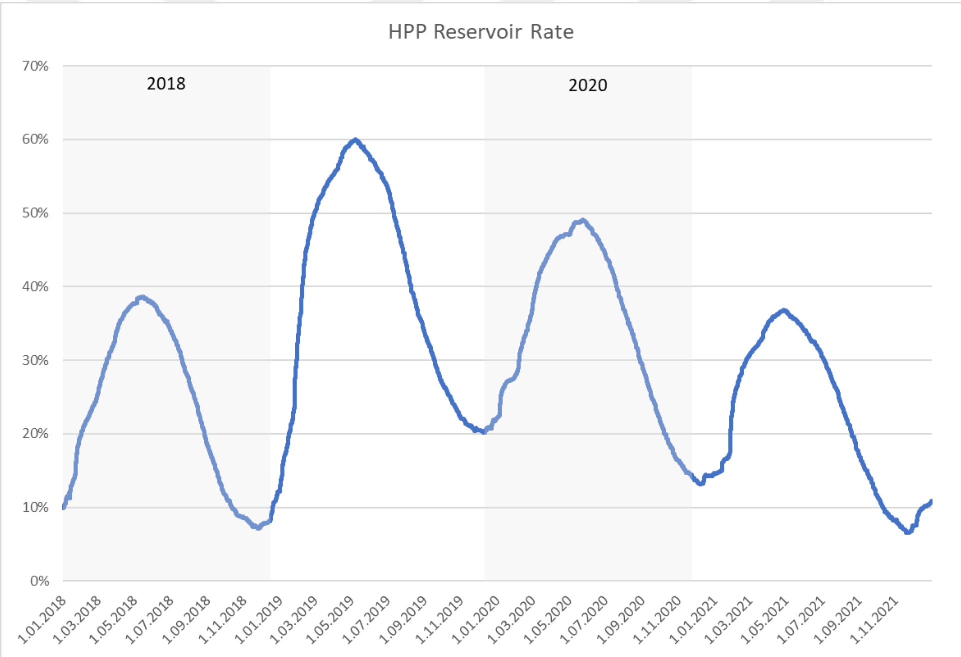

Figure 45 Reservoir Level Rate

Without examining the results, it would be a fair expectation to expect a positive effect on carbon emissions, as the generation of the installed power is a solution that is stored and then given to the system, just like in the wind-solar solution. When the results were analysed, it was seen that this expectation was met. However, when we look at the details of the results, it is understood that in the four-year period, it can only benefit in the summer months of 2019 and 2020. Parallel to the calculation made in Figure 32, the reservoir occupancy ratio of the power plant increased, and the power generated by the turbines increased since 2019 and 2020 were wet years compared to other years as illustrated by Figure 45. During the summer period, generated power by the hydroelectric power plant and floating solar panels could be above the installed power which had a positive effect on greenhouse gas as shown as Figure46.

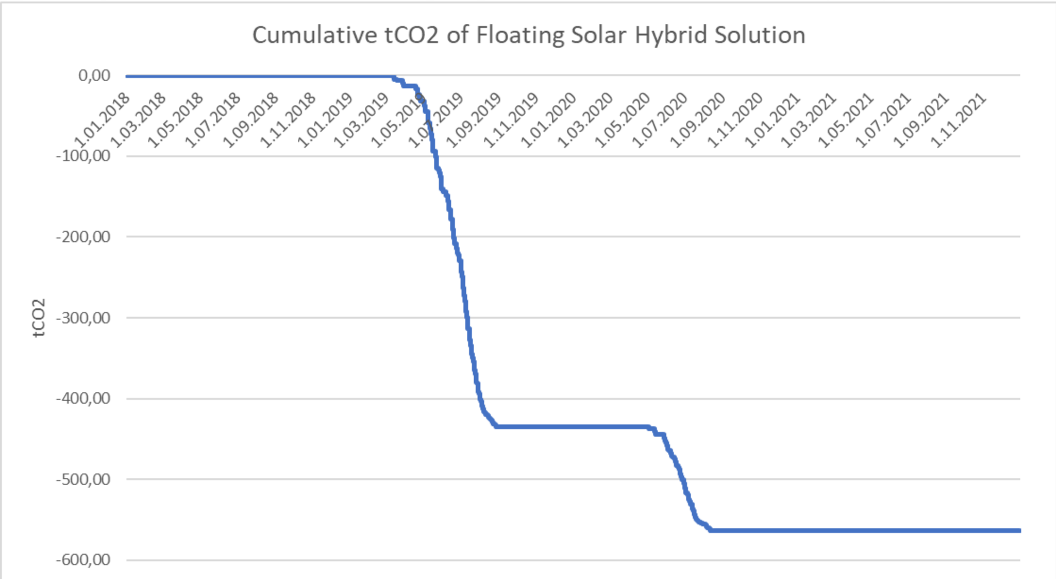

Figure 46 Cumulative tCO2 of floating solar hybrid solution

However, at this point, it is necessary to know how much GHG emissions are caused by the generation of the BESS used and to calculate its net effect. For this purpose, Melin's Analysis study (Melin, 2019), which has examined many different sources and has made a summary report by detailing, is a very good resource. According to the data obtained by the study (Melin, 2019), the process that causes the most carbon emissions in BESS manufacturing, with a rate of 75%, is cell manufacturing. The total GHG effect is calculated as 73 tons/MWh.

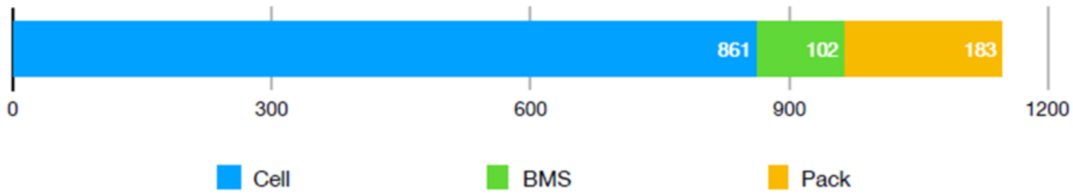

Figure 47 MJ/kWh for a NCM111 battery pack (Melin, 2019)

Benefit calculation was done according to following equations.

1- $a = z \div 4$

2- $Break\ Even\ Time = (x \times y) \div [(a \times b \times d) + (a \times c \times f)]$

a = Total Discharge of Battery Storage System (MWh)

b= Emission Effect of Coal Power Plants (CO2/MWh)

c= Emission Effect of Natural Gas Power Plants (CO2/MWh)

d= Discharge Ratio for Coal Power Plants (%)

f= Discharge Ratio for Natural Gas Power Plants (%)

x= GHG Effect of Battery Storage System Production (CO2/MWh)

y= Installed Power of Battery Storage System (MWh)

z= Total Discharge (MWh)

When these formulas were applied to scenario3 and scenario4, the result was not surprising. The BESS integrated into the hybrid system with wind and solar power plant in scenario 3 eliminated the natural gas power plants in 86% of its discharge and reached the carbon zero position after 4.5 years. In Scenario 4, the BESS, which works with a hybrid system with dam hydroelectric and floating solar panels, eliminated natural gas power plants in 99.9% of its discharges and only reached carbon zero after 10 years. The reason why scenario number 4 was left behind so much was that the filling rates of the dams were at a low level due to the drought, as mentioned before. Although the usage time of the batteries varies according to the battery type and discharge conditions, the results of the research conducted by NREL[22] were used in this study and an average usage time of 10 to 15 years was accepted. Accordingly, while the BESS with scenario-3 is an important force in achieving the GHG targets, the BESS system with scenario-4 is at the very limit.

[22] Referred from https://www.nrel.gov/transportation/battery-lifespan.html

Chapter 4

Discussions and Conclusions

It is a fact that energy storage technologies, especially systems, will offer great convenience to network operators in order to manage technical difficulties and uncertainties in the electricity grid. In particular, it can play a critical role in ensuring the predictability of the generation of wind and solar power plants that depend on VRE and in managing the voltage fluctuations arising from these power plants.

For this reason, the interest in this technology is increasing day by day and the governments of the countries are doing the necessary legal studies to bring this flexibility to their networks. In addition to the R&D programs announced with Green Deal in Europe, the Turkish government has also announced that it has prioritized investments in renewable energy investments and energy storage technologies in the eleventh development plan published in July 2019[23].

However, apart from the technical benefits of the storage technology, the main topic of this thesis was the extent to which it will benefit to achieve the announced 2050 NetZero targets. In IRENA reports (Renewable Energy Agency, 2020), the role of these systems in reducing GHG emissions is considered critical and essential. However, when the results of the calculations made in this thesis and the details of which are given in the previous sections are examined, it is seen that the GHG effect can be quite different from each other according to the type of use of this technology. Among the four different usage methods examined, only the BESS system integrated into the hybrid power plant was able to reduce GHG. Although the energy produced with completely renewable energy is stored in the imbalance management method, this energy is an energy that can be given to the system, unlike the hybrid power plant method. Not giving this energy to grid means not reducing the share of thermal power plants in energy production. In the hybrid power plant method, the energy above the installed power could not be supplied to the electricity system. Therefore, the share of thermal power plants decreases when the stored energy is given to the grid.

[23] Referred from Türkiye Cumhuriyeti Cumhurbaşkanlığı Strateji ve Bütçe Başkanlığı. (2019). *On Birinci Kalkınma Planı*. https://www.sbb.gov.tr/kalkinma-planlari/

The main contribution of this technology in terms of GHG will be to increase the number of renewable energy power plants by making it more attractive for investors and network operators, thus reducing the rate of thermal power plants in electricity generation. The report published by Solar 3GW, which shows that solar power plant investments supported by batteries can replace coal power plants in Turkey, is an important report in terms of showing the real benefit of BESS.

With the current conjuncture, it does not seem possible for BESS to be a feasible investment with only arbitrage, imbalance management, or capacity utilization increase. However, in view of increasing the integration of renewable power plants into the grid and their ability to manage technical constraints, it is essential to introduce incentive systems and define a more detailed strategy. The report by Solar3 GW[24] is a good example to illustrate the strategic perspective required.

In the current market conditions, arbitrage, imbalance management, increasing the capacity utilization, or even taking part in the ancillary service market is not enough when it is used alone in order to ensure the widespread use of this technology. In order to increase the sales channels and make the project feasible, it is necessary to ensure that all usage types can be made together. Despite this, according to the technical criteria published by TEIAS on September 21, 2021[25], BESS integrated into hybrid power plants were prevented from providing ancillary services. Unfortunately, this technology could not be expected to become widespread in this way. In addition, it would be beneficial to increase the number of ancillary services implemented in Turkey and to integrate systems into these markets. Bringing the black start service to the market, which currently has only secondary and primary frequency control, will be very beneficial in terms of the widespread use of technology. In order to improve this work, it would be useful to include research on hydrogen production technology, which is a popular topic in recent times. In the part of meeting the energy need of the produced hydrogen, the effects of BSS can be examined and its effect on CO2 emissions can be approached from a different perspective.

[24] Referred from Solar 3GW. (2022). *Kömür Sahalarının Güneş Potansiyeli.* https://www.solar3gw.org/

[25] Referred from TEİAŞ. (2021). *Elektrik Depolama Tesislerinin Şebekeye Bağlanmasi Ve Yan Hizmetlerde Kullanilmasina Dair Teknik Kriterler.* https://www.teias.gov.tr/tr-TR/haberler/elektrik-depolama-tesislerinin-teknik-kriterleri-hakkinda-duyuru

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