

**MULTI-CRITERIA EVALUATION OF ENERGY STORAGE
TECHNOLOGIES CONSIDERING ELECTRICITY MARKET
REGULATION OF TURKEY**



SELEN YOLDAŞ

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**MULTI-CRITERIA EVALUATION OF ENERGY STORAGE
TECHNOLOGIES CONSIDERING ELECTRICITY MARKET
REGULATION OF TURKEY**

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Program Name:	Energy Systems Operation and Technology
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Prof. Dr. Ahmet ÖNCÜ
Institute Director

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

	Title, Name	Signature
Thesis Advisor:	Assist. Prof. Gürkan Soykan	
2. Member:	Assoc. Prof. Fehmi Görkem Üçtuğ	
3. Member:	Assist Prof. İrem FIRTINA	



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Name, Surname : Selen Yoldaş

Signature :

ABSTRACT

MULTI-CRITERIA EVALUATION OF ENERGY STORAGE TECHNOLOGIES CONSIDERING ELECTRICITY MARKET REGULATION OF TURKEY

Selen Yoldaş

Energy Systems Operation and Technology Master's Program

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Increasing the world population and integration of electrical devices into daily usage more leads to an increase in electricity consumption day by day. Fossil fuels are limited and harmful to the environment. Therefore, governments changed their policies to renewables. An increase in the share of the renewables inflames the hardship of the electricity network since they are intermittent. Moreover, even a short blackout causes big damage to the industry, so electricity must be continuous. All these concerns bring the importance of energy storage for the power network. This thesis gives an overview of energy storage technologies and provides sufficient information. Also, a Multi-criteria decision-making approach is applied to find the suitable storage technology. A model is created considering the legislation of energy storage activities in Turkey by using the integrated AHP-TOPSIS technique. The model is used for two different profiles. All empirical data to establish the model was gathered from the literature and surveys. By considering the results, VRFB is chosen as the best solution for the electricity storage facility adjoined to the consumption facility, and CAES is ranked first for the independent electricity storage facility.

Keywords: Energy Storage, MCDM, AHP, TOPSIS

ÖZ

ENERJİ DEPOLAMA TEKNOLOJİLERİNİN TÜRKİYE ELEKTRİK PİYASASI YÖNETMELİĞİ DİKKATE ALINARAK ÇOK KRİTERLİ DEĞERLENDİRİLMESİ

Selen Yoldaş

Enerji Sistemleri İşletim ve Teknolojileri Yüksek Lisans Programı

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Dünya nüfusunun artması ve elektrikli cihazların günlük kullanıma daha fazla entegre edilmesi, elektrik tüketiminin her geçen gün artmasına neden olmaktadır. Fosil yakıtlar sınırlıdır ve çevreye zararlıdır. Bu nedenle hükümetler politikalarını yenilenebilir enerjiye çevirdi. Yenilenebilirlerin payındaki artış, kesintili oldukları için elektrik şebekesinin zorluğunu alevlendiriyor. Üstelik kısa bir elektrik kesintisi bile sektöre büyük zarar veriyor, dolayısıyla elektriğin sürekli olması gerekiyor. Tüm bu endişeler, güç şebekesi için enerji depolamanın önemini beraberinde getiriyor. Bu tez, enerji depolama teknolojilerine genel bir bakış sunar ve yeterli bilgi sağlar. Ayrıca, uygun depolama teknolojisini bulmak için çok kriterli karar verme yaklaşımı uygulanır. Entegre AHP-TOPSIS tekniği kullanılarak Türkiye'deki enerji depolama faaliyetleri mevzuatı dikkate alınarak bir model oluşturulmuştur. Model iki farklı profil için kullanılmaktadır. Modeli kurmak için tüm ampirik veriler literatürden ve anketlerden toplanmıştır. Sonuçlar göz önünde bulundurularak, tüketim tesisine bütünsel elektrik depolama tesisi için en iyi çözüm olarak VRFB seçilmiş ve müstakil elektrik depolama tesisi için CAES birinci sırada yer almıştır.

Anahtar Kelimeler: Enerji Depolama, ÇKKV, AHS, TOPSIS

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ABBREVIATIONS

AHP	Analytical Hierarchy Process
CAES	Compressed Air Storage
CR	Consistency Ratio
DOE	Department of Energy
EMRA	Energy Market Regulatory Authority
ESFACF	Regulation for The Electricity Storage Facilities Adjoined to The Consumption Facility
ESFACF	Regulation for The Electricity Storage Facilities Adjoined to The Consumption Facility
ESSs	Energy Storage Systems
EST	Energy Storage Technology
FES	Flywheel Energy Storage
MCDM	Multi-criteria Decision Making
MENR	Ministry of Energy and Natural Resources
Na-S	Sodium Sulfur
Ni-Cd	Nickel-Cadmium
Pb-A	Lead-Acid
PHES	Pumped Hydro Energy Storage
TEIAS	Turkish Electricity Transmission Company
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VRFB	Vanadium Redox Flow Batteries
WEC	World Energy Council

Chapter 1

Introduction

1.1 Energy Storage

Literally “Storage” means the process of keeping something in a particular place until it is needed according to Oxford dictionary. Mankind tends to store things since their first existence. They started to store their food first. After the hunter-gatherer lifestyle, mankind who started the agricultural revolution with the increase of agricultural products realized that the products deteriorated after a while, and they started looking for solutions. At that time, the products that could not be consumed were hiding under the snow, deep in the ground, or in cool caves. The act of storing is not only a learned behavior but also an instinctive phenomenon. Considering the human body, excess glucose, which is the main energy source, is stored as fat for later use. When it is checked in dictionaries the meaning of Energy can be seen in different explanations but the most known of them; are “the ability of matter or radiation to work because of its mass, movement, electric charge, etc.” and “a source of power, such as fuel, used for driving machines, providing heat, etc.”¹.

The history of civilization starts with discovering energy sources. Human beings first started to use their muscle power as a source of energy to try to transform nature. Then he moves forward by learning the use opportunities that nature gives him such as using animals’ muscle strength around him and then using natural resources such as wind and rivers. With the discovery of fire and starting the conscious use of it, people began to meet their needs such as warming and enlightenment. Most furniture started to be produced thanks to the use of fire. It can be said that along with the discovery of fire, many developments took place in the world. These developments have led to the emergence of many products that are used today.

Civilization can be split into two periods, before and after the industrial revolution. The pre-industrial revolution era of development can be split into three periods: the period when human beings used their muscle power, the period when

¹ Source: Retrieved from www.oxfordlearnersdictionaries.com at 2021, September 5

they use animals' muscle power around them, and the period when he uses the power of nature (wind, river, and Sun). It is separated into four phases after the industrial revolution: the first, second, third, and fourth industrial revolutions. All these epochs that comprise civilization are shaped according to the extent of our ability to access and control energy resources. On the 18th. Century coal becomes very important both as a source of heat and energy because of the Industrial revolution which also played important role in this revolution as well. Coal resources gain great importance such that Alsace and Lorraine which has coal reserves have long been controversial regions between Germany and France. So much so that, this disputed enclave counts as one of the reasons for I. World War. Energy is generally used as heat and electricity. Regardless of its form, the energy headings for human beings have been gathered in four main subjects from the beginning until today; generate, transmit, distribute, and store. The first three of these cover the steps associated with generating energy and distributing it to the final consumer. The final one, storage, allows using all three titles sustainably and efficiently. While the questions such as which sources should use to produce energy, and how it can be transmitted and distributed are related to first three subjects; answers to the questions such as; how can it quantify the excess energy generated, how can it balance production fluctuations caused by the source of production, how do it can ensure that the transmission is stable and lossless, how can be the end user use the cheapest tariff during peak hours, how can it reduce the load on the grid during peak hours, is it possible to use the energy produced during times when the energy is idle (production is not required) to balance the peak times and reduce the need for new investments are related with storage (MAZMAN and YILMAZ, 2019, p-466).

The oldest battery is a 2,200-year-old clay pot discovered near Baghdad, Iraq. The object, along with others of its kind, is housed at the Iraq National Museum. It appears to be from around 200 BC. Wilhelm Koning, a German archaeologist, was the first to describe it in 1938. It stands about 16 centimeters tall and is about 8 inches thick. When it was discovered, the pot had an asphalt-like cover and an inside copper folio-wrapped pipe at the upper end of the copper cylinder. One quite narrow iron ramrod has been pinned to the bottom bottle and transferred without contacting the interiors of the copper pipe. This ancient battery's operation is related to

fermented vinegar or grapefruit juice in a jar. These acids allow electrons to migrate from a copper tube to an iron ramrod when the two metals are connected at one end, resulting in a low-intensity current. Experiments have revealed that this battery can produce between 1.5 and 2 volts. This is a relatively low power level, but significant in terms of the applications that could be given in the year 200 BC. Unfortunately, even after making numerous assumptions, the specialists were unable to determine what they used these batteries for as of today. One source even claimed that the battery was used to treat pain, as the Greeks did with certain species of electric fish. The most enticing of the hypotheses is that this battery is the Philosopher's Stone, which has been pursued by alchemists for two millennia.

When it is mentioned that energy storage first thing that comes to mind is "Batteries". Benjamin Franklin was one of the first people who came up with the term Electrical Battery. He mentioned this in his letter in 1749 to English journalist Peter Collinson while describing his work related to static electricity using Lead glass. As time passed it became the meaning used today. (Franklin, 2014) Although Franklin was known first person attributed electrical batteries there was a conflict about inventing with capacitor bank. According to Adam Allerhand's study the Leyden Jars Batteries and electrostatic batteries invented by Ewald Georg Jürge von Kleist and Pieter van Musschenbroek in 1745, Kammin of Prussia and Leiden of Holland (Allerhand, 2018). The first scientific studies on electricity were conducted around the same time, pioneering the way for the development of electrochemical energy storage systems. Luigi Galvani and Alessandro Conte di Volta were associated with the first steps, which became known as "galvanic element" and "volt" in history. Galvani discovered when the deceased get in contact with different metals, a frog leg starts to twitch. He deduced from this that there is a link between muscle activity and electricity. Volta, in turn, investigated the effects of different metals in various salt solutions. In a letter to Joseph Banks, in March 1800, Alessandro Volta defined an appliance that could supply uninterrupted power supply. The device (Figure 1), later known as the "Voltaic Pile," was made up of tin or zinc discs paired with copper, brass, or silver discs, with layers of water-soaked paper, fiberboard, or leather between the disc pairs. The experimenter gained access to a constant electric current via cable junction with the discs.

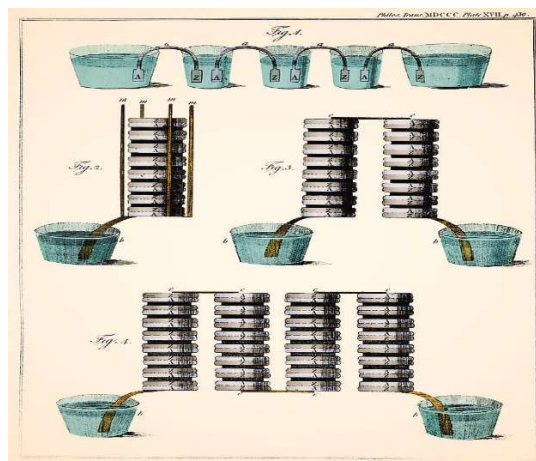


Figure 1. Volta's crown of cups and Voltaic pile (public domain).

It also includes a description of Volta's so-called "crown of cups", a series of modern ones that will be described as simple wet batteries. Slight corrosion sometimes occurs on the cathode disk (copper or silver), but it is not to the same amount as on the anode side. This leads to the believing to conclusion that the current was totally due to the anode reaction at that time. Recognition of the fact that oxidation cannot proceed in the absence of reduction today, Volta and others have noticed that the hydrogen bubbles attached to the electrode surface cause polarization problems, corresponding reduction process in the Volta reactor is reduction to produce hydrogen from water. In the letter, Volta's explanation about his pile was thorough with an exquisite and straightforward design. This allowed experimenters to build replicas very quickly in their labs to apply to their work. Volta's pile was a big event, but the pile was mean nothing without its imitation cause it has limited useful lifetime. After the Voltaic pile, Cruickshank modified it by using grooved wooden and Charles Wilkinson improved Cruickshank's. With the idea two of fluid cells J. Frederic Daniell created a cell called Daniell Cell. William Grove modified Daniell's and he created important changes, so he was able to obtain more electric current. In 1866, France, Georges Leclanché came up with a cell design that can be counted base of today's dry cell. This kind of cell arose out of the needs such as being quite heavy, prone to leakage when moved, and prone to dirty leaks since wet cells include generally corrosive acid solutions, particularly problematic for applications requiring a mobile power source for instance on street cars, railways, or illumination. Battery

history started with wet cells and dry cells continued with Lead-acid (Heth, 2019). Without these experiments, the system lead-acid battery would not have been discovered, and possibly would not have been discovered at all. Gaston Plante was the first one used this system in 1859 to store energy for telegraphy. He used lead electrodes. Unfortunately, these batteries were unable to be used in industrial production (Danila & Asachi, 2010; Heth, 2019).

With the invention of the dynamo and electric light, in the late nineteenth century, electrochemical energy storage operations started to grow quickly. Emile Alphonse Faure cogitate and licensed the so-called sticky plate in 1880 so the mass production of lead acid batteries started. He developed a procedure such as coating lead plates with a putty made from sulfuric acid and lead powder resulting in greater energy storage capacity. This process has proven feasible, and many companies have been born specifically to manufacture these batteries. "Power and Light" was one of them where Lord Kelvin and William Thomson, worked as associate engineers. The next stage for the energy storage development was increasing the electric power and the storage capacity. At that time William Thomson developed a project supplying Buffalo city with electricity from Niagara Falls. He wanted to make 80,000 volts with 40,000 batteries for transportation to the city. Nevertheless, Faure batteries with spirally wound positive and negative poles proved to be not very durable and failed after only a few charge/discharge cycles. Moreover, Sellon patented a procedure that resulting higher storage capacity than Faure's, in 1881. In this procedure, the paste mentioned Faure's process was applied to the perforated plate. After lead- acid batteries understood that can be suitable for static applications but not preferable for portable purposes since their weight and acidic electrolyte; E. W. Junger, 1897, and Thomas Edison, 1901, patented nickel-iron battery (since nickel lower density than lead this kind of batteries there was significant weight reduction). Lithium has lower density but higher activity which makes the battery lighter and has a higher voltage output than zinc batteries. As soon as the potential of lithium was understood by scientists, the rise of lithium-based batteries started (Danila & Asachi, 2010; Heth, 2019).

Producing electricity from the water was an earlier known method but the concept of a pumped storage system started in the 20th century. In 1909, the first

pumped storage plant was built up and started operation, in Schaffhausen, Switzerland according to information obtained from International Water Power and Dam (Douglas, 1990). Pumped hydro type storage technology came out with the use as an alternative for peak load shaving in the early 2000s, since it is economically and technologically acceptable. Moreover, the rise in the integration of solar and wind energy sources with the grid makes more important bulk electricity storage such as pumped hydro since they are intermittent (Rehman et al., 2015). According to U.S Energy Information Administration data; total hydroelectric pumped storage (PHES) installed capacity increased year by year from 2000 to 2020 as it is shown in Figure 2 given below. In 2020, the total world's PHES electricity net generation was noted as 267.357 (billion kWh) and PHES electricity installed capacity was recorded as 168.4782 (million kW). Furthermore, China, Japan and the United States are the first three countries, respectively, which have the highest hydroelectric pumped hydro storage installed capacity as Figure 3 is given below².

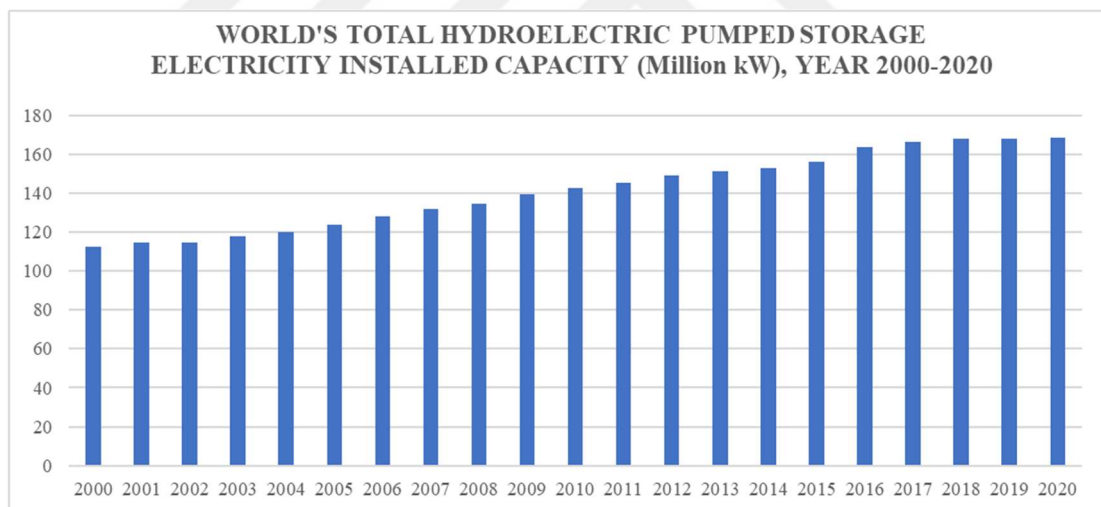


Figure 2. World's total hydroelectric pumped storage electricity installed capacity from 2000 to 2020.

² Source: Retrieved from www.eia.gov at 2021, September 10

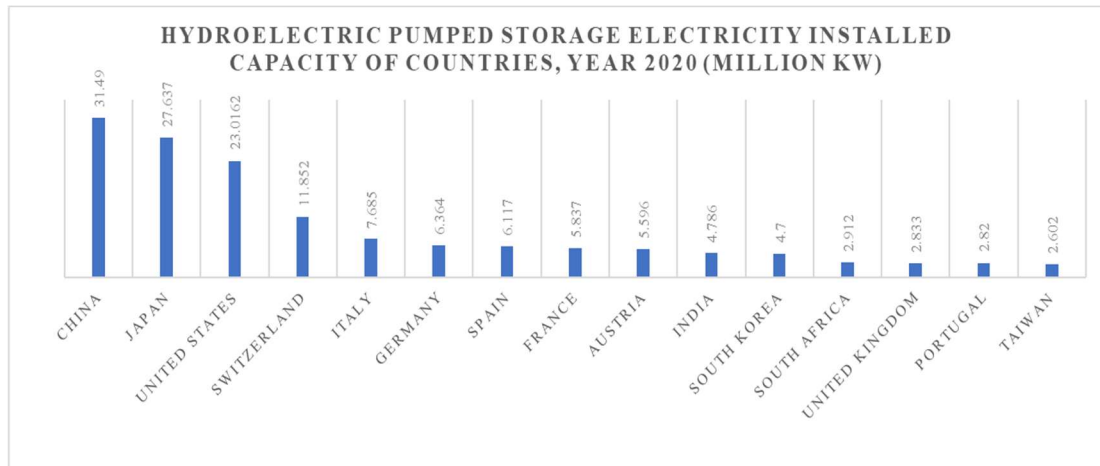


Figure 3. First 15 countries have largest hydroelectric pumped storage electricity installed capacity in 2020.

Today by rising allocation of renewable energy systems in electricity network made obligatory implosion of energy storage systems to grid since renewable energy systems are intermittent and it is wanted grid network to be more reliable, durable, etc.

The importance of electricity is a known fact in today's world. A power blackout occurring for one hour may cause million dollars loss to a producer or it is also meaning time loss for the business world. Therefore, in the light of information mentioned above, it is looking for new solutions for improvements to existing grid.

For the sake of network system and system reliability, a power system must supply electricity demand constantly. Renewable energy technologies like wind and solar are becoming more prevalent in the system. Because they are intermittent and exacerbate the difficulty of stabilizing the power network, primarily due to a supply-demand imbalance, they pose a significant risk to the nationwide transmission and distribution electricity systems' resilience, a flexible power system is required. Furthermore, governments implement policies such as increasing efficiency and lowering CO₂ emissions. As a result, energy storage has emerged as a major player, or as it has been dubbed, a "game changer" (Mondial L, 2016a).

Figure 4 given below shows energy storage installations with rated power from year 2005 to 2020. It can be seen that in 2015 there was huge increase in pumped hydro storage (DOE, 2021).

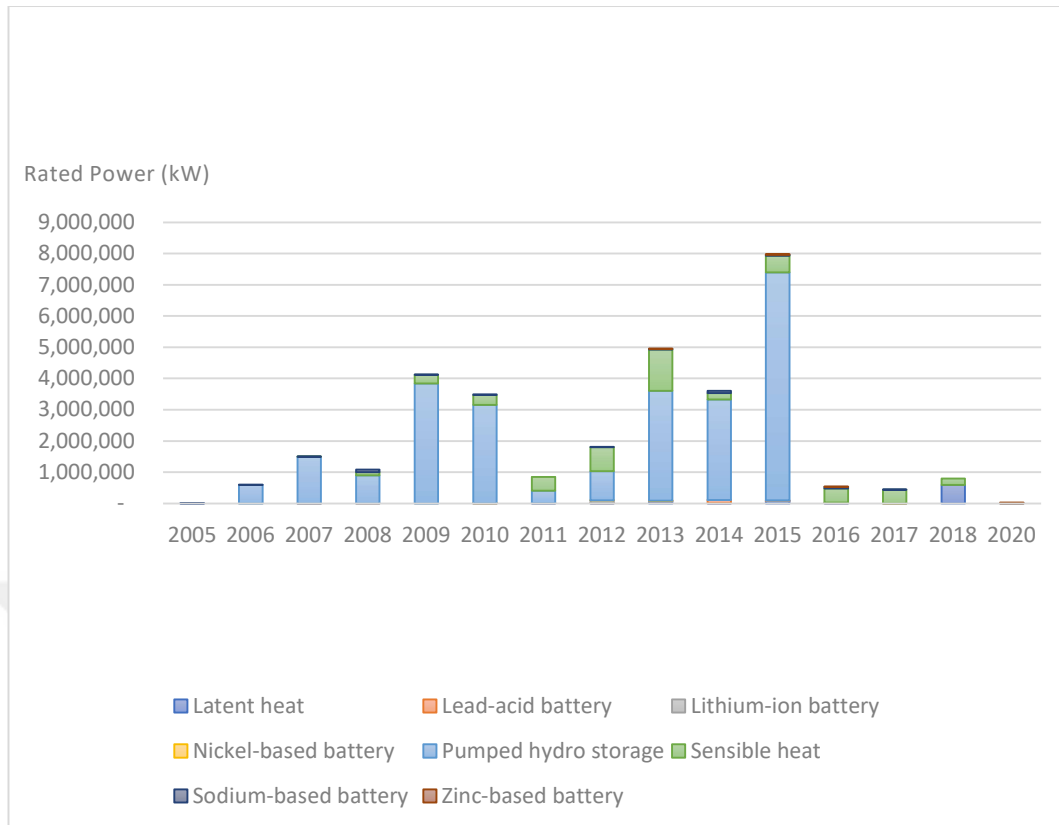


Figure 4. Energy storage installation by year 2005 to 2020 with rated power.

There are various energy storage systems for different purposes. In this research it will be mainly focused on for purpose of electricity market.

1.1.1 Energy storage technologies. From past to today, its mentioned above evolution of energy storage. Since storage technology is in progress, today still new type of storage systems introduces to science with developments in the technology. The function and form of ESSs are two important criteria for classifying these systems. ESSs have a variety of technologies based on their application and use. Moradzadeh et al. published a study in 2021 related to energy storage technology. They did a comprehensive study on storage systems used for energy management, and various types of energy storage technologies investigated in this work and they obtained the figure given below. In Figure 5, storage systems are categorized into 9 sections. These are mechanical, electrochemical, cryogenic, underground, hydrate cold, chemical, electrical, hybrid, and thermal storage systems (Moradzadeh, Nazari-Heris, Mohammadi-Ivatloo, & Asadi, 2021).

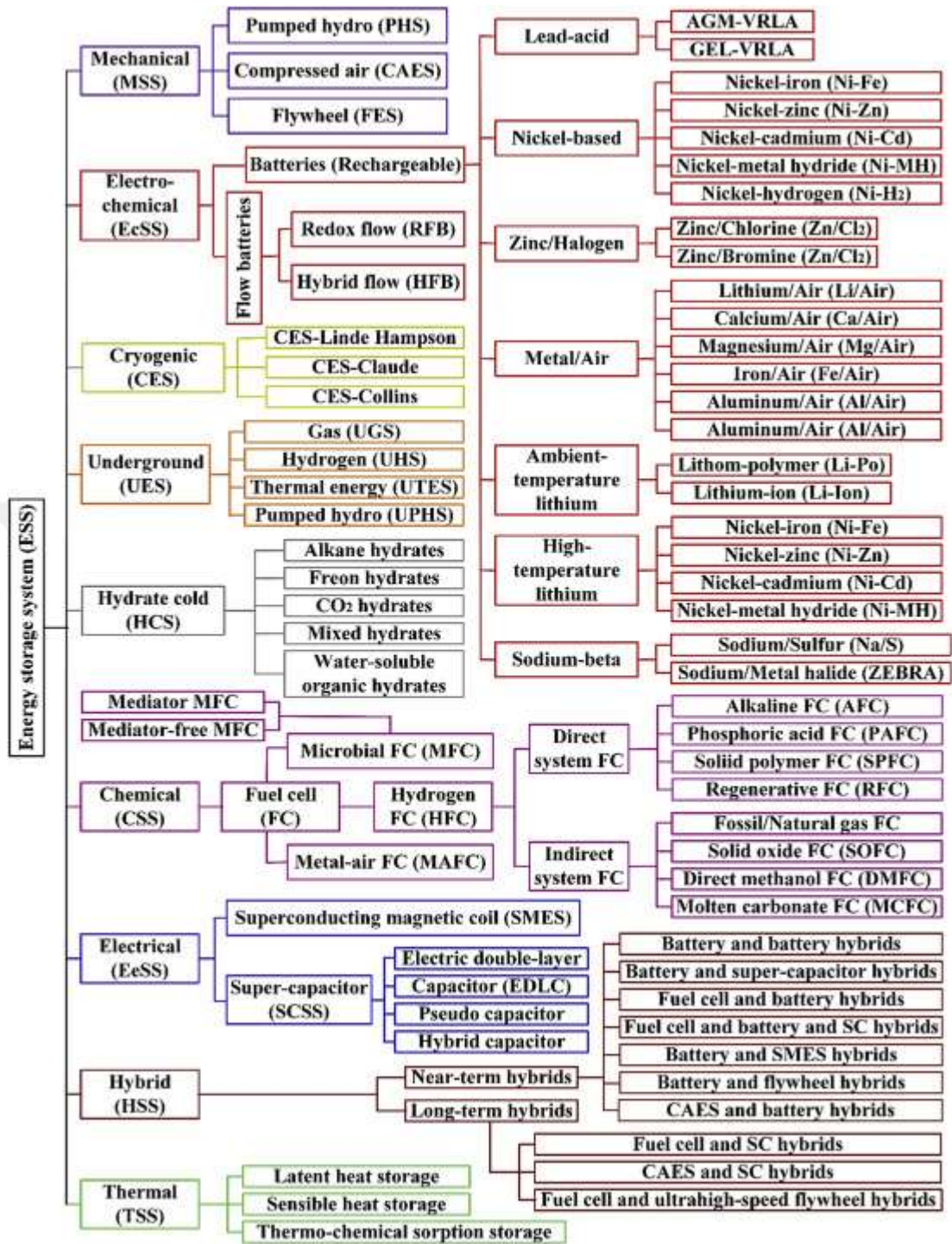


Figure 5. Various types of energy storage systems (Moradzadeh et al, 2021).

According to World Energy Council 2016 “E-storage: Shifting from cost to value Wind and solar applications” report; storage technologies can be classified and clustered in a variety of ways, for example; scientific such as mechanical, thermal, chemical, electro-chemical and electrical, key performance such as according to the discharge time at rated power and energy capacity Storage duration such as seconds to minutes, daily, weekly to monthly, maturity such as research and development, demonstration and deployment, commercialization.

In this study WEC report’s scientific categorization will be used for classifying to ESSs so it will divide into 5 main categories (Mondial L, 2016b).

1.1.1.1 Mechanical. Pumped hydro, compressed air, and flywheel storage can be given as examples of mechanical storage.

Pumped hydro energy storage (PHES) is supplementary to hydropower generation. When the electricity demand is high power plant uses the water in the high-level reservoir. Water from the upper reservoir is expelled vigorously by a hydraulic turbine, and a significant water column stored behind the walls of the dam converts potential energy into mechanical energy through the rotation of the turbine. Turbine combined with a generator that produces a constant power source that can easily meet the load demand. When the demand is low or during the off-peak hours water in the low-level reservoir is pumped to the high-level reservoir to use it to store energy for later generation of electricity during peak hours. The Figure 6 is given below which shows a basic schematic diagram of PHS that helps to understand of working principle of the pumped storage. (Alami, 2020a) PHES technology is known as one of the most cost effective technique as massive (bulk) power storage.

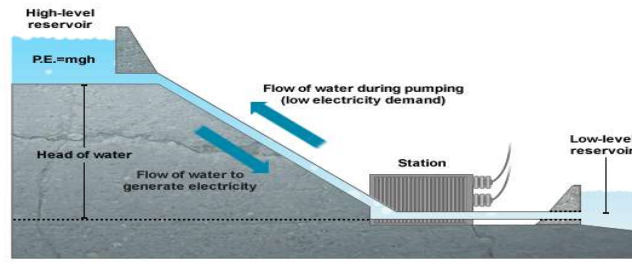


Figure 6. Basic schematic diagram of PHES³.

Compressed air storage (CAES) is one of the storage types of energy which is the use of potential energy stored in the pressurization of a compressible fluid (air). When the demand for energy is low, a fluid is compressed into a large impermeable cavity and stored under high pressure for an extended period. During periods of high demand, the fluid is released from its high-pressure storage and into a rotational air turbine, which converts the fluid's kinetic energy into rotational mechanical energy in a wheel connected to an electrical generator before being returned to the grid in order to electrical supply to be supplemented. The Figure 7 given below represent the operation diagram of large scale CAES. CAES systems can be categorized into 3 different classes in terms of size. These are large scale (more than 100MW), small scale (between few MW to kW) and microscale CAES (around 10 kW). While large scale CAES used for grid applications such as load shaving and shifting, small and micro scale CAES systems are more used for backup power supply (Alami, 2020b).

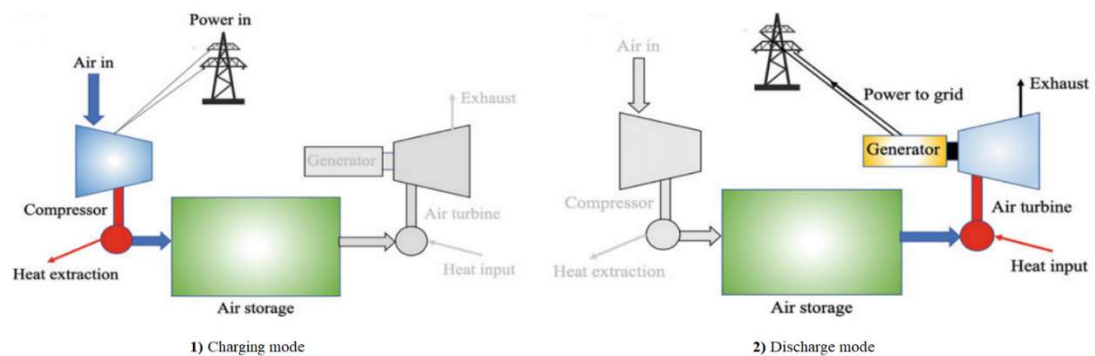


Figure 7. Operation diagram of CAES (Alami, 2020).

³ Source: Retrieved from: www.eseslab.com at 2021, December 14

Flywheel energy storage (FES) technique is another way of stock energy by using rotational kinetic energy. In general, a flywheel system consists of an electric machine coupled to a rotating mass. The variable speed machine's driving torque which is positive torque while charging and negative torque while discharging can be precisely imposed with the help of a power electronic converter, allowing control of the exchanged power level. The interaction of inertia and applied force is the fundamental concept underlying the use of flywheels for energy storage in any mechanism (Rufer, 2021). The Figure 8 given below represents the basic schematic diagram of FES system. Power quality, industrial pulsed power, distributed generation load following, light rail power management and uninterruptible power supply are some of the main application areas for any flywheel developer. Flywheels are generally chosen as best option for aircrafts since their properties such as they are less voluminous than batteries (Alami, 2020c)

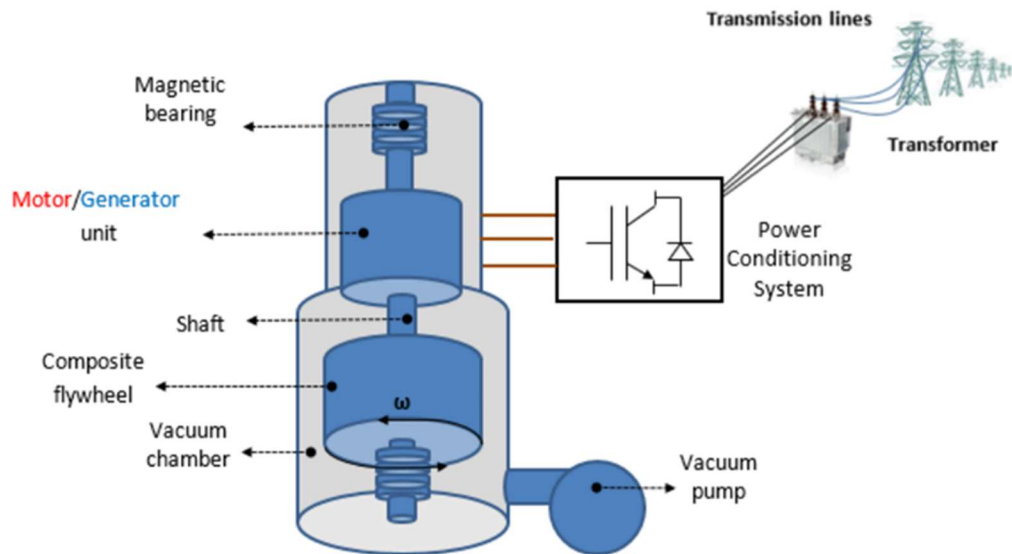


Figure 8. Schematic diagram of flywheel energy storage system (Nikolaidis & Poullikkas, 2017).

1.1.1.2 Electro-chemical. Electro-chemical storage systems can be divided into 2 categories such as batteries (rechargeable), and flow batteries. Flow batteries can be separated as redox flow and hybrid flow. Batteries can be classified as lead-acid, nickel-based, zinc/halogen, metal/air, ambient temperature lithium, high temperature lithium, sodium-beta. Figure 9 given below obtained DOE energy storage database shows that sum of energy storage installation in terms of electro-chemical batteries increased from 2010 up to 2020. It can be understandable that Flow, Lithium-ion, Sodium based batteries are the outstanding headstones of the market.

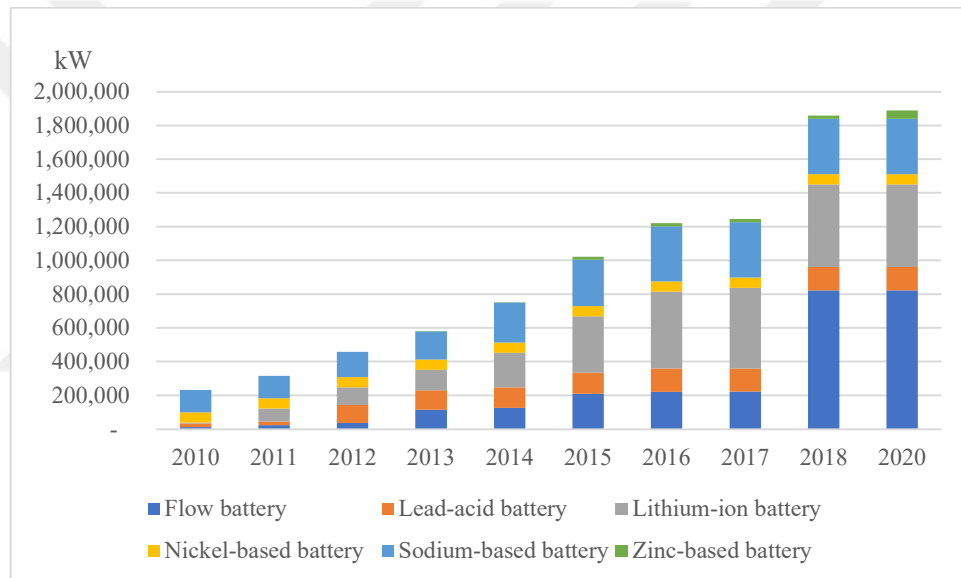


Figure 9. Running sum of electro-chemical battery and chemical energy storage installations by year.

Li-ion batteries are the types of batteries which have specialties such as long distance life, high energy densities and high discharge power. The story of Li-ion batteries started in the early 1980s and is still in progress today with wide range of application areas from portable electronics, electric vehicles to large scale storage systems (Yoshino, 2014). The Li-ion battery operates on the basis of reversible ion extraction on porous electrodes containing foil to provide electrical isolation. As a result, such electrodes and foils are submerged in a Li-ion electrolytic solution prior to extraction (Zubi, Dufo-López, Carvalho, & Pasaoglu, 2018). There are different

types of batteries that use lithium as given in Figure 10 below, Li-ion has the third largest share.

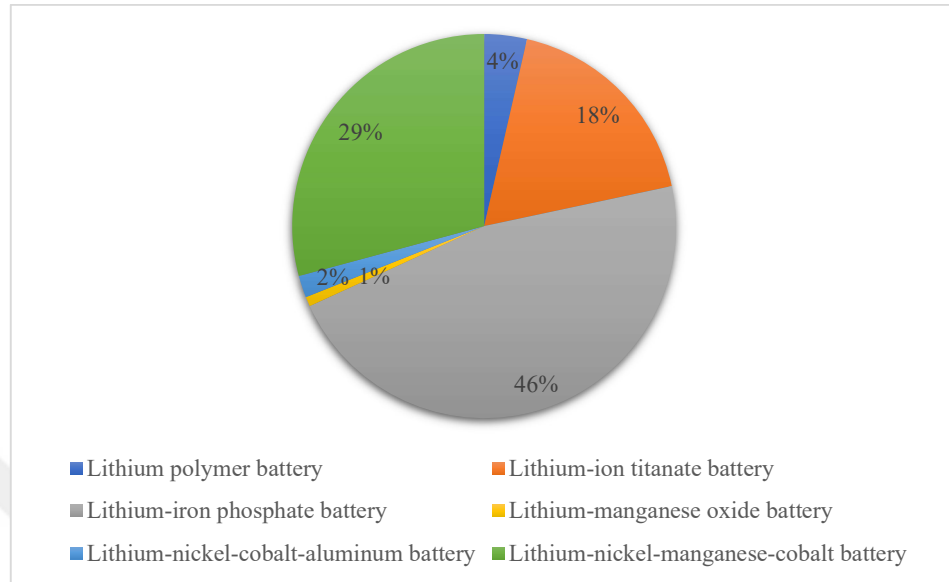


Figure 10. Lithium-ion battery installations by technology type.

Nickel-cadmium (Ni-Cd) batteries are generally used for stationary and portable applications. During the charging position, there is a metallic Cd occurs in the anode side NiOOH (nickel oxyhydroxide) in the cathode side with an alkaline electrolyte and a separator. While discharging state to produce hydroxide ions and Ni(OH)₂ at the anode, the cathode NiO-OH reacts with water in the aqueous potassium hydroxide (Nikolaidis & Poullikkas, 2017). Although there are iron and metal hydrate connected nickel batteries, Nickel-cadmium comprises 99.36% of nickel based battery energy storage installations with 60.000 kW rated power⁴.

Sodium sulfur (Na-S) batteries kind of molten metal batteries made from sulfur and sodium. Developments of Na-s batteries started in the mid-1960s. Since its operating temperature is very high around 350°C and it needs high thermal isolation, it's more used for stationary applications such as electricity grid energy storage. It consists of not expensive materials. Na-S batteries have very high efficiency of discharge and charge around 89% to 92% and high energy density with long life

⁴ Source: Retrieved from <https://sandia.gov/> at 2021, September 15

cycle that's why one of the most commonly used battery types (Asian Development Bank, 2018).

Lead-acid (Pb-A) batteries are one of the most used batteries and can be considered as one of the cheapest solutions for electrochemical storage. When a lead-acid battery is discharged, both the positive and negative plates become lead sulfate. After that, the electrolyte loses a significant amount of its dissolved sulfuric acid and becomes mostly water (Rufer, 2021). Lead-acid batteries have very large application areas both in transportation and stationery from automotive, e-bikes, telecom, low speed EVs to distribution and end user services, renewables integration and microgrid. Figure 11 given below shows the share of total rated power sub-types of lead acid battery technologies in terms of energy storage installation. It can be seen that advanced lead-acid battery, hybrid lead-acid battery or electro-chemical capacitor, lead-carbon and valve regulated lead-acid battery are the 4 main sub-technology types for lead-acid batteries. Advanced lead acid battery type covers 73% of general rated power (Department of Energy, 2020).

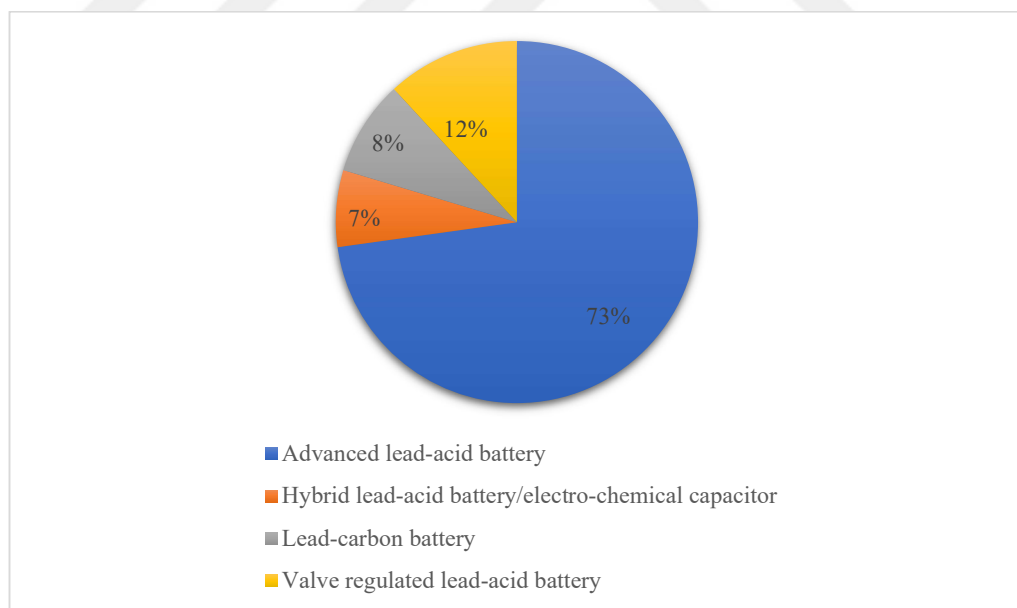


Figure 11. Pie chart of total rated power (kW) of lead-acid batteries along technology sub-type.

Vanadium Redox Flow Batteries (VRFB) are the new types of batteries developed by Miyake and Ashimura in 1971 which consist of two half cells

separated by an anionic or cationic exchange membrane. Electrical energy is stored by liquid electrolyte as a form of dissolvable chemical ions in liquid aqueous or nonaqueous electrolytes. A pump circulates the electrolytes of the negative and positive half-cells in separate circuits. The working principle of VRFB can be understood more easily with Figure 12 given below which represents the basic schematic diagram of VRFB energy storage (Doetsch & Burfeind, 2016). China is the leading country when it is mentioned to the deployment of VRFB. There are many market applications of VRFBs from energy shifting, EV charging to transmission and distribution, commercial, peaking capacity, and frequency regulation. In 2018 sum of the rated power of energy storage installation of flow battery become 3,220,881 kWh. VRFB constitutes 82.69% of total flow battery technologies with 707.565 kW rated power (Department of Energy, 2020).

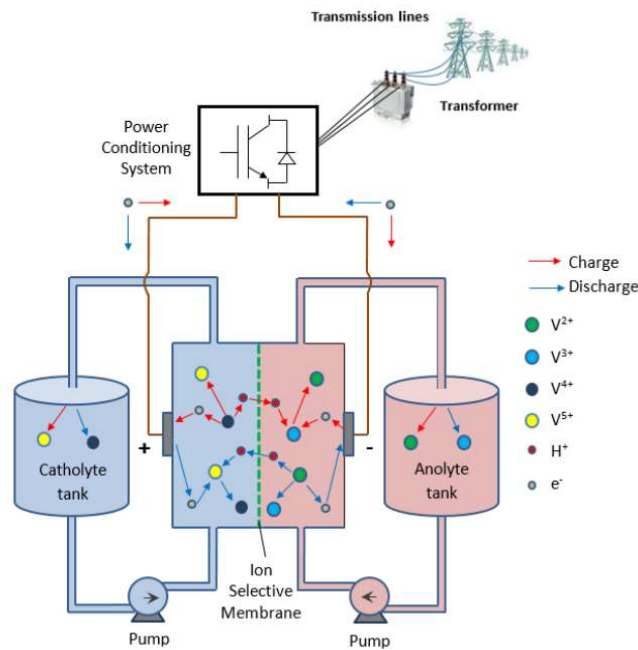


Figure 12. A schematic diagram for VRFB energy storage (Nikolaidis & Poullikkas, 2017).

1.1.1.3 Chemical. Hydrogen storage and synthetic natural gas storage can be given as examples to chemical storage. Moreover, microbial fuel cells and metal air fuel cells can be counted as instances of chemical energy storage systems.

Hydrogen gas become appealing in today's energy market since it is low carbon form of energy source that does not emit CO₂ during use. There are different ways of obtaining hydrogen but mostly its obtained from natural gas. Moreover, it can be made from water and some chemicals such as alcohols. In hydrogen energy storage systems, excessive or off-peak electrical energy is used to produce hydrogen, which is stored. After that, when electrical energy is needed, the stored hydrogen is used as fuel for the power plant. Figure 13 given below is an example to sample hydrogen energy storage system with integrated renewable energy sources. Even though hydrogen storage is feasible now one of the main handicaps of it is low round trip efficiency (Breeze, 2018).

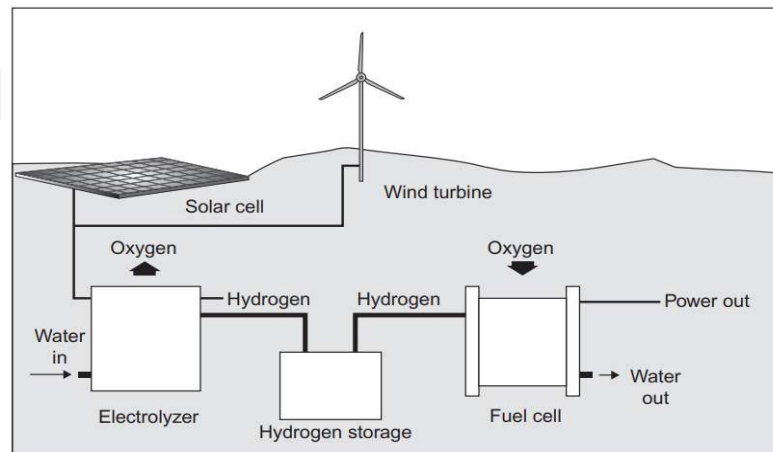


Figure 13. Example for hydrogen energy storage system (Breeze, 2018).

1.1.1.4 Thermal. Thermal energy storage (TES) is the temporary storage of energy by heating or cooling a storage medium in order to use the stored energy later. Latent heat, sensible heat, thermos-chemical sorption storage are subcategories of the thermal ESSs. It has been tested and used in a wide range of applications, including grid-scale electricity production, cold chain logistics, industry, buildings, and district heating and cooling. According to the global energy storage database of DOE, the graph of running sum of energy storage installation by year shows that for the year 2018, while latent heat rated capacity is 965,401 kWh and rated power is 162,797 kW for the sensible heat rated capacity is 34,769,661 kWh and rated power is 5,057,046 kW. TES technologies play important roles in the energy transition, but their full potential has yet to be realized. There is still room for innovation to improve the commercialization readiness of TES technologies (Renewable Energy Agency, 2020).

1.1.1.5 Electrical. Energy is stored in electrical energy storage (EES) technologies by changing magnetic or electrical fields via superconducting magnets or capacitors. The electric grid is confronted with the conjunction of renewable resources with transmission and distribution systems, EES can be seen as an advisable technology to address this issue. Performance of the system can be extremely beneficial in terms of power system operation, enhancing power quality, lowering energy import requirements throughout peak hours, and load balance (Moradzadeh et al., 2021). Superconducting magnetic coil, super-capacitor are the branches of electrical ESSs. Electric double-layer capacitor, pseudo capacitor and hybrid capacitors can be counted as subcategories of the supercapacitors. Supercapacitors, instead of performing any chemistry, theoretically store electric energy in the electrostatic field of the electrochemical double layer, allowing them to be cycled thousands of times and that's why have a much longer lifespan than batteries (Cericola et. al, 2010). In superconducting magnetic storage, electric energy stored in the magnetic field created by the flow of rectified current in a coil made of incredibly low resistance niobium titanium cables stores electric energy. It has a high storage efficiency of up to 98 percent due to nearly zero resistance, which results in negligible energy losses and a quick response when compared to other ESSs, because current can be infused and derived quite fast (Buckles and Hassenzahl, 2000).

1.1.2 Energy storage application areas. US Department of Energy published a technical report called “Energy Storage Grand Challenge: Energy Storage Market Report” in December 2020. In this report, energy storage applications are enclosed in two main headings these are transportation and stationary applications. Transportation application sector can be separated as mobility -battery storage, mobility-hydrogen storage, SLI-starting, lighting, and ignition. Stationary application sector can be categorized as grid-related-utility, grid-related-residential, grid-related-C&I, grid-related-utility/residential and C&I (i.e. EV charging infrastructure), long-duration energy storage, industrial-including military use. While ancillary services, peaking capacity, peaking capacity, transmission-level, distribution-level can be given as examples to grid-related-utility applications; uninterruptible power source (UPS) + data centers, telecom backup power, air conditioning/ refrigeration, hydrogen refueling stations, motive (forklifts) can be instances for the industrial-including military use applications (Department of Energy, 2020). Moreover, in the report “Electricity Storage and Renewables: Costs and Markets to 2030” which was published by IRENA in 2017, services that can be provided by electricity storage are gathered under 7 main headings as can be seen in Figure 14 below. These are bulk energy services, ancillary services, transmission infrastructure services, distribution infrastructure services, customer energy management services, off-grid, transport sector. These 7-category are divided into sub-categories such as; Electric energy time shift (arbitrage), Voltage support, Transmission upgrade deferral, Distribution upgrade deferral, Power quality Power reliability, Demand charge management, Mini-grids: System stability services, Electric 2/3 wheelers, buses, cars and commercial vehicles. Furthermore, in Figure 15 can be seen global energy storage power capacity shares by main use case and technology group. In this graph, energy storage technologies are divided into 4 main groups such as pumped hydro, electro-chemical, electro-mechanical and thermal storage. According to the graph share of total rated power of PHS group is more than 85% for the purpose of electric energy time shift. 50% of the total share of rated power of electro-chemical group is for frequency regulation. In the electromechanical group between 40%-50% of rated power is used for on-site power.

More than 75% of the thermal group utilized for renewables capacity firming (Renewable Energy Agency, 2017).

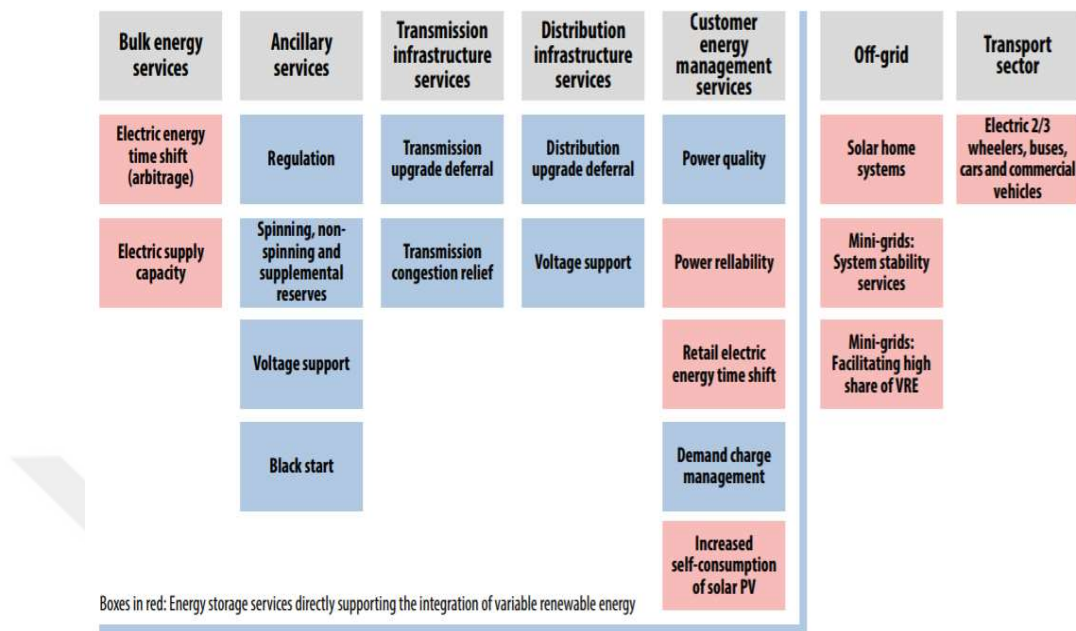


Figure 14. Services can be provided by electricity storage (IRENA,2017).

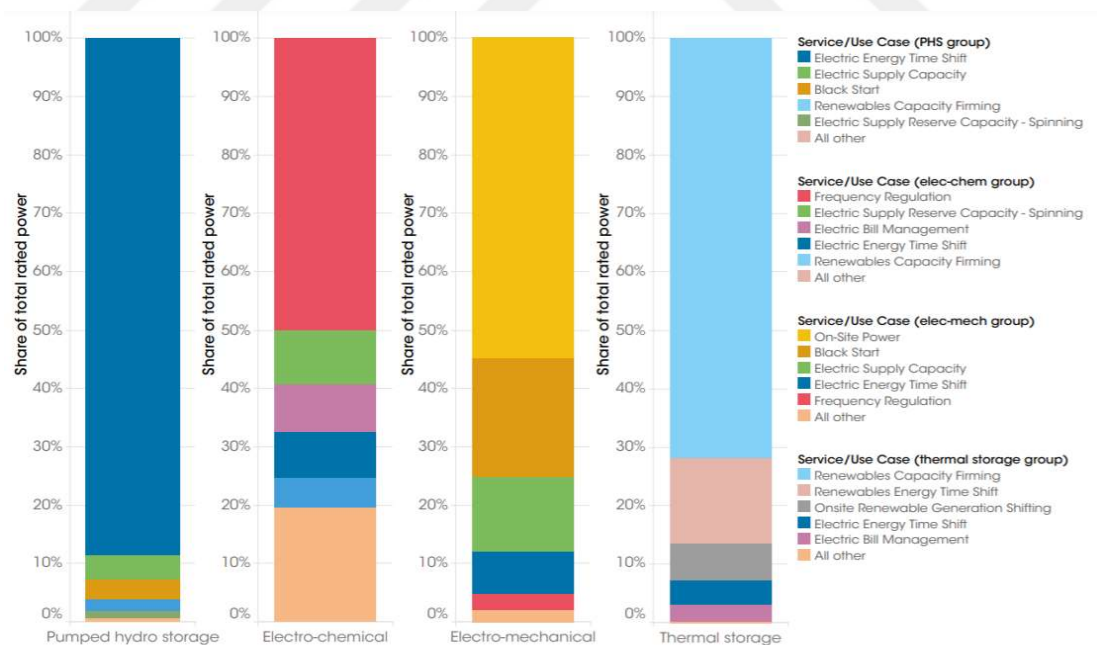


Figure 15. Global energy storage power capacity shares by technology group with main use, mid-2017 (IRENA,2017).

1.1.3 Energy storage in Turkey. Energy storage is a wilderness area in Turkey. Although there are same batteries used for industrial and commercial purposes and it can be seen in solar water heater storage applications on the roof in the Mediterranean region; there is no known type of storage system except for a few demos application in the context of integrated to utility grid. Before explaining the demos applications it's important to make intelligible to significance of energy storage for Turkey. Turkey is a developing country with its population, industrialization, urbanization, economy, etc. With the increase in population and usage of electrical devices or appliances in daily activities highly, consumption of electricity increases day by day. According to data obtained from U.S Energy Information Administration Turkey was the 17th country in net electricity consumption in 2019 with 259.387646 billion kWh⁵. Moreover, Turkey has very weak reserves in terms of fossil fuels and exports them for use of electricity. That's why external dependency on economy is very high. Therefore, the Ministry of Energy and Natural Resources (MENR) of Turkey set new strategies. One of the policies according to this strategy was to increase the share of renewables in electricity production since Turkey has available resources for wind and solar power plants. Table 1 given below shows the total installed capacity and production of Turkey with respect to resource types at the end of the year 2020. It represents hydraulic is the first grade as installed capacity and total production. Natural gas follows it second. It also shows that total installed capacity is 95.890,61MW and total production is 305.330,21 GWh. It can be seen the share of the renewables in electricity production is 16,9% except hydraulic. It was 4% back in 2013 according to data obtained from TEİAŞ (Turkish Electricity Transmission Corporation). It can be understandable ministry put some milestones upon its objectives. Moreover, using energy more efficiently, reducing CO₂ emissions, and having more reliable and more durable utility grid are other objectives of MENR like other countries. With the increase in the share of the renewables and policies importance of energy storage is understood and on 9 May 2021 EMRA published the regulation of energy storage activities in electricity market so operators, procedures or principles could set

⁵ Source: Retrieved from www.eia.gov/international/data/world/electricity/electricity-consumption at 2021, September 20

outbuilding of electricity storage units or facilities, also their connection to distribution and transmission system and use of these units or facilities in the electricity market regarding Electricity Market Law. Furthermore, Figure 16 and Figure 17 give total share of installed capacity and production of resources.

Table 1

Installed Capacity and Production Concerning Resources, End of 2020 Data's (EMRA, 2020)

RESOURCE TYPE	TOTAL INSTALLED CAPACITY ⁶ (MW)	SHARE (%)	TOTAL PRODUCTION* (GWh)	SHARE (%)
HYDRAULIC	30,983.90	32.3	78,114.95	25.6
NATURAL GAS	26,041.93	27.2	69,277.54	22.7
LIGNITE	10,119.92	10.6	38,163.85	12.5
IMPORT COAL	8,986.85	9.4	62,466.47	20.5
WIND	8,832.40	9.2	24,680.83	8.1
SOLAR	6,667.42	7	11,242.48	3.7
GEOHERMAL	1,613.19	1.7	9,929.41	3.3
BIOMASS	1,115.59	1.2	5,501.94	1.8
HARD COAL	810.77	0.8	3,415.83	1.1
ASPHALTITE	405	0.4	2,222.88	0.7
FUEL OIL	305.93	0.3	313.04	0.1
NAPHTA	4.74	0	0	0
LNG	1.95	0	0	0
DIESEL	1.04	0	1	0
TOTAL	95,890.61	100.00	305,330.21	100.00

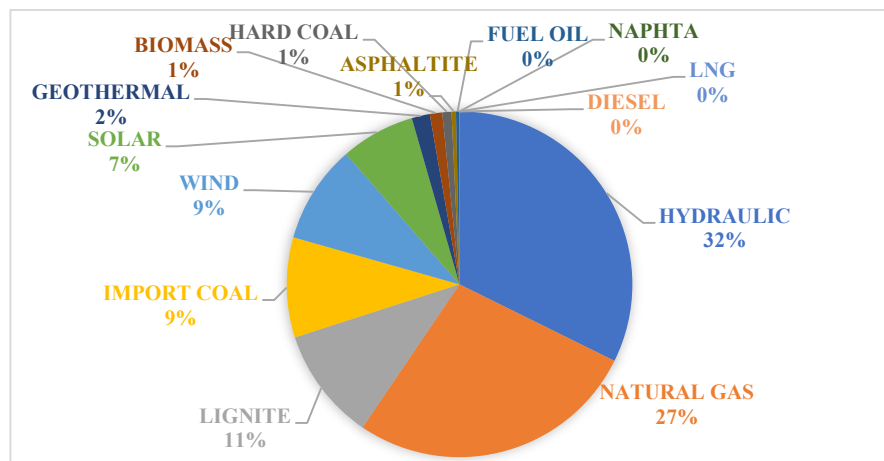


Figure 16. Turkey's total installed capacity share regarding resources.

⁶ Licensed and unlicensed power plants are included.

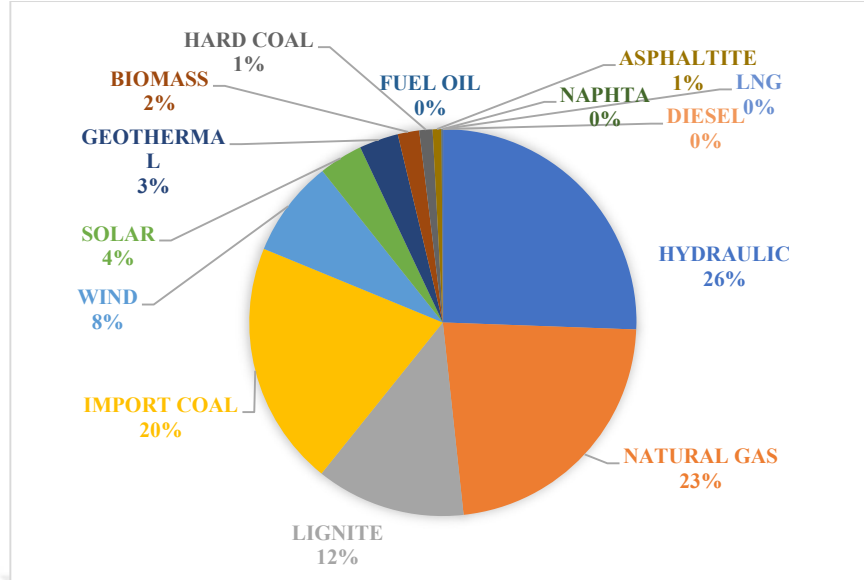


Figure 17. Turkey's total production share regarding resources.

Turkish Academy of Sciences published a report about the energy storage technologies, in the May of 2020. In this report, some demo energy storage applications are mentioned. GİMSA Hypermarket in Eryaman, Ankara, installed Turkey's first commercial and large-scale BED (Ice Energy Storage) application. GİMSA's total daily peak cooling load is 8332 kWh, and the BED system has been integrated to meet the cooling load only between 17.00 and 22.00 during peak electricity tariff periods. Because of the BED usage strategy, chillers are not used between 17.00 and 22.00 hours, when electricity is expensive. The energy stored during off-peak hours provides the cooling load required during these hours, and the total cost of the integrated cooling system with BED is approximately 1.1 million TL. According to this study, the BED system pays for itself after 2.7 years of use. It has the potential to save approximately 1.8 million TL after a 10-year usage period. Moreover, In the project North Marmara and Değirmenköy field; efforts are underway to increase the total storage capacity of Silivri, Kuzey Marmara and Değirmenköy Natural Gas Storage Facility with a capacity of 2.84 billion Sm³, to 4.6 billion Sm³, and to increase the regeneration capacity to 75 million Sm³/day. Two 10 MW compressors and 11 wells are used for Kuzey Marmara Field, one 5 MW compressor and 9 wells are used for Değirmenköy Field, and a 10 MW compressor is designed as a backup to serve both sites. Furthermore, the first phase

of the Tuz Gölü Underground Natural Gas Storage Project, which is under construction, has been completed and natural gas has been started to be stored. By 2023, the total working gas capacity of this underground storage will be increased to 5.4 billion Sm³ and its regenerative capacity will be increased to 80 million Sm³/day. In the project, it is planned to build 12 warehouses in 2 groups of 6, and a total of approximately 1 billion m³ of operating gas will be stored in such a way that approximately 80 million m³ of operating gas will be stored in each warehouse. The report also states that, when it is checked the scientific studies on energy storage technologies in Turkey and the number of completed postgraduate thesis over the years are examined, it is seen that the interest in energy storage in country continues to increase. National or international supported projects and collaborations constitute the most important pillar of this interest (TÜBA, 2020)⁷.

Yahyalı Wind Pumped Storage project is a Hybrid Energy Project occurred by signed protocol between the constitutions such as General Directorate of Renewable Energy (YEGM), Electricity Generation Company (EUAS), The Scientific and Technological Research Council of Turkey (TUBITAK), New Energy and Industrial Technology Development Organization (NEDO), in 2010. The purpose of this project is to reduce the negative impact of wind turbines on the grid in order to maximize the benefits of the country's wind energy potential. The project is still under construction and will build around 10 MW of wind and 4 MW of PHES. In 2011, the Japan International Cooperation Agency (JICA) released the report "The study on optical power generation for peak demand in Turkey." One of the goals of this research is to examine the development plan for pumped storage power projects as a peak power supplier, which is being studied by the General Directorate of Electrical Power Resources Survey Administration (EİE). Following that, it was made a conceptual design of 1400MW Gökçekaya PHES, 1800MW Altınkaya PHES (JICA, 2011). According to the 2020 Investment Program published in the Official Gazette dated February 12, 2020, the investment budget of the project, which will cover the years 2020-2032, will be 6.3 billion TL. The project will be built by

⁷ Türkiye Bilimler Akademisi. (2020). Enerji Depolama Teknolojileri Raporu. Retrieved from www.tuba.gov.tr at 2021 September 28

Kalyon İnşaat in cooperation with Japanese Itochu and Toshiba (Strateji ve Bütçe Başkanlığı, 2020)⁸.

In 2014 Gutierrez and Arantegui of the European Commission's Directorate-General Joint Research Centre, Institute for Energy and Transport, conducted a study that looked at the potential of pumped hydropower storage in Europe. The top five countries are listed in the table below, with Turkey ranking first. According to their research, the data given in Table 2 demonstrates realizable potential, which includes theoretical potential as well as a series of social, infrastructure, and environmental constraints (Gutierrez and Arantegui, 2014).

Table 2

Realizable Potential of The Top Five Europe Countries (Gutierrez and Arantegui, 2014)

Scenario/Country Potential	20 km (TWh)	10 km (GWh)	5 km (GWh)	3 km (GWh)
Turkey	19.63	13	4	0
Albania	2.58	37	8	0
Spain	1.89	362	93	23
Switzerland	1.44	256	28	23
Norway	0.75	212	17	5

1.2 Multi-criteria Decision Making (MCDM)

Multi-criteria decision-making (MCDM) deals with decisions that include selecting the best option from several potential candidates for decision-making, depending on some criteria or attributes that may be specific or ambiguous. It's a stand-alone field. Decision makers (DMs) always try to choose the best solution when making decisions, but it is challenging for many DMs since. Unfortunately, the best solution exists only for a single criterion. In a real decision-making situation, almost every decision involves disagreement or discontent and considering multiple technical and non-technical factors. MCDM methods are used to assist people to make preference-based decisions and create make the best choice among choices

⁸ Strateji Daire başkanlığı. (2020). Retrieved from www.icisleri.gov.tr/strateji/ at 2021 September 28

when there are multiple conflicting criteria. Another term often used to emphasize that a method is intended to help DM make the best decisions is multiple-criteria decision analysis (MCDA), but the method itself cannot make a decision actually, MCDA's main goal is to enable DMs to integrate information so that they can make decisions comfortably and securely. MCDA combines objective measurement and significance judgment and creates direct subjectivity. Decision making is not only about selecting the best alternatives it also prioritizes them according to resource allocation and integrating individuals' strength partiality. Figure 18 given below shows the process of MCDM (Pavan & Todeschini, 2009).

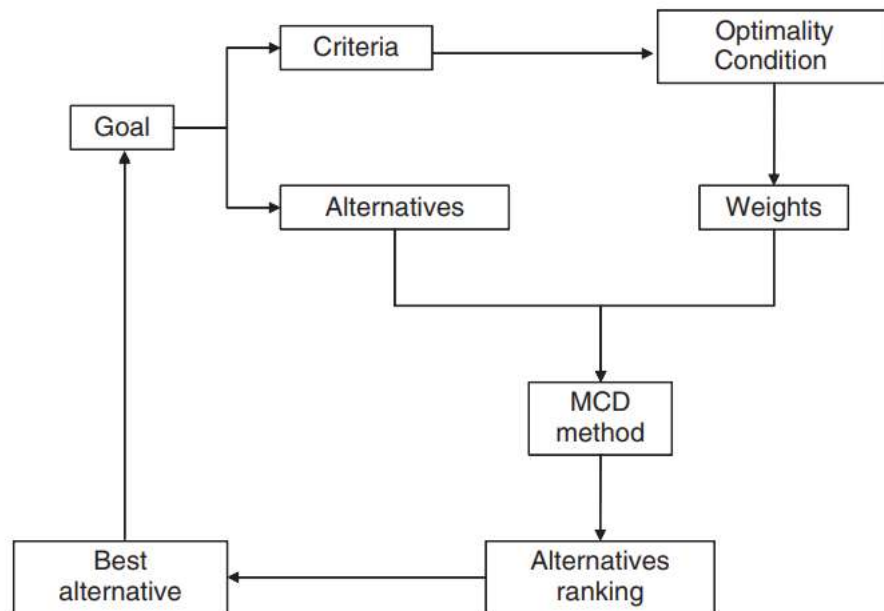


Figure 18. Layout of MCDM process (Pavan and Todeschini, 2009).

MCDM can be used in almost every area that needs to decision making process. The most common ones are; supply chain management, industrial applications, civil engineering, computer and software engineering, automation, climate change, natural resources, military, maritime transportation, finance, investment, sustainable development and more of them. This method becoming more popular in the energy area since it gives flexibility to DMs to make decisions simultaneously while considering all the objectives and criteria (Kumar et al., 2017).

1.2.1 MCDM methods. Multi-criteria decision-making is expressed as determining one or more of the most appropriate options, taking into account the criteria that can influence each other among many options. The literature has methods for selecting, ranking, and evaluating multi-criteria, from simple analytical techniques to complex multi-criteria methods. These methods have advantages and disadvantages depending on the area of the application. It is important to analyze the problem to be solved and determine the best method. It can be said that a good method for solving one problem may not be good for solving another. In the literature there are many MCDM methods these are Pareto optimality, Weighted sum method (WSM), Weighted Aggregates Sum Product Assessment (WASPAS), Simple Additive Ranking (SAR), Weighted Product Model (WPM), Multi attribute Value Theory (MAVT), Simple Multi-Attribute Rating (SMART), Multi-Attribute Utility Theory (MAUT), Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Best Worst Method (BWM), Visekriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Outranking (PROMETHEE (Preference Ranking Organization Method for Enrichment of Evaluations)), ORESTE (The Organisation, Rangement Et Synthèse de données relaTionElles)), ELECTRE (Elimination and Choice Expressing Reality), Hasse Diagram Technique (HDT), Goal Programming (GP), etc. (Pavan and Todeschini, 2009; Baumann et al., 2019), etc.

There are divergent types of MCDM methods with different application techniques. Serrato et al. (2021, P.63-83) made a study about the assessment of MCDM methods for ocean energy. In that study, they classified MCDM methods into 3 groups. Firstly, low complexity algorithms are referred to as elementary methods. Secondly, unique criteria synthesis methods are medium-complexity algorithms that can find both optimal and non-optimal solutions. Thirdly, overcoming methods are defined as algorithms that can be used to develop supremacy relationships between alternatives. MCDM methods within these 3 different categories are given in Table 3 below. From the literature, it can be clearly comprehensible that AHP is one of the most common MCDM methods both in renewable energy and energy storage technologies that can be used as alone or hybrid. Although there are some disadvantages of AHP such as creating model takes

time and effort when the number of stages increases, even for a simple problem, the computational requirements are enormous; there are many advantages such that, it offers a highly adaptable and straightforward model for a given issue, because of its structural pattern the problem can be expressed easily, quantitative or qualitative information or subjective or objective consideration plays an important role in decision making, the consistency of decision maker's judgments is possible to measure. Moreover, TOPSIS is a method used for unique criteria synthesis that includes attribute, weight and ranking (Afonso, Monteiro, & Pinto, 2021; Baumann, Weil, Peters, Chibeles-Martins, & Moniz, 2019; Oğuztimur, 2011).

Table 3

Comparison of MCDM Methods (Serrato et. al, 2021)

MCDM		Attribute	Weight	Ranking
Elementary	WSM	No	Yes	Yes
	WPM	No	Yes	Yes
	Dominance	No	Yes	No
Unique criteria Synthesis	AHP	No	No	Yes
	TOPSIS	Yes	Yes	Yes
	VIKOR	Yes	Yes	Yes
	ELECTRE	No	Yes	No
Overcoming	PROMETHEE I	Yes	Yes	No
	PROMETHEE II	Yes	Yes	Yes

Chapter 2

Literature Review

2.1 MCDM in Energy Storage

Evaluating the ESSs and selecting the most optimal, appropriate, and sustainable one since it includes multiple variables is a complex problem. MCDM has grown in popularity in energy planning because it allows decision makers to consider all available criteria and make appropriate decisions based on their priorities. Because a perfect design is governed by multiple factors, a good decision maker may look for different dimensions such as technical or economic parameters that can be compromised in certain situations. MCDM assists a decision maker by quantifying specific criteria in the presence of other objectives (Kumar et al., 2017).

Baumann et al. made a comprehensive, detailed review about multi-criteria decision-making approaches for evaluating energy storage systems for grid application in 2019. In this study, they examined available studies in the literature that used Multi-Attributed Decision-Making (MADM) approaches to covering different ESSs varying from the electrochemical to electrical. Discussed criteria in the studies are generally assembled in 4 main headings and a lot of sub-criteria. These are social, economic, technological, environmental. Figure 19 given below shows the frequency of the criteria. They surveyed around 15 articles published from 2009 to 2018 in the study and realized most of the studies include AHP combined with another set of methods (Baumann et al., 2019). In this section MCDM methods without AHP technique are covered.

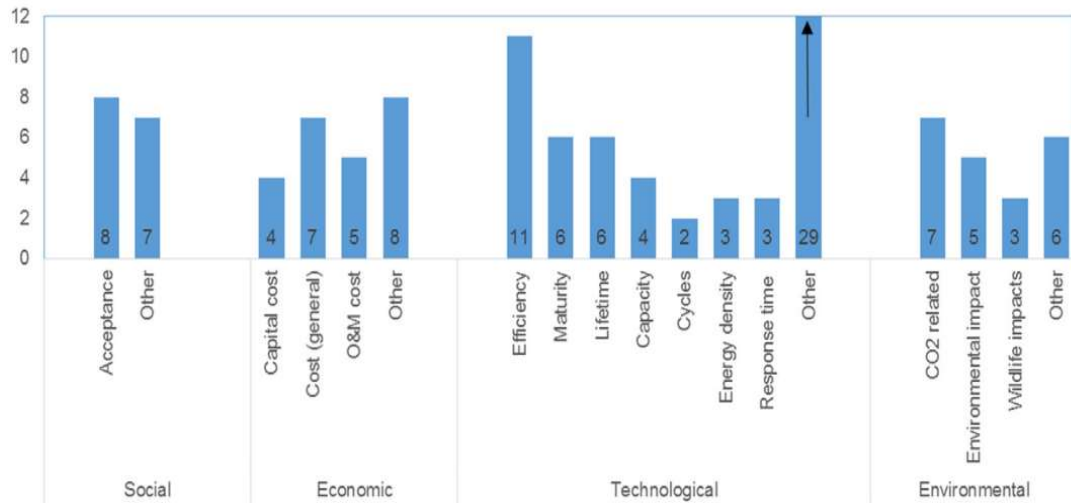


Figure 19. Frequency of used criteria (Baumann et al., 2019).

Reza et al. (2014), used WSM (Weighted Sum Method) to find the most sustainable combination in RES by considering 3 storage options: lead acid, lithium polymer batteries and fuel cell systems. They used 3 evaluating criteria these are economic: cost, technical: reliability, system life, load response, efficiency variables, risk factors, energy density, environmental: environmental impact. Fuel cell systems were discovered to be the most feasible energy storage option, as they can provide long-term energy storage while also being environmentally friendly.

Baumann et al. (2017), used TOPSIS method to evaluate lithium-ion batteries (LFP, LTO, LMO, NCA, NMC), NaNiCl, VRLA and VRFB to obtain the best environmental and techno-economical alternative. Life cycle cost and the carbon footprint were two main criteria for the assessment.

Van de Kaa (2018) used BMW to find sovereignty within various battery technologies such as lithium-ion batteries flow batteries, nickel-based batteries, sodium-based batteries, lead-based batteries in the residential grid storage markets. They applied a characteristic format for the selecting criteria.

Zhao et al. (2018) a model made a study by integrating Fuzzy-Delphi approach, BWM and fuzzy- fuzzy cumulative prospect theory to obtain optimal energy storage system considering risk preferences. Technology, economy, performance, sociality, and environment are the main evaluating criteria. They obtained a result which Li-

ion battery is the optimal solution followed by NaS even though investors and decision makers have different risk weights (Zhao, 2018).

Murrant et al. (2018), focused on an existing project to inform stakeholders in county of Cornwall in the UK by using MAVT method with various alternatives such as liquid air energy storage, battery storage-PV, thermal energy storage, battery storage with wave energy (wave hub) power to gas.

Li et al. (2020), a hybrid MCDM model proposed with integrating entropy weighting approach, Bayesian best-worst method, and grey cumulative prospect theory to select optimal electrochemical energy storage (EES) planning program. 3MW vanadium redox flow battery, 3MW vanadium redox flow battery, 3MW LiFePO lithium-ion battery, 9MW PbC battery, and 2MW vanadium redox flow battery were five EES planning programs to evaluate with five criteria i.e., investment cost, net earnings, battery lifetime, payback period return on investment.

2.2 AHP in Energy Storage

In this part, literature surveyed detailly and searched for works which used AHP technique or AHP integrated MCDM methods.

Cowan et al. (2010), examined technologies such as PHS, incremental-small-micro hydropower, liquid batteries, NaS, flow cells to determine the most sustainable combination of hydro and storage technologies by using AHP software called “Super decisions” and gathering experts from the area with different background. In this study social, economic, technical, and environmental criteria were decided as fallowing; Multipliers effects-perceived acceptability, investment cost-operating cost-storage capacity-operating life cycle-operating efficiency, ecological impact-emissions and pollutants.

Barin et al. (2011) made a study to obtain the most appropriate PQ priority alternative with RES by using AHP and fuzzy logic with economic (cost per kW), technical criteria (load management, technological maturity, power quality (transmission and distribution stabilization, end-use, etc.), Efficiency) and environmental (environmental impacts (visual, biological, and GHG). H₂, VRB flow battery, flywheel, pumped hydro, compressed air energy storage, NaS advanced

batteries, super-capacitors, and lithium-ion storage were the proposed storage systems for this study.

Daim et al. (2012), proposed research by using integrated AHP method for choosing the reliable and cost-effective storage alternative for investor-owned or public utilities within the considered technologies such as PHS, CAES, NaS. Evaluating criteria selected by literature and Fuzzy Delphi method. They used four criteria social, economic, technical, and environmental with sub criteria ordinarily; health and safety, capital cost- O&M cost- Recurrent costs, efficiency-maturity-capacity-durability-autonomy-lifetime, air pollution-water pollution-wildlife impacts.

In the study of Krüger et al. (2012) presented a hybrid model which used AHP to identify the most sustainable strategy for the excess power from the wind. Grid reinforcement (DC underground cables and overhead lines, high temp. transmission lines), H₂ (gas grid and cavern storage), VRFB, ACAES, NaS, PHS (status and new concept), CAES were some proposed alternatives for the research. Four main selecting criteria are used with sub-criteria these are; economic (enhancement of competition, specific cost, export potential), technological (controllability, degree of coverage, innovation potential, implementation time, additional uses, market potential, efficiency), ecology (resources, GHG emissions, risk in cause of failure other emissions, interference with sensitive ecosystems, risks in case of malfunction) and politics and society (compliance with political goals, national independency, job potential, social acceptance, impact on the landscape).

Gumus et al. (2013) integrated Buckley extension based Fuzzy-AHP and linear normalization based Fuzzy-GRA method to choose the most proper Hydrogen Energy Storage method within alternatives which was decided by expert opinions and literature review; chemical storage, tank and metal hydride. Reliability, total system cost, weightlessness, storage loss and leak and capacity were the evaluating criteria for the HES method (Gumus, Yesim Yayla, Çelik, & Yildiz, 2013).

Walker et al. (2015) used AHP method to compare Power to Gas with different storage technologies in various application areas such as; bulk energy storage and renewables integration; ancillary services; utility transmission and distribution support; distributed energy storage systems, commercial applications; and residential energy storage. 5 Power to Gas variations flywheels, lead acid, li-ion, pumped hydro

ACAES NaS, RFB, Zn/Br, Fe/Cr, and ZnAir were the alternatives. Technology, maturity, capacity, power, duration, seasonal storage, efficiency, total cycles, total cost, cost, portability % loss, energy density, transport fuel, consumer acceptability were the evaluating criteria. They found out Power to Gas is preferable when the weighting of the criteria like; energy portability, potential use as mobility and seasonal storage are high (Walker, Mukherjee, Fowler, & Elkamel, 2016).

Ren and Ren (2018) did research by using an integrated model with AHP, nonlinear fuzzy prioritization and interval MADA to prioritize sustainability of 5 energy storage technologies including lithium-ion, pumped hydro, lead-acid, flywheel, and compressed air. Evaluating criteria consist of 4 main categories economic, performance, technological, environmental and sub-criteria such as capital cost, operating cost, maturity, life, performance (energy efficiency, materials intensity, energy density), CO₂ intensity and environmental impact. Pumped hydro was found as the best sustainable option in their study.

In the research of Ren, 2018, four ESTs including flywheel, pumped hydro, lithium-ion, compressed air were examined to prioritize sustainability of ESTs for promoting the development of renewable energy by using hybrid model with interval AHP and intuitionistic fuzzy number. social acceptability, capital cost, operating cost energy, efficiency, energy density, technology maturity, life and CO₂ intensity, environmental impact were the evaluating criteria. He found out that ranking results of ESTs can be changeable according to the varying preferences of the decision makers.

Acar et al. (2019), aimed to assess the sustainability of 5 different energy storage systems for residential applications by using a combined model of Hesitant fuzzy analytic hierarchy process and hesitant fuzzy TOPSIS. Evaluated technologies were pumped hydro, conventional battery, high temperature battery, flow battery and hydrogen with 4 selection criteria: 2 Economic Performance, 4 Environmental, 4 Social, 4 Technical and sub-criteria respectively; power cost energy cost pollutant emissions area requirement water discharge quality, solid waste generation, safety accessibility ease of use public acceptance efficiency storage capacity cycling limit performance degradation. Weight calculation was evaluated by 3 international

experts from the energy sector and found out Hydrogen is the highest score (Acar, Beskese, & Temur, 2019).

Çolak and Kaya, 2020, used an integrated method that includes Delphi, hesitant fuzzy AHP hesitant fuzzy VIKOR to obtain best appropriate EST among the alternatives; pumped hydro, compressed air, flywheel, Supercapacitor, hydrogen, lithium-ion battery, sodium sulfur battery, vanadium redox battery, superconducting magnetic energy for Turkey. Technical, economic, environmental and socio-political were the 4 main categories for the evaluating criteria and the sub-criteria respectively; energy efficiency, energy density, technological maturity, storage capacity reliability and risk; investment cost, operation and maintenance cost and lifetime; intensity, air and water pollution, ecological impact, resource consumption and land disruption; social acceptance, political acceptance, job creation, government incentive, health and safety. They came up with result that compressed air technology was the best solution for Turkey.

According to literature review, it is understood that AHP method can be used alone or hybrid. Evaluating criteria and weighting may change with respect to experts' or stakeholders' preferences. Table 4 given below shows the weighting of 4 main criteria of studies that used AHP and the same criteria. It should note that calculated average values for giving guidance are not an objective comparison since variety of the ways of inquiry, considered technology and calculation methods (Baumann et al., 2019).

Table 4

Studies Which Used AHP and Same Main Criteria Comparison (Adopted from Baumann et al., 2019)

Studies Used Same Main Criteria	Technical	Economic	Environmental	Social	No of Stakeholders for Weighting
Cowan et al. (2010)	0.10	0.41	0.24	0.24	12
Daim et al. (2012)	0.23	0.28	0.26	0.23	12
Krüger et al. (2012)	0.33	0.29	0.29	0.09	By Authors
Ren (2018)	0.37	0.29	0.21	0.13	8
Average	0.26	0.32	0.25	0.17	

It can be recognized from the literature that there are also some MCDM studies which does not include any stakeholder or expert participation. In MCDM works selecting criteria and alternatives and weighting them are generally made by experts or stakeholders but there are also some studies based their works on literature for these processes.



Chapter 3

Storage Activities in The Electricity Market Regulation in Turkey

On the 9 of May 2021, there was a regulation prepared by EMRA (Energy Market Regulatory Authority) published in the official gazette with numbered 31439. Before explaining the regulation it's important to know the role of EMRA (EPDK in Turkish) in the electricity market. EMRA is the agency which is established in 2001. The institution has a public legal personality and administrative and financial autonomy. It is related to the Ministry of Energy and Natural Resources. It is authorized and responsible for granting licenses, defining the rights and obligations of legal entities arising from the activities for which they are authorized, and performing other related transactions in the electricity market: monitoring market performance and setting performance standards; developing and implementing secondary legislation; supervising licensee legal entities; preparing, amending, and enforcing regulated tariffs ensuring that the market complies with the Electricity Market Law. Within the limits set forth in this Regulation, the activities can be carried out through electricity storage units or facilities can be accomplished through 4 different profiles. These are: a) Electricity storage unit adjoined to the generation facility, b) Electricity storage facility adjoined to the consumption facility, c) Independent electricity storage facility, d) Electricity storage facility that can be established by network operators.

In this study only 2 of them are taken into account; the first one is electricity storage facility adjoined to the consumption facility; the second one is independent electricity storage facility. Articles of the regulation related to these two facilities are given below.

Regulation for the electricity storage facilities adjoined to the consumption facility (ESFACF):

“ARTICLE 6 – (1) An electricity storage facility may be established by consumers, provided that an affirmative connection opinion is given by the relevant network operator, its installed capacity does not exceed the contract power of the relevant consumption facility under the connection agreement, and it is at the same measurement point. (2) An electricity storage facility

adjoined to the consumption facility may be established within the scope of sub-paragraph (ç) of the first paragraph of Article 5 of the Unlicensed Electricity Generation in the Electricity Market Regulation published in the Official Gazette dated 12/05/2019 and numbered 30772. (3) An electricity storage facility adjoined to the consumption facility may only be established to meet the needs of the relevant consumption facility. In case energy is supplied to the network from the electricity storage facilities adjoined to the consumption facility, such energy shall not be taken into account in the settlement supply volumes of the relevant supplier. (4) Electricity storage facilities established by the legal personality of an organized industrial zone within the boundaries of the OIZ shall be deemed as electricity storage facilities adjoined to the consumption facility within the scope of this Article.”

Regulation for the Independent electricity storage facilities (IESF):

“ARTICLE 7 – (1) One or more independent electricity storage facilities may be established under the same supply license, on condition of holding a supply license and having no less than 2 MW installed capacity. The energy supplied to and withdrawn from the system by these facilities shall be taken into account in the settlement supply/draw volume of the relevant market participant. (2) Among the electricity storage facilities established within the scope of this Article, those facilities that meet the necessary conditions under the Electricity Market Ancillary Services. Regulation may participate in ancillary services, and those that qualify as balancing units may participate in the balancing power market.” (EPİAŞ, 2021)

Energy storage sector is grooving rapidly all around the world since its understood importance of the storage for the grid. China, Japan, United States are the leading countries with running too many projects right now. Turkey also wants to increase storage activities in the market that’s the reason of the published regulation last year. Here, there is a question that comes to mind about which storage technology should use. This is a kind of problem that can be solved with MCDM methods since it includes some subjectivity. The objective of the thesis is selecting to optimal EST for ESFACF and IESF by using AHP-TOPSIS integrated method.

Chapter 4

Methodology

4.1 AHP

AHP is a useful, one of the most common MCDM methods for solving decision making problems. Myers and Alpet were first introducers of AHP in 1968 and Thomas L. Saaty developed it in 1977. AHP is an analytic hierarchy process of complex problems that can evaluate quantitative and qualitative criteria in decision making and can include group or individual preferences, experiences, intuitions, knowledge, judgments, and thoughts in the decision-making process. increase. This is an MCDM method that allows you to process and resolve within the structure. Decision makers can include both objective and subjective thinking in the decision-making process. As a result, the decision maker is provided the chance to analyze his personal decision-making mechanism (Oktafianto et al., 2018).

In AHP, hierarchies are built on at least three levels. There is a purpose at the top of the hierarchy. Sub-levels contain the main criteria below the main criteria (if any). At the lowest level, there are decision options. To be consistent in pairwise comparisons, you need to correctly determine the number of criteria and define each criterion correctly. The criteria should be classified according to their common features. AHP can be applied with many criteria. It is a very good method for group decisions. The sensitivity analysis allows for an examination of the result's flexibility. Because the design of hierarchy and pairwise comparison matrices is subjective, skilled, and knowledgeable individuals are required.

Methodology of the AHP run by steps as follows (Saaty, 1977): a) Problem definition, b) Hierarchical structure is creation, c) A pairwise comparison matrix creation, d) Pairwise comparison matrices normalization, e) The priority vector calculation, f) The consistency ratio calculation, g) Priority vector of the decision options calculation, h) Ranking of decision alternatives.

The application steps of the AHP were described above as general titles. In this section, the steps will be explained in more detail (Saaty, 1994).

- a) Problem definition: Criteria priorities are determined for the decision by determining the criteria required.
- b) Hierarchical structure creation: The main goal is placed at the top of the hierarchy. Main criteria and sub-criteria are just below of the main goal. At the bottom of the hierarchy, alternatives take place. The following steps in the hierarchy are determined by the problem's intricacy and level of detail. Options on the same level are considered completely different from each other while creating the hierarchy.
- c) A pairwise comparison matrix creation: First the basic criteria then sub-criteria, if there are any, and finally all the criteria are considered in which the decision options are compared according to the criteria matrices, which are created by using importance scale that take values 1 to 9. Comparison matrices are square matrices which diagonal elements equal to 1 (Equation 1). The value of a_{ij} is equal to how much important the i. criterion to the j. criterion of which ratio should be preferred. Each criterion is used to compare decision alternatives separately. Decision matrices are built using Saaty's suggested 1-9 comparison scales (Table 5).

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} = 1/a_{12} & 1 & \dots & a_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ a_{n1} = 1/a_{1n} & a_{n2} = 1/a_{2n} & \dots & 1 \end{bmatrix} \quad (1)$$

Table 5

Fundamental Scale of Saaty for Relative Importance

Intensity of importance on an absolute scale	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very Strong importance
9	Extremely strong importance
2,4,6,8	Intermediate values between two adjacent decisions

d) Pairwise comparison matrices normalization: Every matrix component is normalized by dividing by its column sum. The total of the normalized matrix's columns equals one (Equation 2).

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}, i, j=1, 2, \dots, n \quad (2)$$

e) The priority vector calculation: It is calculated by using Equation 3 thus, Thus, percentage importance distributions showing the importance values of the criteria relative to each other are obtained.

$$w_i = \left(\frac{1}{n}\right) \sum_{i=1}^n a'_{ij}, i, j = 1, 2, \dots, n \quad (3)$$

f) The consistency ratio calculation: To obtain consistency ratio, Consistency Index (CI) needs to be calculated first (Equation 4, Equation 5, Equation 6, Equation 7, Equation 8).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \left(\frac{\sum_{j=1}^n a_{ij} w_j}{w_i} \right) \quad (5)$$

$$A \times W = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21}=1/a_{12} & 1 & \dots & a_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ a_{n1}=1/a_{1n} & a_{n2}=1/a_{2n} & \dots & 1 \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \cdot \\ \cdot \\ w_n \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ x_n \end{bmatrix} \quad (6)$$

$$d_i = \frac{x_i}{w_i}, i, j = 1, 2, \dots, n \quad (7)$$

$$\lambda_{max} = \frac{\sum_{i=1}^n d_i}{n} \quad (8)$$

To evaluate consistency, Random Index (RI) value needs to know. Values clarified for n-dimensional comparison matrices are given in Table 6 below.

Table 6

RI Values According to Dimension of Pairwise Comparison Matrix

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57	1.59

Equation 9 is given below for calculating Consistency Ratio (CR). If the CR value is less than 0.10 that means the pairwise comparison matrix is consistent.

$$CR = \frac{CI}{RI} \quad (9)$$

g) Priority vector of the decision options calculation: The priority vector of the decision options is calculated by creating a pairwise comparison matrix for the criteria. This prioritized vector can also be referred to as the criteria weight vector.

h) Ranking of decision alternatives: The entire priority matrix is obtained by uniting the priority vectors obtained for the criteria. The vector is obtained by multiplying all the priority matrices by the priority vector of the decision options and adding them together. The decision option with the top weight in this vector is chosen to be the best alternative for solving the problem⁹.

4.2 TOPSIS

TOPSIS is a method developed by Hwang and Yoon in 1981. Evaluation of alternatives based on positive and negative ideal solutions. The method can be applicable within 6 steps. a) Creation of decision matrix. b) Creation of normalized matrix. c) Creation of weighted standard decision matrix. d) Obtaining the positive and negative ideal solution values. e) Obtaining distance values from positive and negative ideal solution values. f) Calculating the relative closeness coefficients to the ideal solution.

a) Creation of decision matrix: N*m dimensional decision matrix is created by decision maker after the decision options and assessment criteria are decided Here, n

⁹ 11.Çok Ölçütlü Karar Verme Yöntemleri – III Ankara University Website: Retrieved from acikders.ankara.edu.tr at 15 November 2021

and m are the numbers of decision options and evaluation criteria, respectively (Equation 10).

$$D = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1m} \\ d_{21} & d_{22} & \dots & d_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{n1} & d_{n2} & \dots & d_{nm} \end{bmatrix} \quad d_{ij}, i=1,2,3,\dots,n \text{ and } j=1,2,3,\dots,m \quad (10)$$

b) Creation of normalized matrix: By taking the square root of the sum of the squares of the values of each criterion of the decision matrix and dividing the relevant element of the column by this resulting value standard decision matrix is obtained (Equation 11).

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1m} \\ r_{21} & r_{22} & \dots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \dots & r_{nm} \end{bmatrix} \quad r_{ij} = \frac{d_{ij}}{\sqrt{\sum_{k=1}^n d_{kj}^2}} \quad i=1,2,3,\dots,n \text{ and } j=1,2,3,\dots,m \quad (11)$$

a) Creation of weighted standard decision matrix: The weight values of evaluation criteria are determined. The weighted standard decision matrix, V , is created by multiplying the factors of the R matrix by their corresponding weight values (Equation 12).

$$V = \begin{bmatrix} w_1 r_{11} & w_2 r_{12} & \dots & w_m r_{1m} \\ w_1 r_{21} & w_2 r_{22} & \dots & w_m r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ w_1 r_{n1} & w_2 r_{n2} & \dots & w_m r_{nm} \end{bmatrix} = \begin{bmatrix} v_{11} & v_{12} & \dots & v_{1m} \\ v_{21} & v_{22} & \dots & v_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ v_{n1} & v_{n2} & \dots & v_{nm} \end{bmatrix} \quad \sum_{i=1}^m w_i = 1, w_i = 1,2,\dots,m \quad (12)$$

b) Obtaining the positive and negative ideal solution values: By using the V matrix, positive ideal and negative ideal solution sets are obtained for each criterion according to the purpose of the evaluation criterion of interest. If the evaluation

criteria are in terms of utility, the positive ideal solution is the largest values of the columns of the matrix V , and the negative ideal solution is the smallest values of the columns of the matrix V . Here positive and negative ideal solutions clusters represented as; $V^* = \{v_1^*, v_2^*, \dots, v_m^*\}$, $V^- = \{v_1^-, v_2^-, \dots, v_m^-\}$ respectively.

c) Obtaining distance values from positive and negative ideal solution values: The deviations of the assessment of criteria for each decision option from the positive ideal and negative ideal solution values are computed by using the equations below (Equation 13, Equation 14).

$$S_i^* = \sqrt{\sum_{j=1}^m (v_{ij} - v_j^*)^2}, \quad i = 1, 2, 3, \dots, n \quad (13)$$

$$S_i^- = \sqrt{\sum_{j=1}^m (v_{ij} - v_j^-)^2}, \quad i = 1, 2, 3, \dots, n \quad (14)$$

d) Calculating the relative closeness coefficients to the ideal solution: Relative closeness coefficients can be found by using the equation below (Equation 15)¹⁰.

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-}, \quad i = 1, 2, 3, \dots, n \quad (15)$$

In this research, a model that integrates AHP-TOPSIS method together is presented. The proposed model can be seen in Figure 20 given below.

¹⁰ 10.Çok Ölçütlü Karar Verme Yöntemleri – II Ankara University Website: Retrieved from acikders.ankara.edu.tr at 15 February 2022

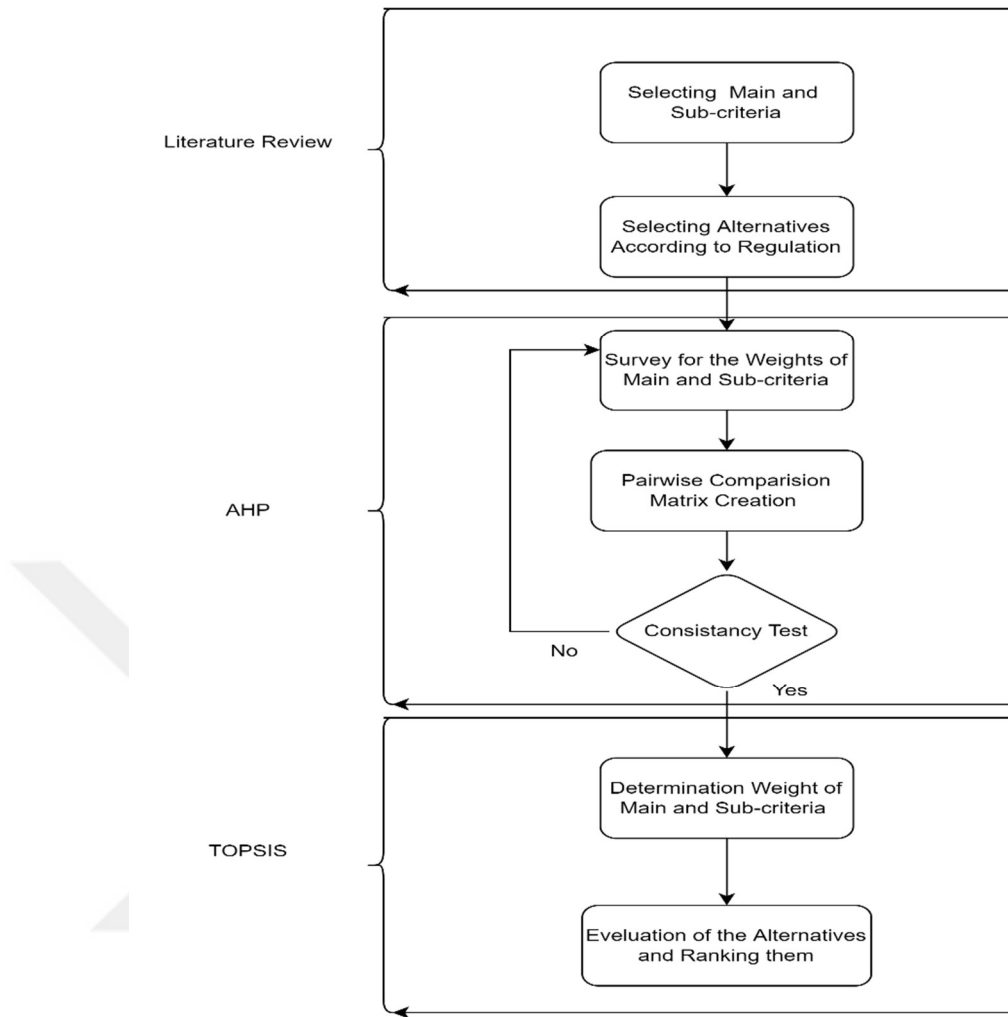


Figure 20. Proposed model.

4.3 Electricity Storage Facilities Adjoined to The Consumption Facility

In this section, it is aimed to select the best storage technology for ESFACF. Main and sub-criteria and alternatives identified according to literature review considering electricity market regulation. It can be seen most used main criteria stated as economic, technological, environmental, and social. Here economic criterion is related with total capital cost and O&M cost. Technological main criterion includes energy efficiency, lifecycle, rated power, specific energy, and discharge at rated capacity. The most preferred environmental criterion is global warming impact in the literature. Social acceptance is selected as social criterion which is also one of the most common selected sub-criteria among the other social

criteria. Possible alternatives are decided on applicability of ESTs to the residential and industrial areas thus PB-A, Li-ion, FES, Na-s, Ni-Cd, VRFB and Hydrogen storage are selected as options. The hierarchical structure of the process is in Figure 21.

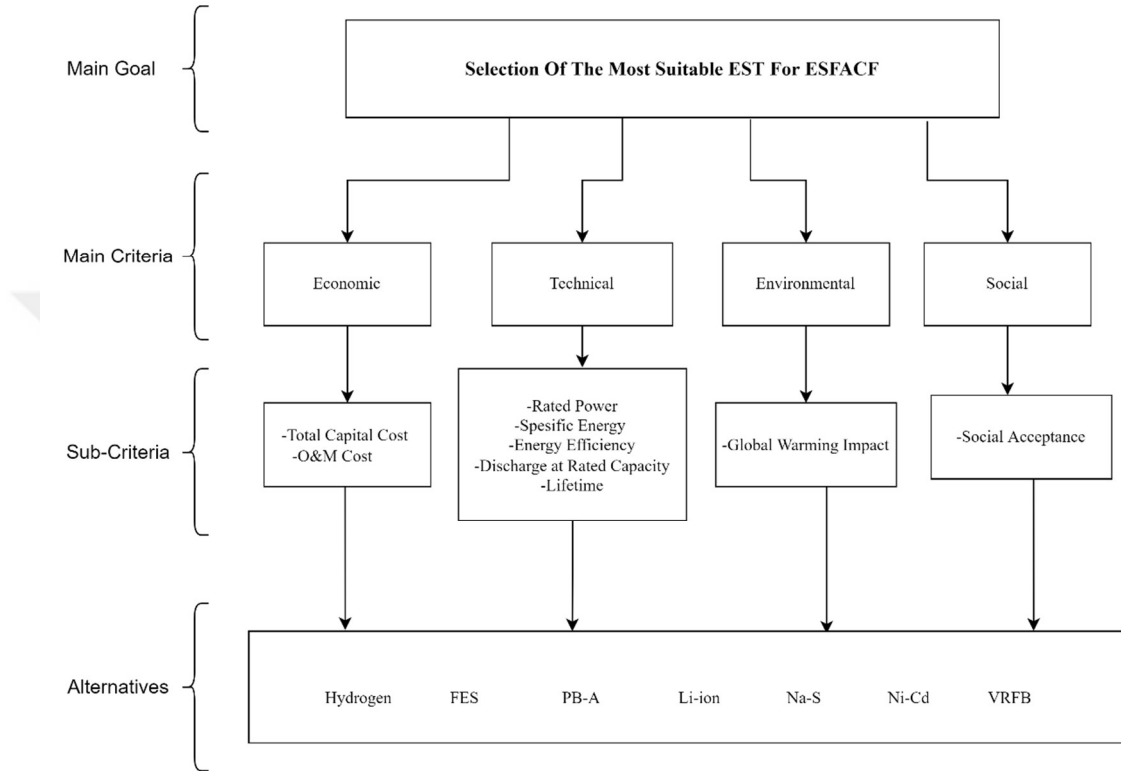


Figure 21. Selection of the most suitable EST for ESFACF.

The weights of the main and the sub-criteria are decided by stakeholders of the energy sector by the survey. 10 experts joined to survey 70% of them from the academia and 30% from the private sector. 60% of them work in the field related with energy storage. They have been working in this area for average 6 years. It is asked to do pairwise comparison of main and sub criteria. Pairwise comparison matrices are created with obtained answers from the experts. Then, it is taken geometric mean of these 10 matrices and checked its consistencies. After that, Table 7 is built given below. Figure 22 represents to pie chart of the main criteria weights for ESFACF. Table 8 and Table 9 represent the weights of economic and technical the sub-criteria.

Table 7

Normalized Matrix of Main Criteria

	Eco.	Tech.	Env.	Soc.	Wi
Eco.	0.43041	0.63028	0.31626	0.33251	0.42737
Tech.	0.12985	0.19015	0.37016	0.29456	0.24618
Env.	0.32779	0.12373	0.24086	0.28644	0.2447
Soc.	0.11195	0.05583	0.07272	0.08649	0.08175
CR=					0.07572

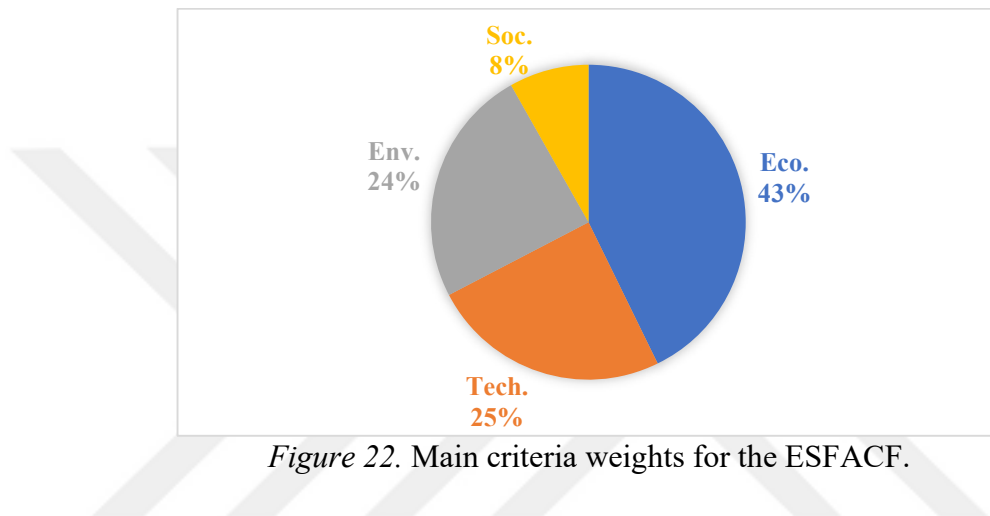
*Figure 22. Main criteria weights for the ESFACF.*

Table 8

Normalized Matrix of Economic Sub-Criteria with Weights for ESFACF¹¹

Economic	TCC	O&M C.	Wi
TCC	0.71401	0.71401	0.71400825
O&M C.	0.28599	0.28599	0.28599175

¹¹ TCC: Total capital cost; O&M C.: Operation and maintenance cost.

Table 9

Normalized Matrix of Technical Sub-Criteria with Weights for ESFACF¹²

Technical	R.P.	S. E.	E.E.	D.R.C	L.T	Wi
R.P.	0.17273	0.33975	0.17118	0.10761	0.13615	0.18548
S. E.	0.09316	0.18325	0.31818	0.19506	0.18536	0.195
E.E.	0.25574	0.14597	0.25345	0.39251	0.30816	0.27116
D.R.C	0.21517	0.12594	0.08656	0.13406	0.16287	0.14492
L.T	0.2632	0.2051	0.17063	0.17077	0.20747	0.20343
CR=						0.06017

Rahman et al. (2020) made a deep literature review related to energy storage technologies. They reviewed 91 publications related to EST with different aspects such as life cycle and techno-economic assessments (Rahman, Oni, Gemechu, & Kumar, 2020). The data for calculating the scores of each alternative was mostly obtained from this study. Tables were created for economical, technical, and environmental (Table 10, Table 11, and Table 12) criteria by calculating data of an average of the min. and max. values for given technology types. Social criteria weights (Table 13) were obtained from the survey. Table 11 indicates the values of technology types with different technical parameters. The total capital cost here is found by the summation of the storage unit, the balance of power (BOP), and power conversion system cost (PCS).

Table 10

Economical Parameters of Different ESTs

	Total Capital Cost			
	PCS Cost (\$/kW)	BOP Cost (\$/kW)	Storage Section Cost (\$/kWh)	O&M Cost (\$/kW-yr.)
Hydrogen	2674.5	27	8.5	32.5
FES	394	177	81108	5.5
VRFB	985.5	81	611	27.5
Li-ion	2240.5	65	2193	62.5
Pb-A	429.5	93	523.5	14.5
Na-S	1730.5	99	637	28
Ni-Cd	318	103	909.5	15
CAES	914	16.5	117	3

¹² R.P.: Rated power; S. E.: Specific energy; E.E.: Energy efficiency; D.R.C: Discharge at rated capacity; L.T: Lifetime

Table 11

Technical Parameters of Different ESTs

Technical	Rated Power (MW)	Specific Energy (Wh/kg)	Energy Efficiency (%)	Discharge at Rated capacity (h)	Lifetime (cycles)
Hydrogen	25	700	38.5	12	103.5
FES	5	42.5	85	0.005	105.5
VRFB	6	22.5	72.5	7	10000
Li-ion	25	137.5	76.5	1.0085	900
Pb-A	20	40	75	3	875
Na-S	17.025	145	78.5	6	3500
Ni-Cd	20	62.5	70	7	2250
CAES	1502.5	45	58	12.5	10000

For the global warming impact, CO₂ emissions from cradle to grave are taken as parameters. Values can be seen in Table 12. Here only FES and Ni-Cd values are taken from different sources.

Table 12

Environmental Parameters of Different ESTs

Environmental	Global Warming Impact (g-CO ₂ eq/kWh)
Hydrogen	543
FES*a ¹³	85
VRFB	480
Li-ion	336.15
Pb-A	437
Na-S	338.95
Ni-Cd*b ¹⁴	990
CAES	383.55

¹³ *a obtained from Rahman, M. M., Gemechu, E., Oni, A. O., & Kumar, A. (2021),

¹⁴ *b obtained from Hammond, G. P., & Hazeldine, T. (2015)

Table 13

Scores for Social Acceptance for ESFACF

Social	Social Acceptance
Hydrogen	50
FES	37
VRFB	31
Li-ion	58
Pb-A	35
Na-S	30
Ni-Cd	39

4.4 Independent Electricity Storage Facility

In this part, storage technologies are examined and evaluated according to the independent electricity storage profile in the electricity market regulation. The main goal is selecting to optimal alternative for IESF. Since installed capacity should not be less than 2MW alternatives are selected according to this rule. Selected possible alternatives are CAES, PB-A, Li-ion, FES, Na-s, Ni-Cd, VRFB, and Hydrogen. Main and sub-criteria took as same with for ESFACF with same reasons as they are stated in part 4.3. The hierarchical structure of this study is given in Figure 23.

To obtain weights of the main and sub-criteria of IESF, 11 stakeholders related to the energy area were surveyed. 54.5% of them are from the private sector and 45.5% of them are from academia. 63.6 % of them work in the energy storage technologies field. They have been working in this area for 5 years on average. The procedure applied to calculate the weight of criteria was the same as in chapter 4.3 but with different results since surveyed group and the main goal were not the same. Weights of the main and sub-criteria with CR for IESF as given in Table 14, Table 15, and Table 16 below. Moreover, the weights of the main criteria for the IESF can be easily seen in Figure 24.

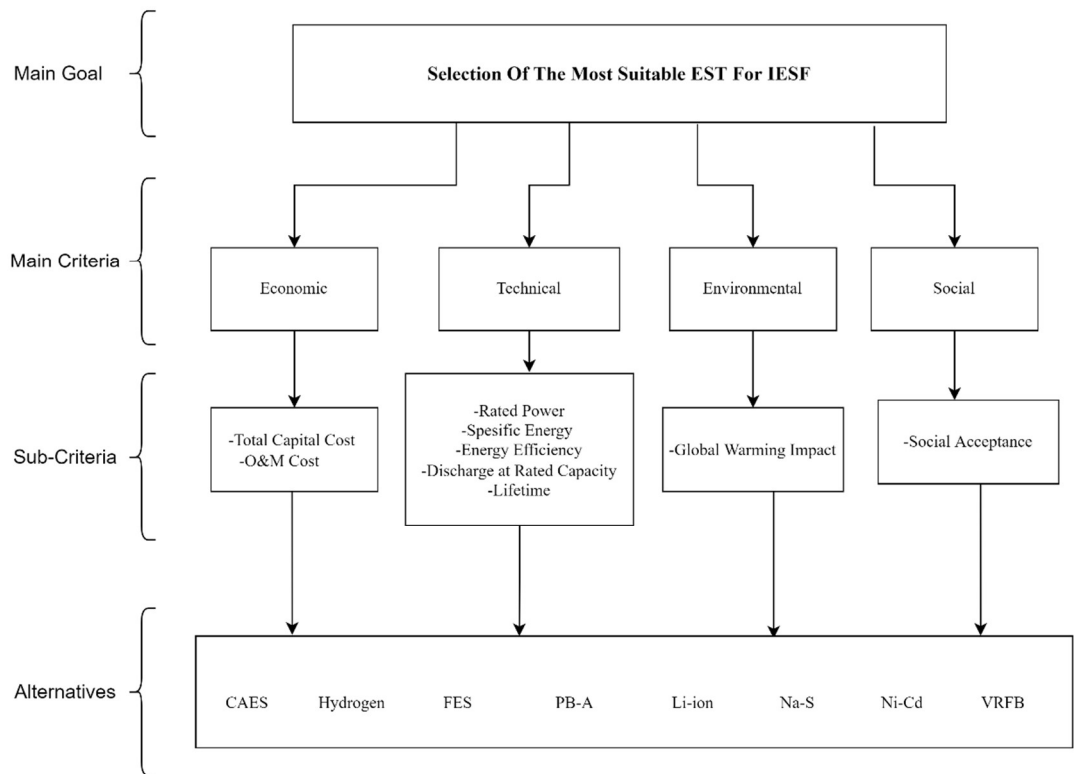


Figure 23. Selection of most suitable energy storage technologies for IESF.

Table 14

Normalized Matrix of Main Criteria with Weights for IESF

Main Criteria	Eco.	Tech.	Env.	Soc.	Wi
Eco.	0.5119	0.69023	0.3974	0.38504	0.49614
Tech.	0.12121	0.16344	0.34068	0.26616	0.22287
Env.	0.2586	0.09631	0.20076	0.26734	0.20575
Soc.	0.10829	0.05002	0.06117	0.08145	0.07523
CR=					0.07621

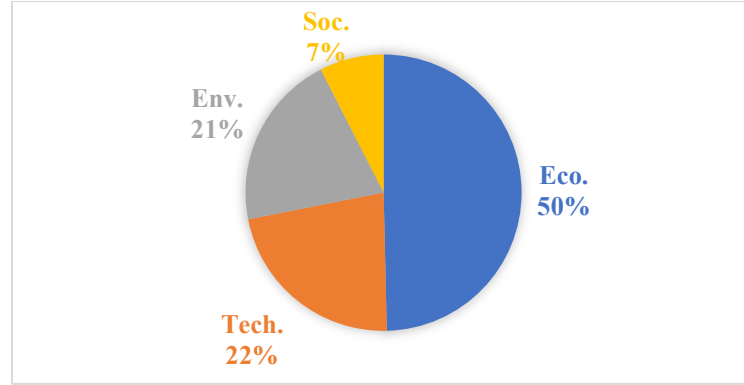


Figure 24. Main criteria weights for the IESF.

Table 15

Normalized Matrix of Economic Sub-Criteria with Weights for IESF

Economical	TCC	O&M C.	Wi
TCC	0.66058	0.66058	0.66058
O&M C.	0.33942	0.33942	0.33942

Table 16

Normalized Matrix of Technical Sub-Criteria with Weights for IESF

Technical	R.P.	S. E.	E.E.	D.R.C	L.T	Wi
R.P.	0.13292	0.22157	0.13047	0.14764	0.0951	0.14554
S. E.	0.08346	0.13912	0.21316	0.13776	0.11143	0.13698
E.E.	0.34895	0.22354	0.34251	0.42782	0.37237	0.34304
D.R.C	0.12029	0.13493	0.10697	0.13361	0.19618	0.13839
L.T	0.31439	0.28084	0.20689	0.15318	0.22493	0.23604
CR=						0.03544

Social acceptance scores obtained from the survey by summing each participant's scores for each alternative result can be seen in Table 17.

Table 17

Scores for Social Acceptance for IESF

Social	Social Acceptance
Hydrogen	50
FES	38
VRFB	29
Li-ion	72
PB-A	54
Na-S	52
Ni-Cd	55
CAES	46



Chapter 5

Results and Discussion

5.1 Electricity Storage Facilities Adjoined to The Consumption Facility

To get the result for ESFACF, firstly, the importance level of each sub-criteria was calculated. It's shown in Table 18 below.

Table 18

Importance Level of Each Sub-Criteria for ESFACF

Main Criteria	Weights of the Main Criteria	Sub-criteria	Weights of the Sub-criteria	Importance Level
Eco.	0.427367906	Total Capital Cost	0.714008253	0.305144212
		O&M Cost	0.285991747	0.122223694
		Rated Power	0.185483452	0.045662556
		Specific Energy	0.19499942	0.04800521
Tech.	0.246181295	Energy Efficiency	0.271163927	0.066755487
		Discharge at Rated Capacity	0.144918933	0.03567633
		Lifetime	0.203434269	0.050081712
Env.	0.244701987	Global Warming Impact	1	0.244701987
Soc.	0.081748812	Social Acceptance	1	0.081748812

By multiplying the importance level and weights of each alternative's decision matrix created in Table 19 is given below.

Table 19

Decision Matrix with Weights of ESFACF

	TCC	O&M C.	R.P.	S. E.	E.E.	D.R.C	L.T	GW	S.A.
Hydrogen	0.035278	0.02141	0.00967	0.02922	0.00518	0.01189	0.00029	0.04139	0.0146
FES	0.12842	0.00362	0.00193	0.00177	0.01144	5E-06	0.0003	0.00648	0.0108
VRFB	0.024923	0.01812	0.00232	0.00094	0.00976	0.00693	0.02824	0.03659	0.00905
Li-ion	0.038822	0.04118	0.00967	0.00574	0.0103	0.001	0.00254	0.02562	0.01693
PB-A	0.020265	0.00955	0.00774	0.00167	0.01009	0.00297	0.00247	0.03331	0.01022
Na-S	0.03643	0.01845	0.00659	0.00605	0.01057	0.00594	0.00988	0.02584	0.00876
Ni-Cd	0.021006	0.00988	0.00774	0.00261	0.00942	0.00693	0.00635	0.07547	0.01139

Furthermore, from the weighted decision matrix, positive and negative ideal solution values obtained as:

$V^* = \{0.020265008, 0.003623883, 0.009672221, 0.029220562, 0.011439952, 0.011887652, 0.028240505, 0.006479446, 0.016933682\},$

$V^- = \{0.128420161, 0.04118049, 0.001934444, 0.000939232, 0.005181625, 4.95319E-06, 0.000292289, 0.075466486, 0.008758801\}.$

After that, distance values from the positive and negative ideal solution are computed. Lastly, relative closeness coefficients to the ideal solution found and alternatives are ranked in Figure 25 given below. It can be seen that VRFB is the first ranked alternative. PB-A and Na-S values are so close to it and FES is the least preferable one.

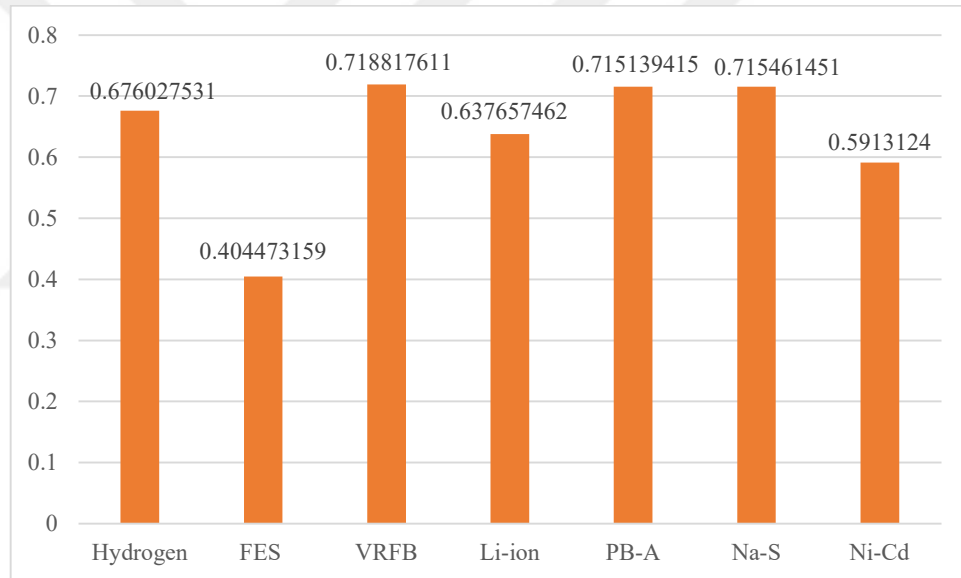


Figure 25. Ranking alternatives of ESFACF.

5.2 Independent Electricity Storage Facility

According to the calculation of weighting of each sub-criterion importance level of sub-criteria was obtained as it is given in Table 20 below.

Table 20

Importance Level of Each Sub-Criteria for IESF

Main Criteria	Weights of the Main Criteria	Sub-criteria	Weights of the Sub-criteria	Importance level
Eco.	0.49614	Total Capital Cost	0.6605766	0.32774023
		O&M Cost	0.3394234	0.1684024
		Rated Power	0.1455394	0.03243672
Tech.	0.22287	Specific Energy	0.1369847	0.03053013
		Energy Efficiency	0.3430375	0.07645364
		Discharge at Rated Capacity	0.1383938	0.03084418
		Lifetime	0.2360446	0.05260785
Env.	0.20575	Global Warming Impact	1	0.2057544
Soc.	0.07523	Social Acceptance	1	0.07523045

By multiplying the importance level with normalized scores decision matrices were obtained with weights as Table 21.

Table 21

Decision Matrix with Weights of IESF

	TCC	O&M C.	R.P.	S. E.	E.E.	D.R.C	L.T	GW	S.A.
Hydrogen	0.03463	0.02903	0.00050	0.01788	0.00531	0.00763	0.00020	0.03109	0.00950
FES	0.13658	0.00491	0.00010	0.00109	0.01173	0.00000	0.00020	0.00487	0.00722
VRFB	0.02527	0.02457	0.00012	0.00057	0.01001	0.00445	0.01897	0.02748	0.00551
Li-ion	0.03879	0.05584	0.00050	0.00351	0.01056	0.00064	0.00171	0.01925	0.01368
PB-A	0.02087	0.01295	0.00040	0.00102	0.01035	0.00191	0.00166	0.02502	0.01026
Na-S	0.03668	0.02501	0.00034	0.00370	0.01083	0.00381	0.00664	0.01941	0.00988
Ni-Cd	0.02175	0.01340	0.00040	0.00160	0.00966	0.00445	0.00427	0.05668	0.01045
CAES	0.01318	0.00268	0.03007	0.00115	0.00800	0.00795	0.01897	0.02196	0.00874

From the weighted decision matrix, positive and negative ideal solution values are found as:

$V^* = \{0.013181734, 0.002680144, 0.030074314, 0.01788376, 0.011730251, 0.007947318, 0.018968722, 0.004866674, 0.013678263\}$,

$V^- = \{0.136578937, 0.05583634, 0.000100081, 0.000574835, 0.005313114, 3.17893E-06, 0.000196326, 0.056682441, 0.0055093\}$.

It is continued by calculating distance values to the positive and negative ideal solution. After that relative closeness coefficients to the ideal solution are calculated and scores of alternatives are found. As a result, CAES is the highest prioritization for IESF followed by Pb-A and VRFB. FES is the least preferable one (Figure 26). According to Çolak and Kaya's study, CAES had the highest score also.

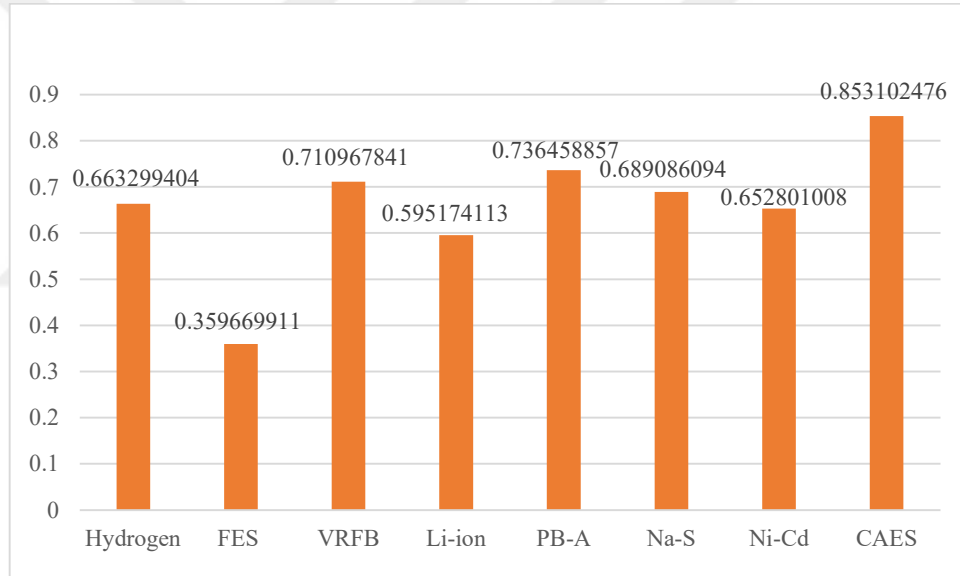


Figure 26. Ranking alternatives of IESF.

Chapter 6

Conclusion

As the world's population grows and more electrical devices are integrated into daily life, electricity consumption rises day by day. After governments realized that fossil fuels, which were the primary source of supply for electricity demand, were limited and harmful to the environment, they changed their policies to favor renewable energy sources. Because renewables are intermittent, an increase in their share exacerbates the difficulty of the electricity network. Furthermore, even a brief blackout causes significant damage to the industry, implying that electricity must be a contentious issue. All these problems highlighted the significance of energy storage. The work provides adequate information about energy storage as well as legislation regarding energy storage activities in the Turkish government. Furthermore, the study provides a literature review on the MCDM procedure and the AHP in the energy storage area. A model is developed to evaluate the most appropriate energy storage technology in terms of regulation using the AHP technique with TOPSIS integrated. All empirical data is obtained from credible resources and surveys to building the model. The model is run in Excel and applied to two different profiles ESFACF and IESF. While VRFB is selected optimal solution for ESFACF, CAES takes a position at the first rank for IESF.

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