FEASIBILITY OF PUMPED-STORAGE HYDRAULIC SYSTEMS BASED ON HOURLY VARIATION OF ELECTRICITY PRICES

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ABSTRACT

FEASIBILITY OF PUMPED-STORAGE HYDRAULIC SYSTEMS BASED ON HOURLY VARIATION OF ELECTRICITY PRICES

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Global energy demand increases every day due to growing needs. The ideal of eco-friendly, sustainable and low cost energy generation relying on countries' own domestic sources increases the interest in renewable energy in the 21st century. However, the intermittent nature of the renewable energy brings the importance of and the need for energy storage to surface. Pumped storage hydroelectricity (PSH) has been in use worldwide for a long time with this purpose thanks to its large scale storage capacity and proven technology. Unlike many countries with pumped storage, Turkey has not needed a PSH facility until very recently in virtue of its significant hydropower capacity. Wind and solar power share in Turkey's electrical grid has increased so far and the first nuclear power plant of the country is planned to start operating in 2023, thus leading to advancement in energy storage and PSH. The high investment costs and long construction period of PSH lead to some significant questions for a projected pumped storage facility in Turkey: technical features, location, investment costs, model, operation initiation day, etc. In this dissertation, potential profitability/unprofitability of a projected PSH facility in Turkey is examined. Within this scope, in order to analyze the requirement for PSH in Turkey, the country's electricity system and market are discussed in detail and compared with countries that have pumped storage. Evaluations are made using real time electricity prices and generation-consumption values through the perspective of both public and private sector. Results show that the current prices in Turkish electricity market are not profitable enough to attract investment by the private sector.

Keywords: Pumped Storage Hydroelectricity, PSH, Energy Storage

ÖZ

ENERJİ ÜCRETLERİNDEKİ SAATLİK DEĞİŞİMİ ESAS ALAN POMPAJ DEPOLAMALI HİDROLİK SİSTEMLERİN UYGULANABİLİRLİĞİ

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Artan ihtiyaçlar dünya genelinde enerjiye olan talebi her geçen gün artırmaktadır. Çevre dostu, sürdürülebilir, ucuz ve ülkelerin kendi kaynaklarına dayanan enerji üretimi isteği de özellikle 21. yüzyılda yenilenebilir enerjiye olan ilginin yükselmesinin gerekçeleri arasında yer almaktadır. Ancak yenilenebilir enerjinin kesintili yapısı, enerji depolamanın önemi ve gerekliliğini de beraberinde getirmiştir. Pompaj depolamalı hidroelektrik tesisler (PHES) büyük depolama kapasiteleri ve kanıtlanmış teknolojileri sayesinde dünya genelinde bu amaçla uzun yıllardır kullanılmaktadır. Dünyadaki yaygın durumun aksine, Türkiye, sahip olduğu hidroelektrik potansiyel sayesinde bu güne kadar PHES'e ihtiyaç duymamıştır. Rüzgar ve güneş enerjisi santrallerinin Türkiye elektrik sistemindeki paylarının artması, ilk nükleer santralin 2023 yılında üretime başlayacak olması ülke açısından enerji depolama konusuna ve onun özelinde de PHES'e olan ilgiyi bir hayli artırmıştır. Bu tesislerin gerektirdiği yüksek yatırım maliyetleri ve inşa sürelerinin uzunluğu, Türkiye açısından, muhtemel bir PHES'in teknik özellikleri, konumu, yatırım maliyeti ve modeli, işletmeye alınması gereken tarih gibi pek çok soruyu da beraberinde getirmektedir. Bu tez çalışmasında bu soruların cevaplanması hedeflenmiş ve bu amaçla, kurulması muhtemel PHES tesislerinin ülke açısından kar-zarar durumları incelenmiştir. Bu bağlamda öncelikle Türkiye elektrik sistemi ve piyasası detaylı olarak ele alınmış, dünyadaki örneklerle karşılaştırılarak Türkiye için PHES'in gerekliliği araştırılmıştır. Gerçek zamanlı elektrik ücretleri ve üretim-tüketim değerleri kullanılarak hem kamunun hem de özel sektörün bakış açısıyla değerlendirmede bulunulmuştur. Sonuçlar Türkiye elektrik piyasasındaki mevcut fiyatların özel sektörün yatırım yapmak isteyeceği karlılıkta olmadığını göstermiştir.

Anahtar Kelimeler: Pompaj Depolamalı Hidroelektrik Tesisler, PHES, Enerji Depolama

To My Father

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Foremost, I would like to express my greatest appreciation to my supervisor Prof. Dr. İsmail Aydın for his guidance and support. I could not have completed this thesis without his patience and help. He trusted in me and encouraged me all the time whenever I struggled with anything related to my research. It has been a great honor working with him.

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TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ASM	: Ancillary Service Market
BOTAŞ	: BOTAŞ Petroleum Pipeline Corporation
BPM	: Balancing Power Market
BSR	: Balancing and Settlement Regulation
DAM	: Day-Ahead Market
DSİ	: General Directorate of State Hydraulic Works
EDF	: Electricity of France
EİE	: Electric Power Resources Survey and Development Administration
ENTSO-E	: European Network of Transmission System Operators for Electricity
EPDK	: Electricity Market Regulation Authority
EPİAŞ	: Energy Exchange Istanbul
ETKB	: Ministry of Energy and Natural Resources
EÜAŞ	: Electricity Generation Corporation
GW	: Gigawatt
GWh	: Gigawatt-hour
HEPP	: Hydroelectric Power Plant
Hz	: Hertz
IDM	: Intra-Day Market
IEA	: International Energy Agency
IHA	: International Hydropower Association

JICA	: Japan International Cooperation Agency
kW	: Kilowatt
kWh	: Kilowatt-hour
MCP	: Market Clearing Price
MRC	: Manning Roughness Coefficient
MTA	: Mineral Research and Exploration General Directorate
MUDB	: Market Financial Reconciliation Centre
MW	: Megawatt
MWh	: Megawatt-hour
MYTM	: National Load Dispatch Operational Directorate
NGPP	: Natural Gas Power Plant
NPP	: Nuclear Power Plant
PSH	: Pumped Storage Hydroelectricity
REN21	: Renewable Energy Policy Network for the 21st Century
SMP	: System Marginal Price
SPP	: Solar Power Plant
TEAŞ	: Turkish Electricity Generation and Transmission Company
TEDAŞ	: Turkish Electricity Distribution Company
TEİAŞ	: Turkish Electricity Transmission Company
TEK	: Turkish Electricity Authority
TETAŞ	: Turkish Electricity Contracting and Trading Company
TÜİK	: Turkish Statistical Institute

TW : Terawatt

TWh : Terawatt-hour

USBR : United States Bureau of Reclamation

WAP : Weighted Average Price

WEC : World Energy Council

WPP : Wind Power Plant

YEGM : General Directorate of Renewable Energy

LIST OF SYMBOLS

h_f : Friction losses (m)

h_m : Minor losses (m)

E_{gen} : Electricity generation (MWh)

E_p : Electricity consumption (MWh)

H_g : Gross head (m)

H_{net} : Net head (m)

H_p : Head of water in pumping mode (m)

P_p : Pumping capacity (MW)

Q_p : Pumping discharge (m^3/s)

η_g : Total generating efficiency

η_{gm} : Efficiency of generator motor

η_p : Total pumping efficiency

η_{pt} : Efficiency of pump-turbine

η_{rt} : Round-trip efficiency

η_{tr} : Efficiency of transformer

η_{wc} : Efficiency of water conductors

hbr : Loss through branch (m)

hel : Bend loss (m)

hen : Entrance loss (m)

hex : Exit loss (m)

hsl : Losses through slots (m)

ht : Trashrack loss (m)

htr : Transition loss (m)

s : Slope of energy grade line

A : Cross-sectional area of flow (m^2)

A_g : Gross area (m^2)

A_n : Net area (m^2)

D : Diameter of the conduit (m)

Kel : Bend loss coefficient

Kel : Branch loss coefficient

Kel : Exit loss coefficient

Ken : Entrance loss coefficient

Ksl : Slot loss coefficient

Kt : Trashrack loss coefficient

Ktr : Transition loss coefficient

L : Length of the tunnel or pipe (m)

P : Installed capacity (MW)

P : Wetted perimeter of conduit (m)

Q : Water flow rate (m^3/s)

R : Hydraulic radius (m)

R_{ave} : Average hydraulic radius (m)

Re : Reynolds number

V : Velocity of fluid (m/s)

$\not{V}$: Volume of water (m^3)

f : Darcy friction factor

g : Acceleration due to gravity (m/s^2)

n : Manning roughness coefficient

ε : Equivalent roughness (mm)

ν : Kinematic viscosity of water (m^2/s)

ρ : Density of water (kg/m^3)

CHAPTER 1

INTRODUCTION

1.1. General

Among various issues that concern modern societies, energy is a highly crucial one. Sustainable, low cost and safe power generation is one of the main targets of many countries around the globe. Electricity consumption, on the other hand, is a significant parameter for country classification based on development level. Power generation from renewable resources is a rising trend, especially for the last three decades. Fossil fuels, proven to be non-eco-friendly, have been largely running short and as a result, mainly lost their popularity. Increasing share of renewable energy appears promising for the future of the planet while bringing out a new challenge along with it: intermittent nature of the source. Therefore, energy storage is a major concern in recent years.

Pumped storage facilities provide the most efficient and practical means for storing large quantities of energy. It is a proven technology and widely used worldwide for more than a century now. Modern pumped storage units use reversible-pump turbines that can be run in one direction as pump and in the other direction as turbine in order to transfer water between upper and lower reservoirs. However, there are energy losses during the storage and re-production phases that must be compensated by the electricity price differences between the two phases.

Unlike many countries with Pumped storage hydroelectricity (PSH), Turkey has not needed a PSH facility until very recently thanks to its significant hydropower capacity. Yet, the share of power generation from hydropower decreased from 40% to 20% since late 1990's. In addition to this, investments made in renewable power have increased so far and the first nuclear power plant (NPP) of the country (Akkuyu NPP) is planned to start operation in 2023, thus leading to advancement in energy storage and PSH.

1.2. Scope of the Study

In this study, feasibility of pumped storage hydraulic system based on hourly variation of electricity prices in Turkey is examined. Gökçekaya and Altınkaya PSHs, projects developed by Japan International Cooperation Agency (JICA), are selected for case study. In the case study, potential profits are estimated using real time hourly electricity prices between 2010 and 2018. In addition to this, the facilities' possible support to power grid in the near future are taken into consideration.

Following the introduction part, main features, pump-turbine equipment and advantages-disadvantages of a PSH are mentioned in Chapter 2. History of PSH and its global status are demonstrated along with examples from studies conveyed in Turkey during recent years. A detailed literature review is provided in this chapter to enable the readers to have a general conception about PSH.

In Chapter 3, Turkey's electricity system is discussed in detail. Among the main topics of this chapter are annual changes in installed power, demand and supply relation, share of sources that are used for energy generation, daily demand curves, transmission and distribution. Besides, estimated values of these features for the near future are also mentioned in this chapter. The main aim of this chapter is to represent the entire Turkish power grid by collecting various dispersed data. Since the data of 2018 had not been published yet by the time this study was carried out, only the statistical information up until 2017 is mentioned in this dissertation.

In Chapter 4, history of electricity and electricity market in Turkey is reviewed. Fundamentals of electricity trade, electricity pricing and the difference between peak and off-peak hour prices are analyzed in detail. Electricity prices are compiled from

Energy Exchange Istanbul (EPİAŞ) between 2010 and 2018 in order to make evaluations on hourly, monthly and yearly basis.

Chapter 5 consists of the process of capacity determination for hydroelectric power plants (HEPP). Calculation of head loss in the system, efficiencies and pump-turbine capacities of a PSH are shown in this chapter. Besides, calculation of minor losses due to disturbances of fluid flow are explained in detail to calculate the net heads of the power plants which are selected for the case study.

Four different scenarios based on Gökçekaya and Altınkaya PSHs are carried out in Chapter 6. First, as mentioned in the previous chapter, friction and minor losses are calculated to obtain the net and the pumping head of these PSHs. Afterwards the installed and pumping capacities of these PSHs are calculated and different operation modes are determined to perform an economic analysis by using the collected hourly electricity prices. The results are discussed in the point of view of both economic and public welfare.

In Chapter 7, the concluding chapter, the study is assessed in a general and broad sense and overall results are demonstrated.

CHAPTER 2

PUMPED STORAGE HYDROELECTRICITY

2.1. General

PSH is the most convenient and effective way of storing energy for many years. Like hydropower itself, the technology of PSH is simple and mature. In conventional HEPP, the reservoir stores water with the help of a dam and that stored water is released through turbines via conduits in order to generate electricity. With the help of an additional reservoir, PSH pumps water from lower reservoir to the higher one when the energy demand is low, and it generates energy in the same way as conventional hydropower when the energy demand is high. The bidirectional flow is the major difference between PSH and typical HEPP, and it enables energy storage for the facility [1].

PSH is in fact an energy consuming facility during pumping process and amount of consumed energy is higher than the generated when it is at the production mode. Nevertheless, the electricity price difference between peak and off-peak hours renders PSH profitable. Because of the high value of peak energy, PSH is widely used especially in industrialized countries like China, US, Japan, Germany and France.

Although the Directive 2009/28/Ec of The European Parliament and of The European Council does not recognize PSH as a renewable energy source and the classification of hydropower as a renewable source is debatable, institutions like REN21, IHA, IEA agree that the electricity generated from hydropower is renewable [2]– [5].

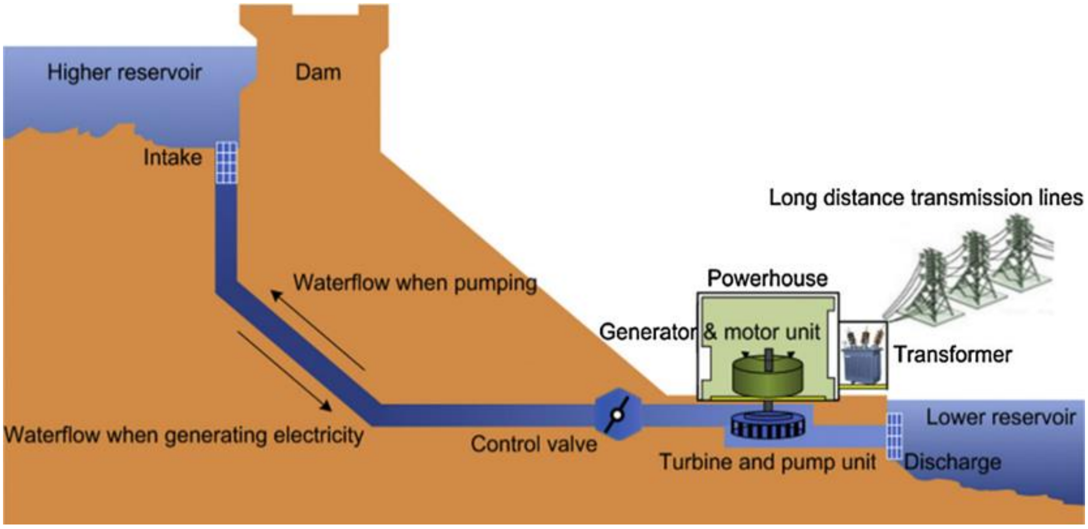


Figure 2.1. Operation cycle of PSH [6]

Figure 2.1 shows the operation cycle of PSH [6]. The main elements of a typical PSH are reservoirs, water conductors like penstocks and tunnels, and powerhouse in which there are turbines, pumps, generators and motor units, control valves and auxiliary equipment such as transformers. The reservoirs may be existing dam reservoirs, constructed artificial pools or natural sources such as lakes or seas.

2.2. Operation of PSH

Operation status of PSH can be classified under three groups: daily, weekly and seasonal operation [7]. In daily application, pumping is operated in early morning hours whereas turbine operation occurs during daily peaks. In weekly operation, PSH supplies peak load demand during the weekdays while refilling the upper reservoir gradually, yet the reservoir is fully filled during the weekends. The seasonal operation requires a considerable amount of water in the reservoir to provide generation for much longer during seasonal peaks. On the other hand, seasonal operation may be helpful to eradicate the imbalance in hydroelectric generation that derives from the difference between dry and wet season rainfall in regions like the Amazon, in Brazil for instance [8]. Figure 2.2 represents the daily operation of PSH [9].

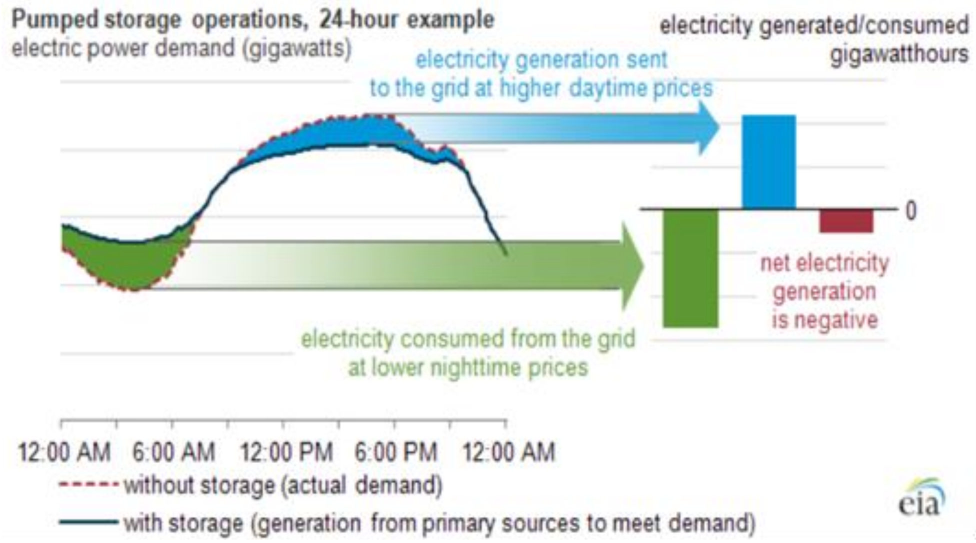


Figure 2.2. Daily operation of PSH [9]

The importance of PSH lies in balancing the energy demand rather than generating electricity. The ability to maintain the reliability of the electric grid is the main benefit of PSH. If there is an excess of generated power, the system frequency increases whereas the frequency decreases if the demand surpasses the generation. With the help of either pumping or turbine modes of operation, PSH helps to maintain the frequency constant in the grid [10]. For example, frequency of network in Turkey is entitled to be 50 Hz due to Electricity Market Network Regulation.

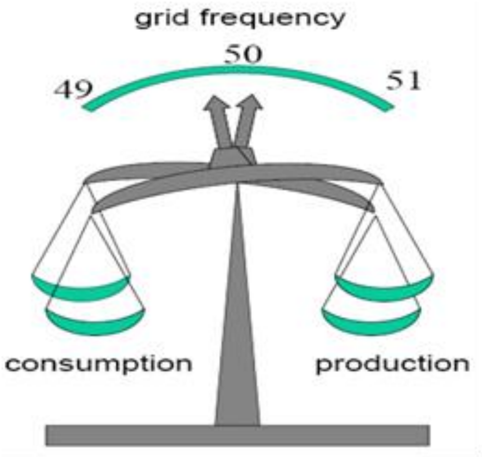


Figure 2.3. Relation between power generation and frequency [11]

Each power grid must have the ability to respond quickly to meet peak demands. If the power plants do not generate power immediately, the system frequency falls and therefore power cut may happen. As in conventional HEPPs, PSH also has the ability of fast start-up compared to other power plants. Table 2.1 represents the start-up times of different power plants following an 8-hour shutdown [12].

Table 2.1. *Startup time following an 8-hour shutdown [12]*

Plant Type	Startup Time
Hydroelectric Power Plant	3-5 Minutes
Natural Gas Power Plant	1 Hour
Oil Power Plant	3 Hours
Coal Power Plant	4 Hours
Nuclear Power Plant	5 Days

Some power plants, such as run-off hydropower or nuclear, keep their energy output constant for an efficient and economic operation. In cases where there is an extra power obtained from these energy sources, PSH is able to compensate for this excess energy by pumping. This function also helps the grid operator during off-peak hours.

2.3. History of PSH

The dating of the very first PSH establishment is widely debated. Guittet et al. [13] suggest that the first PSH was built as early as the 1890s in the alpine regions of Switzerland, Italy and Austria, which benefits from favorable geophysical conditions and topography. Whittingham [14] argues that the earliest PSH was constructed in Schaffhausen, Switzerland in 1909 with a capacity of 1 MW power. In the early years of the PSH technology, European countries and the United States led the sector. The first PSH in the USA was built on the Housatonic River in 1930 by Connecticut Electric and Power Company.

The popularity of PSH began to rise with the availability of reversible hydraulic turbines in 1930s although substantial development started after the World War II [15]. From 1960s until late 1980s, construction and operation of PSH showed great increase due to an increase in the share of nuclear power in electricity generation after the oil crisis in the early 1970s [16]. Japan raised its PSH capacity significantly during the abovementioned years in order to complement its nuclear power production.

In 1990s, PSH popularity decreased in many countries, especially in Europe. The main reason of this is that combined cycle gas turbines became a better option to meet peak demand thanks to their low cost and easy construction [17]. Besides, the European grid become more interconnected, thus the need for meeting peak demand and storage decreased.

In the 21st century, power generation from renewable energy became quite popular because of concerns about climate change and carbon emission. On the other hand, the rise of wind and solar energy technologies brought about problems of intermittency in the power grid. Electricity generation is possible when there is sun and wind, and the surplus power obtained from these resources must be stored in a convenient way. The large-scale solution to this problem is through the PSH technology [18].

Although China stands as a relatively late developer of PSH technology with its involvement in this sector in 1968, the country is currently making a great effort on PSH development [19]. Today, China has the largest PSH capacity in the world on account of its large powered facilities like Guangdong and Huizhou PSH with installed capacities of 2,400 MW each.

2.4. PSH Types

A standard PSH has two reservoirs connected with water conductors that transfer water from one to the other. Although it is a standard, there are different types of PSH applications. PSH classification are under three main groups: Pure or closed-cycle, on-stream integral or pumped-back storage, and hybrid system.

The upper reservoir is located off-stream in a pure pumped storage and if both upper and lower reservoirs are located off-stream, it is called “closed-loop PSH” [20], [21]. Closed-loop type is environmentally advantageous since it has no interference in aquatic ecosystem. However, this type constitutes a challenge: Water losses due to evaporation and leakage along with and finding a suitable location for constructing two reservoirs.

On-stream integral (or pumped-back storage in other words) has two reservoirs that are located in tandem on the same river. An already existing dam can be converted into a PSH with an additional pump-turbine equipment and a lower reservoir at the end of outflow. On-stream integral seems more convenient for potential decrease in construction investment as the upper reservoir already exists [22]. The size of its storage capacity and possibility of monthly and seasonal storage appear to be other advantages of this type.

In hybrid systems, PSH cooperates with wind power plants (WPP) and solar power plants (SPP) in which intermittent power generation is supported by pumped storage. The main idea is the fulfilment of the required pumping energy of PSH from wind and solar power, which therefore provides rise in profit. Although it is challenging to construct PSH, WPP and SPP altogether at the same site, Büyükyıldız, Değer and Kocaman point to the possible benefits of hybrid systems for Turkey [23]– [25]. Figure 2.4 and Figure 2.5 show some examples of the pure pumped storage and the pump-backed storage plants respectively.

Figure 2.4. Goldisthal and Rocky Mountain PSH

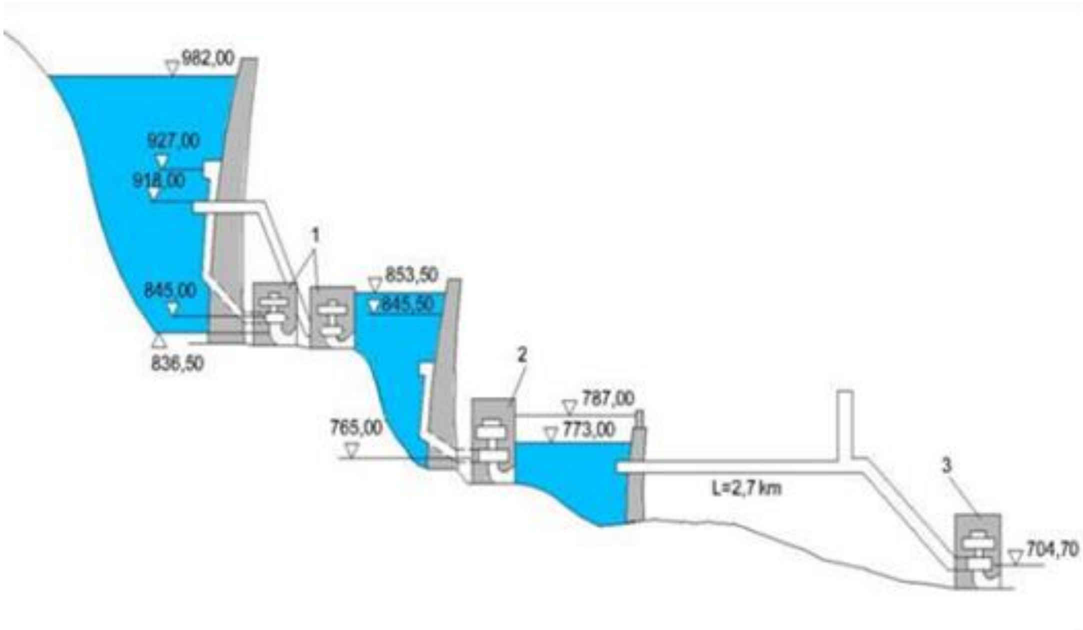


Figure 2.5. Azumi, Midano and Sinrusima PSHs located on the Azusa River [26]

2.5. Advantages and Disadvantages

2.5.1. Advantages

Quick Startup Time: As in conventional HEPPs, PSH is capable of giving fast response when compared to other power plants. This comes as an advantage when unscheduled shutdown of other generating plants occurs.

Black-Start Capability: Unlike most of the power plants, PSH does not need additional power to start generating energy. In cases where there is blackout, PSH becomes a starting point of the restoration process [27].

Load Levelling: PSH supports the grid when there is an instantaneous demand change and provides load shifting as it consumes energy when prices are low and generates energy when they are high.

Large-Scale Energy Storage: PSH is able to provide high amount of flexible storage capacity and improve reliability of electric systems.

Tested Technology: PSH has been used for energy storage all over the world for over a century today, and it is one of the best-proven technologies with its longstanding economy [28].

Supplementary to Renewable Energy: PSH enables an increased usage of intermittent renewable resources like wind and solar energy.

High Efficiency: PSH has the highest cycle efficiency with the range of 75-85% currently available [29].

Reducing Greenhouse Emission: PSH replaces thermal peaking plants during peak hours and supplies increased output by supporting low-carbon generation plants. Therefore, it reduces greenhouse emission.

In addition to the advantages mentioned above, PSH decreases peak hour electricity prices, low operation and maintenance costs, and reduces water wastage by seasonal storage [30].

2.5.2. Disadvantages

Geological Constraints: To establish a PSH facility, mountainous areas are especially required. Besides, site requirements for reservoir construction must be met while water resources must be available in the construction site in question, which make it even more challenging.

High Investment Costs: Construction of a hydropower project with all its equipment included is a highly expensive procedure. In addition to this, the payback period of the investment may take a long time.

Environmental Concerns: The impact of PSH on ecosystems can raise some concerns over large flooding areas, water quality, effect on aquatic ecosystems, etc.

2.6. Status in The World

The usage of PSH has made a significant progress since its first usage in 1890s. In the early designs, separate pump and turbines were employed. The single unit pump-turbines have become popular since the 1950s. PSH significantly developed with the increase in the share of nuclear power in electricity generation [31].

The possibility of large-scale energy storage and load balancing are the main driving forces for PSH usage in various different locations around the world. In comparison with compressed air energy storage and battery technologies, 96% of the global storage is supplied via PSH [32].

PSH installed capacity globally reached 153 GW by the end of 2017 [4]. According to data from EIA, almost 50% of the total installed capacity was set up in the last two decades.

Japan preserved its place as the leading country until China broke through with huge investments in PSH. By 2017, China reached an installed capacity of 28,490 MW and continues to increase this achievement. According to the "13th Five-Year Plan for Electric Power Development" announced by National Energy Administration, China is estimated to have installed a PSH capacity of 60 GW by 2020 [33]. China is currently raising its renewable capacity with great enthusiasm, particularly in wind energy along with PSH as a complement to its nuclear power [34]. Fengning PSH in China is estimated to become world's largest storage facility with 3,600 MW after its construction is completed [35].

Japan and USA has PSH capacities of 27,637 MW and 22,809 MW consecutively. Italy, France and Germany are the first three leading countries in Europe with a total of 51,769 MW installed capacity. When the PSH status in the world is examined, East Asia and Pacific countries appear with their total capacity share of 43% whereas European countries have a part of 34% in the world [4]. The top 20 countries in PSH capacity can be observed from Figure 2.6.

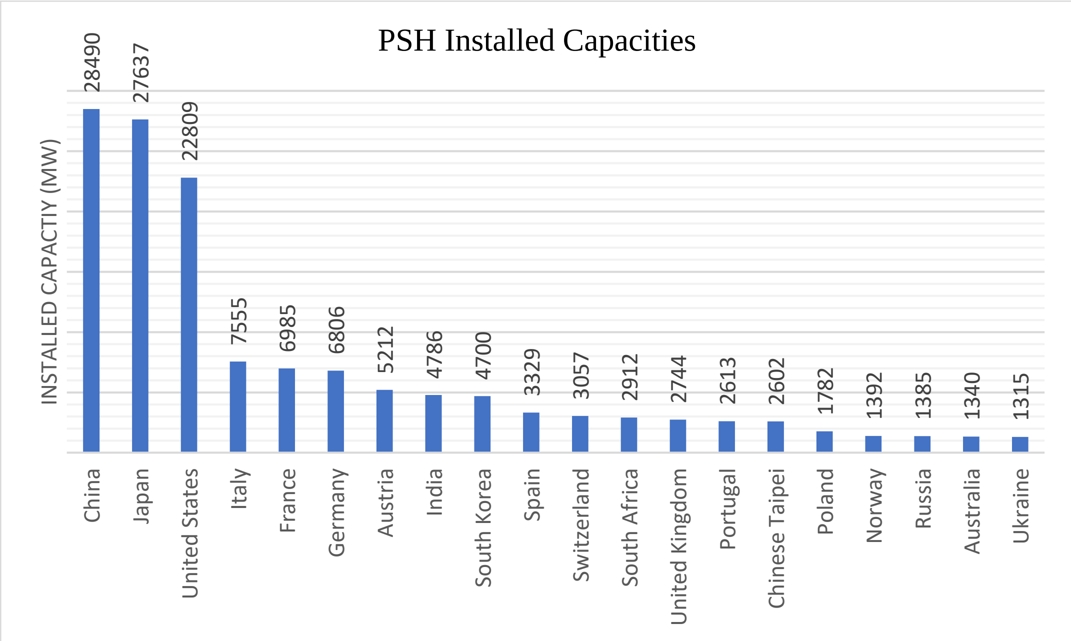


Figure 2.6. Worldwide PSH installed capacities by the end of 2017 (Data are compiled from IHA)

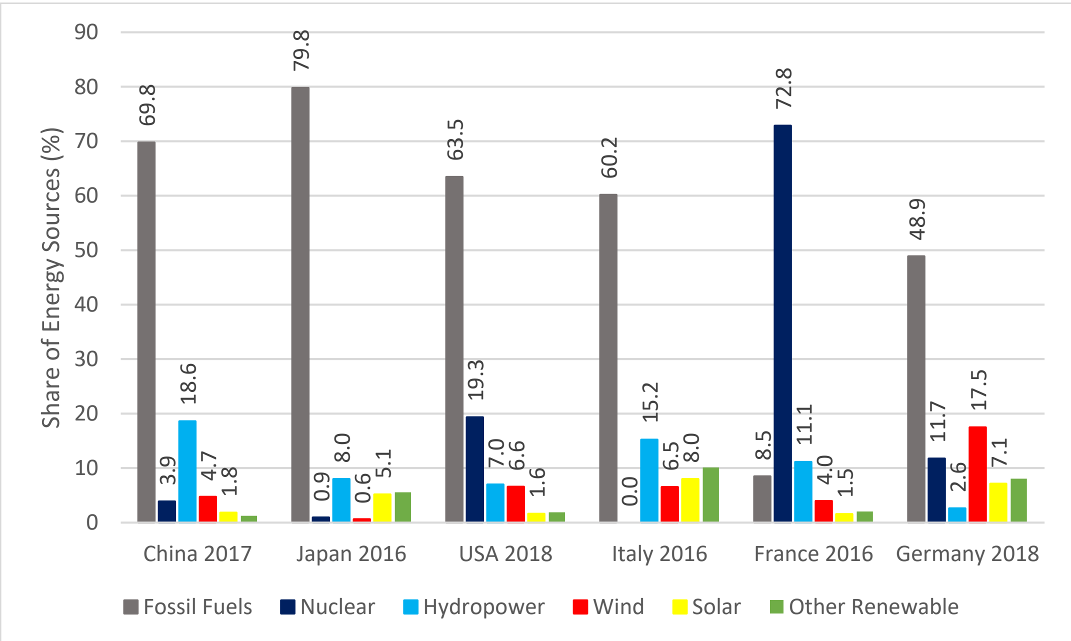


Figure 2.7. Share of energy sources in power production for chosen countries (Data are compiled from IEA, IHA and WEC)

With a quick examination of the share of energy sources in power production of the six leading countries, hydropower appears to be low especially in Japan, USA, France and Germany. Figure 2.7 shows the share of energy sources in power production of top six countries. Table 2.2 on the other hand, indicates the electricity production with reference years.

Table 2.2. *The electric power production from resources for chosen countries (Data are compiled from IEA, IHA and WEC)*

	Fossil Fuels		Nuclear		Hydropower		Wind		Solar		Other Renewable	
Country/Year	**TWh**	**%**	**TWh**	**%**	**TWh**	**%**	**TWh**	**%**	**TWh**	**%**	**TWh**	**%**
China/2017	4,477.0	69.8	248.1	3.9	1,193.1	18.6	303.4	4.7	116.6	1.8	79.0	1.2
Japan/2016	790.0	79.8	9.3	0.9	79.0	8.0	6.0	0.6	51.0	5.1	55.0	5.6
USA/2018	2,651.0	63.5	807.0	19.3	292.0	7.0	275.0	6.6	67.0	1.6	79.0	1.9
Italy/2016	166.0	60.2	0.0	0.0	42.0	15.2	18.0	6.5	22.0	8.0	27.9	10.1
France/2016	45.0	8.5	386.0	72.8	59.0	11.1	21.0	4.0	8.2	1.5	10.8	2.0
Germany/2018	317.2	48.9	76.1	11.7	16.9	2.6	113.3	17.5	46.3	7.1	52.2	8.0

The biggest portion of energy production belongs to fossil fuels in Japan. After Fukushima nuclear disaster in 2011 Japan started to shut down its NPP’s leading to a decrease in NPP’s from %25 to %1 approximately [36]. As reported by the World Energy Council (WEC), noticeable percentage of Japan’s potential hydropower capacity has been fulfilled so far [37]. According to Guittet [13], PSH is the only proven technology for Japan because of the country’s weakness in operational flexibility and lack of export capacity. Although dismantled in 2016 due to its low profitability, Okinawa Seawater Pumped Storage Power Plant in Japan was the first and only PSH in the world that used seawater for energy storage.

Despite having large iconic HEPPs like Hoover, Grand Coulee or Oroville Dams, only 7% of total power generation in the US is procured from the country's HEPPs. Most of the energy is generated by steam turbines using fossil fuels and NPPs. PSH in the US is considered to complement NPP and supply energy for peak load demand. Additionally, Bath County PSH that is located in Virginia has an installed capacity of 3,030 MW and it is currently the largest storage capacity in the world.

France generates about %72 of its electricity from nuclear power and is the world's greatest net exporter of electricity according to World Nuclear Association [38]. France has 58 nuclear reactors operated by Electricity of France (EDF), which is largely owned by the French state, with a total capacity of 63.1 GW. The development of PSH in France is closely related to the increase in NPPs during 1970s and 1980s.

Germany, a neighboring country of France, is in search of solid methods for energy storage because the country has substantially developed renewable power capacity from wind and solar. Neighboring countries with large capacity hydropower plants bring a geographical advantage for Germany, thus provides further flexibility to the country's power grid. On account of this, Germany has an electricity transfer capacity of over 20 GW [39].

Some facts stand out when PSH and NPP are evaluated together:

- All countries with NPP have PSH, except for Armenia,
- PSH is put in electrical grid before NPPs become active,
- The total capacities of PSH and NPP are similar in number [40]

2.7. Status in Turkey

Turkey has an installed hydropower capacity of 27,273 MW by 2017 and 19.6% of total energy generation in this country is obtained through hydropower in 2017. As it can be seen in Chapter 3 in detail, Turkey has a remarkable hydropower capacity and potential. Security of supply, energy independence and reducing greenhouse gas emission constitute evident advantages of hydropower for the country.

Turkey did not need feel the urge to establish PSH until very recently because hydropower could provide adequate flexibility to grid operator so far to meet peak demand. Lack of wind and solar power in the energy grid and absence of NPP were additional causes of not constructing PSH facility throughout the country.

Although PSH has been absent from country's energy grid, several researches and studies have been made by some public intuitions. These studies are demonstrated below:

- 1969: First study on PSH accomplished by abrogated Electric Power Resources Survey and Development Administration (EİE).
- 2005: Initiation of contact with JICA for technical support.
- 2007: Appeal to technical collaboration with JICA.
- 2009: Prefeasibility study of potential 16 PSH sites completed by EİE.
- 2010-2011: JICA's initiation and finalization of "Study on Optimal Power Generation for Peak Demand in Turkey" report in collaboration with Turkish Electricity Transmission Company (TEİAŞ). The study is accepted as the first Master Plan Study of PSH in Turkey, according to which Gökçekaya PSH, Altınkaya PSH and Karacaören II PSH are indicated as primary PSH sites [41].
- 2014: Initiation of Gökçekaya PSH Feasibility Study co-held by JICA, TEİAŞ, General Directorate of State Hydraulic Works (DSİ), General Directorate of Renewable Energy (YEGM), and Electricity Generation Corporation (EÜAŞ).
- 2016: Termination of the feasibility study of Gökçekaya PSH.

- 2018: PSH Roadmap Workshop with the collaboration of public intuitions such as YEGM, EİGM, Electricity Market Regulation Authority (EPDK), DSİ, TEİAŞ, EÜAŞ, EPİAŞ and private sector representatives and related guests [42].

The prefeasibility study of 2009 identifies 16 potential PSH sites with installed capacity of 13,600 MW. Some information on these facilities are given in Table 2.3. It should be noted that some of the design related features of proposed PSHs, including project discharge and installed capacity in EİE's report were changed in JICA's study.

Table 2.3. *Information on the facilities proposed by EİE [43]*

Project Name	Location	Installed Capacity (MW)	Project Discharge (m^3/sec)	Gross Head (m)
Kargı PSH	Ankara	1000	238	496
Sarıyar PSH	Ankara	1000	270	434
Gökçekaya PSH	Eskişehir	1600	193	962
İznik-I PSH	Bursa	1500	687	255
İznik-II PSH	Bursa	500	221	263
Yalova PSH	Yalova	500	147	400
Demirköprü PSH	Manisa	300	166	213
Adıgüzel PSH	Denizli	1000	484	242
Burdur Gölü PSH	Burdur	1000	316	370
Eğridir Gölü PSH	Isparta	1000	175	672
Karacaören-II PSH	Burdur	1000	190	615
Oymapınar PSH	Antalya	500	156	372
Aslantaş PSH	Osmaniye	500	379	154
Bayramhacılı PSH	Kayseri	1000	720	161
Yamula PSH	Kayseri	500	228	260
Hasan Uğurlu PSH	Samsun	1000	204	570

As mentioned before, Karacaören II, Gökçekaya and Altınkaya PSH facilities appear outstanding in the 2011 report of JICA [41]. In addition to geological, topographical and technical advantages of all three sites, Gökçekaya PSH stands out with its advantage of being located close to the locations with considerable electricity consumption and to the center of the transmission lines. The existing Gökçekaya dam is located on the Sakarya River within the borders of Eskişehir. Altınkaya PSH, located on the River Kızılırmak, is near the second future NPP of Turkey, therefore outstanding. It is planned to construct a new artificial pond as upper reservoir for Gökçekaya and Altınkaya PSHs and to use the reservoir of the existing dam as lower reservoir. Figure 2.8 shows the locations of above-mentioned facilities on the map of Turkey.

The conceptual designs of Gökçekaya and Altınkaya PSHs are mentioned in the report of JICA [41]. Table 2.4 represents the main characteristics of these plants.

Discussing Turkey's exigence for PSH in Turkey, previous studies basically focus on PSH's function of supplying peak demand. Tutuş (2010), Saraç (2009), Yorgancılar (2009), Karaçay (2010) and Çetinkaya (2014) both point out in their studies that some problems in supplying peak demand are likely to occur in the following years and suggest that PSH may be a solution for Turkey [43]– [46] [30]. Sezgin (2010) and Büyükyıldız (2012) discuss PSH and WPP hybrid systems whereas Kocaman (2017) is rather interested in PSH and SPP hybrid systems' potential benefits for Turkey [23], [25], [47].

Turkey's renewable energy capacity has grown rapidly since the last decade and the first unit of Akkuyu NPP is estimated to start generation by 2023. According to the report of PSH Roadmap Workshop in 2018 [48], PSH is presumed be a necessity for Turkey on account of its load balancing mechanism rather than its ability of supplying peak demand. PSH's introduction to Turkey's power grid will provide flexibility to the grid operator in the cases where minimum generation surpasses the minimum consumption.

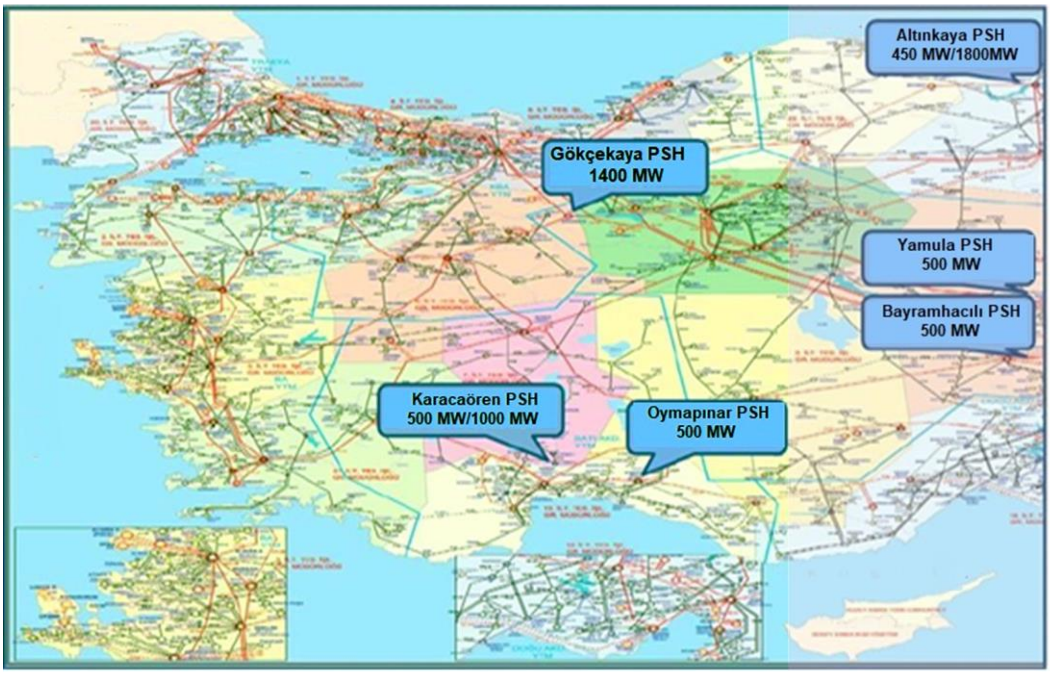


Figure 2.8. The locations of proposed PSHs [49]

Table 2.4. *The main characteristics of Gökçekaya and Altınkaya PSH [41]*

Main Features of Gökçekaya and Altınkaya PSH				
Description			Unit	
Gökçekaya	Installed Capacity	P	MW	1,400
	Designed Discharge	Qd	m^3/s	428
	Effective Head	Hd	m	379.5
	Peak Duration Time		hrs	7
	Estimated Project Cost		$	$1,098 \times 10^6$
	Turbine Type			Single-Stage Francis
	Turbine Number		Unit	4
Altınkaya	Installed Capacity	P	MW	1,800
	Designed Discharge	Qd	m^3/s	350
	Effective Head	Hd	m	611
	Peak Duration Time		hrs	7
	Estimated Project Cost		$	$1,201 \times 10^6$
	Turbine Type			Single-Stage Francis
	Turbine Number		Unit	4

2.8. Pump-Turbines of PSH

In conventional HEPPs, potential energy of stored water transforms to mechanical rotational energy with the help of hydraulic turbines. There are basically two types of hydraulic turbines: reaction and impulse. The pressure of water applies a force on the runner blades in the reaction turbines. The turbine must be completely immersed when in operation. Kaplan and Francis turbines belong to this category. The potential energy of water is transformed into kinetic energy in a jet of water striking bowl-shaped buckets of the impulse runner [7]. The most usual impulse turbine is Pelton. Figure 2.9 shows the schematic drawings of impulse (on the left) and reaction turbine installation (on the right) [7].

Pelton turbine is preferred for high head power plants. Although it is highly efficient in partial loads, the main disadvantage of this type is its high cost [50].

High range of operation head and operation discharge, low cost and high efficiency are the main advantages of Francis turbines [50]. Kaplan turbines are also quite efficient during water flow changes, however they constitute off-putting costs due to their large volumes.

There are some criteria in order to choose the suitable turbine type of hydropower plants:

- Net Head
- Discharge Range
- Impeller Speed
- Cavitation Problem
- Prices [51]

Table 2.5 shows the convenient head ranges for these hydraulic turbines.

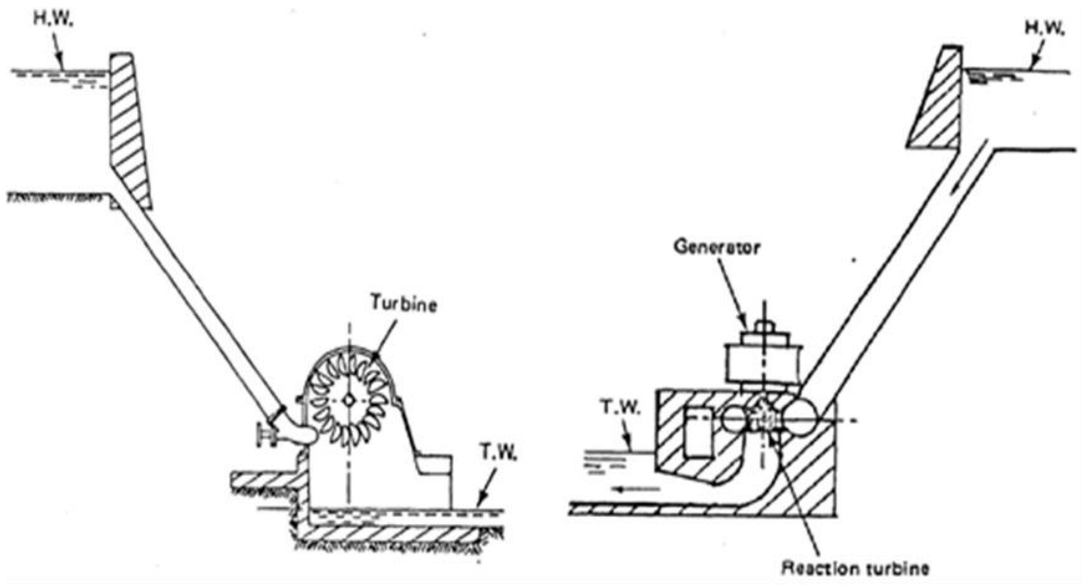


Figure 2.9. Schematic drawings of impulse & reaction turbines [7]

Table 2.5. *Head ranges for hydraulic turbines [52]*

Turbine Type	**Head Ranges (m)**
Kaplan	2<H<40
Francis	25<H<350
Pelton	50<H<1300

The separate turbine-generator and pump-motor units, which are placed on their own shaft, were used in the early applications of PSH. A single shaft with a turbine at the bottom, a pump in the middle and a motor-generator at the top later got into usage in PSH. The single unit pump-turbines became commercially available by the mid-20th century and thus standardized for most of the PSH. They are respectively called “four-machine scheme”, “three-machine scheme” and “two-machine scheme” [53].

As Raabe reports [54], the pump-turbines were first installed in early 1930s at German Baldeney (2 MW) and Brazilian Pedreira (4 MW). Post World War II, significant progress in pump-turbine technology was made in the US. The limit of 250 MW was surpassed by the implementation of the two Taum Sauk pump-turbine in 1964. The installation of four units of capacity with 392 MW at Racoon Facility and six units of 457 MW in Bath County were also remarkable. Unlike American practice, European countries developed combinations of three-machine scheme [7]. Figure 2.10 shows the ternary-machine system of KOPS II PSH in Austria [11].

Three-machine scheme offers a fast response for starting in the pumping mode or changing between operating modes. On the other hand, the reversible units require less space for installation and has significant economic advantages [55]. Switching from turbine mode to pumping mode takes 420 seconds for reversible systems and 30 seconds for ternary systems. The required time from start-up to pumping mode is 340 seconds for reversible systems and 120 seconds for ternary systems [56]. One should notice that if the head is higher than 600-700 m, it becomes necessary to use multistage reversible units or three-machine scheme [53].

Whereas constant speed pump-turbines are widely used in worldwide PSH, Japan differs from many countries with its adjustable speed technology in pump-turbines. This technology can be defined as a system that can adjust the rotating speed of the pump-turbine unit. In this system, pump input power can be adjusted through varying rotating speed and thus network frequency can be controlled. Unlike adjustable speed system, constant speed pumped storage system cannot control its pump input power, therefore cannot regulate frequency during pumping mode. Higher efficiency in generation mode and wider turbine operation range are the additional advantages of adjustable speed systems [12]. Table 2.6 compares adjustable speed system and constant speed system [57].

Table 2.6. *Comparison of adjustable speed system and constant speed system [57]*

	Constant Speed	Adjustable Speed	Remarks
Dam Volume	Almost Same		Adjustable speed system can utilize water level much lower than constant speed system
Cavern Volume	100%	105%	Adjustable speed system needs additional space for rotor and excitation system.
Cost for Turbine & Generator Including AC-Excitation System	100%	140%	Cost for adjustable speed system is more expensive because of special rotor design and AC-Excitation system.
Turbine Efficiency in Generating Mode	Base	+ 0.5% at max output, + 2.5% at partial load	In generating mode, adjustable speed system can operate at optimum speed for improved efficiency
Operation Range in Generating Mode	50-100%	30-100%	In adjustable speed system, improvement of turbine efficiency can extend operation range
Operation Range in Pumping Mode	Constant	70-100%	Adjustable speed system can adjust pump input. (input power changes in proportion to the cube of rotating speed)
Response Time of Output/Input	0-100 % / 60 sec	20 MW / 0.1 sec	Adjustable realize fast power control by absorbing/releasing flywheel energy to power grid.

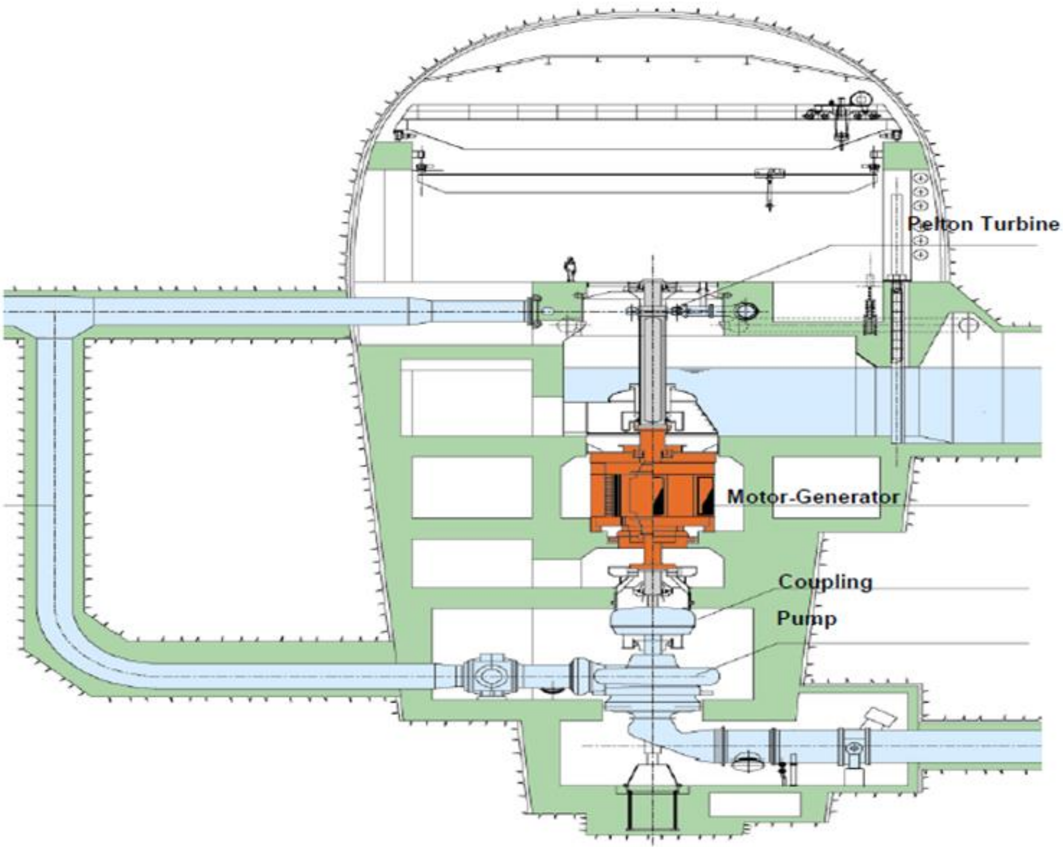


Figure 2.10. Ternary-machine system [11]

CHAPTER 3

GENERAL VIEW OVER TURKEY'S ELECTRICITY SYSTEM

3.1. Installed Capacity

Turkey's installed capacity reached 85,200 MW by the end of 2017. Thermal power plants have a share of 55.1% while hydropower has 32%, geothermal 1.2%, wind 7.6% and solar 4.0%. Figure 3.1 and Table 3.1 show the annual development of Turkey's installed capacity. The average annual increase in installed capacity is 7.66% from 2007 to 2017.

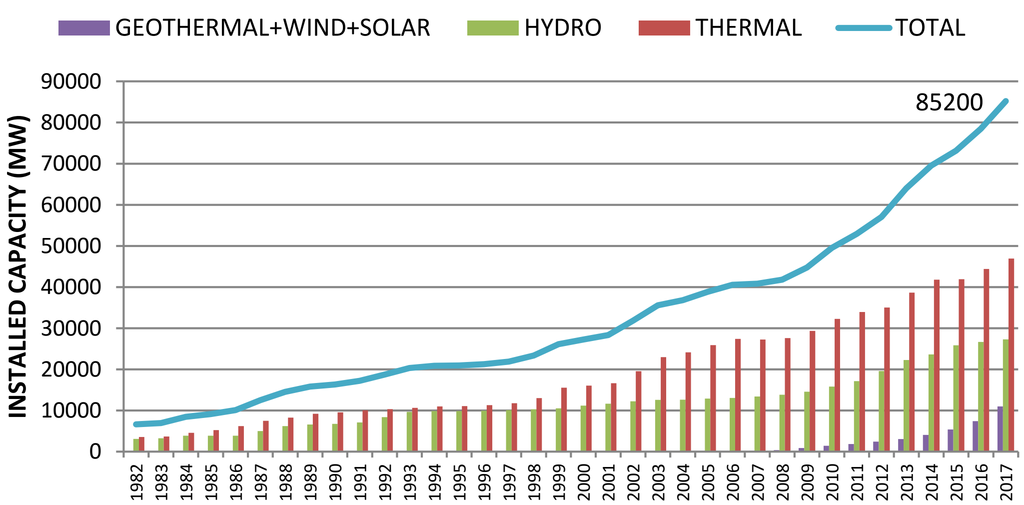


Figure 3.1. Annual development of Turkey's installed capacity (Data are compiled from TEİAŞ)

Table 3.1. *Annual development of Turkey's installed capacity (Data are compiled from TEİAŞ)*

	YEARS	2007 (MW)	2008 (MW)	2009 (MW)	2010 (MW)	2011 (MW)	2012 (MW)	2013 (MW)	2014 (MW)	2015 (MW)	2016 (MW)	2017 (MW)
SINGLE FUEL FIRED	HARD COAL	1,986	1,986	2,391	3,751	4,351	4,383	4,383	6,533	6,825	8,229	9,576
	LIGNITE	8,211	8,205	8,199	8,199	8,199	8,193	8,223	8,281	8,696	9,126	9,129
	LIQUID FUELS	2,000	1,819	1,699	1,593	1,300	1,286	616	595	523	445	380
	NATURAL GAS	11,647	10,657	11,826	13,302	13,144	14,116	17,171	18,724	18,528	19,564	22,002
	RENEWABLE+WASTES + WASTE HEAT	43	60	87	107	126	169	235	299	370	496	642
	TOTAL	23,888	22,726	24,201	26,953	27,120	28,147	30,628	34,432	34,942	37,861	41,730
MULTI FUEL FIRED	SOLID+LIQUID	471	471	416	453	478	599	612	586	583	583	603
	LIQUID+NATURAL GAS	2,913	4,398	4,722	4,873	6,333	6,282	7,408	6,784	6,378	5,968	4,594
	TOTAL	3,384	4,869	5,138	5,326	6,811	6,881	8,020	7,369	6,961	6,551	5,197
TOTAL	THERMAL TOTAL	27,272	27,595	29,339	32,279	33,931	35,027	38,648	41,802	41,903	44,412	**46,926**
	HYDRO	13,395	13,829	14,553	15,831	17,137	19,609	22,289	23,643	25,868	26,681	**27,273**
	GEOTHERMAL	169	30	77	94	114	162	311	405	624	821	**1,064**
	WIND		364	792	1,320	1,729	2,261	2,760	3,630	4,503	5,751	**6,516**
	SOLAR								40	249	833	**3,421**
	TOTAL	**40,836**	**41,817**	**44,761**	**49,524**	**52,911**	**57,059**	**64,008**	**69,520**	**73,147**	**78,497**	**85,200**
	INCREASE (%)		2.40	7.04	10.64	6.84	7.84	12.18	8.61	5.22	7.31	8.54

As seen in the figure below (Figure 3.2), the share of renewable resources in Turkey's installed capacity has developed considerably for a decade now owing to investments made especially in solar and wind power areas.

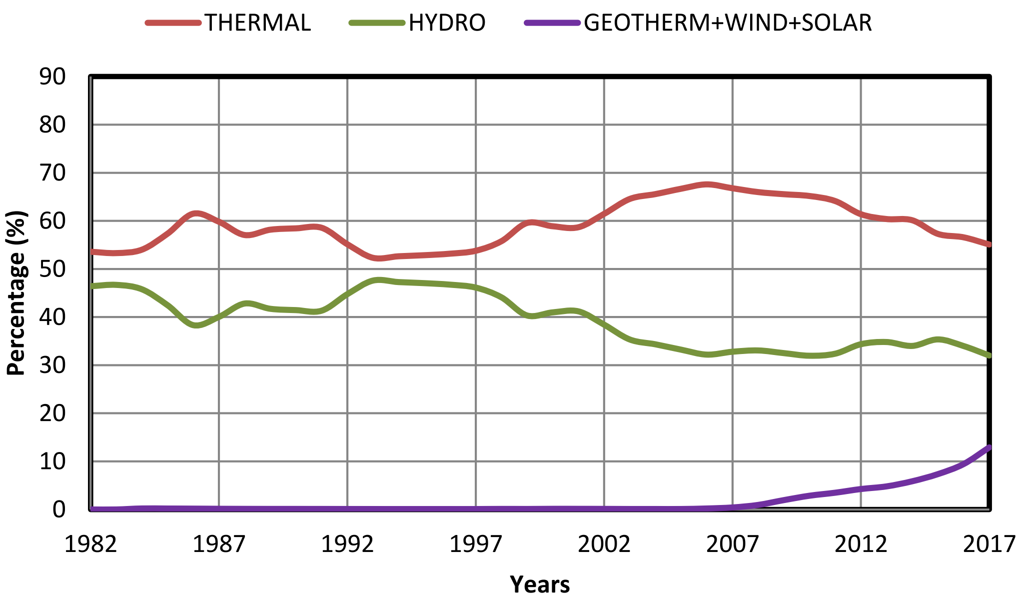


Figure 3.2. Share of primary energy resources in Turkey's installed capacity (Data are compiled from TEİAŞ)

3.2. Electricity Generation and Consumption

The gross electricity generation in Turkey reached 297 billion kWh by the end of 2017. The 71.4% of electricity production was obtained from thermal power plants, 19.6% from hydropower, 8.1% from geothermal and wind and 0.9% from solar energy. As shown in the Table 3.2, electricity generation in Turkey in the last ten years has increased annually except for the year 2009, average increase ratio being 4.92%. Should the generation values of 2009 and 2013 be excluded due to the economic recessions of 2008 and 2012, the average increase happens to be 6.18%.

Table 3.2. *Annual development of Turkey's electricity generation by primary energy resources (Data are compiled from TEİAŞ)*

	YEARS	2007 (GWh)	2008 (GWh)	2009 (GWh)	2010 (GWh)	2011 (GWh)	2012 (GWh)	2013 (GWh)	2014 (GWh)	2015 (GWh)	2016 (GWh)	2017 (GWh)
THERMAL	HARD COAL + ASPHALTITE	3,289.6	3,290.8	3,782.4	4,572.6	4,529.6	4,113.7	4,070.3	4,561.3	4,843.9	5,985.3	5,663.8
	IMPORTED COAL	11,846.6	12,566.7	12,813.2	14,531.7	22,817.9	29,210.5	29,453.7	35,086.0	39,986.0	47,717.9	51,118.1
	LIGNITE	38,294.7	41,858.1	39,089.5	35,942.1	38,870.4	34,688.9	30,262.0	36,615.4	31,335.7	38,569.9	40,694.4
	FUEL-OIL	6,469.6	7,208.6	4,439.8	2,143.8	900.5	981.3	1,192.5	1,662.9	980.4	969.1	520.6
	DIESEL OIL	13.3	266.3	345.8	4.3	3.1	657.4	546.3	482.4	1,243.6	957.2	679.3
	LPG	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	NAPHTHA	43.9	43.6	17.6	31.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	NATURAL GAS	95,024.8	98,685.3	96,094.7	98,143.7	104,047.6	104,499.2	105,116.3	120,576.0	99,218.7	89,227.1	110,490.0
	RENEWABLE+ WASTES+ WASTE HEAT	213.7	219.9	340.1	457.5	469.2	720.7	1,171.2	1,432.6	1,758.2	2,371.6	2,972.3
TOTAL	TOTAL THERMAL	155,196.2	164,139.3	156,923.4	155,827.6	171,638.3	174,871.7	171,812.5	200,416.6	179,366.4	185,798.1	212,138.5
	HYDRO	35,850.8	33,269.8	35,958.4	51,795.5	52,338.6	57,865.0	59,420.5	40,644.7	67,145.8	67,230.9	58,218.5
	GEOTERMAL+ WIND	511.1	1,008.9	1,931.1	3,584.6	5,418.2	6,760.1	8,921.0	10,884.1	15,077.0	20,335.6	24,031.3
	SOLAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.4	194.1	1,043.1	2,889.3
	TOTAL	**191,558.1**	**198,418.0**	**194,812.9**	**211,207.7**	**229,395.1**	**239,496.8**	**240,154.0**	**251,962.8**	**261,783.3**	**274,407.7**	**297,277.5**
	INCREASE (%)	8.65	3.58	-1.82	8.42	8.61	4.40	0.27	4.92	3.90	4.82	8.33

As seen in Figure 3.3, the share of hydropower in Turkey's gross electricity generation has decreased for the last two decades. The hydro-thermal balance in the grid was protected for years but it began to change starting from mid-1990's to the detriment of hydropower. This might be regarded as an alert of possible difficulties in load balancing since using thermal plants for balancing might result in decrease of efficiency in these said plants and cause high operational costs [44].

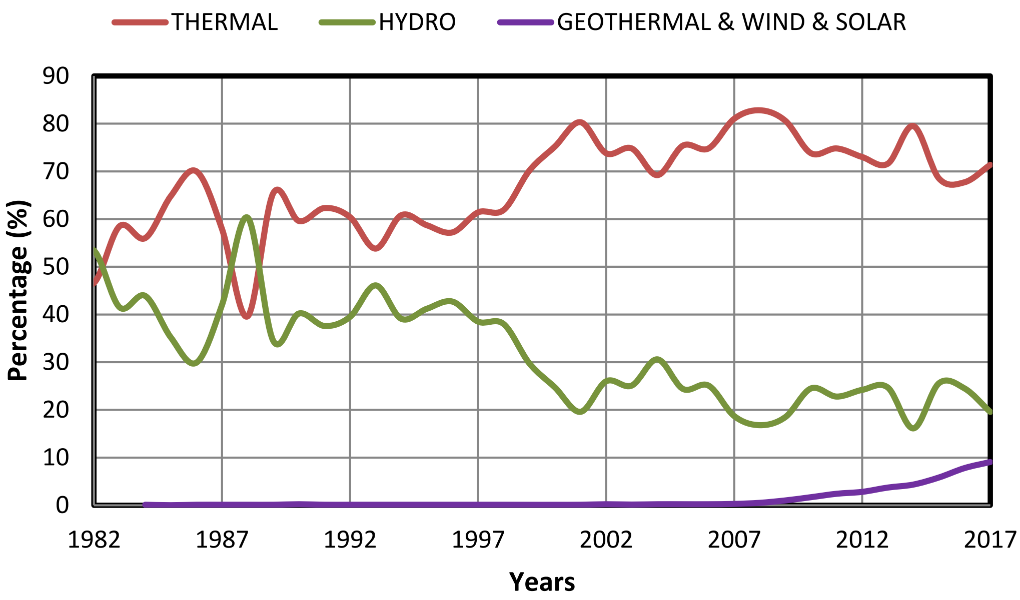


Figure 3.3. Share of primary energy resources in Turkey's gross electricity generation (Data are compiled from TEİAŞ)

Since the 1990's Turkey has invested considerably in thermal power plants and especially in natural gas power plants (NGPP). As a result, share of imported resources in total electricity generation increases. Figure 3.4 shows the annual change since 1985.

Peak load defines the maximum electricity consumption recorded instantaneously in a year. It is important to correspond the peak load instantaneously in order to secure the system reliance. If the power plants are not able to generate the required power, system frequency decreases and power cut occurs. The long-standing power cuts in 1 July 2006 and 31 March 2015 are examples for this situation.

Peak power demand in Turkey reached 47,660 MW and gross energy demand reached 296,702 GWh by the year of 2017. Figure 3.5 and Table 3.3 present the annual values and increase ratio of peak load and gross energy demand.

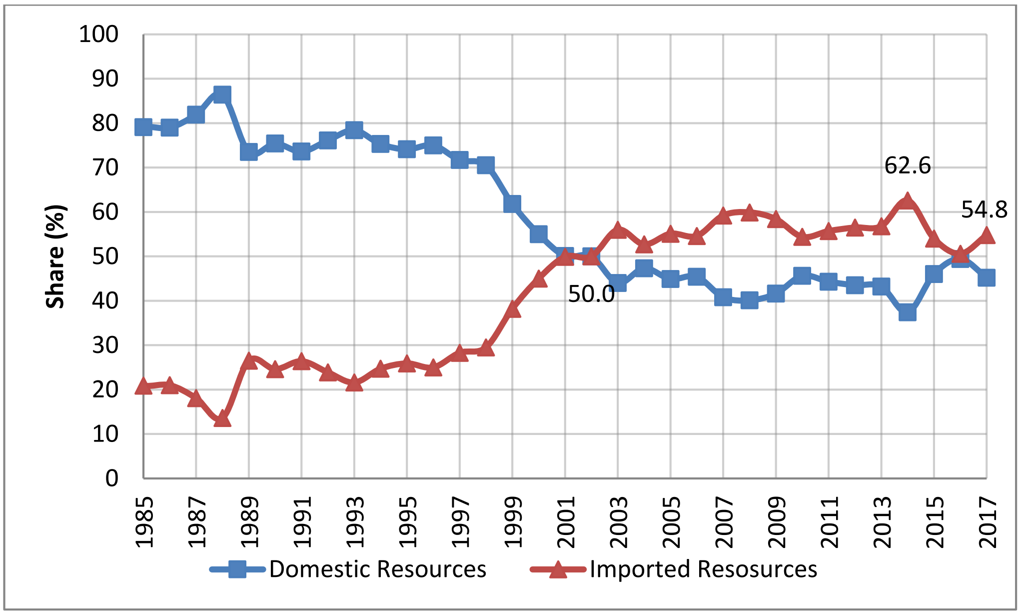


Figure 3.4. Domestic and imported resources based electricity generation share in Turkey total electricity generation (Data are compiled from TEİAŞ)

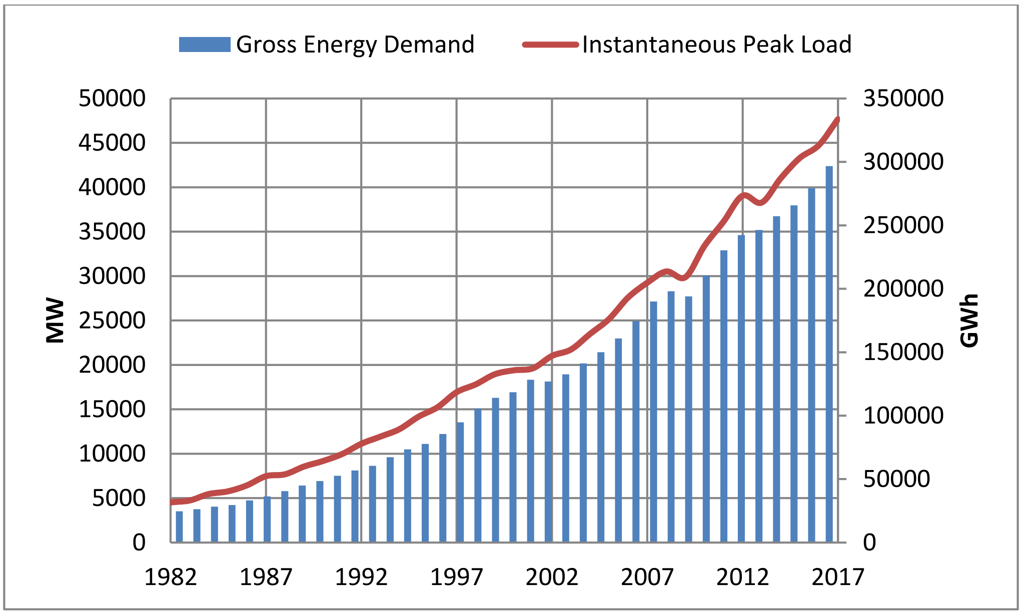


Figure 3.5. Annual development of gross energy demand and peak load in Turkey (Data are compiled from TEİAŞ)

Table 3.3. *Annual development values of gross energy demand and peak load in Turkey (Data are compiled from TEİAŞ)*

YEAR	Instantaneous Peak Load (MW)	Increase (%)	Gross Energy Demand (MWh)	Increase (%)
2000	19,389.9	2.39	128,275.6	8.26
2001	19,612.0	1.15	126,871.3	-1.09
2002	21,005.6	7.11	132,552.6	4.48
2003	21,728.9	3.44	141,150.9	6.49
2004	23,485.3	8.08	150,017.5	6.28
2005	25,174.2	7.19	160,794.0	7.18
2006	27,594.4	9.61	174,637.3	8.61
2007	29,248.5	5.99	190,000.2	8.80
2008	30,516.8	4.34	198,085.2	4.26
2009	29,870.0	-2.12	194,079.1	-2.02
2010	33,391.9	11.79	210,434.0	8.43
2011	36,122.4	8.18	230,306.3	9.44
2012	39,044.9	8.09	242,369.9	5.24
2013	38,274.0	-1.97	246,356.6	1.64
2014	41,002.9	7.13	257,220.1	4.41
2015	43,289.3	5.58	265,724.4	3.31
2016	44,734.0	3.34	279,286.4	5.10
2017	47,659.7	6.54	296,702.1	6.24

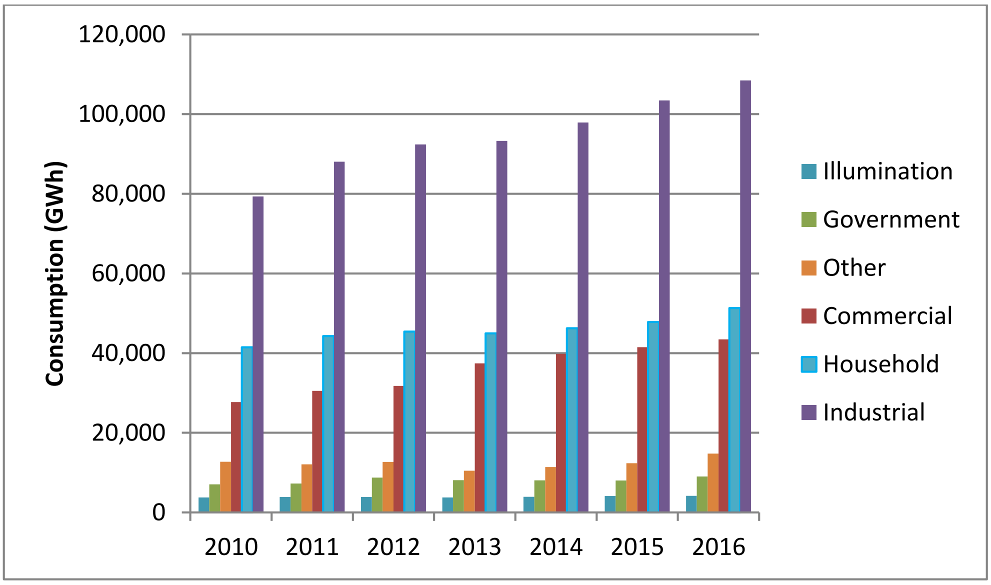


Figure 3.6. Distribution of net electricity consumption by sectors (Data are compiled from TÜİK)

Note that the shares of electricity consumer groups are significant for the analysis of the electricity system in a country. Figure 3.6 represents the net electricity consumption by sectors in Turkey between 2010 and 2016.

3.3. Demand Curve

The Load Duration Curve of 2017 is shown in Figure 3.7. Operating status of power plants at instantaneous peak load and minimum consumption occurrence day in Turkey's power grid are demonstrated in Figure 3.8 and Figure 3.9 respectively.

Load duration curve is one of the most significant parameters to analyze the electricity system and capacity projection. It is obtained from load curve and plotted in the order of descending magnitudes. In the graph, the peak load is on the left whereas the lower loads are towards the right. The graph shows how many days the system meets the maximum load. Figure 3.7 indicates that the demand in 2017 varied from 47,660 MW to 18,851 MW.

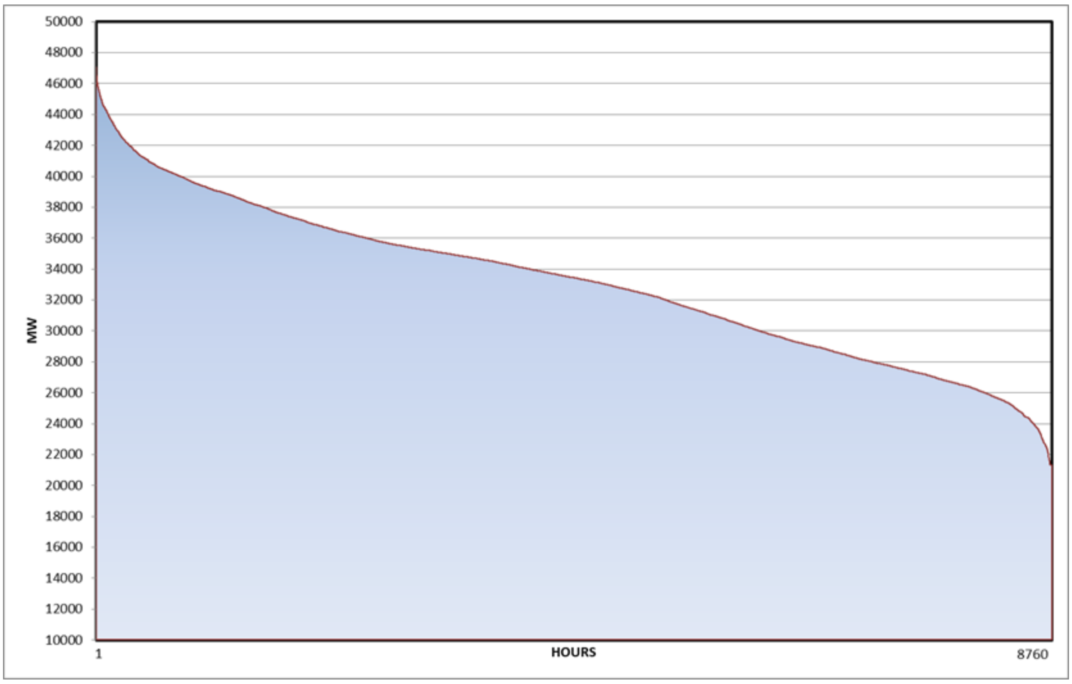


Figure 3.7. Load duration curve of 2017 [58]

As mentioned in Chapter 1 thermal power plants are used especially to meet base demand. Hydropower, thermal peaking plants and imported power can be used for meeting the peak load demand and the role of hydropower can be seen in Figure 3.8 and Figure 3.9 for Turkey.

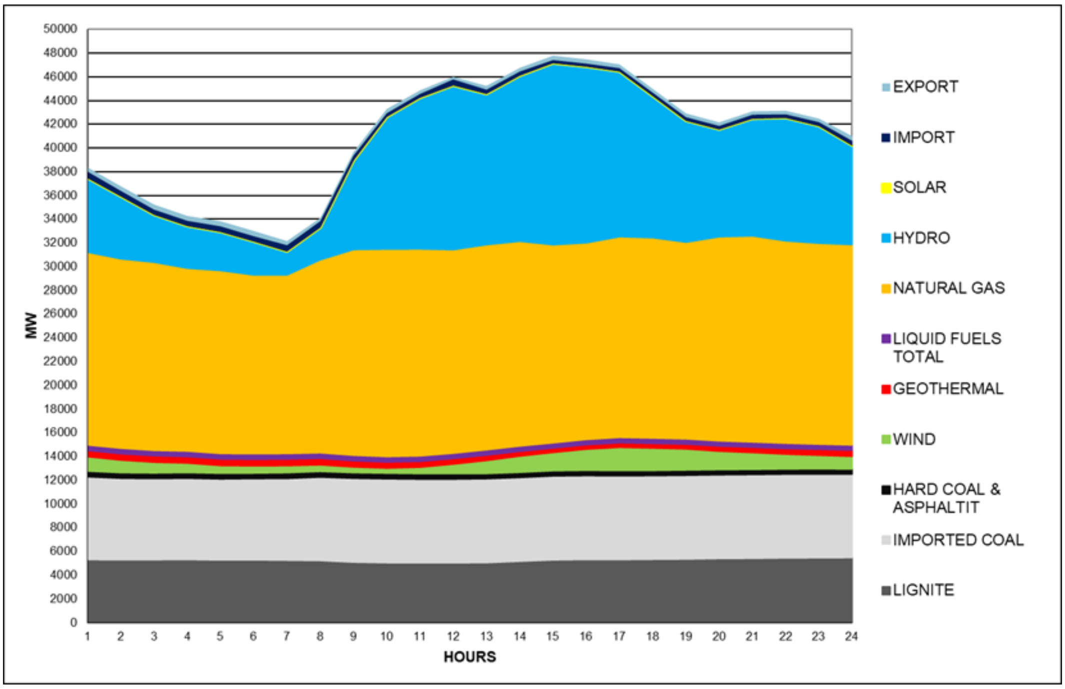


Figure 3.8. Operating status of power plants when meeting the instantaneous peak load of Turkey Interconnected System in 2017 [58]

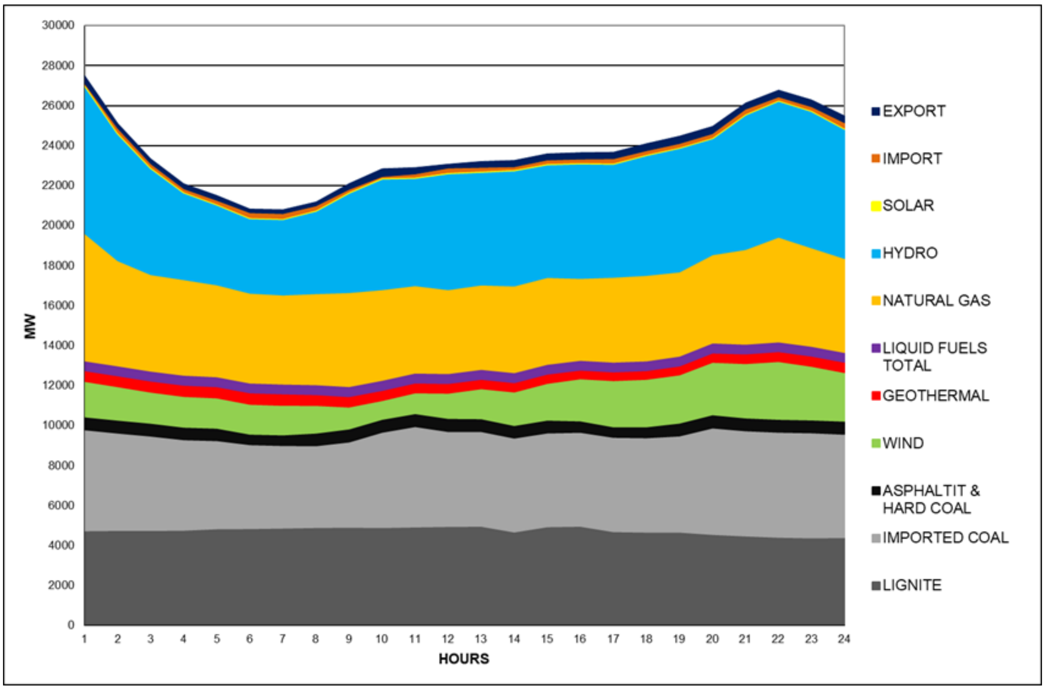


Figure 3.9. Operating status of power plants when the minimum consumption occurs in 2017 [58]

According to the data gathered from TEİAŞ, hourly peak power demands occurred in January and December between 2001 and 2007. It is established that utilization of air conditioners causes great increase in the demand, mainly during summertime. Therefore, peak power demand occurrence season shifted from winter (December) to summer (July & August) starting from 2008. Figure 3.10 shows the proportion of monthly peak power demands over the annual peak power demand of that year.

Figure 3.11 shows some daily demand curves on maximum peak power demand occurrence days from 2013 to 2018. The y-axis of the graph presents the ratio between hourly demands over maximum demands in order to make a clear statement.

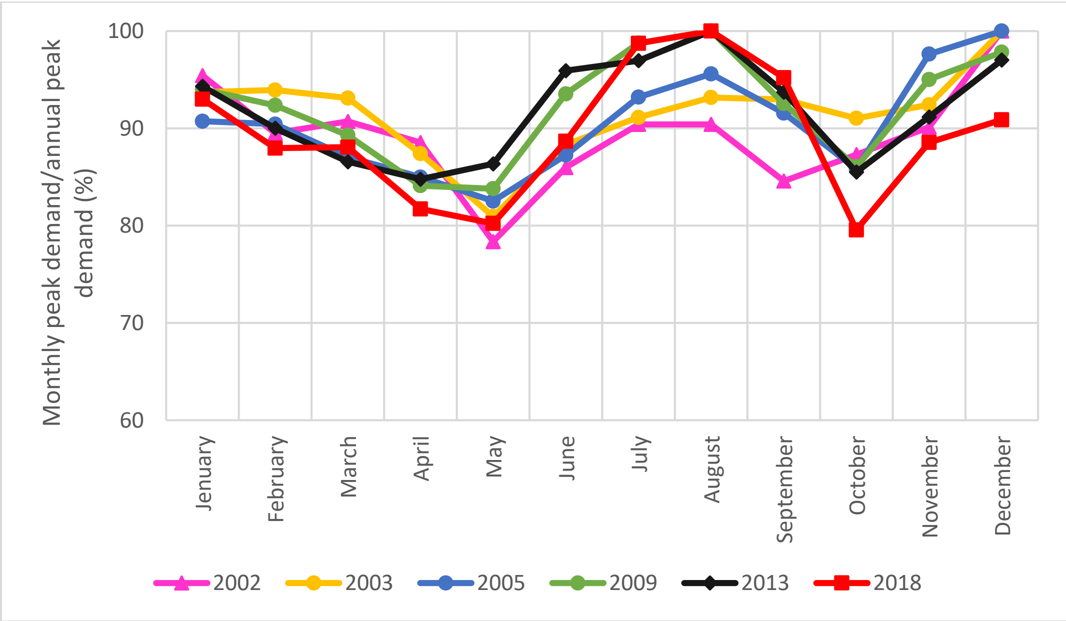


Figure 3.10. Monthly peak power demands over annual peak power demand (Data are compiled from TEİAŞ)

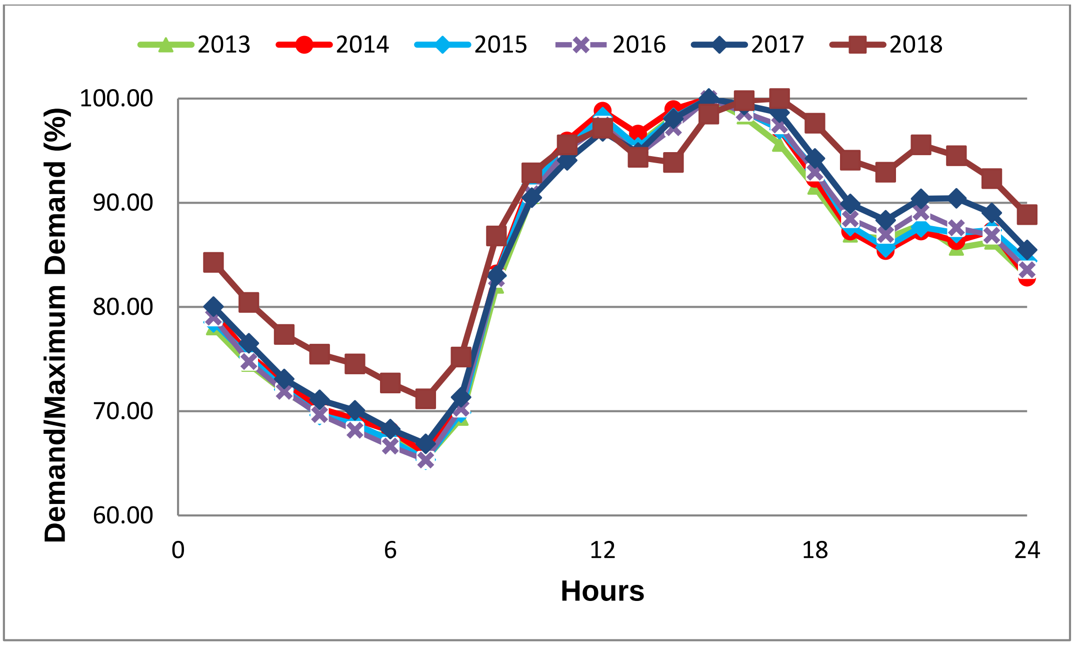


Figure 3.11. Demand curve on peak power demand occurrence days in summer in Turkey (Data are compiled from TEİAŞ)

Table 3.4. *Demand values of maximum demand occurrence days in summer in Turkey (Data are compiled from TEİAŞ)*

YEAR	2013 (MW)	2014 (MW)	2015 (MW)	2016 (MW)	2017 (MW)	2018 (MW)
HOUR/DATE	**29.08.13**	**14.08.14**	**05.08.15**	**11.08.16**	**26.07.17**	**03.08.18**
01:00	29,733	32,389	33,363	35,039	37,667	38,768
02:00	28,399	30,717	31,951	33,154	36,013	37,001
03:00	27,398	29,616	30,619	31,886	34,398	35,583
04:00	26,617	28,625	29,586	30,896	33,459	34,719
05:00	25,977	28,215	29,212	30,231	32,982	34,282
06:00	25,766	27,752	28,556	29,559	32,134	33,442
07:00	24,944	26,875	27,763	28,964	31,469	32,744
08:00	26,428	28,803	29,681	31,163	33,578	34,592
09:00	31,255	33,893	35,245	36,684	39,072	39,934
10:00	34,533	37,564	38,976	40,292	42,586	42,713
11:00	36,313	39,089	40,467	42,152	44,270	43,949
12:00	37,253	40,249	41,725	43,214	45,577	44,688
13:00	36,428	39,358	40,492	41,958	44,622	43,402
14:00	37,459	40,310	41,691	43,100	46,149	43,178
15:00	38,116	40,734	42,482	44,341	47,062	45,307
16:00	37,446	40,229	41,971	43,748	46,771	45,900
17:00	36,447	39,544	41,234	43,215	46,423	45,996
18:00	34,877	37,596	39,593	41,203	44,359	44,906
19:00	33,123	35,540	37,288	39,222	42,300	43,273
20:00	32,987	34,774	36,415	38,556	41,568	42,741
21:00	33,505	35,539	37,240	39,509	42,535	43,955
22:00	32,646	35,162	37,002	38,843	42,556	43,469
23:00	32,865	35,559	37,118	38,521	41,895	42,460
00:00	31,635	33,738	35,865	37,059	40,228	40,868

The data in Figure 3.11 demonstrate that;

- The minimum demand occurs between 06:00 and 07:00
- The peak demand time shifted from 12:00 to 15:00 (17:00 for 2018)
- Evening lighting peak occurs around 20:00-23:00.
- The peak time zones are about 9 hours from about 10:00 to 19:00

Load factor can be defined as the ratio of average load within a specific period (year, month, day, etc.) to maximum load within the same period. Both load factor and base over peak load ratio are fundamental parameters of defining the efficiency of electricity system. When the load factor rate increases, efficiency increases as well. Decreasing the peak load and convergence of maximum consumption to base consumption would also increase the load factor and therefore the efficiency. It cannot be expected from load factor to significantly increase year by year. However, retaining the level may be considered as a positive step for the system [59].

Figure 3.12 demonstrates that the load factor changes from 70% to 75% between 2001 and 2017 whereas base over peak load ratio range fluctuates between 34% and 44%.

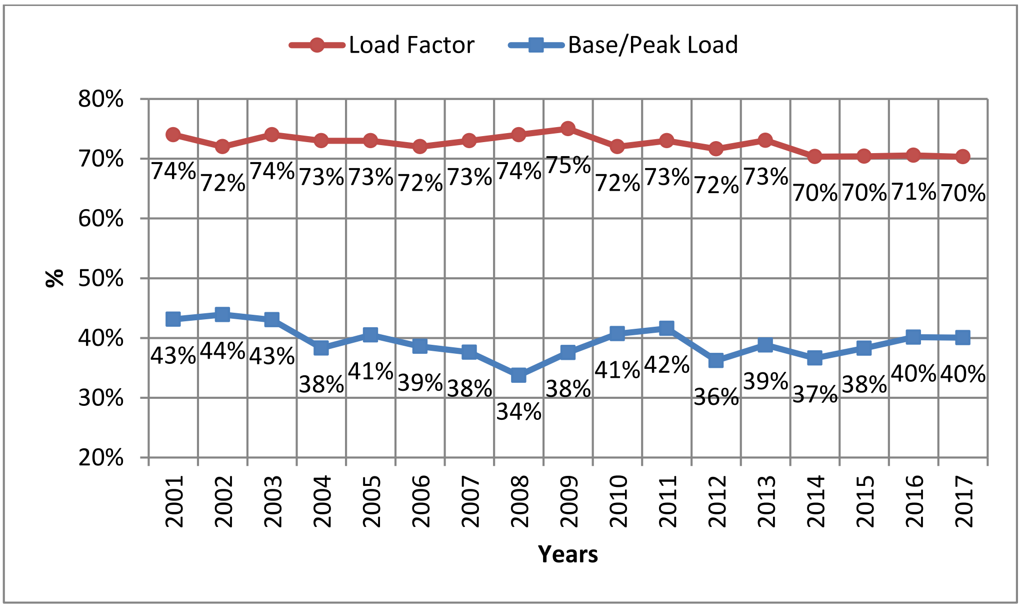


Figure 3.12. Load factors and base over peak load ratios from 2001 to 2017 (Data are compiled from TEİAŞ)

3.4. Capacity Factor

Capacity factor is defined as the total energy produced by a unit within a given time period (MWh) divided by unit capacity (MW) and the number of hours in the time period.

Operation condition of power plants varies due to energy source, plant type, meteorological condition and etc. The insufficiencies of water source for hydropower, cloudiness of sky for solar plants, intermittency of wind power are examples of factors that decrease the capacity factor. Also system failure of power plants or lower demands then the maximum generation could reduce too. It is important to know available power output in order to make a reliable system planning. Table 3.5 and Figure 3.13 shows the capacity factor of power plants from 2013 to 2017 in Turkey.

Table 3.5. *Available operation ratios for power plants from 2013 to 2017 [58]*

YEARS	RENEWABLE ENERGY								THERMAL		TOTAL INSTALLED CAPACITY (MW)
	WIND		SOLAR		HYDRO		GEOTHERMAL				
	INSTALLED CAPACITY (MW)	AVERAGE OPERATION RATIO (%)	INSTALLED CAPACITY (MW)	AVERAGE OPERATION RATIO (%)	INSTALLED CAPACITY (MW)	AVERAGE OPERATION RATIO (%)	INSTALLED CAPACITY (MW)	AVERAGE OPERATION RATIO (%)	INSTALLED CAPACITY (MW)	AVERAGE OPERATION RATIO (%)	
2013	2,760	31.3			22,289	30.2	311	50.1	38,647	49.0	64,008
2014	3,629	26.8			23,643	19.6	405	66.6	41,601	53.4	69,520
2015	4,498	29.6			25,868	29.5	624	62.7	41,846	48.9	73,147
2016	5,738	30.8	13	2.3	26,678	28.8	821	67.0	44,309	47.8	78,497
2017	6,482	31.5	18	15.7	27,266	24.5	1,064	64.1	46,725	51.4	85,200

As can be seen in Table 3.5, capacity factor of power plants in Turkey varies;

- For wind power plants from 26% to 32%
- For hydro power plants from 19% to 30%
- For geothermal power plants from 50% to 67%
- For thermal power plants from 47% to 54%

It should be noted that SPP operation started in late 2016 with incomplete capacity, which is why the average operation ratio for SPP was 2.3% during the entire year.

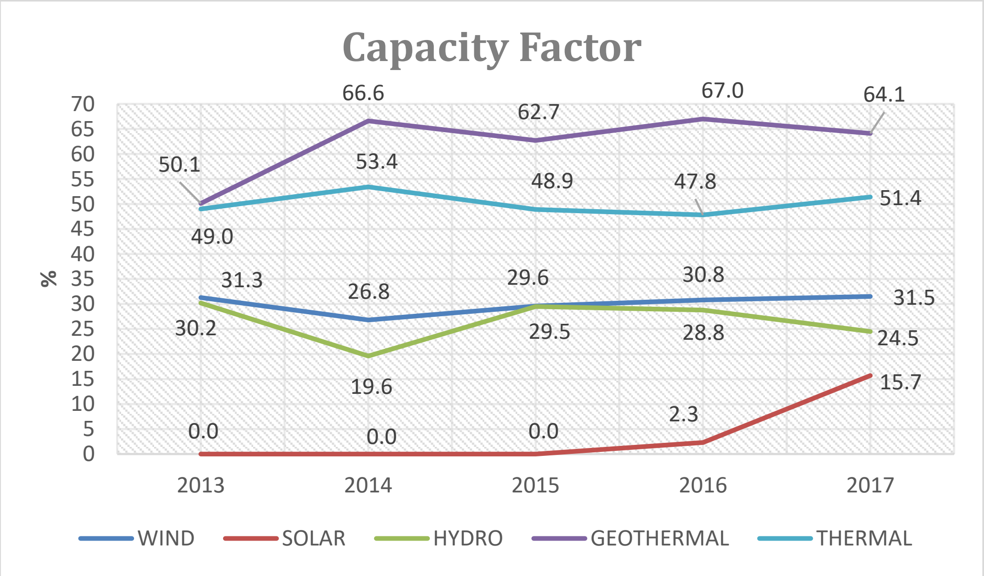


Figure 3.13. Capacity factor development for power plants from 2013 to 2017 [58]

3.5. Transmission and Distribution

Electric power transmission is supplied with interconnected network, which delivers electricity from generation stations to individual consumers. The network is called grid, power grid or national grid in different countries. The main elements are generation stations, transformers, high voltage transmission lines, distribution lines and consumers. Figure 3.14 shows these elements in the following sketch [60].

National energy transmission grid of Turkey is an essential part of the power grid, connecting the country's regions, power plants and demand centers. A public enterprise, TEİAŞ, is responsible for system operation and investments in the transmission infrastructure. As can be seen from Figure 3.15, transmission lines are mainly settled over the country from eastern parts to the western. The demand in the west is higher due to population and industrial density, compared to the east where various high capacity power-generating plants are established.

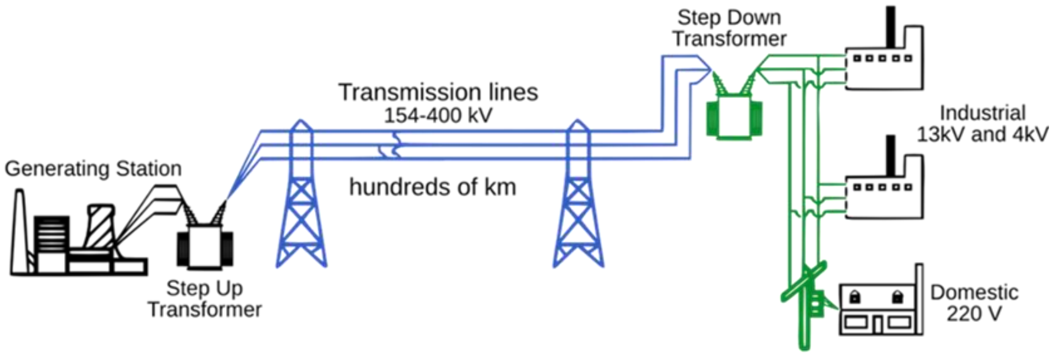


Figure 3.14. Basic transmission sample [60]

Electricity generation and transmission system are controlled by National Load Dispatch Operational Directorate (MYTM) with the help of 9 regional load dispatch center located in Adapazarı, Samsun, Elazığ, İzmir, Ankara, İstanbul, Erzurum, Adana and Antalya. By 2017, Turkey has 342.6 km of 154 kW, 73.7 km of 400 kW underground and 15.96 km of 400 kW undersea transmission line. Table 3.6 shows the development of aerial cable lengths from 2002 to 2017 in terms of kilometers.

Turkey's electric power transmission system is synchronized with European Network of Transmission System Operators for Electricity (ENTSO-E) with 400 kW transmission lines in Greece and Bulgaria in September 2010. Frequency stability and reserve sharing among ENTSO-E countries are the vital advantages of the synchronizing [61]. Power imports and exports are made with Georgia and Armenia in the east, with 220 kW transmission lines that suit their voltage levels [58].

Table 3.6. *Development of aerial cable lengths (km) from 2002 to 2017 (Data are compiled from TEİAŞ)*

YEARS	400 kW	220 kW	154 kW	66 kW	TOTAL
2002	13,626	85	30,163	671	44,545
2003	13,958	85	30,962	719	45,724
2004	13,970	85	31,006	719	45,780
2005	13,977	85	31,030	719	45,811
2006	14,307	85	31,163	477	46,032
2007	14,338	85	31,383	477	46,283
2008	14,420	85	31,654	509	46,668
2009	14,623	85	31,932	509	47,149
2010	15,734	85	32,906	509	49,234
2011	15,978	85	32,878	509	49,450
2012	16,344	85	33,481	509	50,419
2013	16,808	85	33,943	509	51,345
2014	17,683	85	35,132	509	53,409
2015	19,071	85	37,449	140	56,745
2016	21,029	85	36,682	139	57,935
2017	22,506	85	43,152	110	65,853

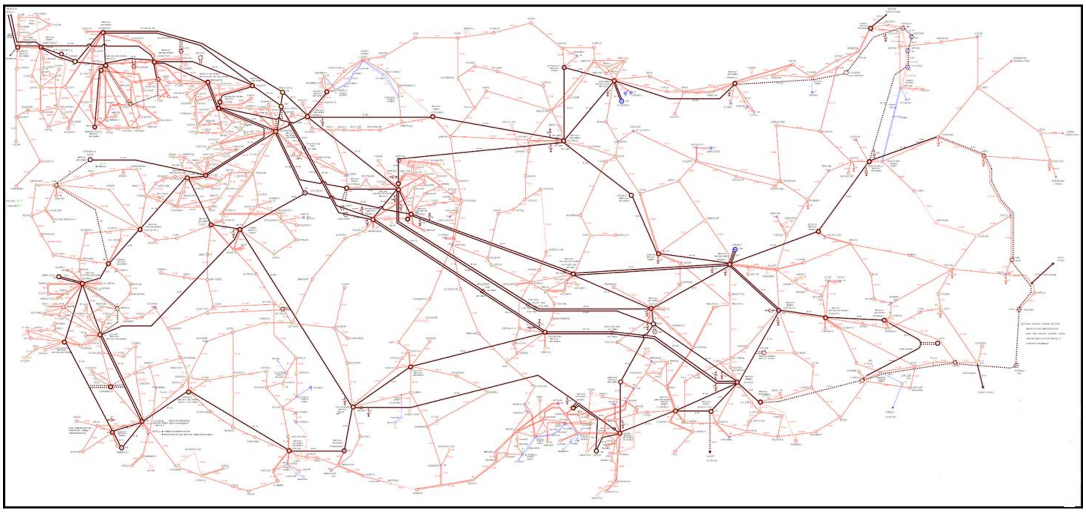


Figure 3.15. Settlement of transition lines in Turkey (TEİAŞ)

3.6. Demand Forecast

3.6.1. Power and Peak Load Demand

Turkey Electric Power Demand Projection report is prepared by the Ministry of Energy and Natural Resources (ETKB) biennially. In order to estimate demand values, ETKB consider various parameters like;

- Economy
- Population
- Temperature
- Electric Vehicles
- Energy Productivity
- System/Network Losses [62]

Results are obtained for three different - low, base (reference) and high – scenarios. Average demand increase is calculated 3.8% for low scenario, 4.6% for base scenario and 5.8% for high scenario. Table 3.7 and Table 3.8 show the values of demand projection from 2019 to 2027.

TEİAŞ and other public enterprises consider base scenario for preparing capacity projection and transmission system development reports and investment plan for power plants [63].

Table 3.7. *Gross electricity consumption projection from 2019 to 2027 (ETKB)*

YEAR	LOW (GWh)	INCREASE (%)	BASE (GWh)	INCREASE (%)	HIGH (GWh)	INCREASE (%)
2019	315,807		319,457		323,788	
2020	328,409	4.0	334,985	4.9	343,242	6.0
2021	341,037	3.8	350,696	4.7	363,443	5.9
2022	354,156	3.8	367,263	4.7	384,848	5.9
2023	367,876	3.9	384,638	4.7	407,889	6.0
2024	381,814	3.8	402,308	4.6	431,664	5.8
2025	396,139	3.8	420,509	4.5	456,471	5.7
2026	410,530	3.6	439,171	4.4	482,263	5.7
2027	424,973	3.5	457,876	4.3	508,611	5.5

Table 3.8. *Peak power demand projection from 2019 to 2027 [64]*

YEAR	LOW (MW)	INCREASE (%)	BASE (MW)	INCREASE (%)	HIGH (MW)	INCREASE (%)
2019	50,071		50,650		51,336	
2020	52,069	4.0	53,112	4.9	54,421	6.0
2021	54,071	3.8	55,602	4.7	57,623	5.9
2022	56,151	3.8	58,229	4.7	61,017	5.9
2023	58,326	3.9	60,984	4.7	64,670	6.0
2024	60,536	3.8	63,786	4.6	68,440	5.8
2025	62,807	3.8	66,671	4.5	72,373	5.7
2026	65,089	3.6	69,630	4.4	76,462	5.6
2027	67,379	3.5	72,596	4.3	80,640	5.5

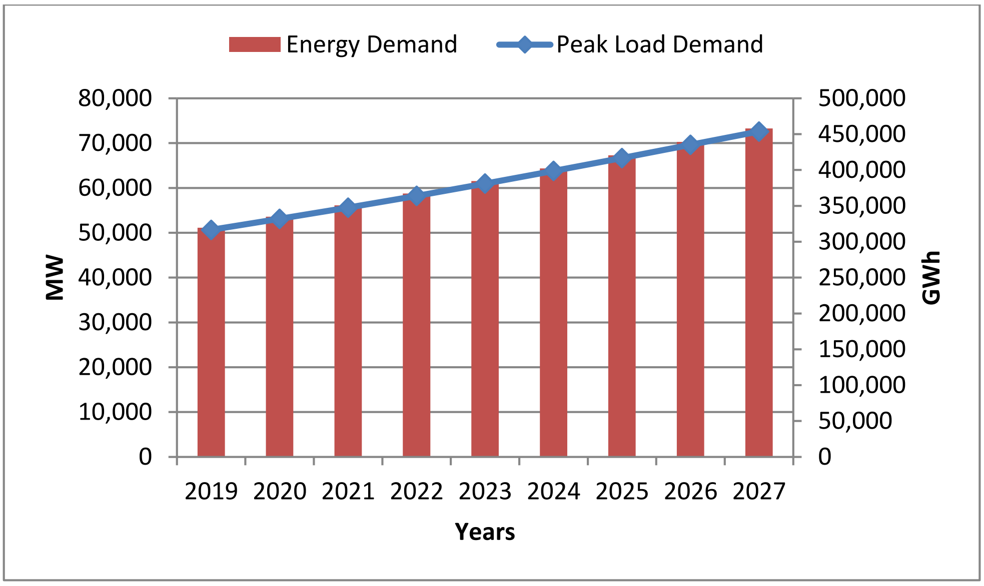


Figure 3.16. Peak load and energy demand projection for base scenario [64]

TEİAŞ estimates peak power demand projection values annually by using gross electricity consumption demands calculated by ETKB. It is assumed that the load factor is 72% and the load duration curve characteristic will not change [64].

3.6.2. Available Capacity

As pointed out before, the power plants could not generate energy with their maximum capacity for all the time. Available capacity is the efficient capacity which is ready to generate electricity at any time. Possible failures, fuel shortage for thermal power plants and lack of sufficient water, sun or wind for renewable power plants are the main reasons for decrease in the capacity. Figure 3.17 illustrates available capacity values for ten years by monthly from 2008 to 2017.

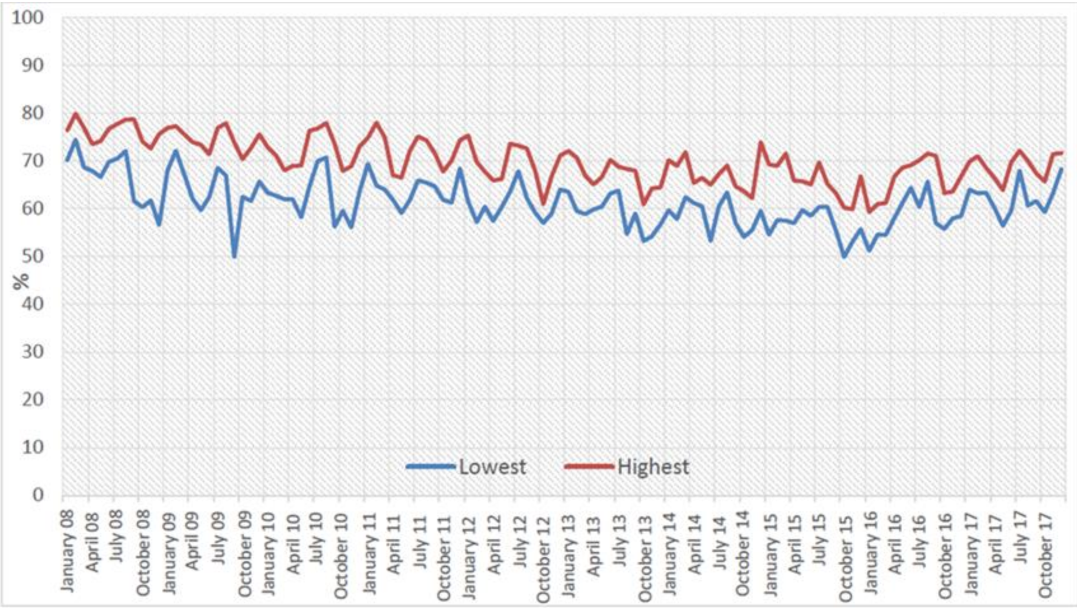


Figure 3.17. The ratio of maximum and minimum available capacity over total installed capacity by monthly period [58]

Table 3.9 shows us annual average capacity ratios of thermal, hydro and wind power facilities. Maximum and minimum data picked up month by month for a year and with their average the annual values are calculated. TEİAŞ use the data from 2008 to 2017 in order to forecast the forthcoming years. TEİAŞ assumed that there may be improvement of fuel conditions so again available capacity of thermal power plants could be highest. On the other hand, the same tendency could be expected for hydropower and wind power because of the unpredictability of natural conditions.

Table 3.9. *Average available capacity ratios from 2008 to 2022 [58]*

%	THERMAL	HYDRO	WIND	TURKEY TOTAL
2008	69.5	75.2	41.3	**71.5**
2009	65.4	77.5	44.6	**69.3**
2010	62.0	79.0	41.1	**67.2**
2011	65.2	75.4	41.3	**68.1**
2012	63.7	71.0	37.1	**65.0**
2013	60.8	71.3	39.8	**63.0**
2014	67.1	61.0	33.8	**63.1**
2015	62.2	65.1	36.8	**61.3**
2016	62.9	65.4	46.9	**62.1**
2017	65.5	69.0	60.5	**65.6**
2018	66.3	65.8	63.8	**62.0**
2019	67.1	65.3	67.2	**61.7**
2020	67.9	64.8	70.8	**61.4**
2021	68.7	64.3	74.5	**61.1**
2022	69.5	63.9	78.5	**60.8**

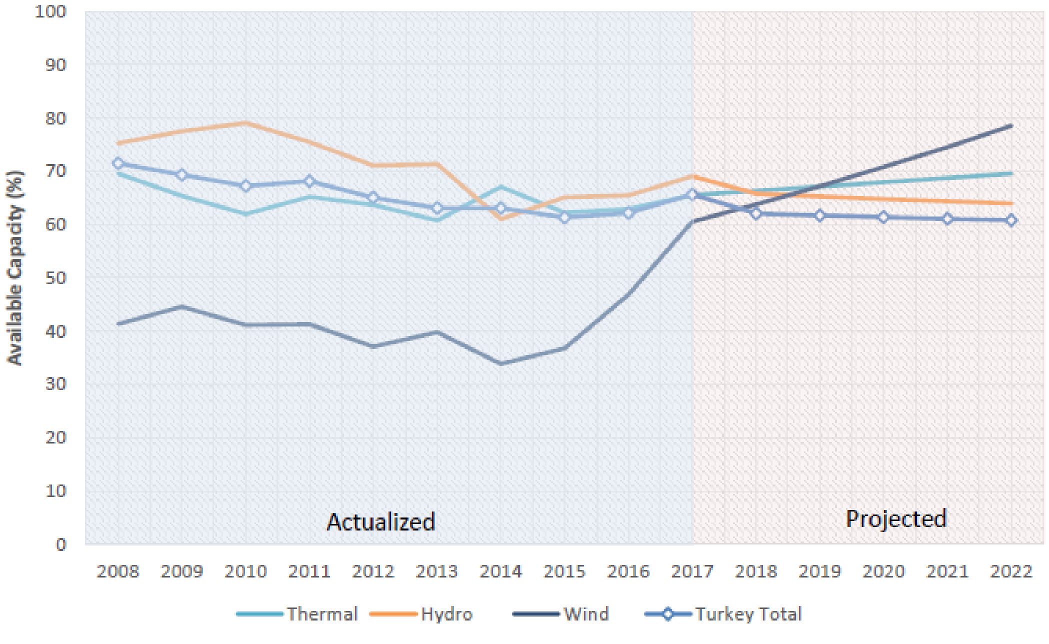


Figure 3.18. Available capacity ratios from 2008 to 2022 [58]

3.6.3. Demand Curve Projection

3.6.3.1. From the Perspective of Peak Power Demand

It is widely accepted that the power demand is difficult to be estimated accurately. Like power demand, daily demand curve also depends on industrial production, economic growth, consumption habits, etc. On the other hand, data from previous years can help investigating future trends.

Table 3.10 demonstrates the daily demand values of the days with maximum peak power demand over the last ten years. As can be seen in the table, demand increases by an average of 1,745 MW at 15:00 and 1,905 MW at 17:00. The demand increase rate at 07:00 is 5.96% whereas at 15:00 4.94% and at 17:00 5.41%.

It would be beneficial to know the peak power demand hour and peak power demand periods in the near future in order to determine the duration of a peaking power plant. Figure 3.19, prepared to respond to this requisite, shows the forecasted demand curves for 2025 and 2030 on the condition that the increase tendency from 2009 to 2018 is assumed to keep its rate until 2030 for all time zones.

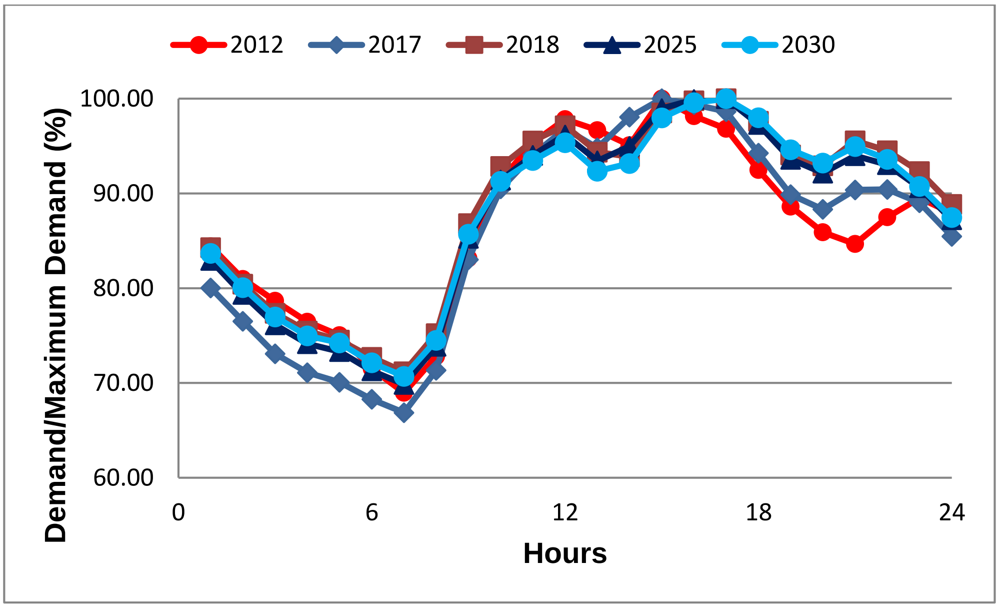


Figure 3.19. Demand curve projection for 2025 and 2030

Table 3.10. *Annual peak power demands for the last decade (Data are compiled from TEİAŞ)*

HOUR	2009 (MW)	2010 (MW)	2011 (MW)	2012 (MW)	2013 (MW)	2014 (MW)	2015 (MW)	2016 (MW)	2017 (MW)	2018 (MW)	Average Increase	
											(MW)	**(%)**
01:00	23606	27683	28062	32446	29733	32389	33363	35039	37667	38768	**1,685**	**5.92**
02:00	22473	26400	26749	31122	28399	30717	31951	33154	36013	37001	**1,614**	**5.97**
03:00	21461	25772	25583	30235	27398	29616	30619	31886	34398	35583	**1,569**	**6.12**
04:00	20929	25317	24715	29384	26617	28625	29586	30896	33459	34719	**1,532**	**6.16**
05:00	20528	24747	24652	28839	25977	28215	29212	30231	32982	34282	**1,528**	**6.21**
06:00	20141	23804	24026	27484	25766	27752	28556	29559	32134	33442	**1,478**	**6.02**
07:00	19685	22647	23888	26506	24944	26875	27763	28964	31469	32744	**1,451**	**5.96**
08:00	21119	23730	25557	27983	26428	28803	29681	31163	33578	34592	**1,497**	**5.75**
09:00	24746	27491	30088	31960	31255	33893	35245	36684	39072	39934	**1,688**	**5.53**
10:00	27208	30314	33211	35125	34533	37564	38976	40292	42586	42713	**1,723**	**5.22**
11:00	28527	31683	34548	36644	36313	39089	40467	42152	44270	43949	**1,714**	**4.99**
12:00	29249	32235	35492	37600	37253	40249	41725	43214	45577	44688	**1,715**	**4.90**
13:00	28782	31881	34573	37154	36428	39358	40492	41958	44622	43402	**1,624**	**4.76**
14:00	29215	32487	35110	36544	37459	40310	41691	43100	46149	43178	**1,551**	**4.55**
15:00	29604	33191	35634	38431	38116	40734	42482	44341	47062	45307	**1,745**	**4.94**
16:00	29204	32965	35509	37724	37446	40229	41971	43748	46771	45900	**1,855**	**5.24**
17:00	28853	32377	34827	37210	36447	39544	41234	43215	46423	45996	**1,905**	**5.41**
18:00	27324	31186	33430	35541	34877	37596	39593	41203	44359	44906	**1,954**	**5.76**
19:00	25931	29932	31880	34058	33123	35540	37288	39222	42300	43273	**1,927**	**5.95**
20:00	25579	29029	31181	33014	32987	34774	36415	38556	41568	42741	**1,907**	**5.93**
21:00	26612	29231	32277	32540	33505	35539	37240	39509	42535	43955	**1,927**	**5.78**
22:00	26803	29751	32561	33624	32646	35162	37002	38843	42556	43469	**1,852**	**5.60**
23:00	26742	29956	32238	34406	32865	35559	37118	38521	41895	42460	**1,746**	**5.37**
00:00	25615	29307	31045	33791	31635	33738	35865	37059	40228	40868	**1,695**	**5.47**

The data in Figure 3.19 demonstrate that;

- The peak demand time is expected to shift from 15:00 to 17:00 (as in 2018),
- Difference between evening lighting peak and daily peak is presumed to decrease,
- The peak time zone is expected to expand up to 13 hours approximately, from about 10:00 to 23:00.

3.6.3.2. From the Perspective of Minimum Power Demand

As mentioned in Chapter 2, PSH is not only used to meet peak power demand, it is also helpful for load balancing. Public authorities in Turkey draw attention to the fact that balancing electricity generation and consumption will prove difficult to provide when the NPPs are included in Turkey's power grid [48].

As the table below displays in a detailed manner, minimum available installed capacity in Turkey is expected to rise up to 31,750 MW by 2025. The peak power demand on the other hand, is estimated to increase up to 59,825 MW for the base scenario. The ratio of minimum load over maximum peak load is assumed to be 45-50% and therefore the value of minimum power demand is calculated to be in the range of 26,500-30,000 MW. The difference between minimum generation and minimum consumption is presumed to be about 5,000 MW, and adding PSH into the electric grid of Turkey will become a requirement as it was emphasized in the PSH Roadmap Workshop of 2018.

Table 3.11. *Estimated minimum power generation capacities for 2025 [49]*

SOURCE TYPE	Installed Capacity (MW)	Minimum Available Installed Capacity (MW)
Nuclear	2,400	2,280
Wind	16,000	4,800
Solar	9,000	900
Geothermal	2,000	1,500
Other Renewable Sources	1,300	650
Run off River Hydro	12,000	9,000
Dams	25,000	6,250
Import	-	1,370
Coal	15,000	5,000
Natural Gas	28,000	
Imported Coal	20,000	
Total	130,700	31,750

According to the data compiled from TEİAŞ, minimum power demands occurred during public holidays between 2001 and 2018. The same data displays the average ratio of minimum power demand over peak power demand, which appears as 39.4%. TEİAŞ's Capacity Projection Report 2018 on the other hand, expresses the peak power demand estimation as 66,671 MW in the base scenario [58]. Using these figures from 2001-2018, daily demand curve of 2025 is estimated to appear as 26,700 MW for minimum power demand. Red area in Figure 3.20 below represents the required additional electricity consumption, which is calculated to be 32.5 GWh approximately.

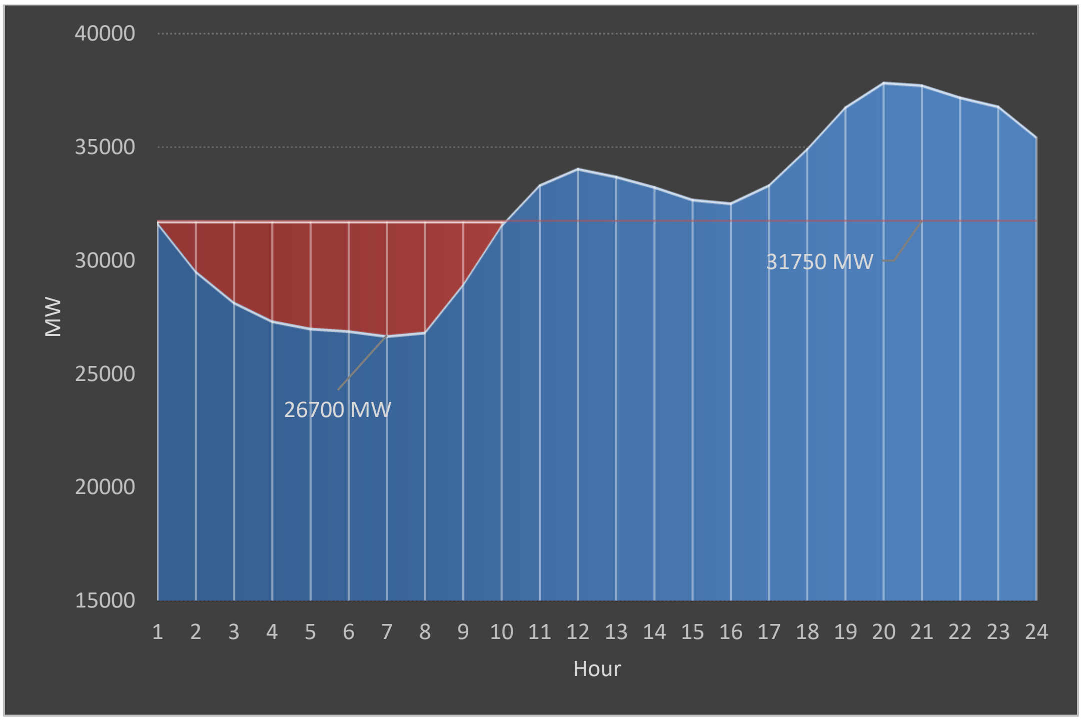


Figure 3.20. Daily demand curve of 2025 for minimum power demand

CHAPTER 4

ELECTRICITY MARKET IN TURKEY

4.1. History

The history of electricity in Turkey dates back to 1902 in Tarsus [65]. Austrian company Dörfler built a small HEPP with a capacity of 2 kW in order to supply lighting the streets. Later, Ganz Electric Company built a thermal power plant, Silahtarağa Power Plant, with an installed capacity of 13.4 MW in Istanbul. The generated electricity was used for tramways, street lighting and Dolmabahçe Palace where the Ottoman Sultan dwelled.

The development of electric power and operation of power plants in Turkey were under foreign investors' initiative until early 1930s. The young Turkish Republic laid emphasis in developing electricity due to its growing population. Economic downturn in industrialized countries in 1929 was also a driving force to nationalize electricity facilities since it showed that the foreign investors could possibly fall short of supporting country's electricity demands. Under the leadership of M. Kemal Atatürk, founder of the Republic of Turkey, public institutions were established to develop and regulate energy affairs. Among these institutions were İller Bankası (1933), Etibank (1935), EİE (1935), Mineral Research and Exploration General Directorate (MTA-1935). DSİ, on the other hand was founded in 1954 with the purpose of developing water and land resources and grew into a major focus for hydropower.

Turkish electricity sector can be analyzed in different periods starting from 1970: Partial monopoly period between 1970 and 1982, monopoly period between 1982 and 1983, opening up to private sector between 1984 and 2001 and free market period since 2001 [66].

In order to monopolize electricity affairs, Turkish Electricity Authority (TEK) was founded in 1970 and took on the responsibility of generating, transmitting, distributing and trading electricity. Later in 1984, Act 3096 allowed establishment of power plants and holding operating right for private entities, therefore revoked the monopoly of TEK.

TEK split into two public institutions in 1994: Turkish Electricity Generation and Transmission Company (TEAŞ) and Turkish Electricity Distribution Company (TEDAŞ). Privatization of the Turkish electricity market was initiated in 1984, however major implementations were made mainly in 2001 with the Act 4628.

TEAŞ was split into three public intuitions in 2001: TEİAŞ, EÜAŞ and Turkish Electricity Contracting and Trading Company (TETAŞ). EPDK was founded in the same year. The privatization of TEDAŞ was initiated in 2004 and the institution was split into 21 private companies by the end of 2013. Private companies took the lead in the overall business by generating, distributing and trading electricity, yet a regulating authority to supply-demand and market organization was needed. For this purpose, Balancing and Settlement Regulation (BSR) was announced in 2004 and it came into effect in 2006. Day-ahead planning started in 2009 and Day-Ahead Market (DAM), Balancing Power Market (BPM) and Ancillary Service Market (ASM) were established between 2009 and 2011. Real time balancing is today provided in BPM and ASM, which are controlled by TEİAŞ. Intra-Day Market (IDM) was established in 2015 in order to give more flexibility to the operators while balancing their portfolios. TETAŞ was abrogated in 2018 and their trade agreements were transferred to EÜAŞ.

MYTM, which controlled by TEİAŞ, regulates real time balancing of supply and demand. Market Financial Reconciliation Centre (MUDB) under the auspices of TEİAŞ as well, was responsible for financial settlement of market until it got replaced by EPİAŞ in 2015. Figure 4.1 is prepared to clarify the abovementioned historical development.

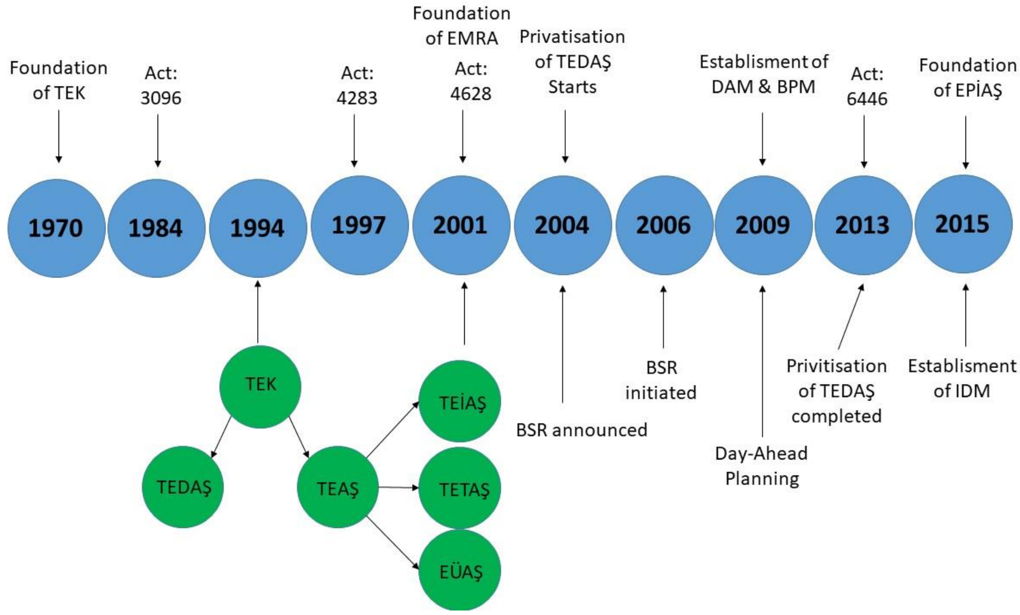


Figure 4.1. Historical development of electricity markets in Turkey

4.2. Electricity Markets in Turkey

Turkish wholesale market consists of three main markets:

1. Day-Ahead Market,
2. Intra-Day Market,
3. Balancing Power Market.

DAM and IDM are operated by EPİAŞ, the market operator of Turkey whereas TEİAŞ, the grid operator regulates BPM.

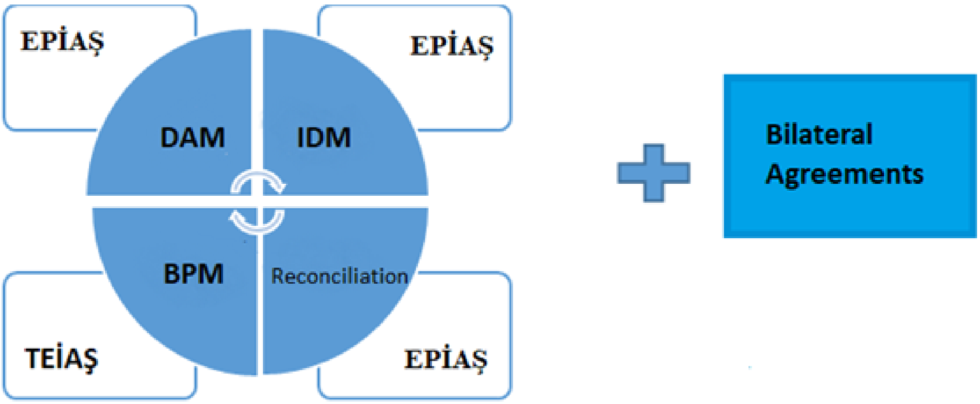


Figure 4.2. Electricity markets and their operators in Turkey

Reconciliation is calculation of debits and credits of IDM, DAM and BPM and controlled by the market operator. In addition to market operations, electricity trade is also conducted by bilateral agreements between producers and consumers.

Electricity prices are determined on an hourly basis. Bids and offers are announced before the bidding period is over and the market is regulated correspondingly. Bidding period for the DAM is over by 12:30 for the following day. IDM bid and offers may be introduced as early as 18:00 for the following day until one hour in advance for the real time. BPM starts after the DAM is settled at 14:00 and bids and offers can be declared until 16:00.

4.2.1. Day-Ahead Market

The main target of DAM is the determination of the reference electricity market price, which is based on supply and demand. Market participants have the opportunity to purchase and sale electricity in DAM in addition to their bilateral contracts. Provision of a balanced system for the grid operator is an additional goal of this market operation. Consumers and producers are not necessarily entitled to participate in this market.

Bids and offers may be hour/block-hour based or flexible for the DAM. The determination of Market Clearing Price (MCP) follows the following stages:

- DAM participants submit their offers for next day until 12:30 to the market operator,
- Market operator verifies the offers between 12:30 and 13:00,
- MCP and trade volume are determined hourly for the following day via an optimization program between 13:00 and 13:30 and these values are announced to market participants at 13:30.
- Participants can object to the proposed prices between 13:30 - 13:50.
- Market operator evaluates the objections between 13:50 - 14:00 and final prices and matched volume for the following day are announced at 14:00.

Figure 4.3 shows the abovementioned steps.

Figure 4.3. Steps in the DAM mechanism

4.2.2. Intra-Day Market

IDM was established in 2015 in order to encourage participants to actively take responsibility in the market [67]. Main targets of IDM are listed below:

- IDM gives participants the chance to balance their short-term portfolios and almost real-time trading in addition to operation at DAM and BPM.

- IDM acts as a bridge between DAM and BPM, thus it contributes to the balancing and the sustainability of the electricity market.
- With the help of IDM, factors that result in imbalance such as plant failures or fluctuations of power generation from renewables can be eliminated. IDM allows participants to minimize or balance positive/negative imbalances that they may experience during the day. For instance, it is difficult to estimate the following day wind values, thus IDM is a chance for WPP operator to eliminate its imbalances.
- After DAM is closed, participants can make use of their unused capacities with IDM, therefore additional trading ground is established and liquidity of the market increases.

Participants submit their offers until 60 minutes before the physical delivery and the offers can be updated, cancelled or rendered inactive. IDM begins at 00:00 and ends at 00:00 the following day and trade is carried out on hourly basis.

The trading size of IDM is relatively limited because the main target of this market is portfolio balancing rather than energy trade [68]. IDM can be defined as a supplementary of DAM and the price in this market is called Weighted Average Price (WAP).

4.2.3. Balancing Power Market

In theory, grid operator obtains a balanced system in terms of production and consumption amounts, with the help of DAM and IDM. In reality, grid operator may come face to face with imbalances due to unplanned shutdowns, starting or stopping of large-scale power plants, etc. BPM allows grid operator to provide system safety and manage deviations in supply and demand.

BPM prices, namely System Marginal Price (SMP) reflects the unpredicted supply and demand deviations. The generation of the power plant must be controllable to be able to join the BPM, which is why renewable power plants are not convenient for this market, with the exception of hydropower facilities with reservoirs.

Participants in BPM inform the operator about their available capacities and hourly loading/deloading offers until 16:00 on daily basis. The operator sorts each offer and notifies the relevant participant about its endorsed offer in the cases where there is a surplus of production or consumption.

To estimate SMP, net instruction volume is considered starting from the lowest loading offer price if there is energy deficit in the grid or the highest deloading price if there is energy surplus in the grid.

BPM is in fact designed to balance the system rather than for trading because it contains more risk compared to DAM or IDM [69]. Figure 4.4 expresses the regulation of MCP for DAM and SMP for BPM [70].

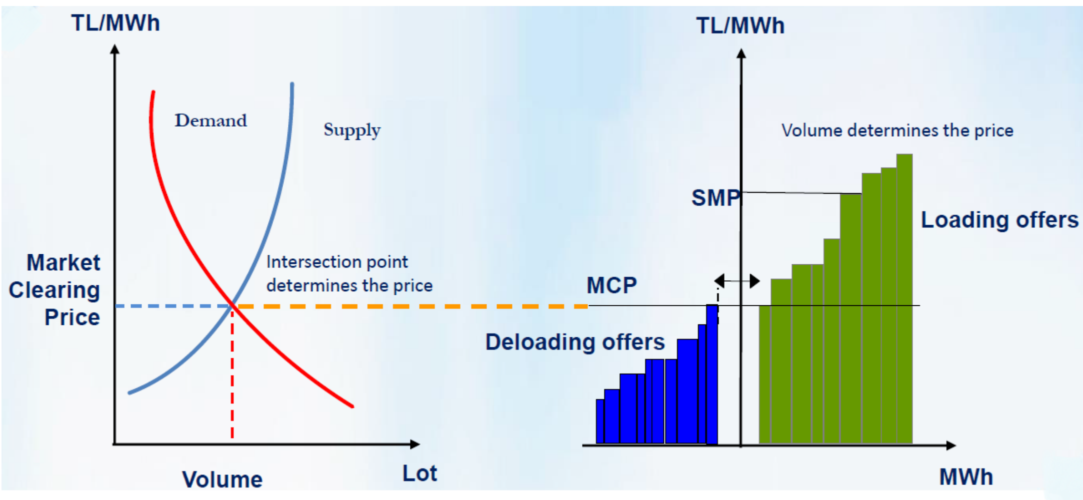


Figure 4.4. MCP and SMP regulation [70]

Briefly, electricity trade can be conducted via bilateral agreements or in spot markets. Both producers and consumers decide on the electricity prices in their bilateral agreements and it does not affect the prices in spot markets. MCP is determined by the intersection of supply and demand offers for each hour. IDM can be defined as a bridge between DAM and BPM where the participants get the chance to manage their unutilized capacities. Grid operator controls BPM with the aim of real time balancing. Participation in both DAM and IDM is not obligatory neither for consumers nor for producers whereas it is compelled in BPM. Facilities and participants that can comply with the directive of load/deload of minimum 10 MW within 15 minutes are obligated to participate in BPM. Figure 4.5 summarizes the abovementioned process:

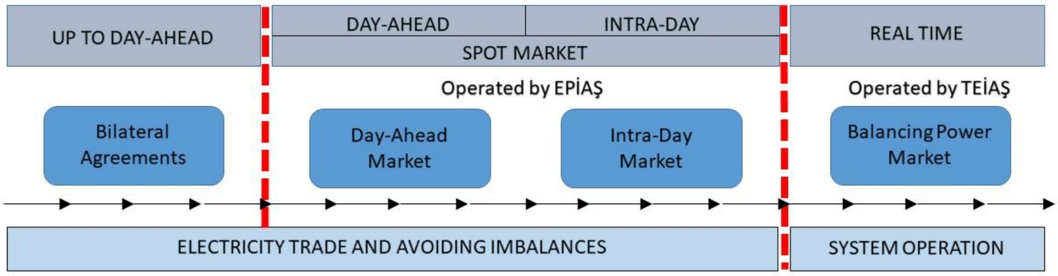


Figure 4.5. Electricity trade process

Figure 4.6 demonstrates the distribution of market volumes between 2016 and 2018. As can be seen in the chart, the highest market share in electricity trade belongs to bilateral contracts. Volume of DAM increases up to 37.1% and volume of BPM decreases down to 2% by 2018. IDM volume does not even reach 1%.

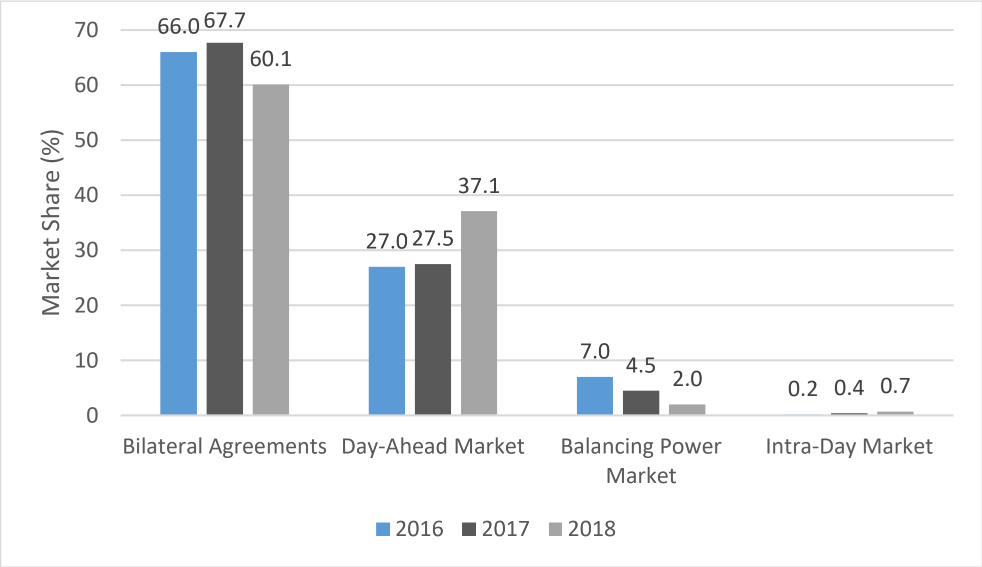


Figure 4.6. Distribution of market share between 2016 and 2018 (Data are compiled from EPİAŞ)

4.3. Analysis of Electricity Prices

Determination of electricity prices is closely related to demand and supply of energy. Succeeding or failing in producing sufficient energy affects the prices vis-à-vis increasing electricity demand. Moreover, change in the costs of raw materials such as coal, natural gas or petrol has an impact on prices. For instance, devaluation of Turkish Lira against US Dollar in the summer of 2018 resulted in an increase in imported energy source prices. Consequently, prices of MCP of DAM were recorded as 185.62 (TL/MWh) in June 208.13 (TL/MWh) in July, 298.91 (TL/MWh) in August and 327.27 (TL/MWh) in September respectively. MCP and SMP are analyzed in detail under the following sub-chapters.

Figure 4.7 demonstrates the electricity price and demand-supply relation based on average hourly demand and average hourly MCP of 2018. Low prices are recorded between midnight and morning hours when demand is low. High prices, on the other hand are recorded during peak demand hours, especially at noon and evenings.

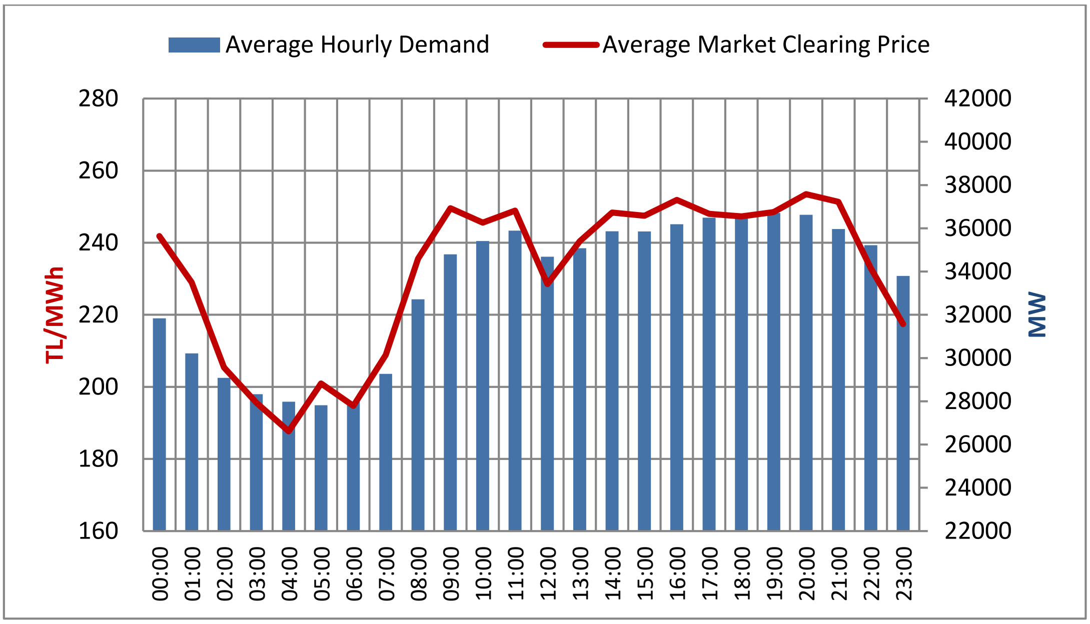


Figure 4.7. Average of hourly demands and MCPs of 2018 (Data are compiled from EPİAŞ and TEİAŞ)

4.3.1. Hourly Analysis of Electricity Prices

DAM and BPM were opened on 1 July 2009 and IDM on 1 July 2015. The first six months in both markets can be considered as a training for the participants. Thus, prices of these months are disregarded in analysis.

Figure 4.8, Figure 4.9 and Figure 4.10 represent the MCP, SMP and WAP of IDM respectively and they show the average of 365 days and 24 hours for each. The prices of 2018 are the highest among all and the main reason for this significant difference is the sharp increase of US dollar against Turkish Lira. Highest prices in average correspond to the time period between 11:00-12:00 and second highest prices in average are mainly between 14:00 and 15:00 for every year except for 2018. The first average (11:00-12:00) shifted to 16:00-17:00 and the latter (14:00-15:00) to 20:00-21:00 by 2018

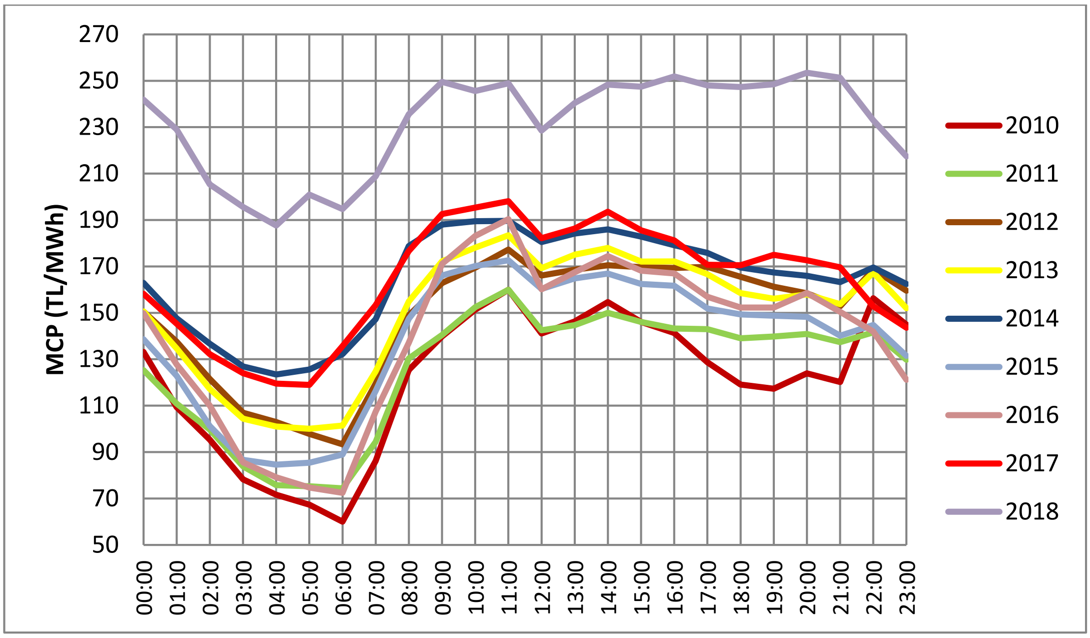


Figure 4.8. Hourly averages of Market Clearing Price

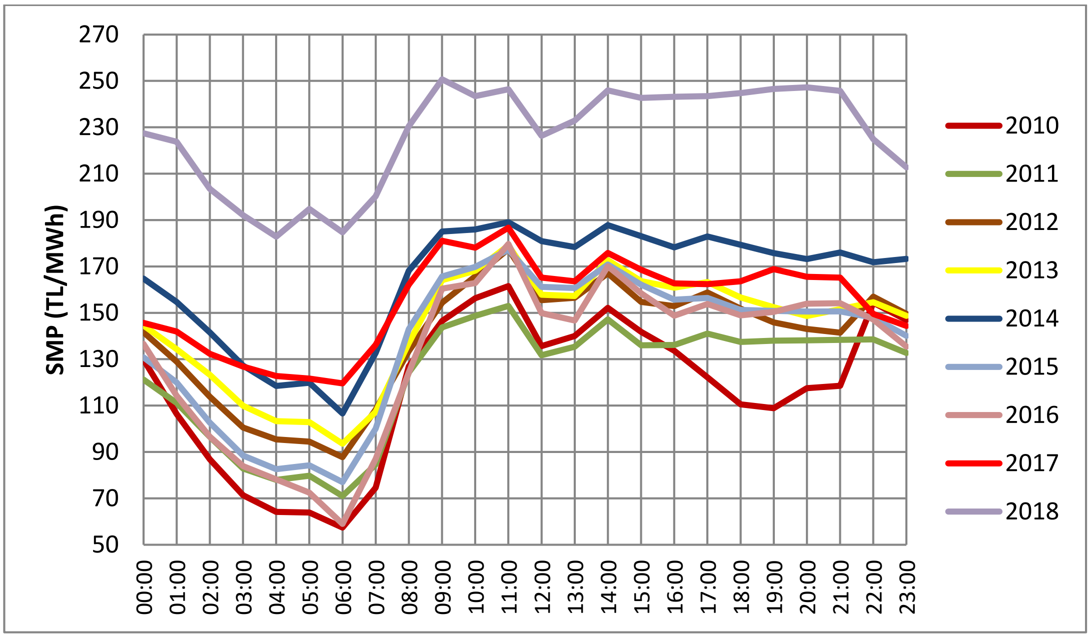


Figure 4.9. Hourly averages of System Marginal Price

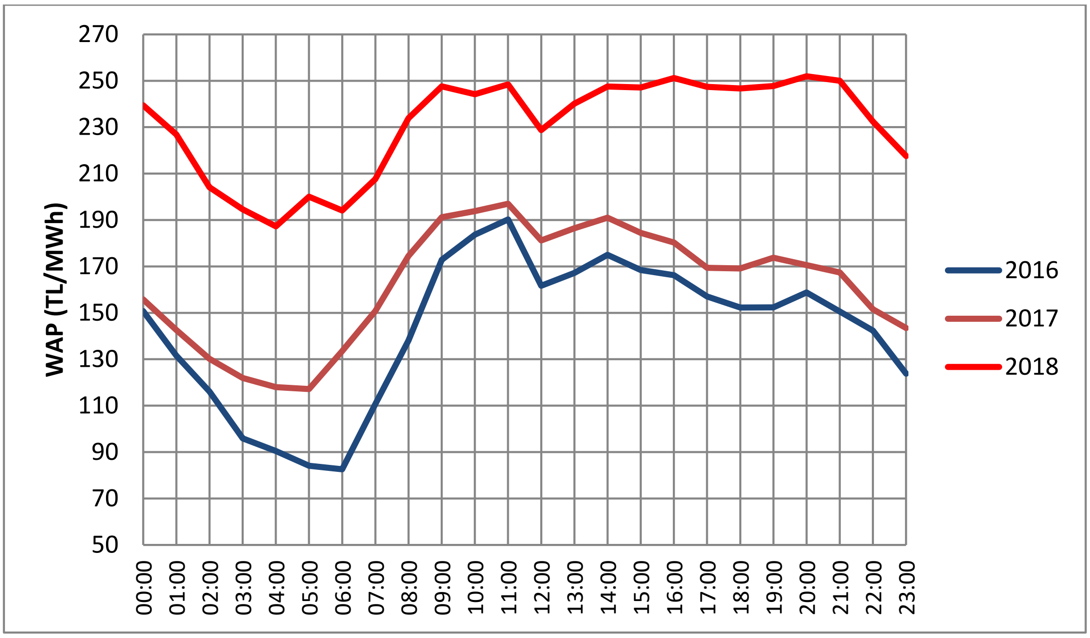
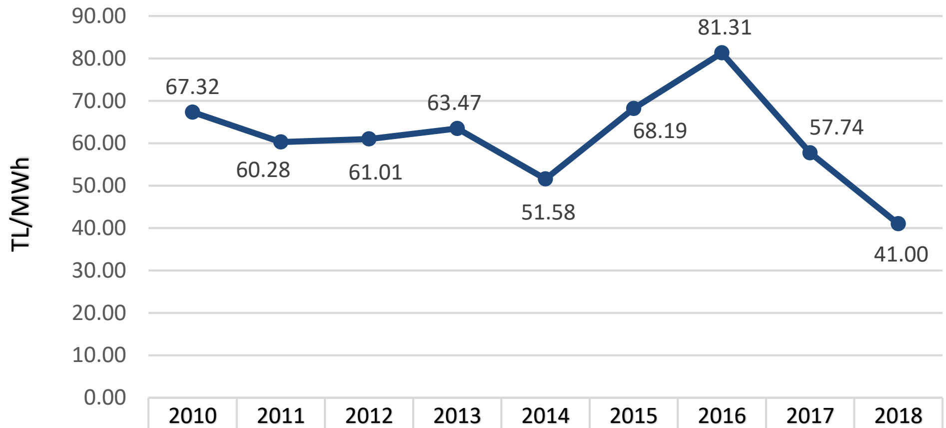


Figure 4.10. Hourly averages of Weighted Average Price of IDM

Traditionally, profitability of PSH depends on the price differences between peak and off-peak hours. Figure 4.11 shows the average hourly MCP differences between peak and off-peak periods between 2010-2018. The difference range is between 50 to 70 TL/MWh except for 2016 and 2018. EPİAŞ started to use a new software for price determination and this is one of the reasons why the price difference has decreased since 2016 [71].

According to Beisler [72], peak and off-peak price ratio should be approximately 3:1 in order to make a project feasible. This ratio is 1.58:1 when the average between 2010 and 2018 in Turkey is calculated. Estimating whether price differences will increase or not in the upcoming years based on evidence from previous years is highly challenging though. Regarding this, feasibility of PSH projects for Turkey remains quite dubious.



	2010	2011	2012	2013	2014	2015	2016	2017	2018
01:00-07:00	81.18	87.74	111.37	111.97	134.25	98.03	94.01	132.68	203.13
09:00-15:00	148.50	148.02	172.38	175.45	185.82	166.22	175.32	190.42	244.14
Difference	67.32	60.28	61.01	63.47	51.58	68.19	81.31	57.74	41.00

Figure 4.11. Average hourly MCP differences between high and low demand

4.3.2. Monthly Analysis of Electricity Prices

Electricity generation from hydropower increases during flood season, in springs. As it can be seen in Figure 4.12 and Figure 4.13, electricity prices are lower during springs compared to other seasons. Summers are remarkable with high electricity consumption rates due to air conditioners and low hydroelectricity generation, resulting in high prices.

Energy generated from NGPPs had a share of 44% in average between 2007 and 2017, constituting the biggest share in electricity generation during those years. In addition to electricity generation, natural gas is widely used for heating. Correspondingly, electricity prices have a concrete tie to natural gas supply, especially for winter periods. For instance, extreme prices for electricity usage in February 2012 and in December 2016, were mainly the consequences of the natural gas crisis in Turkey. Petroleum Pipeline Corporation (BOTAŞ) limited the natural gas utilization of power plants then due to cold weather conditions and lack of provision, therefore electricity prices increased. Prices were recorded as 2,000 TL/MWh on 13 February 2012 and 1,899.99 TL/MWh on 23 December 2016.

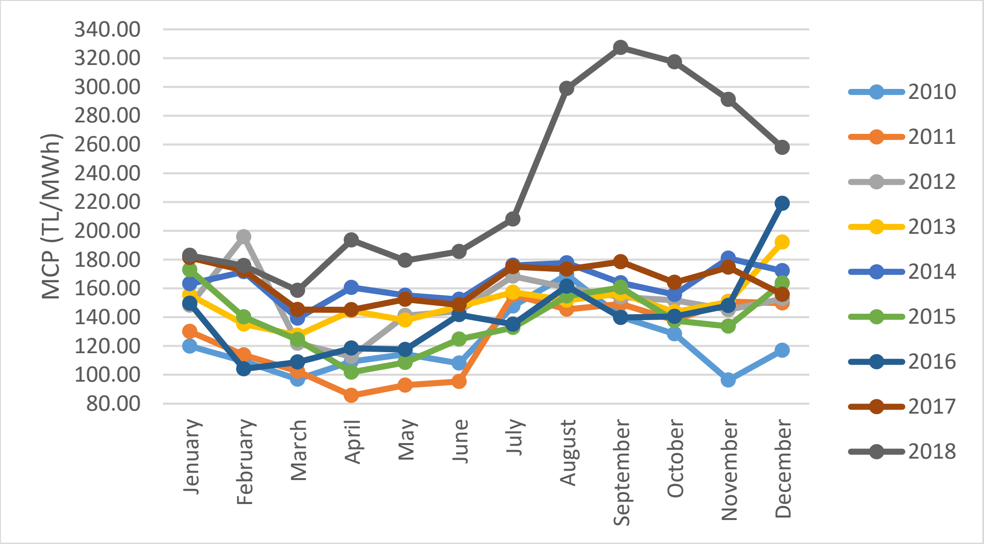


Figure 4.12. Monthly averages of Market Clearing Price

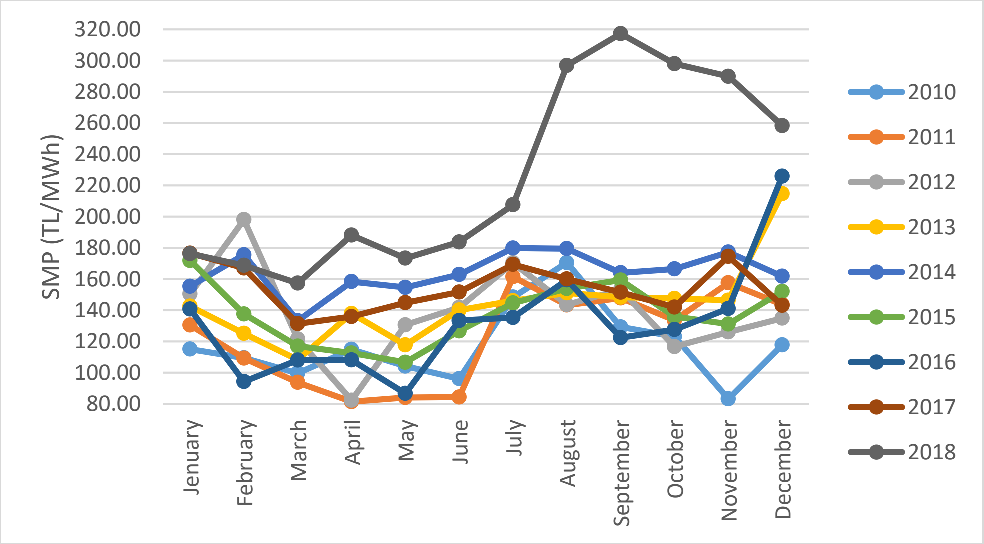
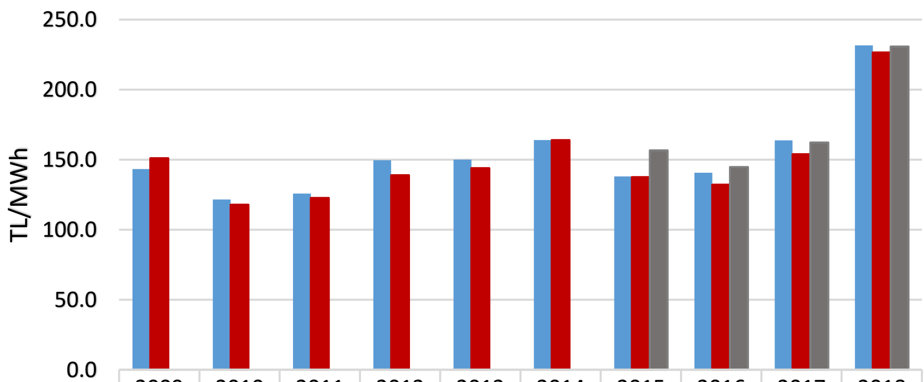


Figure 4.13. Monthly averages of System Marginal Price

4.3.3. Yearly Analysis of Electricity Prices

Figure 4.14 demonstrates the annual averages of MCP and SMP since 2009 and WAP since 2015. MCP, the reference electricity price increased by 41.4% in 2018 compared to the previous year.



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
MCP	143.4	121.6	125.9	149.6	150.1	164.0	138.0	140.7	163.8	231.6
SMP	151.0	117.8	122.7	138.9	144.0	163.9	137.5	132.2	153.9	226.5
WAP							156.6	144.8	162.3	230.7

Figure 4.14. Annual averages of MCP, SMP and WAP.

CHAPTER 5

CAPACITY DETERMINATION OF PSH

5.1. Calculations of Installed and Pumping Capacities

The calculation of installed capacity of hydropower plant is related to water flow rate Q (m^3/s) through the turbines and the water head H (m). Actually, the same equation is used in order to calculate the power output of PSH. Installed capacity of a PSH, P (MW), is determined as follows:

$$P = \rho \times g \times Q \times H_{net} \times \eta_g \times 10^{-6} \tag{1}$$

in which ρ (kg/m^3) is the density of water, g (m/s^2) is the acceleration due to gravity and η_g is the total generating efficiency. The net head, H_{net} (m) is the difference between gross head, H_g (m), and total head losses, $h_f + h_m$ (m). The elevation difference between upper and lower reservoir is equal to gross head. h_f refers to friction losses and h_m to minor losses in the water-carrying channels.

$$H_{net} = H_g - (h_f + h_m) \tag{2}$$

As shown in Equation 1, the head, the water flow rate and the generating efficiency are changeable variables. There is an important relation between the head and the discharge. If the head is higher, the need for water flow can be minimized and vice versa.

The power input in pumping mode or pumping capacity of PSH, P_p (MW) in other words is determined by the following equation:

$$P_p = \rho \times g \times Q_p \times H_p \times 10^{-6} / \eta_p \quad (3)$$

where Q_p (m^3/s) is the pumping discharge, H_p (m) is the head of water in pumping mode and η_p is the total pumping efficiency. The pumping mode head, as demonstrated in the following equation is always higher than the generating mode head, since in the first case losses are added to gross head and in the second case subtracted from it. Thus, heads of these modes are different [53].

$$H_p = H_g + (h_f + h_m) \quad (4)$$

The pumping discharge is related to flow rate during electricity generation and the operation time of pump and turbine modes. In order to calculate Q_p, volume of water ($\forall$ (m^3)) during turbine mode should be calculated at first.

$$\forall = Q \times Hour\ of\ Generation \times 3600 \quad (5)$$

Subsequently, the flow rate during pumping mode can be calculated from the following equation:

$$Q_p = \forall / (Hour\ of\ Pumping \times 3600) \quad (6)$$

Calculations of electricity generation, E_{gen} (MWh), and electricity consumption during pumping, E_p (MWh), can be made with the help of the following equation for daily, monthly or annual periods.

$$E_{gen} = P \times Hour\ of\ Generation \times Number\ of\ Operation\ Days \quad (7)$$

$$E_p = P_p \times Hour\ of\ Pumping \times Number\ of\ Operation\ Days \quad (8)$$

Round-trip or turnaround efficiency of the PSH is the ratio of the generated energy to consumed energy during the same period.

$$\eta_{rt} = E_{gen} / E_p \quad (9)$$

The round-trip efficiency of PSH is in the range of 75-80% [73].

5.2. Head Losses in The System

It is significant to calculate the head losses between upper and lower reservoirs in order to determine accurately installed capacity of hydroelectric power plant. The total loss can be considered to be the sum of friction loss in pipes and local losses.

5.2.1. Friction Losses

Two well established equations, Manning and Darcy-Weisbach, can be used to calculate the friction losses. The Manning Equation is as follows:

$$Q = \frac{A}{n} \times R^{2/3} \times s^{1/2} \tag{10}$$

$$R = A/P \tag{11}$$

where Q (m^3/s) is the discharge, R (m) is the hydraulic radius, n is the Manning roughness coefficient, s is the slope of energy grade line, A (m^2) is the cross-sectional area of flow, P (m) wetted perimeter of conduit.

Slope of energy can be calculated as follows should the Equation 10 be modified for pipe flow:

$$s^{1/2} = n \times 4^{\frac{2}{3}} \times Q \Big/ \frac{\pi}{4} \times D^{\frac{8}{3}} \tag{12}$$

The Manning Roughness Coefficient (MRC) for different materials can be found in any fluid mechanics book. Table 5.1 shows the range of MRC for tunnel and penstock design [74].

Table 5.1. *MRC for penstock and tunnel design [74]*

	Maximum	*Minimum*
Concrete pipe or cast-in-place conduit	0.014	0.008
Steel pipe with welded joints	0.012	0.008
Unlined rock tunnel	0.035	0.020

Head losses due to friction (h_f) can be calculated by Equation 13:

$$h_f = s \times L \tag{13}$$

where L (m) stands for the length of the tunnel or pipe. The Darcy-Weisbach Equation, on the other hand is as follows:

$$h_f = f \times \frac{L}{D} \times \frac{V^2}{2g} = \frac{8 \times f \times L}{g \times \pi^2 \times D^5} \times Q^2 \tag{14}$$

$$f = func\left(\frac{\varepsilon}{D}, Re\right) \tag{15}$$

$$Re = \frac{VD}{\nu} \tag{16}$$

where f stands for the Darcy Friction Factor, L (m) for the length of a pipe, D (m) for the diameter of the conduit, V (m/s) for the velocity of fluid, ε (mm) for the equivalent roughness , Re for the Reynolds number, and ν (m^2/s) for the kinematic viscosity of water. Darcy Friction Factor can be calculated by the famous Moody's Chart or equations such as:

Colebrook-White

$$\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \tag{17}$$

Swamee and Jain

$$f = \frac{1.325}{\left[\ln\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \tag{18}$$

which is valid for $10^{-6} < \varepsilon/D < 10^{-2}$ and $5000 < Re < 10^8$

The values of equivalent roughness can also be found in any fluid mechanics book. In order to determine hydropower installed capacities, equivalent roughness value of smooth and rough steel pipes can be selected between 0.02-0.05 mm and 0.3-3mm for concrete pipes [75].

5.2.2. Minor Losses

In addition to friction losses in a pipe system, there are minor losses due to disturbances of fluid flow. Fluid passes through inlets, bends, elbows, expansions and contractions, valves, gates etc. and because of these interruptions additional losses occurs.

5.2.2.1. Intake Losses

Energy loss at intakes is mainly the result of several changes in cross section and of intake velocity. Possible losses are:

- Trashrack losses
- Entrance losses
- Losses through slots
- Transition losses
- Friction losses due to transition [76].

<u>Trashrack Losses:</u>

Trashracks are used to prevent the entrance of ice or trash into power tunnels or penstocks. Therefore, it produces unwanted energy losses due to presence of debris or eddies and vortices. Losses can be calculated by the following equation;

$$ht = Kt \times \frac{V^2}{2g} \qquad (19)$$

$$Kt = 1.45 - 0.45\left(\frac{A_n}{A_g}\right) - \left(\frac{A_n}{A_g}\right)^2 \quad (20)$$

where ht (m) represents the trashrack loss whereas Kt is the trashrack loss coefficient, A_n (m^2) is the net trashrack area, and A_g (m^2) is the gross trashrack area.

<u>Entrance Loss:</u>

The loss of head at the entrance of a conduit can be calculated by Equation 21:

$$hen = Ken \times \frac{V^2}{2g} \quad (21)$$

where hen (m) is the entrance loss, and Ken is the entrance loss coefficient. Table 5.2 shows the values of the entrance loss coefficients:

Table 5.2. *Loss coefficients for conduit entrances [74]*

	Discharge coefficient, C			Loss Coefficient, Ken		
	Max	Min	Avg.	Max	Min	Avg.
Gate in thin wall - unsuppressed contraction	0.70	0.60	0.63	1.80	1.00	1.50
Gate in thin wall - bottom and sides suppressed	0.81	0.68	0.70	1.20	0.50	1.00
Gate in thin wall - corners rounded	0.95	0.71	0.82	1.00	0.10	0.50
Square-cornered entrances	0.85	0.77	0.82	0.70	0.40	0.50
Slightly rounded entrances	0.92	0.79	0.90	0.60	0.18	0.23
Fully rounded entrances (r/D ≥ 0.15)	0.96	0.88	0.95	0.27	0.08	0.10
Circular bellmouth entrances	0.98	0.95	0.98	0.10	0.04	0.05
Square bellmouth entrances	0.97	0.91	0.93	0.20	0.07	0.16
Inward projecting entrances	0.80	0.72	0.75	0.93	0.56	0.80

Losses Through Slots:

The head losses through gate slots can be computed by:

$$hsl = Ksl \times \frac{V^2}{2g} \tag{22}$$

where hsl (m) is the losses through slots, and Ksl is the slot loss coefficient. Ksl can be taken as 0.05 for main gates and 0.02 for auxiliary gates [77].

Transition Loss:

Transition losses take place due to change of shape or cross-sectional area of the conduits. They can be calculated by the following equation:

$$htr = Ktr \times \frac{V_2^2 - V_1^2}{2g} \tag{23}$$

where htr (m) is the transition loss, Ktr is the transition loss coefficient, V_1 (m/s) is the velocity of fluid at the beginning of the transition, and V_2 (m/s) is the velocity of fluid at the end of the transition. Figure 5.1 represents the Ktr values of circular contracted conduits:

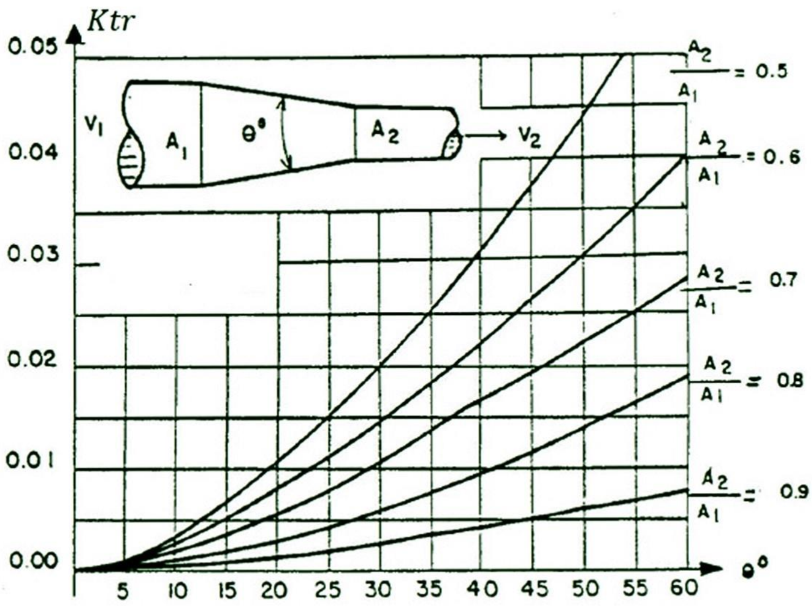


Figure 5.1. Transition loss coefficients for circular contracted conduits [77]

<u>Friction Loss due to Transition:</u>

The modification of Manning Equation can be useful for calculating friction losses in the transition section.

$$h_f = \frac{n^2 \times Q^2}{A_{ave}^2 \times R_{ave}^{4/3}} \times L \tag{24}$$

In the equation above, Q (m^3/s) is the discharge, R_{ave} (m) is the average hydraulic radius, n is the Manning roughness coefficient, A_{ave} (m^2) is the average cross-sectional area of flow and L (m) is the length of transition.

5.2.2.2. Bend (Elbow) Loss

Bend loss in pressurized pipes is a function of the bend radius, the pipe diameter and the angle through which the bend turns. It can be calculated as follows:

$$hel = Kel \times \frac{V^2}{2g} \tag{25}$$

in which hel (m) is the bend loss and Kel is the bend loss coefficient. Figure 5.2 clarifies the selection of the value of Kel. According to Mosonyi [78], average values of Kel can be picked between 0.05 and 0.15.

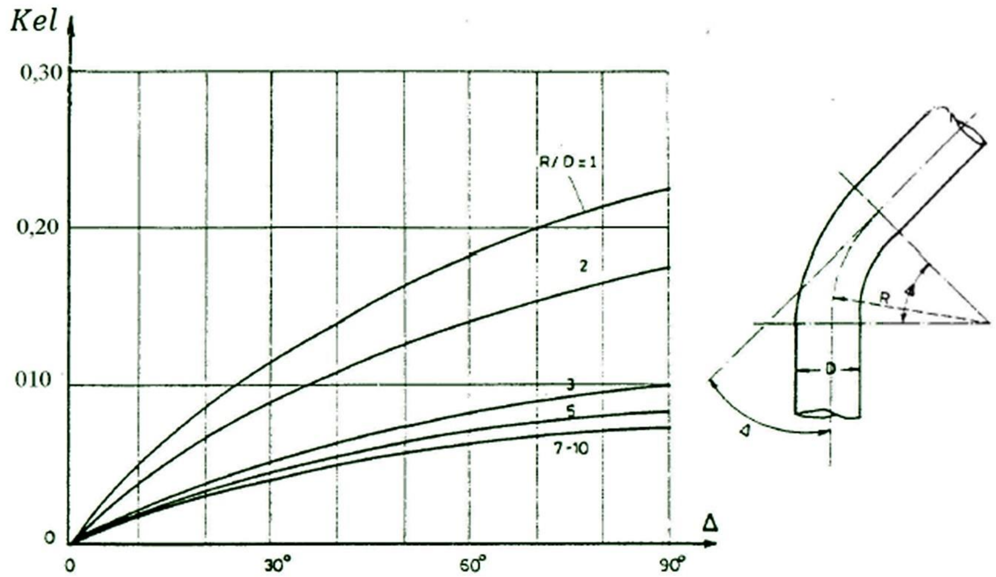


Figure 5.2. Bend loss coefficient [77]

5.2.2.3. Branch Loss

The head losses due to bifurcation depend on:

- Direction of flow which may be dividing or combining
- Branching angle
- Percentage of discharge diverted to or received from a branch
- Area relations between branches and inlet pipe [79].

It can be calculated by:

$$hbr = Kbr \times \frac{{V_b}^2}{2g} \tag{26}$$

$$Kbr = \left[K_1 + K_2 \left(\frac{Q_1}{Q_2}\right)^2 \left(\frac{A_2}{A_1}\right)^2\right] \tag{27}$$

where hbr (m) is the loss through branches, Kbr is the branch loss coefficient, V_b (m/s) is the velocity of fluid in branched pipe, K_1 and K_2 are branch coefficients, Q_1 (m^3/s) is the discharge in main pipe, Q_2 (m^3/s) is the discharge in branch pipe, A_1 (m^2) is the main pipe cross-sectional area and A_2 (m^2) is the branch pipe cross-sectional area. Figure 5.3 demonstrates how K_1 and K_2 values are selected:

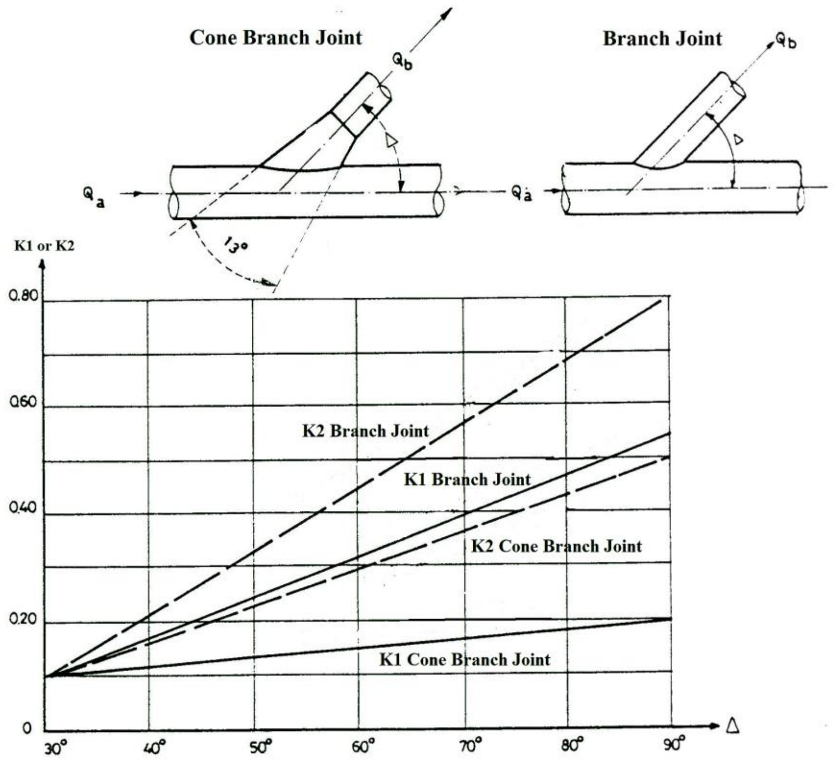


Figure 5.3. Branch coefficients [77]

5.2.2.4. Expansion Loss

The head loss due to expansion in the pipe cross-section can calculated by:

$$hex = Kex \times \frac{{V_1}^2 - {V_2}^2}{2g} \tag{28}$$

in which hex (m) is the expansion loss, Kex is the expansion loss coefficient, V_1 (m/s) is the velocity of fluid at the beginning of the expansion, and V_2 (m/s) is the velocity of fluid at the end of expansion. Figure 5.4 represents the loss coefficient for a gradual expansion.

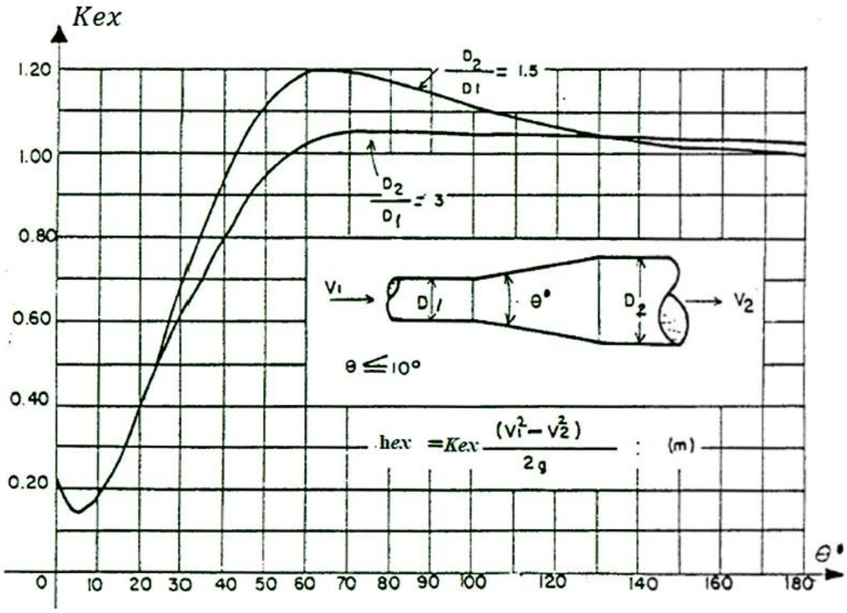


Figure 5.4. Expansion loss coefficient [77]

5.2.2.5. Exit Loss

The exit loss, $hext$ (m), can be calculated by the following equation;

$$hext = Kext \times \frac{V^2}{2g} \tag{29}$$

According to USBR [74], the loss coefficient $Kext$ equals 1.0.

5.3. Efficiencies

The efficiency of pump-turbines has a great effect on power input or output gathered from PSH. The following equations represent the obtaining of generation and pump mode efficiencies, η_g and η_p.

$$\eta_g = \eta_{pt} \times \eta_{gm} \times \eta_{wc} \times \eta_{tr} \quad (30)$$

$$\eta_p = \eta_{pt} \times \eta_{gm} \times \eta_{wc} \times \eta_{tr} \quad (31)$$

where η_{pt} is the efficiency of pump-turbine, η_{gm} is the efficiency of generator motor, η_{wc} is the efficiency of water conductors and η_{tr} is the efficiency of transformer. Table 5.3 represents the range of efficiency of each PSH component.

Table 5.3. *Cycling efficiency of a PSH [80]*

	Low %	*High %*
Generating Components		
Water conductors	97.40	98.50
Pump turbine	91.50	92.00
Generator motor	98.50	99.00
Transformer	99.50	99.70
Subtotal	87.35	89.44
Pumping Components		
Water conductors	97.60	98.50
Pump turbine	91.60	92.50
Generator motor	98.70	99.00
Transformer	99.50	99.80
Subtotal	87.80	90.02
Operational	98.00	99.50
Total	**75.15%**	**80.12%**

CHAPTER 6

CASE STUDY AND SCENARIOS

6.1. General

In this chapter, potential profitability/unprofitability of a projected PSH facility in Turkey is examined. In addition to the economic aspect, possible benefits for Turkey's electricity system are analyzed from the perspective of public welfare.

As mentioned in Chapter 2, Karacaören II, Gökçekaya and Altınkaya PSH facilities appear outstanding in the 2011 report of JICA and the conceptual designs of Gökçekaya and Altınkaya PSHs are shown in the same report. Table 6.1 and 6.2 represents the main features of these plants [41].

Concerning the calculations, some of the required parameters such as generation discharge, waterway diameters and lengths, water levels of upper and lowers reservoirs are obtained from JICA's report, whereas all other necessary data to calculate head losses such as minor loss coefficients or equivalent roughness values are determined through stages that are mentioned in Chapter 5.

Table 6.1. *Main features of Gökçekaya and Altınkaya PSHs I [41]*

Main Features of Gökçekaya and Altınkaya PSH					
Description			Unit	Gökçekaya PSH	Altınkaya PSH
General	Designed Discharge	Q	m^3/s	428	350
	Turbine Type			Single-Stage Francis	Single-Stage Francis
	Turbine Number		unit	4	4
Upper Reservoir	Type			Full Face Pond (Asphalt)	Concrete Gravity Dam
	Height	H	m	35	79
	Crest Length	L	m	2,700	330
	Dam (Bank) Volume	V	m^3	1,557,000	467,000
	Reservoir Area	Ra	km^2	0.5	0.5

Table 6.2. *Main features of Gökçekaya and Altınkaya PSHs II [41]*

Main Features of Gökçekaya and Altınkaya PSH					
Description			Unit	Gökçekaya PSH	Altınkaya PSH
Upper Reservoir	Catchment Area	Ca	km^2	4.8	60.6
	H.W.L		m	800	829
	L.W.L		m	770	802
	Usable Water Depth		m	30	27
	Effective Reservoir Capacity		10^6 m^3	10.8	8.9
Lower	H.W.L		m	389	190
	L.W.L		m	377.5	160
	Usable Water Depth		m	11.5	30
	Effective Reservoir Capacity		10^6 m^3	214	2,892
Waterway	Intake	L(m) x n	m	Bellmouth 34 x 1, Tunnel 396 x 1	Open 60 x 1, Tunnel 99 x 1
	Headrace	L(m) x n	m	2,028 x 1	2,083 x 1
		D	m	9.2	8.4
	Penstock	L(m) x n	m	662 x 2 , 110 x 4	1,066 x 2, 110 x 4
		D	m	5.3 , 3.7	4.8 , 3.4
	Tailbay	L(m) x n	m	125 x 4 , 116 x 2	105 x 4, 112 x 2
		D	m	4.6 , 6.5	4.2 , 5.9
	Tailrace	L(m) x n	m	476 x 1	1,694 x 1
		D	m	9.2	8.4
	Outlet	L(m) x n	m	Tunnel 53 x 1, Open 51 x 1	Tunnel 37 x 1, Open 45 x 1
	Total Length	Lt	m	4,051	5,411
Powerhouse	Type			Egg-shape (Underground)	Egg-shape (Underground)
	Overburden		m	365	437
	Height		m	57.5	56.1
	Width		m	37	36
	Length		m	210	213.5
	Cavern Volume		m^3	266,000	266,000

6.2. Determining the Capacity of Gökçekaya PSH

6.2.1. Total Installed Capacity

As mentioned in Chapter 5, one should calculate friction and minor losses first in order to determine the installed capacity of a hydropower plant. Friction losses in the Gökçekaya PSH system are calculated by the Darcy-Weisbach equation as shown in Equation 14 and Darcy Friction Factor is calculated by Swamee and Jain equation as shown in Equation 18. The equivalent roughness, ε (mm) is taken as 0.035 mm for steel pipes (penstocks) and 0.5 mm for concrete pipes (tunnels). Table 6.3 represents the calculation of the friction losses of Gökçekaya PSH.

Minor losses in the water carrying system of Gökçekaya PSH are shown in the Table 6.4. The required data collected from JICA's report and minor loss coefficients are determined as mentioned in Chapter 5. After obtaining the total head loss, the net head can be calculated as follows:

$$H_{net} = 392.5 - (13.7373 + 4.1723) = 374.59\ m$$

The efficiency of water conductors can be calculated by Equation 32. η_{wc} of Gökçekaya PSH is accordingly calculated below:

$$\eta_{wc} = \left(1 - \frac{h_f + h_m}{H_g}\right) \times 100 \qquad (32)$$

$$\eta_{wc} = \left(1 - \frac{13.7373 + 4.1723}{392.5}\right) \times 100 = 95.44\%$$

The efficiency of pump-turbine (η_{pt}), the efficiency of generator motor (η_{gm}) and the efficiency of transformer (η_{tr}) are taken as 92%, 99% and 99.7% respectively.

Therefore generation mode efficiency of Gökçekaya PSH (η_g) can be calculated by Equation 30:

$$\eta_g = \eta_{pt} \times \eta_{gm} \times \eta_{wc} \times \eta_{tr} = 0.92 \times 0.99 \times 0.9544 \times 0.997 = 86.66\%$$

Finally, the installed power of Gökçekaya PSH can be calculated by Equation 1. It is assumed that all of the four turbines are operated at full capacity.

$$\begin{aligned} P = \ & \rho \times g \times Q \times H_{net} \times \eta_g \times 10^{-6} \\ & = 1000 \times 9.81 \times 428 \times 374.59 \times 0.8666 \times 10^{-6} \\ & = 1{,}362.56\ MW \end{aligned}$$

Table 6.3. *Friction losses of Gökçekaya PSH in the water carrying system during generation*

Friction Losses During Generation with Darcy-Weisbach							
Intake					**Headrace**		
Intake Tunnel Dia.		m	9.2		Headrace Tunnel Dia.	m	9.2
Tunnel Length		m	396		Tunnel Length	m	2,028
Number of Tunnel		#	1		Number of Tunnel	#	1
Velocity in Tunnel		m/s	6.44		Velocity in Tunnel	m/s	6.44
Re			5.92E+07		Re		5.92E+07
ftunnel			0.0074		ftunnel		0.0108
ε/D			3.80E-06		ε/D		5.43E-05
hf		**m**	**0.6773**		**hf**	**m**	**5.0195**
Penstocks							
Section I	Penstock Diameter I	m	5.3	Section II	Penstock Diameter II	m	3.7
	Penstock Length I	m	662		Penstock Length II	m	110
	Number of Penstock I	#	2		Number of Penstock II	#	4
	Velocity in Penstock I	m/s	9.70		Velocity in Penstock II	m/s	9.95
	Re		5.14E+07		Re		5.27E+07
	fpenstock I		0.0079		fpenstock II		0.0079
	ε/D		6.60E-06		ε/D		6.60E-06
	hf1	**m**	**4.7549**		**hf2**	**m**	**1.1901**
Tailbays							
Section I	Tailbay Diameter I	m	4.6	Section II	Tailbay Diameter II	m	6.5
	Tailbay Length I	m	125		Tailbay Length II	m	116
	Number of Tailbay I	#	4		Number of Tailbay II	#	2
	Velocity in Tailbay I	m/s	6.44		Velocity in Tailbay II	m/s	6.45
	Re		2.96E+07		Re		2.97E+07
	ftailbay I		0.0083		ftailbay II		0.0083
	ε/D		7.61E-06		ε/D		7.61E-06
	hf1	**m**	**0.4739**		**hf2**	**m**	**0.3123**
Tailrace							
Tailrace Diameter		m	9.2		Re		5.92E+07
Tailrace Length		m	529		ftailrace		0.0108
Number of Tailrace		#	1		ε/D		5.43E-05
Velocity in Tailrace		m/s	6.44		**hf**	**m**	**1.3093**
						Σhf=	**13.7373**

Table 6.4. *Minor losses of Gökçekaya PSH in the water carrying system during generation*

Minor Losses During Generation					
Trashrack Loss			**Branch Loss**		
ht	**m**	**0.0082**	**hbr**	**m**	**2.0414**
Ktr		0.645	K1		0.15
An/Ag		0.7	K2		0.29
V	m/s	0.50	Q1	m^3/s	214
Entrance Loss			Q2	m^3/s	107
hen	**m**	**0.0011**	A1	m^2	22.06
Ken		0.05	A2	m^2	10.75
V	m/s	0.65	Kbr		0.43
Friction Loss due to Transition			V	m/s	9.70
hf	**m**	**0.0011**			
A1	m^2	660.52	**Expansion Losses**		
A2	m^2	66.48	**hex**	**m**	**0.0049**
P1	m	91.11	Kex		0.70
P2	m	28.90	v1	m/s	6.45
R1	m	7.25	v2	m/s	6.44
R2	m	2.30	**Losses Through Slots**		
Aave	m^2	363.50	**hsl**	**m**	**0.0652**
Rave	m	4.78	Ksl		0.05
L	m	33.70	Gate Width	m	9.20
Elbow (Intake Tunnel)			Water Height	m	9.20
hel	**m**	**0.3382**	V	m/s	5.06
R	m	20	**Friction Loss due to Transition**		
D	m	9.2	**hf**	**m**	**0.0234**
Δ	degree	90	A1	m^2	23.70
Kel		0.16	A2	m^2	78.20
V	m/s	6.44	P1	m	23.55
Losses Through Slots			P2	m	35.40
hsl	**m**	**0.0652**	R1	m	1.01
Ksl		0.05	R2	m	2.21
Gate Width	m	9.20	Aave	m^2	50.95
Water Height	m	9.20	Rave	m	1.61
V	m/s	5.06	L	m	51.00

Table 6.4. (Continued)

Branch Loss				Trashrack Loss		
hbr	**m**	**0.5871**		**htr**	**m**	**0.1257**
K1		0.15		Ktr		0.65
K2		0.29		An/Ag		0.70
Q1	m^3/s	428		An	m^2	54.74
Q2	m^3/s	214		Ag	m^2	78.20
A1	m^2	66.48		V	m/s	1.95
A2	m^2	22.06		**Exit Loss**		
Kbr		0.28		**hext**	**m**	**0.0955**
V	m/s	6.44		Kext		1
Elbow (Penstock)				Gate Width	m	8.50
hel	**m**	**0.8155**		Gate Height	m	9.20
R	m	20		V	m/s	1.37
D	m	5.3				
Δ	degree	90				
Kel		0.085				
n	#	2				
V	m/s	9.70		**Σhminor=**	**m**	**4.1723**

6.2.2. Total Pumping Capacity

In order to determine pumping capacity of a PSH, the first thing to calculate is the pumping discharge which is related to discharge during electricity generation and the operation time of pump and turbine modes. For the analysis in this thesis, daily operation is referred to since Gökçekaya is planned to be a pure PSH and the upper reservoir capacity is limited. Therefore, evaporation and leakage losses are ignored and the volume of water is assumed to be equal during generation and pumping operations. For instance, 5 hours of generation and 7 hours of pumping are used to calculate the pumping discharge as shown below:

$$\not{V} = 428 \times 5 \times 3600 = 7{,}704{,}000\ m^3$$

$$Q_p = 7704000/(7 \times 3600) = 305.71\ m^3/sec$$

Having obtained Q_p, friction and minor losses during pumping mode are calculated and represented in Table 6.5 and Table 6.6. The net pumping head is determined as follows:

$$H_p = 392.5 + (7.0734 + 2.8296) = 402.40\ m$$

The efficiency of water conductors (η_{wc}) is calculated below:

$$\eta_{wc} = \left(1 - \frac{7.0734 + 2.8296}{392.5}\right) \times 100 = 97.48\%$$

The efficiency of pump-turbine (η_{pt}), the efficiency of generator motor (η_{gm}) and the efficiency of transformer (η_{tr}) are taken as 92.5%, 99% and 99.8% respectively. Accordingly, pumping mode efficiency of Gökçekaya PSH (η_g) is calculated below:

$$\eta_g = \eta_{pt} \times \eta_{gm} \times \eta_{wc} \times \eta_{tr} = 0.925 \times 0.99 \times 0.9748 \times 0.998 = 89.09\%$$

Finally, total pumping input of Gökçekaya PSH for 5 hours of generation and 7 hours of pumping can be calculated by Equation 3:

$$P_p = \rho \times g \times Q_p \times H_p \times 10^{-6} \div \eta_p$$
$$= 1000 \times 9.81 \times 305.71 \times 402.40 \times 10^{-6} \div 0.8909$$
$$= 1{,}354.22\ MW$$

Table 6.5. *Friction losses of Gökçekaya PSH in the water carrying system during pumping*

Friction Losses During Pumping with Darcy-Weisbach								
Intake					Headrace			
Intake Tunnel Dia.		m	9.2		Headrace Tunnel Dia.	m	9.2	
Tunnel Length		m	396		Tunnel Length	m	2,028	
Number of Tunnel		#	1		Number of Tunnel	#	1	
Velocity in Tunnel		m/s	4.60		Velocity in Tunnel	m/s	4.60	
Re			4.23E+07		Re		4.23E+07	
ftunnel			0.0076		ftunnel		0.0108	
ε/D			3.80E-06		ε/D		5.43E-05	
hf		**m**	**0.3519**		**hf**	**m**	**2.5672**	
Penstocks								
Section I	Penstock Diameter I	m	5.3	Section II	Penstock Diameter II	m	3.7	
	Penstock Length I	m	662		Penstock Length II	m	110	
	Number of Penstock I	#	2		Number of Penstock II	#	4	
	Velocity in Penstock I	m/s	6.93		Velocity in Penstock II	m/s	7.11	
	Re		3.67E+07		Re		3.77E+07	
	fpenstock I		0.0080		fpenstock II		0.0080	
	ε/D		6.60E-06		ε/D		6.60E-06	
	hf1	**m**	**2.4605**		**hf2**	**m**	**0.6157**	
Tailbays								
Section I	Tailbay Diameter I	m	4.6	Section II	Tailbay Diameter II	m	6.5	
	Tailbay Length I	m	125		Tailbay Length II	m	116	
	Number of Tailbay I	#	4		Number of Tailbay II	#	2	
	Velocity in Tailbay I	m/s	4.60		Velocity in Tailbay II	m/s	4.61	
	Re		2.12E+07		Re		2.12E+07	
	ftailbay I		0.0084		ftailbay II		0.0084	
	ε/D		7.61E-06		ε/D		7.61E-06	
	hf1	**m**	**0.2463**		**hf2**	**m**	**0.1622**	
Tailrace								
Tailrace Diameter		m	9.2		Re		4.23E+07	
Tailrace Length		m	529		ftailrace		0.0108	
Number of Tailrace		#	1		ε/D		5.43E-05	
Velocity in Tailrace		m/s	4.60		**hf**	**m**	**0.6696**	
						Σhf=	**7.0734**	

Table 6.6. *Minor losses of Gökçekaya PSH in the water carrying system during pumping*

Minor Losses During Pumping					
Entrance Loss			**Expansion Losses**		
hen	**m**	**0.0078**	**hex**	**m**	**0.0900**
Ken		0.16	Kex		0.70
V	m/s	0.98	v1	m/s	7.11
Trashrack Loss			v2	m/s	6.93
ht	**m**	**0.0641**	**Elbow (Penstock)**		
Ktr		0.645	**hel**	**m**	**0.4161**
An/Ag		0.70	R	m	20
An	m^2	54.74	D	m	5.3
Ag	m^2	78.20	Δ	degree	90
V	m/s	1.40	Kel		0.085
Transition Loss			n	#	2
htra	m	**0.1445**	V	m/s	6.93
Ktra		0.30	**Expansion Losses**		
A1	m2	78.20	**hex**	**m**	**0.8900**
A2	m2	23.70	Kex		0.65
V1	m/s	0.98	v1	m/s	6.93
V2	m/s	3.22	v2	m/s	4.60
Friction Loss due to Transition			**Losses Through Slots**		
hf	**m**	**0.0119**	**hsl**	**m**	**0.0333**
A1	m^2	78.20	Ksl		0.05
A2	m^2	23.70	Gate Width	m	9.20
P1	m	35.40	Water Height	m	9.20
P2	m	23.55	V	m/s	3.61
R1	m	2.21	**Elbow (Intake Tunnel)**		
R2	m	1.01	**hel**	**m**	**0.1725**
Aave	m^2	50.95	R	m	20
Rave	m	1.61	D	m	9.2
L	m	51.00	Δ	degree	90
			Kel		0.16
			n	#	1
			V	m/s	4.60

Table 6.6. (Continued)

Losses Through Slots				Friction Loss due to Transition		
hsl	**m**	**0.0333**		**hf**	**m**	**0.0006**
Ksl		0.05		A1	m^2	66.48
Gate Width	m	9.20		A2	m^2	660.52
Water Height	m	9.20		P1	m	28.90
V	m/s	3.61		P2	m	91.11
Branch Loss				R1	m	2.30
hbr	**m**	**0.4734**		R2	m	7.25
K1		0.15		Aave	m^2	363.50
K2		0.29		Rave	m	4.78
Q1	m^3/s	305.71		L	m	33.70
Q2	m^3/s	152.86		**Trashrack Loss**		
A1	m^2	66.48		**htr**	**m**	**0.0086**
A2	m^2	33.18		Ktr		0.65
Kbr		0.44		An/Ag		0.70
V	m/s	4.60		V	m/s	0.51
Branch Loss				**Exit Loss**		
hbr	**m**	**0.4771**		**hext**	**m**	**0.0065**
K1		0.15		Kext		1
K2		0.29		V	m/s	0.36
Q1	m^3/s	152.86				
Q2	m^3/s	76.43				
A1	m^2	33.18				
A2	m^2	16.62				
Kbr		0.44				
V	m/s	4.61		**Σhminor=**	**m**	**2.8296**

6.2.3. Operation Modes

As mentioned in Chapter 2, different types of pump-turbines can be used in the application of PSH. One of these types, adjustable speed technology, has an advantage of controlling input power during pumping mode by adjusting the rotation speed of the unit. Therefore, this type of PSH can help the power grid to improve frequency control capacity during pumping mode. According to JICA's projected conceptual design for Gökçekaya PSH, adjustable speed pump-turbine is planned to be used. Pump characteristics are shown in Figure 6.1 [12].

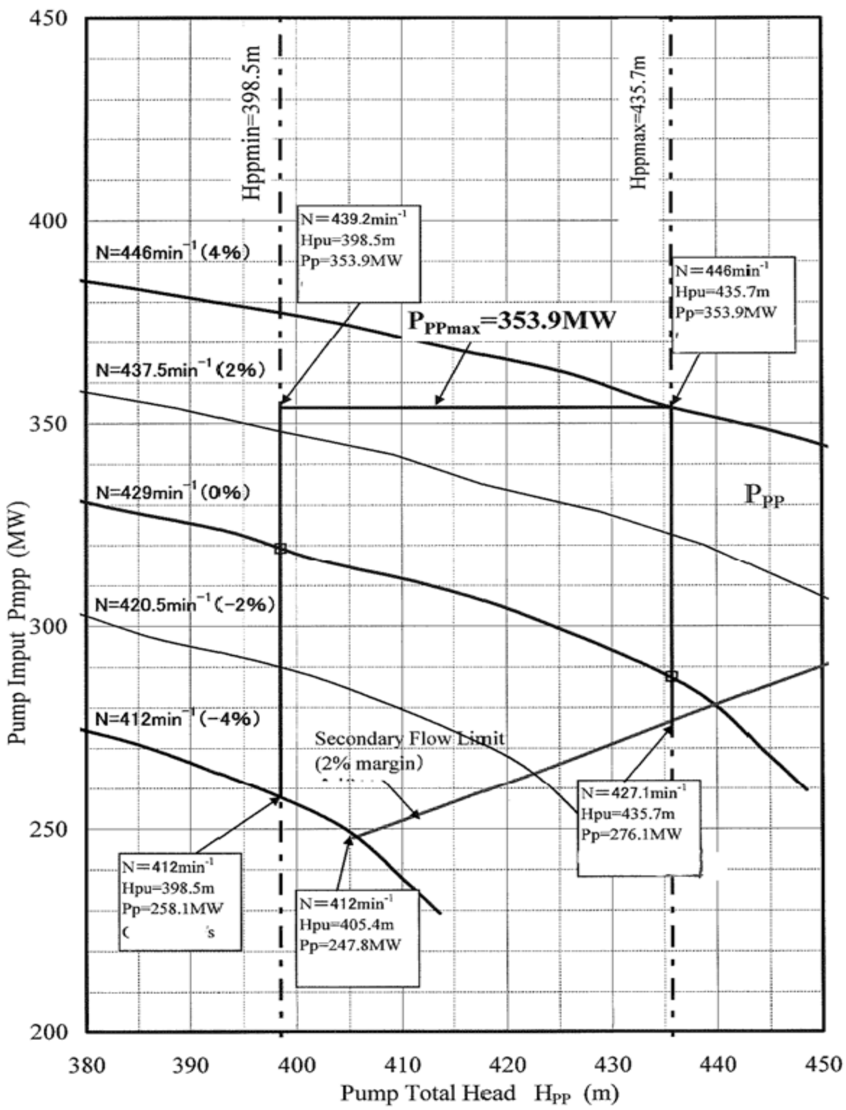


Figure 6.1. Pump Characteristics of Gökçekaya PSH [12]

According to the figure above, adjustable range of pumping capacity is between 258.1 MW and 353.9 MW for Gökçekaya PSH. Besides, maximum pumping head is 435.7 m and minimum pumping head is 398.5 m.

Ten different operation modes are determined for Gökçekaya PSH as mentioned in the calculations of 5 hour-generation and 7 hour-pumping operation mode. Table 6.7 represents these variety of modes with their main characteristics. In order to avoid unrealistic operation modes, remaining within the limits specified in the Figure 6.1 was carefully looked out for.

Table 6.7. *Different operation modes of Gökçekaya PSH*

Generation Hour (hr)	Pumping Hour (hr)	Pumping Discharge (m^3/sec)	Pumping Head (m)	Pumping Capacity of 1 Unit (MW)	Total Pumping Capacity (MW)
3	5	256.80	399.52	280.23	1,120.92
4	6	285.33	401.14	313.96	1,255.82
4	7	244.57	398.87	266.01	1,064.04
5	7	305.71	402.40	338.55	1,354.22
5	8	267.50	400.11	292.78	1,171.14
6	9	285.33	401.14	313.96	1,255.82
6	10	256.80	399.52	280.23	1,120.92
7	10	299.60	402.02	331.13	1,324.51
7	11	272.36	400.38	298.53	1,194.11
7	12	249.67	399.14	271.92	1,087.68

6.3. Determining the Capacity of Altınkaya PSH

6.3.1. Total Installed Capacity

Hydraulic properties of Altınkaya PSH are determined based on the same procedure as Gökçekaya PSH. Necessary data is collected from JICA's report and head loss calculations are represented in Table 6.8 and 6.9. The equivalent roughness, ε (mm) is taken as 0.040 mm for steel pipes (penstocks) and 0.5 mm for concrete pipes (tunnels). Installed capacity is determined by the following stages:

$$H_{net} = 642 - (21.1166 + 6.5126) = 614.37\ m$$

$$\eta_{wc} = \left(1 - \frac{21.1166 + 6.5126}{642}\right) \times 100 = 95.70\%$$

The efficiency of pump-turbine (η_{pt}), the efficiency of generator motor (η_{gm}) and the efficiency of transformer (η_{tr}) is taken as 91.5%, 98.5% and 99.5% respectively. Generation mode efficiency of Altınkaya PSH can be therefore calculated as follows:

$$\eta_g = \eta_{pt} \times \eta_{gm} \times \eta_{wc} \times \eta_{tr} = 0.915 \times 0.985 \times 0.957 \times 0.995 = 85.82\%$$

Finally, the installed power of Altınkaya PSH can be determined using Equation 1. It is assumed that all the four turbines are operated at full capacity.

$$\begin{aligned} P = {} & \rho \times g \times Q \times H_{net} \times \eta_g \times 10^{-6} \\ & = 1000 \times 9.81 \times 350 \times 614.37 \times 0.8582 \times 10^{-6} \\ & = 1{,}809.65\ MW \end{aligned}$$

Table 6.8. *Friction losses of Altınkaya PSH in the water carrying system during generation*

Friction Losses of Altınkaya PSH During Generation with Darcy-Weisbach							
Headrace							
Headrace Tunnel Dia.		m	8.4		Re		5.31E+07
Tunnel Length		m	2,182		ftailrace		0.0110
Number of Tunnel		#	1		ε/D		5.95E-05
Velocity in Tunnel		m/s	6.32		**hf**	**m**	**5.79**
Penstocks							
Section I	Penstock Diameter I	m	4.8	Section II	Penstock Diameter II	m	3.40
	Penstock Length I	m	1,066		Penstock Length II	m	110
	Number of Penstock I	#	2		Number of Penstock II	#	4
	Velocity in Penstock I	m/s	9.67		Velocity in Penstock II	m/s	9.64
	Re		4.64E+07		Re		3.28E+07
	fpenstock I		0.0082		fpenstock II		0.0086
	ε/D		8.3E-06		ε/D		1.2E-05
	hf1	**m**	**8.6651**		**hf2**	**m**	**1.3228**
Tailbays							
Section I	Tailbay Diameter I	m	4.2	Section II	Tailbay Diameter II	m	5.90
	Tailbay Length I	m	105		Tailbay Length II	m	112
	Number of Tailbay I	#	4		Number of Tailbay II	#	2
	Velocity in Tailbay I	m/s	6.32		Velocity in Tailbay II	m/s	6.40
	Re		2.65E+07		Re		3.78E+07
	ftailbay I		0.0085		ftailbay II		0.0081
	ε/D		9.5E-06		ε/D		6.8E-06
	hf1	**m**	**0.4319**		**hf2**	**m**	**0.3196**
Tailrace							
Tailrace Diameter		m	8.4		Re		5.31E+07
Tailrace Length		m	1731		ftailrace		0.0110
Number of Tailrace		#	1		ε/D		6.0E-05
Velocity in Tailrace		m/s	6.32		**hf**	**m**	**4.5905**
						Σhf=	**21.1166**

Table 6.9. *Minor losses of Altınkaya PSH in the water carrying system during generation*

Minor Losses of Altınkaya PSH During Generation						
Entrance Loss				**Branch Loss**		
hen	**m**	**0.0080**		**hbr**	**m**	**3.5913**
Ken		0.16		K1		0.3
V	m/s	0.99		K2		0.45
Trashrack Loss				Q1	m^3/s	175
ht	**m**	**0.0661**		Q2	m^3/s	87.5
Ktr		0.645		A1	m^2	18.10
An/Ag		0.70		A2	m^2	9.08
V	m/s	1.42		Kbr		0.75
Transition Loss				V	m/s	9.67
htra	m	**0.2850**		**AFTER POWER HOUSE**		
Ktra		0.30		**Expansion Losses**		
A1	m^2	88.20		**hex**	**m**	**0.0205**
A2	m^2	19.76		Kex		0.37
V1	m/s	0.99		v1	m/s	6.40
V2	m/s	4.43		v2	m/s	6.32
Friction Loss due to Transition				**Losses Through Slots**		
hf	**m**	**0.0166**		**hsl**	**m**	**0.0627**
A1	m^2	88.20		Ksl		0.05
A2	m^2	19.76		Gate Width	m	8.40
P1	m	37.80		Water Height	m	8.40
P2	m	21.50		V	m/s	4.96
R1	m	2.33		**Friction Loss due to Transition**		
R2	m	0.92		**hf**	**m**	**0.3960**
Aave	m^2	53.98		A1	m^2	19.76
Rave	m	1.63		A2	m^2	61.32
L	m	61.50		P1	m	21.50
Losses Through Slots				P2	m	31.40
hsl	**m**	**0.0627**		R1	m	0.92
Ksl		0.05		R2	m	1.95
Gate Width	m	8.40		Aave	m^2	40.54
Water Height	m	8.40		Rave	m	1.44
V	m/s	4.96		L	m	43.90

Table 6.9. (Continued)

Minor Losses of Altınkaya PSH During Generation						
Branch Loss				**Trashrack Loss**		
hbr	**m**	**1.0004**		**htr**	**m**	**0.1367**
K1		0.30		Ktr		0.645
K2		0.45		An/Ag		0.70
Q1	m^3/s	350		An	m^2	42.92
Q2	m^3/s	175		Ag	m^2	61.32
A1	m^2	55.42		V	m/s	2.04
A2	m^2	18.10		**Exit Loss**		
Kbr		0.49		**hext**	**m**	**0.1038**
V	m/s	6.32		Kext		1
Elbow (Penstock)				Gate Width	m	7.30
hel	**m**	**0.7630**		Gate Height	m	8.40
R	m	20		V	m/s	1.43
D	m	4.80				
Δ	degree	45				
Kel		0.08				
n	#	2				
V	m/s	9.67		**Σhminor=**	**m**	**6.5126**

6.3.2. Total Pumping Capacity

Pumping capacity of Altınkaya PSH are determined based on the same procedure as Gökçekaya PSH. For instance, 4 hours of generation and 6 hours of pumping are used to calculate the pumping discharge as shown below:

$$\forall = 350 \times 4 \times 3600 = 5{,}040{,}000\ m^3$$

$$Q_p = 5040000/\ (6 \times 3600) = 233.33\ m^3/sec$$

The head loss calculations are shown in Table 6.10 and 6.11. The net head can be found after calculations of head losses are done:

$$H_p = 642 + (9.4781 + 2.8787) = 654.36\,m$$

$$\eta_{wc} = \left(1 - \frac{9.4781 + 2.8787}{642}\right) \times 100 = 98.08\%$$

$$\eta_g = \eta_{pt} \times \eta_{gm} \times \eta_{wc} \times \eta_{tr} = 0.916 \times 0.987 \times 0.9808 \times 0.995$$
$$= 88.23\%$$

Finally, total pumping capacity is calculated as follow:

$$P_p = \rho \times g \times Q_p \times H_p \times 10^{-6} \div \eta_p$$
$$= 1000 \times 9.81 \times 654.36 \times 233.33 \times 10^{-6} \div 0.8823$$
$$= 1{,}697.14\,MW$$

Table 6.10. *Friction losses of Altınkaya PSH in the water carrying system during pumping*

Friction Losses of Altınkaya PSH During Pumping with Darcy-Weisbach							
Headrace							
Headrace Tunnel Diameter		m	8.4		Re		3.54E+07
Tunnel Length		m	2,182		ftailrace		0.0110
Number of Tunnel		#	1		ε/D		5.95E-05
Velocity in Tunnel		m/s	4.21		**hf**	**m**	**2.58**
Penstocks							
Section I	Penstock Diameter I	m	4.8	Section II	Penstock Diameter II	m	3.40
	Penstock Length I	m	1,066		Penstock Length II	m	110
	Number of Penstock I	#	2		Number of Penstock II	#	4
	Velocity in Penstock I	m/s	6.45		Velocity in Penstock II	m/s	6.42
	Re		3.09E+07		Re		2.18E+07
	fpenstock I		0.0083		fpenstock II		0.0088
	ε/D		8.3E-06		ε/D		1.2E-05
	hf1	**m**	**3.9134**		**hf2**	**m**	**0.5975**
Tailbays							
Section I	Tailbay Diameter I	m	4.2	Section II	Tailbay Diameter II	m	5.90
	Tailbay Length I	m	105		Tailbay Length II	m	112
	Number of Tailbay I	#	4		Number of Tailbay II	#	2
	Velocity in Tailbay I	m/s	4.21		Velocity in Tailbay II	m/s	4.27
	Re		1.77E+07		Re		2.52E+07
	ftailbay I		0.0087		ftailbay II		0.0082
	ε/D		9.5E-06		ε/D		6.8E-06
	hf1	**m**	**0.1961**		**hf2**	**m**	**0.1450**
Tailrace							
Tailrace Diameter		m	8.4		Re		3.54E+07
Tailrace Length		m	1731		ftailrace		0.0110
Number of Tailrace		#	1		ε/D		6.0E-05
Velocity in Tailrace		m/s	4.21		**hf**	**m**	**2.0465**
						Σhf=	**9.4781**

Table 6.11. *Minor losses of Altınkaya PSH in the water carrying system during pumping*

Minor Losses of Altınkaya PSH During Pumping					
Entrance Loss			**Branch Loss**		
hen	**m**	**0.0074**	**hbr**	**m**	**0.7170**
Ken		0.16	K1		0.31
V	m/s	0.95	K2		0.45
Trashrack Loss			Q1	m^3/s	116.67
ht	**m**	**0.1367**	Q2	m^3/s	58.33
Ktr		0.645	A1	m^2	27.34
An/Ag		0.70	A2	m^2	13.85
V	m/s	2.04	Kbr		0.77
Transition Loss			V	m/s	4.27
htra	m	**0.2689**	**Elbow (Penstock)**		
Ktra		0.30	**hel**	**m**	**0.3391**
A1	m^2	61.32	R	m	20
A2	m^2	19.76	D	m	4.80
V1	m/s	1.43	Δ	degree	45
V2	m/s	4.43	Kel		0.08
Friction Loss due to Transition			n	#	2
hf	**m**	**0.0110**	V	m/s	6.45
A1	m^2	61.32	**Losses Through Slots**		
A2	m^2	19.76	**hsl**	**m**	**0.0279**
P1	m	31.40	Ksl		0.05
P2	m	21.50	Gate Width	m	8.40
R1	m	1.95	Water Height	m	8.40
R2	m	0.92	V	m/s	3.31
Aave	m^2	40.54			
Rave	m	1.44			
L	m	43.90			
Losses Through Slots					
hsl	**m**	**0.0279**			
Ksl		0.05			
Gate Width	m	8.40			
Water Height	m	8.40			
V	m/s	3.31			

Table 6.11. (Continued)

Minor Losses of Altınkaya PSH During Pumping						
Expansion Loss				**Friction Loss due to Transition**		
hex	**m**	**0.6077**		**hf**	**m**	**0.0074**
Kex		0.5		A1	m^2	19.76
V1	m/s	6.45		A2	m^2	88.20
V2	m/s	4.21		P1	m	21.50
Branch Loss				P2	m	37.80
hbr	**m**	**0.6762**		R1	m	0.92
K1		0.31		R2	m	2.33
K2		0.45		Aave	m^2	53.98
Q1	m^3/s	233.33		Rave	m	1.63
Q2	m^3/s	116.67		L	m	61.50
A1	m^2	55.42		**Trashrack Loss**		
A2	m^2	27.34		**htr**	**m**	**0.0294**
Kbr		0.75		Ktr		0.645
V	m/s	4.21		An/Ag		0.70
				An	m^2	61.74
				Ag	m^2	88.20
				V	m/s	0.94
				Exit Loss		
				hext	**m**	**0.0223**
				Kext		1
				Gate Width	m	10.50
				Gate Height	m	8.40
				V	m/s	0.66
				Σhminor=	**m**	**2.8787**

6.3.3. Operation Modes

According to JICA's projected conceptual design for Altınkaya PSH, adjustable speed pump-turbine is planned to be used [41]. The maximum pumping head is 687.5 m and minimum pumping head is 625.5 m. Based on this data, 9 different operation modes are determined for Altınkaya PSH and Table 6.12 represents these modes with their main characteristics:

Table 6.12. *Different operation modes of Altınkaya PSH*

Generation Hour (hr)	Pumping Hour (hr)	Pumping Discharge (m^3/sec)	Pumping Head (m)	Pumping Capacity of 1 Unit (MW)	Total Pumping Capacity (MW)
3	5	210.00	652.11	379.19	1,516.76
4	6	233.33	654.36	424.28	1,697.14
4	7	200.00	651.22	360.13	1,440.53
5	8	218.75	652.92	396.00	1,583.98
6	9	233.33	654.36	424.28	1,697.14
6	10	210.00	652.11	379.19	1,516.76
7	10	245.00	655.57	447.18	1,788.73
7	11	222.73	653.31	403.67	1,614.70
7	12	204.17	651.58	368.05	1,472.22

6.4. Scenarios and Results

The real time MCPs are obtained from EPİAŞ between 01.01.2010 00:00 and 31.12.2018 23:00 to perform an economic analysis for all scenarios. All prices are converted to US dollar with daily rates obtained from The Central Bank of the Republic of Turkey. Daily operation is considered and system is operated on the profitable days only.

In calculations, the lowest MCPs of the day are used for pumping while the highest MCPs are used for generation. All economic analysis is performed using MS Excel.

Scenario I: PSH is operated with each operation mode in order to spot which operation mode is more profitable for that year.

Scenario II: In addition to the first scenario, prices of two successive days which are unprofitable are taken into consideration. The water is stored by pumping on the first day and electricity is generated on the following day if the electricity price difference on these days is fit to make profit.

Scenario III: PSH is operated by the most profitable operation mode for each day and therefore the potential maximum benefit is examined for each year.

Scenario IV: PSH's potential solutions to possible challenges that Turkey's electricity grid might face in the near future on the days with minimum demand is examined excluding benefit-cost calculations.

The results derived from these scenarios are given below:

Table 6.13. *Results based on scenario I and II for Gökçekaya PSH*

SCENARIO 1	2010		2011		2012		2013		2014	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
5 hr Gen.-7 hr Pump.	95,391,416	344	63,007,050	304	46,696,291	252	43,358,841	314	18,022,487	269
4 hr Gen.-6 hr Pump.	87,243,639	347	59,275,760	325	45,352,371	285	42,126,350	327	18,947,104	286
5 hr Gen.-8 hr Pump.	88,040,641	337	57,025,121	298	41,967,832	234	38,695,856	303	15,981,445	260
6 hr Gen.-9 hr Pump.	90,700,325	328	56,967,605	271	41,166,951	212	36,814,960	286	13,326,793	226
4 hr Gen.-7 hr Pump.	81,558,199	345	54,106,830	324	40,902,456	275	38,241,776	329	17,301,621	283
7 hr Gen.-10 hr Pump.	89,847,403	313	55,150,082	242	39,109,915	180	33,111,543	264	10,021,047	185
3 hr Gen.-5 hr Pump.	74,112,600	357	51,778,666	349	40,634,343	309	37,483,365	340	17,623,643	303
6 hr Gen.-10 hr Pump.	82,793,008	322	50,767,728	259	36,800,287	200	32,104,827	278	11,159,637	212
7 hr Gen.-11 hr Pump.	81,596,558	310	49,225,344	230	35,102,199	167	28,589,737	247	8,227,802	175
7 hr Gen.-12 hr Pump.	73,952,322	304	43,905,191	219	31,696,646	154	24,439,183	235	6,613,236	150
SCENARIO 1	**2015**		**2016**		**2017**		**2018**		**AVERAGE**	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
5 hr Gen.-7 hr Pump.	44,866,004	313	65,481,696	351	18,806,228	328	7,690,279	140	**44,813,366**	**291**
4 hr Gen.-6 hr Pump.	41,779,692	320	59,503,915	352	18,629,485	337	8,178,968	180	**42,337,476**	**307**
5 hr Gen.-8 hr Pump.	40,997,165	312	60,873,365	351	17,419,833	326	6,656,370	132	**40,850,847**	**284**
6 hr Gen.-9 hr Pump.	41,410,971	303	63,537,614	351	16,179,828	307	5,968,749	105	**40,674,866**	**265**
4 hr Gen.-7 hr Pump.	38,438,873	322	55,504,029	352	17,392,566	335	7,098,567	167	**38,949,435**	**304**
7 hr Gen.-10 hr Pump.	40,116,443	289	63,863,975	349	13,954,033	266	5,116,709	82	**38,921,239**	**241**
3 hr Gen.-5 hr Pump.	36,044,769	328	50,237,992	353	17,016,792	347	8,097,099	211	**37,003,252**	**322**
6 hr Gen.-10 hr Pump.	37,327,809	301	58,770,795	351	14,456,322	294	5,044,510	98	**36,580,547**	**257**
7 hr Gen.-11 hr Pump.	36,014,641	283	58,892,050	348	12,254,190	248	4,318,347	69	**34,913,430**	**231**
7 hr Gen.-12 hr Pump.	32,206,718	278	54,134,002	347	10,612,252	233	3,675,579	59	**31,248,348**	**220**

SCENARIO 2	2010		2011		2012		2013		2014	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
5 hr Gen.-7 hr Pump.	95,453,705	344	63,300,367	308	46,661,654	255	43,441,177	314	18,380,770	274
4 hr Gen.-6 hr Pump.	87,307,935	348	59,467,428	325	45,372,401	285	42,137,559	327	19,205,611	291
5 hr Gen.-8 hr Pump.	88,077,904	337	57,313,745	301	42,014,030	240	38,861,019	304	16,588,817	266
6 hr Gen.-9 hr Pump.	90,833,277	329	57,459,162	277	41,440,684	219	37,154,136	289	14,051,152	234
7 hr Gen.-10 hr Pump.	90,183,438	315	55,385,654	256	39,505,564	191	33,832,365	268	11,032,465	193
4 hr Gen.-7 hr Pump.	81,614,818	346	54,294,441	324	41,028,700	276	38,258,585	329	17,557,215	287
3 hr Gen.-5 hr Pump.	74,159,063	357	51,828,911	349	40,707,274	310	37,483,377	341	17,818,630	305
6 hr Gen.-10 hr Pump.	82,998,333	325	51,624,720	269	37,052,511	210	32,546,406	281	11,963,800	222
7 hr Gen.-11 hr Pump.	81,859,209	310	50,111,782	242	35,941,868	179	29,355,829	252	9,525,023	184
7 hr Gen.-12 hr Pump.	74,234,960	304	44,877,544	232	32,881,878	163	25,217,354	241	8,284,885	165
SCENARIO 2	**2015**		**2016**		**2017**		**2018**		**AVERAGE**	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
5 hr Gen.-7 hr Pump.	44,895,119	314	65,540,573	351	18,882,087	330	7,817,652	151	**44,930,345**	**293**
4 hr Gen.-6 hr Pump.	41,796,230	322	59,538,024	352	18,665,815	338	8,289,655	188	**42,420,073**	**308**
5 hr Gen.-8 hr Pump.	41,035,012	313	60,931,366	351	17,508,233	329	6,785,851	144	**41,012,886**	**287**
6 hr Gen.-9 hr Pump.	41,502,377	304	63,610,765	351	16,341,771	310	6,185,013	117	**40,953,148**	**270**
7 hr Gen.-10 hr Pump.	40,232,645	291	63,950,447	349	14,549,419	270	5,294,270	95	**39,329,585**	**248**
4 hr Gen.-7 hr Pump.	38,454,947	324	55,537,671	352	17,434,834	337	7,195,437	175	**39,041,850**	**306**
3 hr Gen.-5 hr Pump.	36,054,967	329	50,263,936	353	17,025,327	348	8,147,408	218	**37,054,322**	**323**
6 hr Gen.-10 hr Pump.	37,427,326	302	58,843,976	351	14,660,320	295	5,241,586	110	**36,928,775**	**263**
7 hr Gen.-11 hr Pump.	36,137,370	285	58,977,353	348	12,852,739	251	4,500,729	82	**35,473,545**	**237**
7 hr Gen.-12 hr Pump.	32,353,327	281	54,309,115	348	11,287,204	239	3,918,568	74	**31,929,426**	**227**

Table 6.14. *Results based on scenario I and II for Altınkaya PSH*

SCENARIO 1	**2010**		**2011**		**2012**		**2013**		**2014**	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
4 hr Gen.-6 hr Pump.	113,120,944	345	76,239,758	317	57,590,525	274	52,964,114	320	22,403,572	275
5 hr Gen.-8 hr Pump.	113,101,973	333	72,640,595	283	52,776,032	221	47,588,410	294	17,926,427	242
6 hr Gen.-9 hr Pump.	116,058,761	321	72,395,477	256	51,547,891	196	44,631,604	278	14,383,960	200
4 hr Gen.-7 hr Pump.	105,151,167	344	69,055,897	305	51,464,987	255	47,416,665	316	19,937,179	272
7 hr Gen.-10 hr Pump.	114,452,438	310	69,957,599	230	48,887,839	167	39,662,882	240	10,285,753	157
3 hr Gen.-5 hr Pump.	96,271,237	351	66,662,091	340	51,701,068	303	47,386,412	332	21,102,260	292
6 hr Gen.-10 hr Pump.	105,184,049	314	64,009,256	242	45,704,875	179	38,141,131	260	11,556,668	184
7 hr Gen.-11 hr Pump.	103,055,134	303	61,958,464	218	43,597,631	153	33,495,955	227	8,016,411	133
7 hr Gen.-12 hr Pump.	92,564,469	298	54,788,304	208	39,114,379	138	28,094,164	202	6,227,000	108
SCENARIO 1	**2015**		**2016**		**2017**		**2018**		**AVERAGE**	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
4 hr Gen.-6 hr Pump.	53,834,256	315	77,542,943	351	22,829,659	329	9,908,943	157	**54,048,302**	**298**
5 hr Gen.-8 hr Pump.	52,137,172	306	78,635,360	351	20,595,595	319	7,921,430	112	**51,480,333**	**273**
6 hr Gen.-9 hr Pump.	52,297,706	297	81,704,152	349	18,762,346	284	7,074,564	93	**50,984,051**	**253**
4 hr Gen.-7 hr Pump.	49,137,972	315	71,970,822	351	20,969,173	329	8,441,791	144	**49,282,850**	**292**
7 hr Gen.-10 hr Pump.	50,327,973	278	81,663,719	348	15,914,704	244	6,089,665	66	**48,582,508**	**227**
3 hr Gen.-5 hr Pump.	46,584,175	323	65,614,613	353	21,060,519	342	9,831,158	196	**47,357,059**	**315**
6 hr Gen.-10 hr Pump.	46,637,756	291	75,057,063	349	16,404,112	267	5,876,623	80	**45,396,837**	**241**
7 hr Gen.-11 hr Pump.	44,650,022	272	74,719,412	347	13,629,803	221	5,111,651	54	**43,137,165**	**214**
7 hr Gen.-12 hr Pump.	39,505,670	259	68,113,964	344	11,513,342	204	4,313,851	47	**38,248,349**	**201**

SCENARIO 2	**2010**		**2011**		**2012**		**2013**		**2014**	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
4 hr Gen.-6 hr Pump.	113,200,849	346	76,508,280	320	57,804,939	276	52,979,263	320	22,739,127	281
5 hr Gen.-8 hr Pump.	113,156,498	333	73,176,014	289	52,941,178	225	47,817,057	296	18,656,039	249
6 hr Gen.-9 hr Pump.	116,276,494	325	73,459,597	268	51,803,629	206	45,275,399	281	15,327,331	209
4 hr Gen.-7 hr Pump.	105,217,425	344	69,358,678	309	51,388,601	258	47,504,248	316	20,301,755	276
7 hr Gen.-10 hr Pump.	114,853,484	312	70,995,232	241	49,779,650	178	40,979,459	246	12,108,712	170
3 hr Gen.-5 hr Pump.	96,345,263	351	66,730,020	342	51,794,819	303	47,386,697	333	21,347,133	297
6 hr Gen.-10 hr Pump.	105,606,634	317	64,140,591	256	46,126,980	191	38,979,262	264	12,623,064	191
7 hr Gen.-11 hr Pump.	103,470,324	303	62,893,322	229	44,973,718	160	34,825,979	233	10,315,008	154
7 hr Gen.-12 hr Pump.	93,158,904	299	55,835,565	221	40,637,487	148	29,472,027	213	8,726,511	132
SCENARIO 2	**2015**		**2016**		**2017**		**2018**		**AVERAGE**	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
4 hr Gen.-6 hr Pump.	53,843,945	316	77,608,773	351	22,912,054	330	10,065,947	166	**54,184,797**	**301**
5 hr Gen.-8 hr Pump.	52,211,717	306	78,713,808	351	20,738,846	321	8,094,346	123	**51,722,834**	**277**
6 hr Gen.-9 hr Pump.	52,406,502	298	81,803,009	349	19,196,650	286	7,300,997	104	**51,427,734**	**258**
4 hr Gen.-7 hr Pump.	49,146,590	316	72,033,451	351	21,054,055	331	8,570,087	154	**49,397,210**	**295**
7 hr Gen.-10 hr Pump.	50,468,296	280	81,780,498	348	16,590,335	249	6,327,932	79	**49,320,400**	**234**
3 hr Gen.-5 hr Pump.	46,607,132	325	65,649,719	353	21,098,723	344	9,918,112	203	**47,430,846**	**317**
6 hr Gen.-10 hr Pump.	46,756,600	292	75,156,086	349	16,986,830	271	6,075,662	92	**45,827,968**	**247**
7 hr Gen.-11 hr Pump.	44,851,150	276	74,952,289	348	14,590,754	229	5,371,783	67	**44,027,148**	**222**
7 hr Gen.-12 hr Pump.	39,752,808	263	68,329,608	345	12,551,684	214	4,527,446	62	**39,221,338**	**211**

Table 6.15. *Results based on scenario III for Gökçekaya PSH*

GÖKÇEKAYA SCENARIO 3	2010		2011		2012		2013		2014	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
5 hr Gen.-7 hr Pump.	42,777,114	149	37,034,119	146	19,007,832	75	28,165,440	148	8,426,420	79
7 hr Gen.-10 hr Pump.	42,837,911	97	18,259,947	42	17,544,017	22	3,749,353	11	728,687	3
4 hr Gen.-6 hr Pump.	6,031,445	37	4,844,933	38	8,194,564	66	7,685,158	82	5,163,713	72
3 hr Gen.-5 hr Pump.	5,507,458	57	6,017,315	116	5,986,787	131	3,516,995	85	3,691,410	105
6 hr Gen.-9 hr Pump.	2,012,744	10	1,188,013	6	1,050,446	5	702,393	6	581,646	6
7 hr Gen.-11 hr Pump.	691,607	3	0	0	379,341	1	102,232	1	88,538	1
5 hr Gen.-8 hr Pump.	437,779	3	0	0	332,883	3	389,163	3	984,591	16
7 hr Gen.-12 hr Pump.	685,007	1	0	0	0	0	1,406,191	1	101,398	1
4 hr Gen.-7 hr Pump.	0	0	19,858	1	142,423	5	96,454	3	696,518	18
6 hr Gen.-10 hr Pump.	0	0	0	0	74,506	1	0	0	110,403	2
Nonworking	0	8	0	16	0	57	0	25	0	62
Total	**100,981,064**	**357**	**67,364,186**	**349**	**52,712,798**	**309**	**45,813,379**	**340**	**20,573,324**	**303**
GÖKÇEKAYA SCENARIO 3	**2015**		**2016**		**2017**		**2018**		**AVERAGE**	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
5 hr Gen.-7 hr Pump.	27,526,543	161	35,245,521	206	9,151,167	117	2,033,792	23	**23,263,105**	**123**
7 hr Gen.-10 hr Pump.	11,466,207	47	25,030,726	92	2,580,010	21	2,547,556	11	**13,860,490**	**38**
4 hr Gen.-6 hr Pump.	3,574,805	42	1,616,904	18	3,730,364	74	2,129,802	33	**4,774,632**	**51**
3 hr Gen.-5 hr Pump.	2,070,372	55	337,069	6	2,606,094	94	2,735,116	132	**3,607,624**	**87**
6 hr Gen.-9 hr Pump.	1,293,805	10	1,958,693	16	1,529,806	23	0	0	**1,146,394**	**9**
7 hr Gen.-11 hr Pump.	99,254	1	3,321,766	4	0	0	0	0	**520,304**	**1**
5 hr Gen.-8 hr Pump.	253,133	4	323,579	4	221,205	6	93,035	3	**337,263**	**5**
7 hr Gen.-12 hr Pump.	0	0	226,357	2	64,180	1	0	0	**275,904**	**1**
4 hr Gen.-7 hr Pump.	319,959	7	179,581	5	209,926	9	166,314	9	**203,448**	**6**
6 hr Gen.-10 hr Pump.	78,015	1	0	0	97,546	2	0	0	**40,052**	**1**
Nonworking	0	37	0	13	0	18	0	154	**0**	**43**
Total	**46,682,094**	**328**	**68,240,197**	**353**	**20,190,298**	**347**	**9,705,615**	**211**	**48,029,217**	**322**

Table 6.16. *Results based on scenario III for Altınkaya PSH*

ALTINKAYA SCENARIO 3	**2010**		**2011**		**2012**		**2013**		**2014**	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
7 hr Gen.-10 hr Pump.	64,275,257	115	34,834,142	63	24,439,577	25	5,279,924	12	805,455	2
4 hr Gen.-6 hr Pump.	30,408,192	110	31,266,178	130	25,000,416	114	35,664,864	195	13,472,390	123
6 hr Gen.-9 hr Pump.	19,928,928	52	9,428,279	29	6,639,763	17	5,440,138	20	1,025,416	8
3 hr Gen.-5 hr Pump.	7,267,205	57	7,572,337	112	7,911,061	133	5,132,463	93	5,189,786	116
5 hr Gen.-8 hr Pump.	4,035,785	14	786,391	4	1,124,575	6	1,832,255	8	2,324,387	24
7 hr Gen.-11 hr Pump.	739,622	2	0	0	0	0	0	0	0	0
7 hr Gen.-12 hr Pump.	907,144	1	0	0	0	0	1,835,945	1	118,162	1
4 hr Gen.-7 hr Pump.	0	0	150,684	2	482,183	8	449,054	3	978,749	18
6 hr Gen.-10 hr Pump.	0	0	0	0	0	0	0	0	0	0
Nonworking	0	14	0	25	0	63	0	33	0	73
Total	**127,562,134**	**351**	**84,038,011**	**340**	**65,597,575**	**303**	**55,634,643**	**332**	**23,914,346**	**292**

ALTINKAYA SCENARIO 3	**2015**		**2016**		**2017**		**2018**		**AVERAGE**	
Operation Status	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation
7 hr Gen.-10 hr Pump.	23,860,446	73	44,235,593	129	3,621,847	23	3,320,783	11	**22,741,447**	**50**
4 hr Gen.-6 hr Pump.	20,471,233	128	23,166,905	129	11,344,293	147	4,106,157	43	**21,655,625**	**124**
6 hr Gen.-9 hr Pump.	7,485,867	35	11,487,559	60	3,078,388	32	186,317	1	**7,188,962**	**28**
3 hr Gen.-5 hr Pump.	2,948,244	59	621,795	10	3,639,193	106	3,199,910	125	**4,831,333**	**90**
5 hr Gen.-8 hr Pump.	3,146,837	23	2,295,540	19	2,034,171	22	621,508	10	**2,022,383**	**14**
7 hr Gen.-11 hr Pump.	118,277	1	4,114,019	2	0	0	0	0	**552,435**	**1**
7 hr Gen.-12 hr Pump.	0	0	204,631	1	73,109	1	0	0	**348,777**	**1**
4 hr Gen.-7 hr Pump.	241,631	4	87,511	2	388,071	10	260,883	7	**337,641**	**6**
6 hr Gen.-10 hr Pump.	0	0	65,686	1	40,950	1	0	0	**11,848**	**0**
Nonworking	0	42	0	13	0	23	0	168	**0**	**50**
Total	**58,272,535**	**323**	**86,279,239**	**353**	**24,220,021**	**342**	**11,695,558**	**197**	**59,690,451**	**315**

Table 6.17. *Monthly analysis based on scenario III for Gökçekaya PSH*

Scenario 3	January		February		March		April		May		June		Half Year Total	
	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	**B-C (USD)**	**# of Operation**
3 hr Gen. 5 hr Pump.	211,579	6.6	179,268	5.4	175,863	5.8	184,444	5.4	153,819	4.0	321,242	8.4	**1,226,215**	**35.7**
4 hr Gen. 6 hr Pump.	393,278	3.9	285,095	3.7	310,991	3.4	232,458	2.9	312,141	3.3	417,399	4.9	**1,951,362**	**22.1**
4 hr Gen. 7 hr Pump.	13,344	0.4	30,982	0.9	27,229	0.9	9,321	0.2	40,363	1.1	12,819	0.4	**134,058**	**4.0**
5 hr Gen. 7 hr Pump.	2,354,410	11.3	1,863,897	9.0	2,535,566	11.6	1,899,693	9.1	2,003,175	10.6	2,422,486	10.3	**13,079,227**	**61.9**
5 hr Gen. 8 hr Pump.	9,676	0.1	31,683	0.4	25,180	0.3	44,420	0.8	13,836	0.2	34,493	0.6	**159,287**	**2.4**
6 hr Gen. 9 hr Pump.	21,865	0.2	123,110	0.7	140,503	1.0	178,498	1.0	210,414	1.6	51,588	0.3	**725,978**	**4.8**
6 hr Gen. 10 hr Pump.	0	0.0	6,559	0.1	0	0.0	8,278	0.1	8,668	0.1	5,532	0.1	**29,038**	**0.4**
7 hr Gen. 10 hr Pump.	1,041,534	3.7	2,513,199	4.4	1,347,995	3.8	2,245,056	5.4	2,677,532	6.9	948,589	2.6	**10,773,905**	**26.8**
7 hr Gen. 11 hr Pump.	47,467	0.2	42,149	0.1	24,635	0.1	13,640	0.1	11,359	0.1	0	0.0	**139,251**	**0.7**
7 hr Gen. 12 hr Pump.	0	0.0	0	0.0	6,224	0.1	76,112	0.1	0	0.0	0	0.0	**82,336**	**0.2**
Total	4,093,152	26.4	5,075,943	24.8	4,594,186	27.0	4,891,921	25.2	5,431,308	27.9	4,214,147	27.7	**28,300,656**	**159.0**
Scenario 3	**July**		**August**		**September**		**October**		**November**		**December**		**Annual Total**	
	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	B-C (USD)	# of Operation	**B-C (USD)**	**# of Operation**
3 hr Gen. 5 hr Pump.	500,046	11.4	734,408	10.6	271,229	5.3	324,665	9.7	323,878	7.2	227,184	6.9	**3,607,624**	**87**
4 hr Gen. 6 hr Pump.	413,457	4.9	534,365	4.8	656,334	7.0	296,950	3.2	535,136	5.2	387,027	4.1	**4,774,632**	**51**
4 hr Gen. 7 hr Pump.	8,406	0.2	9,001	0.4	6,184	0.2	36,616	1.0	5,347	0.2	3,836	0.2	**203,448**	**6**
5 hr Gen. 7 hr Pump.	1,243,972	8.4	1,644,767	10.0	2,127,253	12.0	1,484,907	9.9	1,786,010	9.8	1,896,969	10.7	**23,263,105**	**123**
5 hr Gen. 8 hr Pump.	25,081	0.2	18,513	0.4	5,243	0.1	34,339	0.7	6,577	0.1	88,223	0.7	**337,263**	**5**
6 hr Gen. 9 hr Pump.	25,717	0.3	59,303	0.7	49,215	0.4	97,387	1.4	146,861	1.0	41,933	0.4	**1,146,394**	**9**
6 hr Gen. 10 hr Pump.	6,735	0.1	0	0.0	0	0.0	0	0.0	4,279	0.1	0	0.0	**40,052**	**1**
7 hr Gen. 10 hr Pump.	469,005	1.3	218,314	1.0	408,279	1.7	617,089	2.7	681,058	2.6	692,841	2.4	**13,860,490**	**38**
7 hr Gen. 11 hr Pump.	0	0.0	0	0.0	11,028	0.1	0	0.0	9,838	0.1	360,188	0.3	**520,304**	**1**
7 hr Gen. 12 hr Pump.	7,131	0.1	0	0.0	0	0.0	11,266	0.1	0	0.0	175,170	0.2	**275,904**	**1**
Total	2,699,551	27.1	3,218,670	27.9	3,534,765	26.9	2,903,220	28.7	3,498,984	26.3	3,873,371	26.0	**48,029,217**	**322**

Table 6.13 and 6.14 show the annual revenues obtained from different operation modes between 2010 and 2018 for scenario I and II. As can be seen, 5 hour generation-7 hour pumping mode is the most profitable one for Gökçekaya PSH whereas it is 4 hour generation-6 hour pumping mode for Altınkaya PSH. 7 hour generation-12 hour pumping mode is the least profitable for both power plants. In scenario II, using the most profitable operation mode for both facilities, number of profitable days is 293 on an average yearly basis for Gökçekaya PSH and nearly 45 million US dollars in average are spared annually, while Altınkaya PSH brings profit during an average of 301 days in a year and 54 million US dollars are spared in average.

In the third scenario, the most profitable operation mode is chosen for each day. For the case of Gökçeaya PSH, the number of profitable days is 322 and the maximum annual revenue is 48 million US dollars on a yearly average. The operation modes of 5 hour generation-7 hour pumping, 7 hour generation-10 hour pumping, 4 hour generation-6 hour pumping and 3 hour generation-5 hour pumping are the top four profitable operation modes respectively. Again respectively, they are utilized for 123, 38, 51 and 87 days on an annual average. The other 6 operation modes are used altogether only for 23 days in a year and the facility is not operated for 43 days in average due to low and unprofitable prices. Table 6.15 and Table 6.16 shows the employment of operation modes and their yearly profits for both power plants.

Table 6.17 and Figure 6.2 represent the average monthly revenues based on Scenario III. Maximum monthly revenue appears to be 5.4 million US dollars and it is obtained in May.

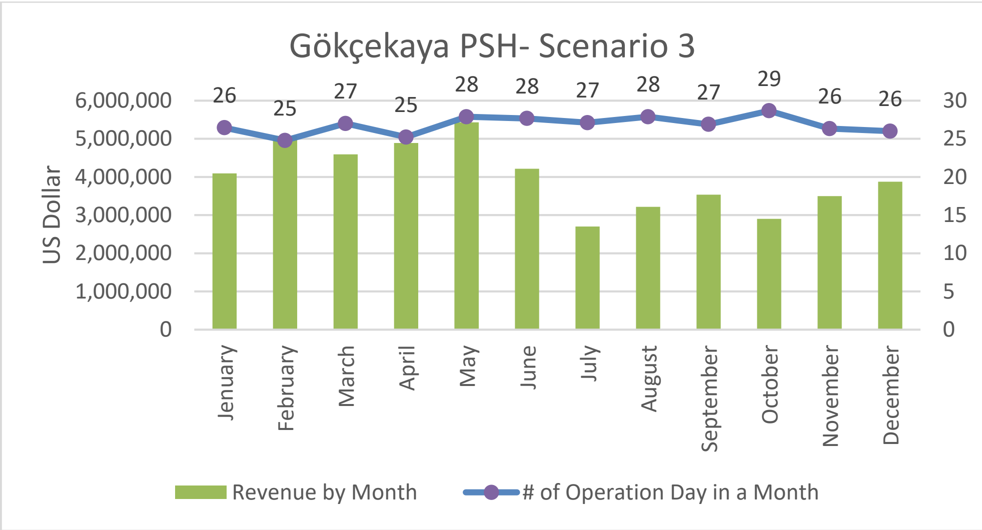


Figure 6.2. Monthly average revenues based on Scenario III

According to JICA's report, estimated construction costs of Gökçekaya and Altınkaya PSHs are 1.098 billion and 1.201 billion US dollars respectively. When the average revenue based on scenario III is considered, the payback period of Gökçekaya PSH is 22.86 years while Altınkaya PSH's is 20.12 years. Figure 6.3 summarizes the maximum possible profits based on different scenarios for both Gökçekaya and Altınkaya PSH.

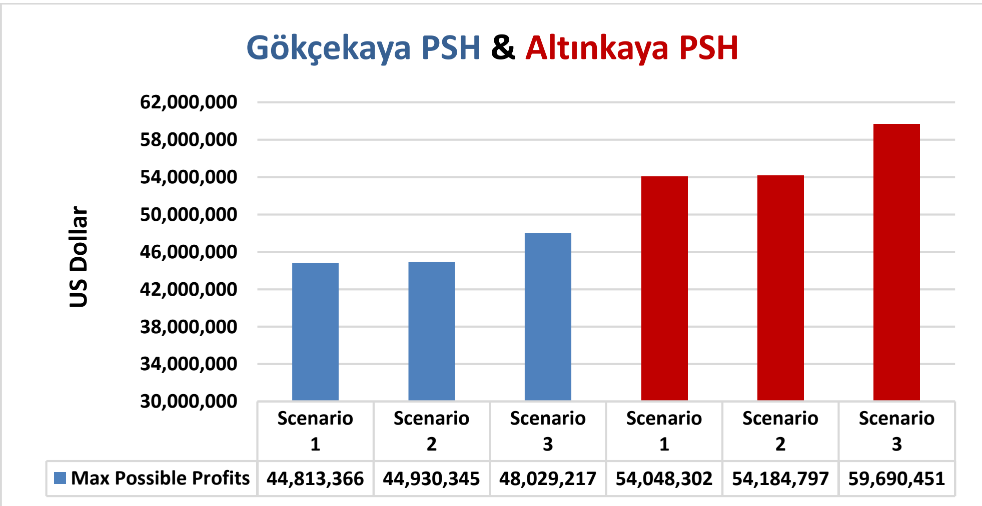


Figure 6.3. Profit comparison based on scenarios

Figure 6.4 and 6.5 represent the annual revenues and number of operation days based on scenario III. For Gökçekaya PSH, the highest revenue is 100 million US dollars and it is obtained in 2010. Up until 2014, the revenue decreases until it meets its second apogee in 2016. Another decrease appears following 2016 and up until 2018 with the lowest profit of 9.7 million US dollars. The drop in profits mean that the price difference between peak and off-peak hours decreases as well. Altınkaya PSH shows resemblance to the case of Gökçekaya PSH concerning profits.

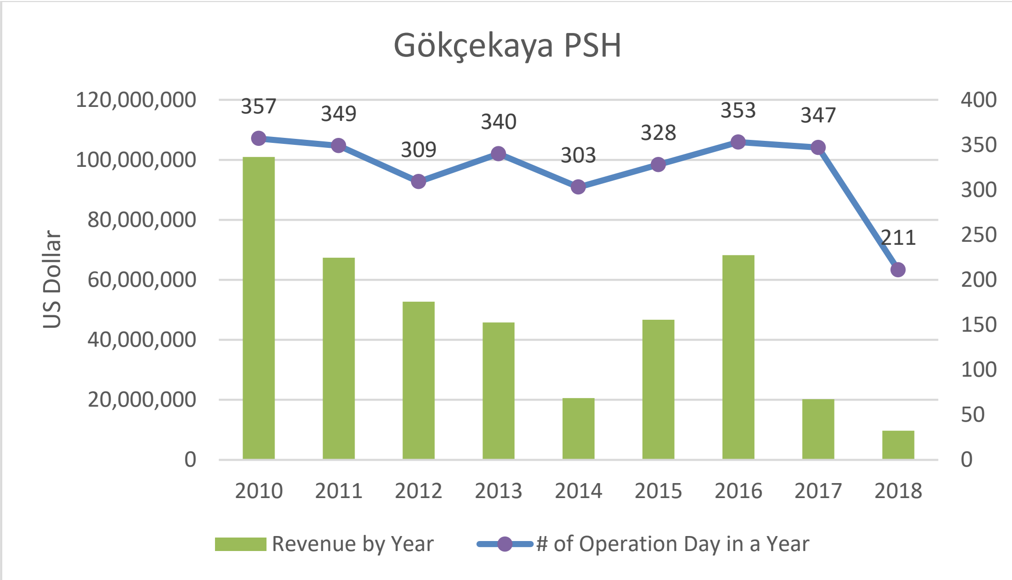


Figure 6.4. Annual revenues based on scenario III for Gökçekaya PSH

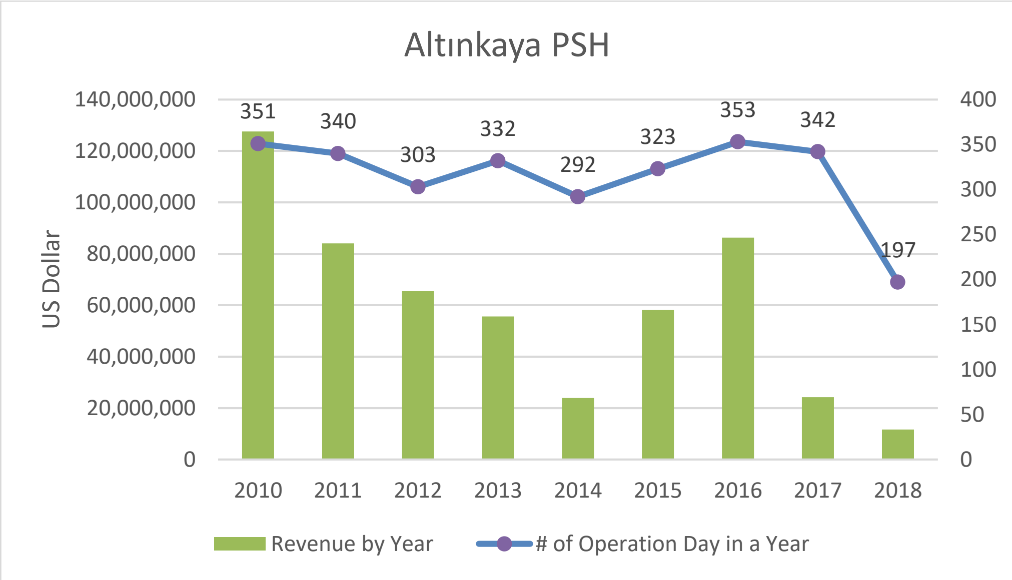


Figure 6.5. Annual revenues based on scenario III for Altınkaya PSH

As mentioned in Chapter 3, there may be a difference between minimum electricity generation and minimum electricity consumption in 2025. Turkey's power grid may need additional electricity consumption on the days with minimum power demand. Figure 3.20 shows that the minimum power generation (31,750 MW) is approximately 20% higher than the minimum power demand (26,700 MW).

Data compiled from TEİAŞ is analyzed for the years between 2001 and 2018 in order to estimate the number of days the system would require additional consumption. The data indicates that 20% more than the minimum consumption is reached within an average of 8 days. Table 6.19 shows the top ten days with minimum power demand between 2001 and 2018.

Possible daily load curves of these 7 days of required additional consumption is calculated via using these data. Total required value is calculated as 91.8 GWh within 7 days. If operation of Gökçekaya PSH starts by 2025, the facility might consume electricity of 1,350 MWh hourly by pumping mode and the total consumption of 46.4 GWh within these 7 days might be met by the power plant.

In the fourth scenario, 51% of required additional electricity consumption is to be met by Gökçekaya PSH and it is shown by the green area in Figure 6.6 on a daily basis. Table 6.18 summarizes these values.

In this case, grid operator does not need to stop WPPs or run-off HPPs completely to decrease power generation. In addition to this, stored water in the upper reservoir during pumping mode can be used when needed and additional power generation can be supplied from PSH.

Table 6.18. *Minimum power demand values between 2001 and 2018*

	1st Day	2nd Day	3rd Day	4th Day	5th Day	6th Day	7th Day	Total
Minimum Power Demand (MW)	26,700	27,707	28,393	29,344	30,202	30,718	31,631	
Required Consumption (MWh)	32,489	22,486	17,305	11,294	5,415	2,748	57	91,795
Consumption Met by Gökçekaya PSH (MWh)	11,451	10,243	8,851	7,724	5,288	2,748	57	46,362

Table 6.19. *Minimum power demand values between 2001 and 2018*

		Minimum Power Demand Occurrence Days									
		1st Day	**2nd Day**	**3rd Day**	**4th Day**	**5th Day**	**6th Day**	**7th Day**	**8th Day**	**9th Day**	**10th Day**
2001	**Day**	6 March	5 March	13 Apr	7 March	8 March	18 Dec	17 Dec	20 May	23 Apr	28 May
	Demand MW	8336	8594	8695	8836	9123	9317	9339	9362	9548	9609
	Increase %		3.10	4.31	6.00	9.44	11.77	12.03	12.31	14.54	15.27
2002	**Day**	6 Dec	23 Feb	7 Dec	22 Feb	24 Feb	5 Dec	25 Feb	8 Dec	20 May	19 May
	Demand MW	9127	9398	9425	9646	9670	9909	10092	10223	10312	10431
	Increase %		2.97	3.27	5.69	5.95	8.57	10.57	12.01	12.98	14.29
2003	**Day**	26 Nov	27 Nov	25 Nov	12 Feb	19.May	13 Feb	11 Feb	4 May	2 June	1 June
	Demand MW	9270	9847	9929	10392	10428	10568	10651	10697	10757	10771
	Increase %		6.22	7.11	12.10	12.49	14.00	14.90	15.39	16.04	16.19
2004	**Day**	15 Nov	14 Nov	16 Nov	2 Feb	1 Feb	3 Feb	23 Jan	4 Feb	17 Nov	31 Sep
	Demand MW	8888	9456	9629	10380	10725	10747	10971	11004	11097	11537
	Increase %		6.39	8.34	16.79	20.67	20.92	23.44	23.81	24.85	29.80
2005	**Day**	4 Nov	5 Nov	21 Jan	20 Jan	22 Jan	3 Nov	6 Nov	23 Jan	1 Jan	5 June
	Demand MW	10120	10551	10761	10928	11197	11232	11639	11773	11931	12074
	Increase %		4.26	6.33	7.98	10.64	10.99	15.01	16.33	17.90	19.31
2006	**Day**	24 Oct	23 Oct	25 Oct	11 Jan	12 Jan	10 Jan	13 Jan	26 Oct	22 Oct	14 Jen
	Demand MW	10545	11053	11178	11243	11687	11731	12105	12660	12830	12887
	Increase %		4.82	6.00	6.62	10.83	11.25	14.79	20.06	21.67	22.21
2007	**Day**	13 Oct	14 Oct	12 Oct	1 Jan	2 Jan	15 Oct	3 Jen	21 Dec	20 Dec	20 May
	Demand MW	10965	11536	12106	12787	13117	13510	13705	13856	14049	14124
	Increase %		5.21	10.41	16.62	19.63	23.21	24.99	26.37	28.13	28.81
2008	**Day**	1 Oct	2 Oct	30 Sep	9 Dec	8 Dec	10 Dec	3 Oct	11 Dec	29 Sep	7 Dec
	Demand MW	10409	10865	11495	12234	12320	12390	12818	12874	13077	13898
	Increase %		4.38	10.43	17.53	18.36	19.03	23.14	23.68	25.63	33.52
2009	**Day**	21 Sep	22 Sep	20 Sep	28 Nov	29 Nov	27 Nov	30 Nov	23 Sep	3 May	17 May
	Demand MW	11083	11812	12250	13019	13312	13708	14199	14419	14607	14942
	Increase %		6.58	10.53	17.47	20.11	23.68	28.12	30.10	31.80	34.82

Table 6.19. (Continued)

Year		Minimum Power Demand Occurrence Days									
		1st Day	2nd Day	3rd Day	4th Day	5th Day	6th Day	7th Day	8th Day	9th Day	10th Day
2010	Day	17 Nov	16 Nov	18 Nov	10 Sep	11 Sep	19 Nov	1 Jan	3 Jan	9 Sep	2 Jan
	Demand MW	13513	14010	14036	14054	14789	14938	15033	15418	15496	15620
	Increase %		3.68	3.87	4.00	9.44	10.55	11.25	14.10	14.67	15.59
2011	Day	7 Nov	31 Aug	8 Nov	6 Nov	1 Sep	9 Nov	22 May	30 Aug	13 June	29.May
	Demand MW	14822	15198	15407	15465	16295	16377	17078	17212	17243	17291
	Increase %		2.54	3.95	4.34	9.94	10.49	15.22	16.12	16.33	16.66
2012	Day	26 Oct	25 Oct	27 Oct	28 Oct	29 Oct	20 Aug	21 Aug	24 Sep	23 Apr	20.May
	Demand MW	13922	14052	14591	15058	16082	16209	17140	17723	17825	18039
	Increase %		0.93	4.80	8.16	15.51	16.42	23.11	27.29	28.03	29.57
2013	Day	16 Oct	15 Oct	17 Oct	18 Oct	9 Aug	19 Oct	10 Aug	14 Oct	19 May	30 Sep
	Demand MW	14800	14997	15529	16005	16394	16846	17626	17659	18342	18509
	Increase %		1.34	4.92	8.14	10.77	13.82	19.09	19.32	23.93	25.06
2014	Day	5 Oct	4 Oct	6 Oct	7 Oct	29 July	8 Sep	30 July	3 Sep	8 June	19 May
	Demand MW	14927	15387	15440	16210	17987	18557	19093	19142	19509	19565
	Increase %		3.08	3.44	8.59	20.50	24.32	27.91	28.23	30.70	31.07
2015	Day	25 Sep	26 Sep	24 Sep	18 July	27 Sep	19 July	1 Jan	17 July	23 Sep	28 Sep
	Demand MW	16269	16755	16937	17285	17339	18136	19602	19665	20197	20207
	Increase %		2.99	4.11	6.25	6.58	11.48	20.49	20.88	24.15	24.21
2016	Day	13 Sep	6 July	14 Sep	15 Sep	12 Sep	7 July	16 Sep	5 July	29 May	8 July
	Demand MW	17796	17974	18377	18950	19007	19190	20330	20610	20939	21096
	Increase %		1.00	3.26	6.48	6.80	7.83	14.23	15.81	17.66	18.54
2017	Day	26 June	2 Sep	27 June	25 June	3 Sep	1 Sep	1 May	4 Sep	28 May	16 Apr
	Demand MW	18851	19949	19961	20393	20543	21318	21501	21598	21742	22014
	Increase %		5.82	5.89	8.18	8.98	13.09	14.06	14.57	15.33	16.78
2018	Day	16 June	17 June	15 June	22 Aug	20 May	18 June	21 Aug	23 Aug	27 May	29 Oct
	Demand MW	18497	18974	20929	21700	22092	22100	22213	22475	22521	22654
	Increase %		2.58	13.15	17.32	19.43	19.48	20.09	21.50	21.75	22.47
AVE INCREASE (%)			**3.77**	**6.34**	**9.90**	**13.11**	**15.05**	**18.47**	**19.88**	**21.45**	**23.01**

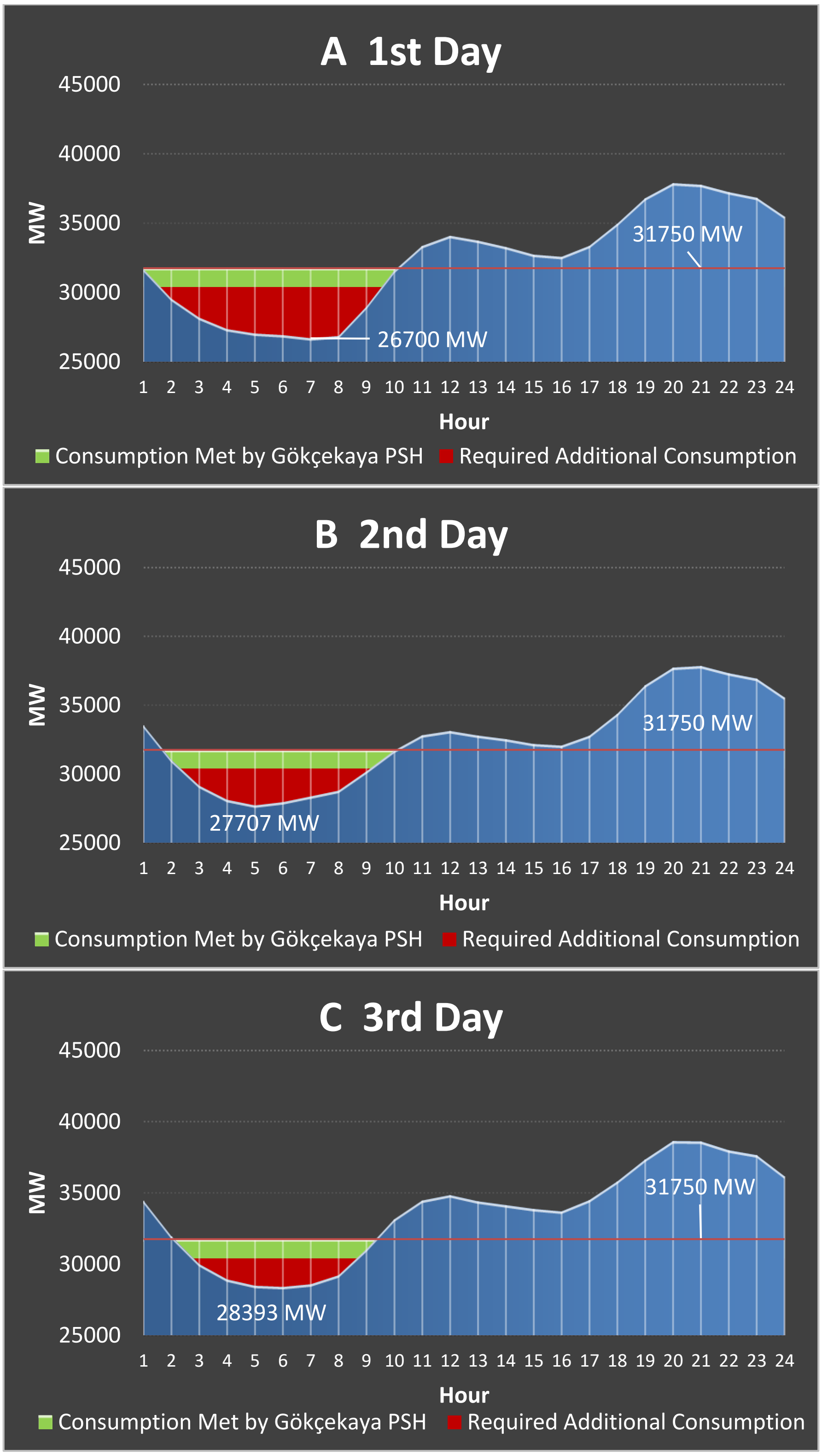


Figure 6.6. Daily demand curves of minimum demand occurrence days in 2025

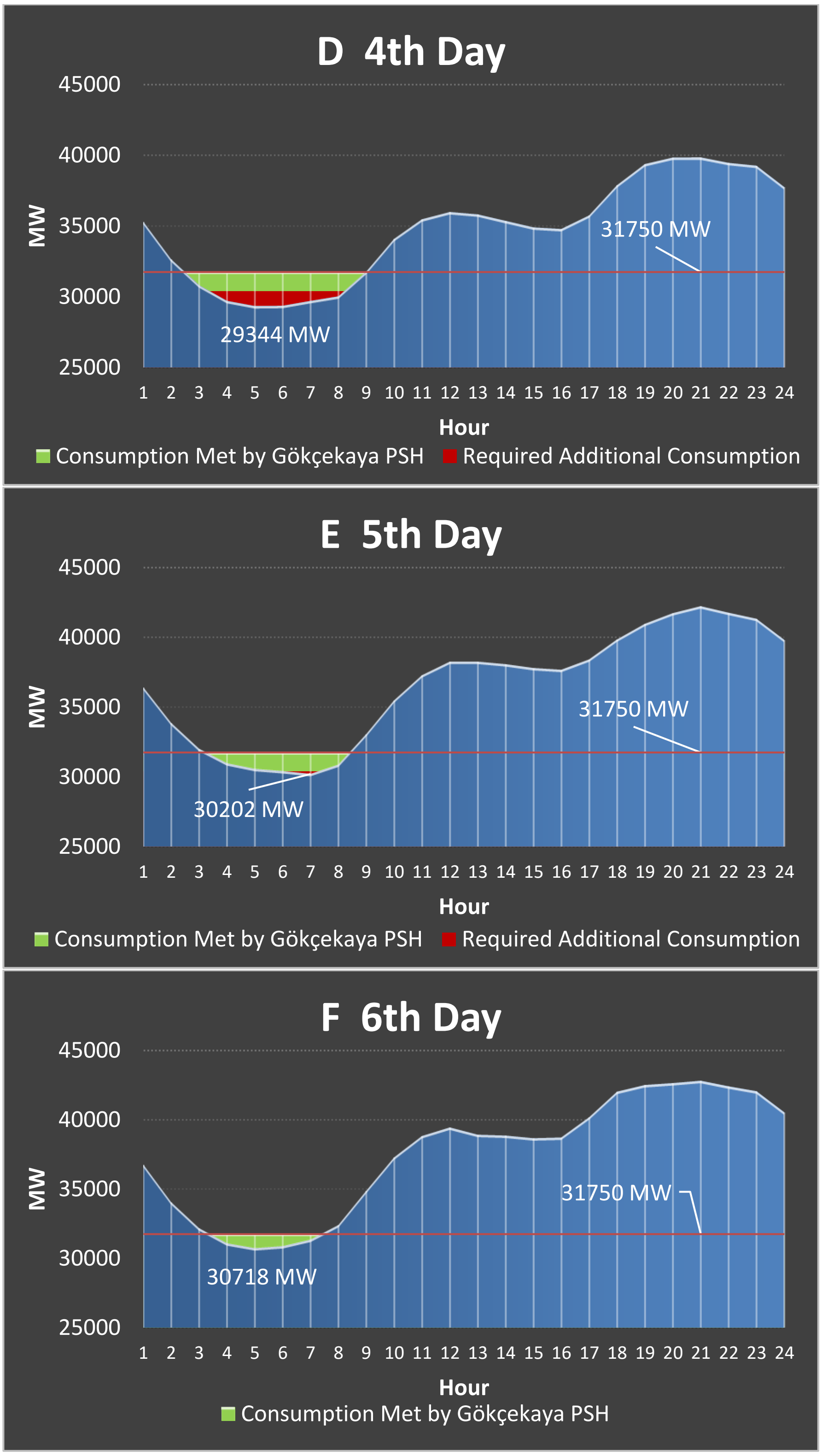


Figure 6.6. (Continued)

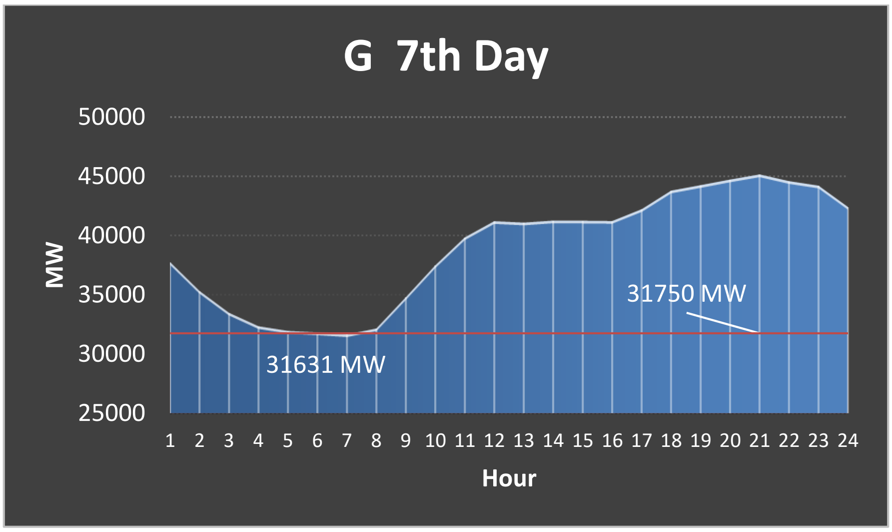


Figure 6.6. (Continued)

CHAPTER 7

CONCLUSIONS

Sustainable economic growth and energy security are two of the most crucial concerns that entail Turkey to reduce its external dependence in energy. The first NPP of Turkey, Akkuyu NPP is known to start generating by 2023. Although this nuclear facility is controversial one with regards to environmental and economic concerns, the initiative itself reflects the country's motivation to enhance and diversify its energy sources. On the other hand, Turkey's current efforts to raise its renewable energy capacity appears to be a favorable development in respect to increasing usage of natural resources in power generation.

Turkey's hydropower capacity is the second highest among other European countries after Norway. Hydropower in Turkey has a share of approximately 30% in total installed capacity and 20% approximately in total energy generation. The country has not needed a PSH facility until very recently because HEPPs could already supply the flexibility needed by the grid operator. Nevertheless, it is obvious that the country is to meet with challenges under current circumstances where the share of hydropower decreases whereas renewable power plants and base load power plants such as nuclear or thermal become more widespread.

Such developments in the Turkish electricity system drew an interest into the energy storage systems. Some sort of a consensus has been built upon the establishment of energy storage capacity concerning the country's system security. What really sparks the debate are the methods and models that would be required to achieve this objective.

This study intends to analyze the potential benefits of PSH facilities, such as the long-debated Gökçekaya and Altınkaya PSHs. First of all, generation and pumping capacities of these power plants are calculated. In the sequel, potential profits are estimated using real time hourly electricity prices between 2010 and 2018. In addition to these, potential adversities and difficulties that might occur in relation to load balancing in the near future are taken into consideration and the facilities' possible support under conditions are forecast.

According to the results, it is seen that 5 hours of electricity generation is more profitable for Gökçekaya PSH than 7 hours with current electricity prices. Therefore, reducing the upper reservoir volume will help reduce the investment cost.

Additionally, Gökçekaya or Altınkaya PSHs might not only serve to meet peak power demand, but also become very useful for load balancing. Public authorities in Turkey draw attention to the fact that Turkey's power grid may need additional electricity consumption in 2025 on the days with minimum energy demand due to difference between minimum electricity generation and consumption. This study shows that nearly half of the required additional electricity consumption can be met by Gökçekaya PSH.

Turkish electricity market prices hardly assures entrepreneurs in the private sector who would be willing to invest in PSH in this country. Price differences between peak and off-peak hours which have quite a vital importance for the application of PSH, fluctuates significantly year over year. Retaining the current circumstances will possibly prevent the private sector from investing. Current prices and high investment costs as well as the divergence between ex ante costs and costs during application prolong altogether the return of an investment in PSH. Additionally, it is significant to make a price projection for the upcoming years by modelling the relation between energy production-consumption and peak-off peak energy prices before any potential investment.

Through various warrants and governmental incentives, entrepreneurs in the private sector are involved in facility construction via build-operate-transfer model. Should this model be chosen where the electricity price gap reduces, there would be a public loss. Increase in the PSH installed capacity in the power grid on the other hand, would reduce the prices during peak hours. Approximate investment cost of 1.1 billion US dollars for Gökçekaya PSH appears quite high as it will depend on public funding.

The dams which are already owned by private sector and located in tandem on the same rivers, might be converted to PSH with low investment costs. This type of PSH would be capable of storing released water during flood seasons and could be operated seasonally. However, it should be kept in mind that opting for seasonal storage will cut down on the number of days that the facility is active during the year and therefore decrease the profitability on a large scale. Herein, what concerns many investors are the regulatory gaps on the water rights, whether the system will operate within the market schedule or according to the orders of the grid operator along with whether governmental incentives could be used or not.

Another significant option is the conversion of the existing public dams into PSH by a modification on their lower reservoirs. Casting aside the question of profit/loss, it is fairly appropriate to state that a PSH facility under public control would eventually contribute to public welfare. Such conversions would also encourage increment of the country's hydropower potential. Moreover, converting dam projects currently at planning phase into PSH and conducting their feasibility studies accordingly would be beneficial.

After all, Turkey's breakthrough in energy storage is a long awaited matter for the country's welfare. What has been discussed and eventually found advantageous in this study is the conversion of existing dams into PSH facilities, therefore proliferating country's hydropower sources. It is also fairly evident that the public good should be sought and the facilities should be operated under public will and control.

The potential benefits of a pure PSH are analyzed in this study. For future works, it would be useful to dwell on the feasibility of PSH facilities that are planned to be converted from existing cascade dams. Under favorable precipitation conditions, the volume of water in the upper reservoir of such on-stream integral PSH will be greater than the upper reservoir of pure PSH. In such a case, the plant can be used for energy production for most part of the day. Since the pumping time and cost will decrease, the profitability rate will increase.

In addition, feasibility part of this study was carried out using merely Market Clearing Prices which are the reference electricity prices. However, PSH can also be operated within the ancillary services market and capacity mechanism, both controlled by TEİAŞ. It is thought that the PSH operator can participate in secondary frequency control, reactive power support and system restoration by making various agreements. In future studies, this situation can be considered both alone and integrated into the day-ahead market, therefore feasibility study can be further developed.

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