ECONOMIC AND OPERATIONAL ANALYSIS OF COMPRESSED AIR ENERGY STORAGE SYSTEMS

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Economic and Operational Analysis of Compressed Air Energy Storage Systems

Abstract

A Compressed Air Energy Storage System (CAES) is a way to store energy to be used when the demand for energy is high. In this system, the air is pumped into a cavern when the power price is low and the air is used in a natural gas fired turbine to generate power when the price is high aiming to make profit from this price difference. The system can pump or generate or do both. Typically the power price is low at nights and high during the daytime. However, the power and natural gas price along with the heat rate of the turbine should be included to the model to determine when the air should be pumped and when the power should be generated to maximize the revenue. In this research, a mixed integer programming method is developed to determine a pumping-generation schedule for the CAES given that market and natural gas price for each hour can be forecasted. Appropriate forecasting methods are used to simulate the power and natural gas prices for the analysis. The model is coded in General Algebraic Modeling System (GAMS) and a case study is presented to validate the model. In addition to scheduling of the CAES, another important contribution of this research is to develop a framework for investor companies who wish to build a CAES system. We develop 30-years long market price and natural gas price scenarios and we find annual profits through optimum scheduling of the CAES plant given that market price and natural gas prices are variable. Then we use appropriate engineering economics tools to estimate a Net Present Worth value of each different scenario for the decision makers of the investment companies.

Basınçlı Hava Enerji Depolama Sistemlerinin Ekonomik ve Operasyonel Analizi

Özet

Enerji, basınçlı hava enerji depolama sistemiyle talebin fazla olduğu zamanlarda kullanılmak üzere depolanır. Bu sistem ile hava elektrik fiyatının düşük olduğu zamanlarda depoya pompalanır ve elektrik fiyatının pahalı olduğu zamanlarda doğal gaz ile yakılarak elektrik enerjisine çevrilir. Havanın pompalanması ve elektrik enerjisinin üretimi sırasında elektrik fiyatı farklıdır. Elektrik fiyatındaki bu fark ile kar elde etmek amaçlanır. Basınçlı Hava Enerji Depolama sisteminde havanın pompalanması işlemi ve elektriğin üretimi farklı zamanlarda yapılabileceği gibi her iki işlemde aynı zamanda yapılabilir. Genellikle elektrik fiyatları gece saatlerinde ucuz olurken gün içerisinde pahalı olur. Doğal gaz ve elektrik fiyatlarıyla birlikte türbin ısı oranının modele dahil edilmesi geliri maksimize edebilmek için gerekmektedir. Bu çalışmada tahmin edilen elektrik ve doğal gaz fiyatlarıyla pompalama ve üretim zamanlarını belirleyebilmek için uygun karışık tamsayılı bir programlama yöntemi geliştirildi. Uygun tahmin modelleri elektrik ve doğal gaz fiyatlarını tahmin etmek için kullanılır. Model Genel Cebirsel Modelleme Sistemi (GAMS) programında kodlandı ve modeli doğrulamak için bir örnek çalışması sunuldu. Bu araştırmada CAES planlamasının yanı sıra CAES sistemi kurmak isteyen yatırımcılar için de önemli katkılar sağlandı. Araştırmamızda 30 yıllık elektrik ve doğal gaz senaryoları geliştirildi. Piyasa ve doğal gaz fiyat değişkenlerini göz önüne alarak CAES tesisi için optimum zamanlama ile yıllık kar bulundu. Daha sonra mühendislik ekonomisi araçlarını kullanarak yatırım şirketlerinin karar vericileri için her bir farklı senaryonun Net Bugünkü Değerlerini hesaplandı.

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To my father

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NO_x: mono-nitrogen oxides

CO: Carbon monoksit

CO_2: Carbon dioksit

PMIO: Perilenmanoimidoksit

SO_x: mono-sulfur oxides

ZnBr: Zinc Bromide

NaBr: Sodium Bromide

NaS: Sodium Sulfur

$X_{t:}$ is 1 if the power generated in hour t, 0 otherwise,

$Y_{t:}$ is 1 if the pumping unit pumps in hour t, 0 otherwise,

$I_{t:}$ is the compressed air inventory, in hours of generation available, in hour t,

$I_{first:}$ is the inventory of compressed air in the first hour,

$I_{last:}$ is the inventory of compressed air in the last hour,

LMP: Locational Market Price,

GP: Gas Price,

$P_{CAES:}$ is the MW rating of the generating unit,

$LMP_{t:}$ is the load/gen LMP at the pumped air station bus,

$MP_{GAS:}$ is the gas price in hour t,

$P_{PUMPING:}$ the MW Rating of the pumping unit,

TLAST (T): last period,

Gen_cap: Generation Capacity,

Gas_CT: The Mw rating of gas Ct,

pump_cap: Pumping capacity of the unit,

$HR_{GAS:}$ the heat rate of the gas CT,

VOM: Variable operating maintenance cost,

VOM_{gen}: the VOM generation cost,

PH: Assumed capacity of the facility in total pumping hours, NPH: Number of pumping hours consumed by each generating hours,

NGH: Number of generating hours possible for each pumping hours,

pump_stpcost: pump startup cost,

gen_stpcost: generator startup cost,

Cef: Compressor Efficiency,

Tsef: Turbine Efficiency,

VOMcm: VOM compressor,

X (T): Generation,

P (T): Pumping,

I (T): Compressed Air Inventory,

Ps (T): Pump Startup time,

Gs (T): Generator Startup time,

Z: Total Cost,

NETREV: Total Cost

INV (T): Inventory Constraint

UPPERX (T): Upper bound x

UPPERP (T): Upper bound p

UPPERI (T): Upper bound I

GEN (T): Generation contraint

IFIRST: Initial inventory

TC (T): Terminal condition

PSE (T): Pumping startup equation

GSE (T): Generator startup equation

UPPER gs (T): Upper on gs

UPPER ps (T): Upper on ps

LOWER ps (T): Lower on ps

LOWER gs (T): Lower on gs;

UPPERP 1(T): Upper bound p

$U_t^{c:}$ If compressor started up at hour t,

$U_t^{g:}$ If generator is started up at hour t,

S_t^c: Started- up cost of the compressor,

S_t^g: Started- up cost of the generator,

$P_{comp:}$ the MW Rating of the pumping unit,

¥: the number of pumping hours consumed by each generating hour,

β: the number of generating hours possible for each pumping hour,

μ: the assumed capacity of the facility in total pumping hours,

η_c: Efficiency of the compressor.

η_t: Turbine efficiency.

List of Abbreviations

CAES: Compressed Air Energy Storage

MW: Megawatts

EU: European Union

USA: united States of America

AEC: Alabama's Electric Cooperative

ESC: Energy Storage Council

FERC: Federal Energy Regulatory Commission

RTO: Regional Transmission Organization

SMES: Superconducting Magnetic Energy Storage

UWIG: Utility Wind Integration Group

AFS: American Flywheel Systems

EÜAŞ: Elektrik Üretim Anonim Şirketi

T.A.O: Türkiye Anonim Ortaklığı

US EPA: United State Environmental Protection Agency

NY DEC: New York State Department of Environmental Conservation

DSİ: Devlet Su İşleri

ISO: International Organization for Standardization

NY ISO: New York State International Organization for Standardization

ISEP: Iowa Stored Energy Park

VAR: Value at Risk

PHS: Pumped-hydro storage

RFC: Regenerative Fuel Cells

FES: Flywheel Energy Storage

TVA: Tennessee Valley Authority

MARR: Minimum Acceptable Rate of Return

VOM: Variable Operation Maintence

LMP: Locational Market Price

GP: Gas Price

CT: Cycle Turbine

GT: Gas Turbine

CCGT: Combined Cycle Gas Turbine

ROR: Rate of Return

NPV: Net Present Value

SDF: System Imbalance Price (Sistem Dengesizlik Fiyatı)

SMF: System Marginal Price (Sistem Marjinal Fiyatı)

BEP: Break even Point

Chapter 1
Introduction

Renewable energy sources are necessary for energy efficiency. The world is focused on energy to increase efficiency. Energy security, climate change, fluctuating and rising oil prices are substantiated issues. The introduction of integrated storage technologies is a future sustainable energy system. CAES is an integrated storage techonology. CAES is a low cost technology for storing large quantities of electric energy with high pressure air. With this technology, air is injected at high pressure into natural caverns. This compressed air assists the operation of natural gas-fired turbines at the times when there is an increased need for electricity. For generating electricity, the compressed air makes it possible for to use less natural gas. In this system, the air is usually pumped into large storage tanks or natural caverns. This system stores the low-cost off-peak power. During the sale period, the electricity will be sold when it is more valuable. This report is intended to examine Economic and Operational Analysis of Compressed Air Energy Storage Systems.

The rest of the thesis is organized as follows. Chapter 2 presents an overwiew of Compressed Air Energy Storage System. In this chapter, descriptions of the system are detailed. The other energy storage techonologies, importance of natural gas, opportunities of the market, the necessity of modeling, the necessity of analysis and Turkey's energy policy are explained in detail. Chapter 3 presents the engineering economics and analysis. I explain economical terms and I show the economical equations which I used to calculate NPV and PP. The problem formulation and the model of our problem are presented in Chapter 4. In this chapter the model is given and explained. Chapter 5 indented the forecasting system of LMP and GP, in which I developed the GP and LMP estimations with six different scenarios. Chapter 6 presents the economical analysis of CAES system for N years. The revenue and cost of the system is calculated in this chapter and the technical and economical data of the CAES plant is also given. Chapter 7 presents a numerical analysis to validate our model. This chapter is based on the analysis of the CAES which is given in Chapter 6. The last chapter presents the conclusion of our report. In this chapter, I evaluate the financial results which are obtained in Chapter 7.

Chapter 2

Overview of Compressed Air Energy Storage

2.1 Compressed Air Energy Storage (CAES)

Compressed air energy storage (CAES) is a hybrid generation or storage technology. With this technology, air is injected at high pressure into natural caverns. This compressed air assists the operation of natural gas-fired turbines at times there is an increased need for electricity. For generating electricity; the compressed air permits the turbines by using less natural gas. Load-leveling is adopted via CAES because CAES is created in capacities of a few hundred MW and clearance over long (4-24 hours) periods of time. The potential energy of pressurized gas has a technique of storing energy which named as Compressed Air Energy Storage (CAES). In this system, the air is usually pumped into large storage tanks or natural caverns. Figure 2.1 shows a schematic of the approach.[1]

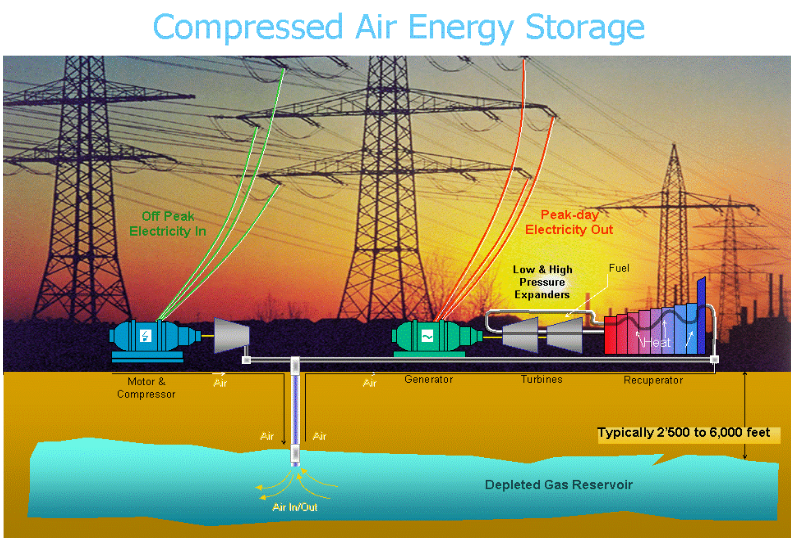

Figure 2.1: Conceptual representation of CAES

(http://www.pangeaexploration.com/compressed_air_energy_storage.htm)

In CAES systems, if the energy is available, the air will run the air compressors. Then the compressors will pump the air into the storage cavern. When the electricity is demanded, it is expanded via conventional gas turbine expanders.

Huntorf Plant is the world's first compressed air storage power station. In 1978, the Huntorf Plant has been ready for use. Huntorf is located in Bremen, Germany. The capacity of the plant was 290 MW. Providing peak shaving, spinning reserves and VAR support is done at Huntorf plant. Total volume of the plant is 11 million cubic feet. This plant has two underground salt caverns which is pressures up to 1000 psi inside and also situated 2100-2600 feet below the surface. The system is fully recharging 12 hours of off-peak power, and the delivering full output capacity of the system is up to 4 hours. [2]

Alabama's Electric Cooperative (AEC) is the world's second CAES facility. AEC has been ready for use since 1991. It is called the McIntosh project. AEC is 110 MW units. Storing off-peak power, generating peak power and providing spinning reserve is using for commercial inference. The volume of the plant is 19 million cubic feet. The pressure of the system is up to 1080 psi and the deep of the system is up to 2500 feet. Full power output of the system is 26 hours. This system recovers waste heat. Fuel consumption is reduced via the waste heat. The waste heat is 25% less than the Huntorf Plant.[2] http://www.caes.net/mcintosh.html

The Iowa Association of Municipal Utilities and the Department of Energy associated for creating the Iowa Stored Energy Park. They announced their decision in January of 2007. Their plan is integrating wind farm with underground CAES. The wind farm capacity is defined as a 75 to 150 MW and the capacity of CAES is defined as 3000 ft below the surface.[2] http://www.isepa.com

The world's first wind turbine-air compressor is produced by Technology which is a compressor company in the Boston area. The capacity of these new wind turbines are nearly 1.5 MW.

Each wind turbine will pump air into CAES instead of generating electricity. With this approach; elimination of the intermediate and needless electrical generation between the turbine and the air compressor improve overall efficiency. And it also has the potential for saving money. http://generalcompression.com

According to research entitled CAES Scoping Workshop; there are several components for developing a successful CAES facility. First of all you need to have a Suitable Storage site. It has two types like above ground or below ground. Then the availability of transmission, fuel source and environmental and permitting issues are also very important for developing successful CAES system. For a successful CAES, there should be some several Permits. Air permits created by US EPA or NYS DEC. Some permits should be created such as; Water discharge (brine) permits, electric and gas sitting licenses and environmental permits, well drilling and testing permits, electric interconnect application process at NY ISO, Archaeological surveys for developing successful CAES facility. [3]

The CAES value proposition and the best aspects is the other important subject for CAES system. More flexible generating alternatives are provided to Regional Transmission Organization (RTO) by CAES system. In generation, there is intrinsic value which can be rapidly rising and failing. There are fast ramping rates at CAES. Another result of the CAES Scoping Workshop research shows that; the valued capacity of CAES system can be operated among to 20% and 100%. Transmission constrains flexibility provides the RTO with means to maintain system security. The ability to store clean and off-peak generation until the peak hours are important advantages of CAES for the complete system. CAES has benefits in terms of cost and environment. Again, as we see in the research; the basic CAES internal value proposition items are providing energy at a thermal efficiency equal or higher to a combined cycle gas turbine with less than half the fuel and emissions of the former, capacity, and ancillary services. The external value proposition comes from the ability to dispatch lower cost or sustainable and renewable energy resources to meet hourly loads on demand. The ancillary and arbitrage benefits of adding the system in the grid is an advantage of the economical benefits of CAES. Optimizing the new build requirements for transmission is also advantage of the economical benefits of CAES. In cost analysis, the current production of RTO systems is necessary to make model. Determining the cost benefits of the CAES system is possible via determining total system cost, and again with strategically situated CAES. A model using a specific RTO's set of circumstances is more effective than a generic model. The value of CAES is affected by the current load patterns and generation blend on the system. The CAES type is important for implementation of maximum CAES benefits to non carbon discharge generation. For instance, CAES has direct benefit with wind resources. If the system absorbed the much wind energy, CAES should reduce the transmission constraints. Energy stored off-peak and distributed on-peak is an advantage for all electric users. It decreases the on-peak prices.[3]

According to research entitled CAES Scoping Workshop ; the best ways for improving the capital cost and operational performance of CAES components and an integration to overall CAES plant via cut into 3 different parts.[3]

Near term: In Huntorf and MCLntosh, at the operational existing first generation CAES plants, the cost and performance of CAES equipment are well studied and at the second generation CAES design, the cost and performance of CAES equipment have been improved from the application of industry standard components. In the US, the CAES plants are supported by first generation or second generation CAES for improving cost and operation in the near-term. The CAES plants also based on improving the productivity of construction and consolidating operating experience and expertise.

Mid Term: a) an air driven turbine is necessary for the industry. Few suppliers are ready to supply larger than 85 MW air turbines. They give guarantees for performance. Operational flexibility is necessary for high pressure fired expanders

b) Incorporating low emission or renewable energy heat sources for expanding the compressed air could minimize the use of fossil fuels.

c) The industry needs to develop semi-adiabatic systems. The new design’s compression discharge temperatures should be higher than current designs. The use of fuel is reduced via enabling efficient heat storage and recuperation.

Long Term: Advanced adiabatic systems can eliminate the use of fuel. High heat production needs compressors, heat capture and transfer media systems for studying.

Another result of the CAES Scoping Workshop shows that; there are some specific action items. These items would be very beneficial for a clear presentation of the CAES technology, CAES concepts, benefits and the operation of the two existing first Generation CAES plants. The items are: [3]

- An industry report will published on the subject.
- The different concepts of the studies are direct through at journals and they are published in industry journals.
- The items are current at RTO market participant workshops.
- RTO planners have a come across discretely relationship with items.
- UWIG organization is an example for identification of synergy. Working together is necessary to promote beneficial market rules.

Some several environmental advantages are defined in the introduction of CAES: [3]

- The amount of wind curtailment is decreased by strategically sited CAES. Otherwise that would occur their surplus generations without the ability of store.
- Operating at a somewhat higher capacity level in off-peak hours with less clean technologies is permitted by CAES. Because, if we run the system, it will be more productive and clean range as a result of this permit.
- Clean technologies and enable it to be delivered during peak hours increase the percentage of power generation in CAES system.

According to research entitled CAES Scoping Workshop ; If CAES produce less NOx, CO, CO2, PM10, SOx and other toxic emissions; CAES could be “greener” over its life cycle. Designing or choosing of fuel, considering the best available technology in term of low emissions and higher efficiencies, Controlling systems for better grid management, Using less water, Dry cooling, Preventing any direct environmental impact, and using pre-existing underground storage are all important issues for creating a greener CAES.[3]

As can be seen CAES system has several advantages and disadvantages. According to research of Boise State University is about the advantages of the CAES system. The advantages of CAES systems are; First of all, Ancillary services which are provided to the grid have important advantage for implementing a CAES. Peak shaving; spinning reserve; VAR support; and arbitrage are included in Applications[3].This system is enable to stored the energy for later time. In this system the energy can stored to use better time. Perhaps, it is an advantage to use energy when it is more valuable. If the CAES coupled with an irregular source such as wind energy, the benefits of CAES will especially compelling.[1]

Another result of the Boise State University research shows that CAES systems have several disadvantages. According to this research; there will be sure losses with any energy conversion. CAES system is a similar system with storage. Some of these losses are reduced in the procedure used by using the wind turbine to compress the air directly. The requirement for additional heating in the expansion process is the most important disadvantage of CAES. Generating should be 3 times to natural gas. For every 3 kWh generations from a CAES system; 1 kWh worth of natural gas is necessary. If the natural gas prices increase, the marginal economics of present CAES could fail.[1]

2.2 Why do we still need natural gas?

The requirements for additional fuel in the expansion process are one of the confusing aspects of the CAES. Gas compression and expansion are the reasons of the fundamental physics. Air compressors have cooling fins because when a gas is compressed, it gets warmer. Conversely, frost builds up on the shuttle fueling lines because when it expands, it gets cold.

In the CAES expander systems, exist of the turbine would be nearly cryogenic in nature. A conventional gas turbine is a compressor-turbine combination, as seen in Figure 2.2. [1]

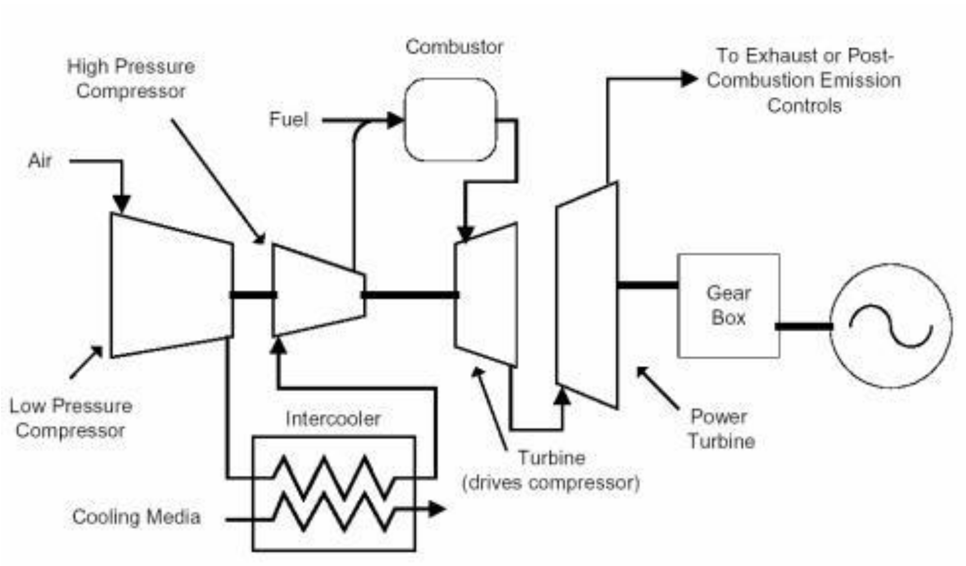

Figure 2.2: Conventional gas turbine with two-stage compressor and expander. (http://www.energysolutionscenter.org)

Conventional gas turbine has a two-stage expander section. In the first expander section stage is committed to running the two-stage compressor and all of the energy goes to generating electricity. The mechanical energy generated in a conventional gas turbine. The quantity of the mechanical energy which used to run the compressor sections of the turbine is nearly 2/3. The expander does not drive the compressor when CAES system is used the air is already compressed.

According to this result, the net yield of the expander is increased by 3 times. Decreasing of the amount of gas required during expansion is proposed by different concepts. Waste heat from the compression cycles is recovered in the McIntosh Plant. The McIntosh Plant is reducing natural gas more than the Huntorf Plant. Decreasing gas consumption, eliminating fuel all over by capturing, storing and re-using heat are some of the hypothesis.[3]

2.3. Energy Storage Technologies

Energy storage is an economic decision. In the new power market, energy storage has vitally important role. The direct storage of electricity is very expensive so the electricity is stored in other forms. If the system needs electricity, the system will transform the electricity. The storing of power production is cheap at night so the system is storing power at night. There is five parts of the electric power market. Fuel/energy source, Generation, Transmission and marketing, Distribution, and Energy services are five base parts of the electric power market. Energy storage is very important issue and it is the “sixth dimension” of the electric power market. Integrating the existing segments and creating a more responsive market is the critical issues for Electric power market. Storage will improve the reliability of electricity supply. Increasing the productivity of existing power plant and transmission facilities can be done with storage. Storage also necessary to reduce the investment necessary in these facilities.[4] there are also some basic benefits of Energy Storages. We can show the challenges and benefits of the Energy Storage in Figure 2.3. In this figure we can see the benefits of the energy Storage with the challenges. [4]

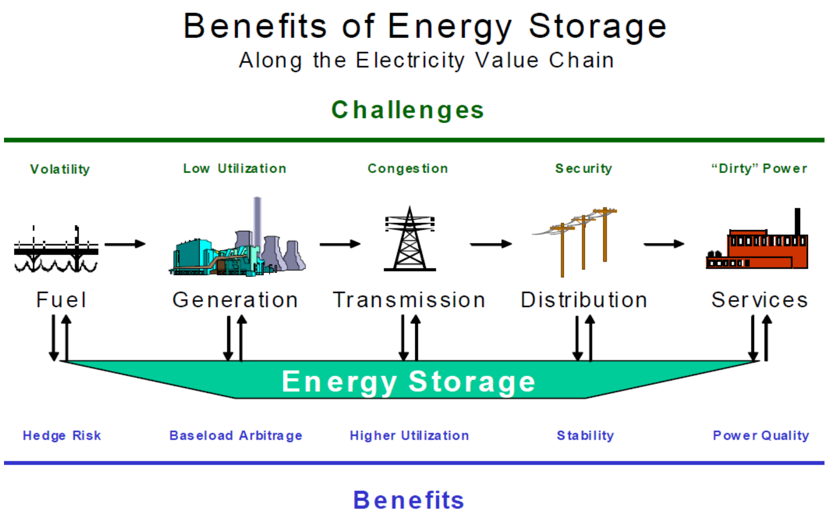

Figure 2.3 Benefits of Energy Storage along the Electricity Value Chain

Technologies are used commercially. Energy storage technologies are Pumped-Hydro Storage, Compressed Air Energy Storage, Regenerative Fuel Cells, Batteries, Superconducting Magnetic Energy Storage, Flywheels, Thermal and Hydrogen. [4]

2.3.1 Pumped-Hydro Storage:

The oldest and largest technology of all the commercially available energy storage technologies is Pumped-hydro storage (PHS). The capacity of the storage is size up to 1,000 MW. Conventional pumped hydro facilities have two large reservoirs. One of the reservoirs is located at a low level and the other of the reservoir is situated at a higher elevation. Water is stored at reservoir. The water is pumped from the lower to the upper reservoir, during off-peak hours. At electricity generation; the water is released back down to the lower reservoir, passed through hydraulic turbines and generate an electricity power. Generally, Pumped-hydro storage facilities operate on a daily schedule. There are only a few facilities because of the high construction costs, long construction times, and the requirement of large amounts of land.[4]

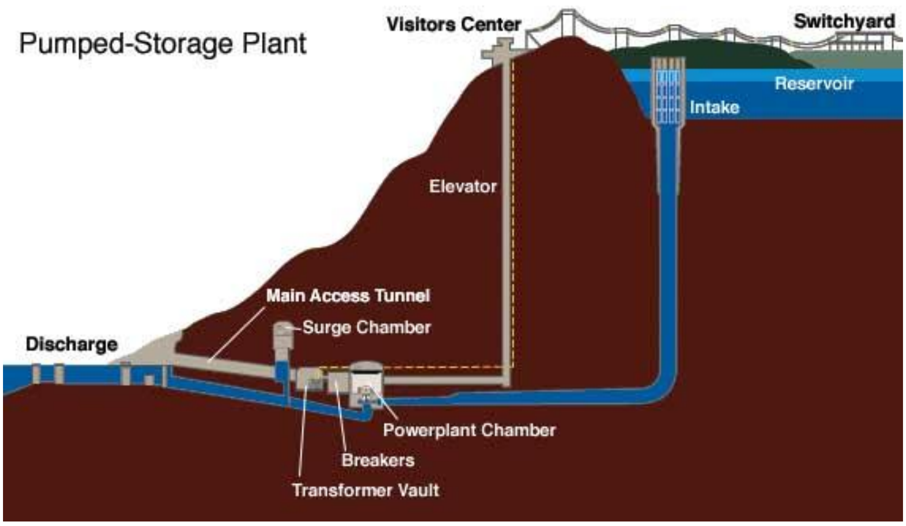

Figure 2.4 Schematic of a pumped-hydro storage plant (http://www.tva.gov/power/hydro.htm)

2.3.2 Compressed Air Energy Storage (CAES):

Pressing air into an underground reservoir via using off- peak power is defined as Compressed air energy storage (CAES) systems. The underground reservoirs can be salt cavern, abandoned hard rock mine, or aquifer. Then for power production, the system releases during peak daytime hours to power a turbine or generator. In this technology, the low-cost power from an off-peak base load facility is replaced for the more expensive gas turbine-produced power to compress the air for combustion. Nearly two thirds of the energy produced is used to pressurize the air, in a gas turbine. The only other commercially available technology is Compressed air energy storage. The great system energy storage ability is provided via CAES. The commodity storage or other large- scale setting is delivered ability by the great system energy storage. [4]

2.3.3 Regenerative Fuel Cells:

Regenerative fuel cells are capable of storing and releasing energy. It is also known as redox flow-cell batteries. This is an energy which is through a reversible electrochemical reaction between two salt solutions (electrolytes).

There are some different designs exist. The electrolytes of the around exists are; zinc bromide (ZnBr), and sodium bromide (NaBr). In this system; the electrical energy is transformed to potential chemical energy. Then an electrochemical cell is created the release of the potential energy. An ion-exchange membrane is physically separated to each electrolyte. There is no discharge of the regenerative electrolyte solutions from the facility because the technology is a closed loop cycle. The size of the electrolytic tanks is defined in the scale of facility. Joining into CAES is promised via this technology and in this technology, hydro is pumped as large-scale energy storage options. [4]

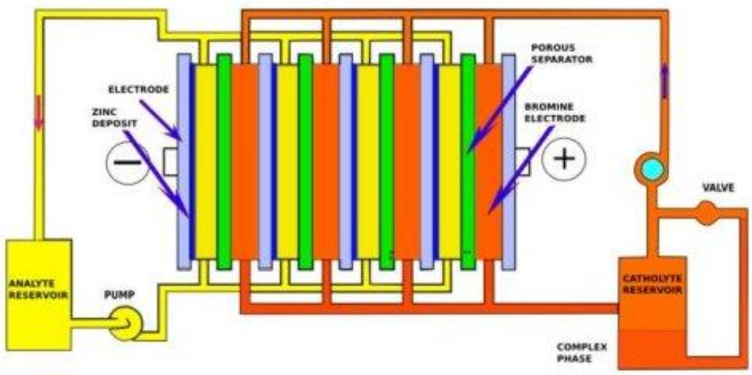

Figure 2.5 Schematic of a RFC plant
(http://www.zestenergy.com/technology.php)

2.3.4 Batteries:

Battery technologies are using like utility-scale energy storage facilities. First of all, these installations have been lead-acid. Sodium sulfur (NaS) and Lithium ion are the other battery technologies. These technologies are conversional to commercially available. All batteries are electrochemical cells. Two electrodes are composed electrochemical cells. Electrolyte is separated the electrodes. Anode is the first electrode and cathode is the second electrode. During discharge, ions from the anode are released into the solution and deposit oxides on the cathode. The system recharges the battery is reversing the electrical charge. This information is given at the ESC white paper research. “When the cell is being recharged, the chemical reactions are reversed, restoring the battery to its original condition” [4]

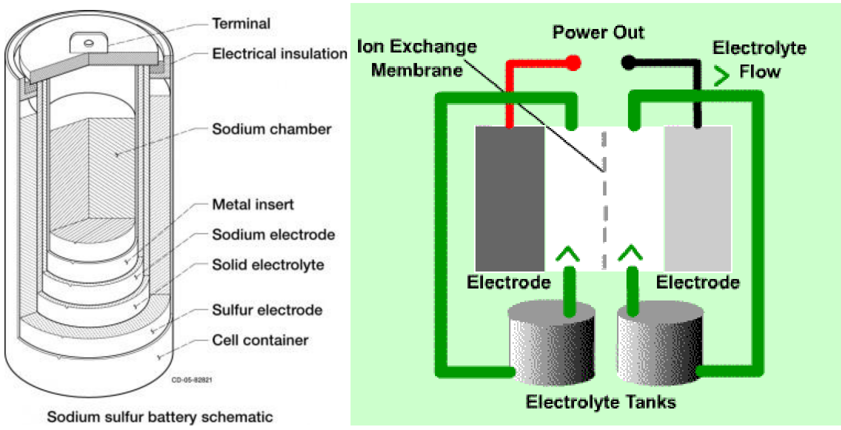

Figure 2.6 Schematic of Battery technologies (http://willyyanto.wordpress.com/2010/07/09/energy-storage-technologies-for-electricity-grid-infrastructure)

2.3.5 Superconducting Magnetic Energy Storage (SMES):

Superconducting Magnetic Energy Storage (SMES) is an emerging technology. In this technology systems store energy in the magnetic field. The flow of direct current creates energy in a coil of cryogenically cooled, superconducting material. Superconducting coil, power conditioning system, cryogenic refrigerator, and cryostat or vacuum vessel are parts of SMES system. The coil at the low temperature required can be keep with these components and maintaining of the coil in a superconducting state is possible with these components. SMES are greater than 95% efficient at storing electricity but the operating cost is very high because the construction of the system is very expensive. Just becasue of this, they are best suited to provide constant. SMES has deep discharges and constant activity. The size of facilities is around to 3 MW units.

Generally, the grid stability in a distribution system and the power quality at manufacturing facilities requiring ultra-clean power such a chip fabrication facility are providing via these facilities. [4]

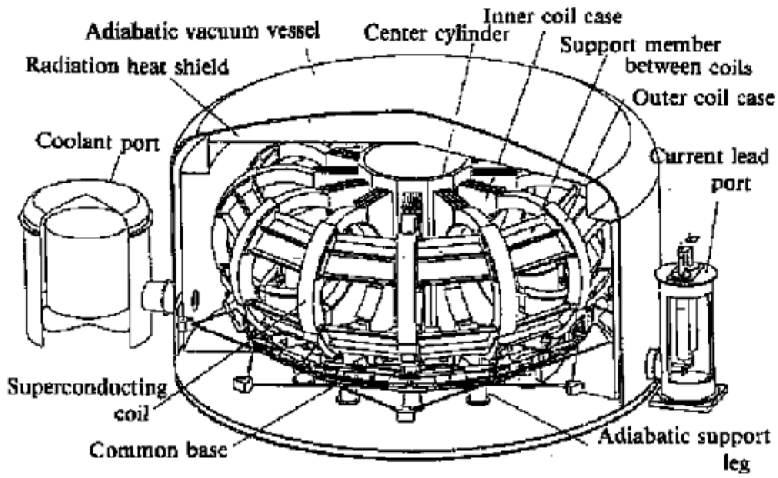

Figure 2.7 Schematic of SMES

2.3.6 Flywheels:

A flywheel energy storage system (FES) works by accelerating a rotor (flywheel) to a very high speed. Then the flywheel maintained the energy in the system as rotational energy. The advantages of the flywheel stores energy are high power output, long life, Unaffected by ambient temperature extremes. The challenges of the system are; Reduce cost of flywheel rotor and advanced magnetic bearing, mass produce with quantity, develop lightweight vacuum containment vessel, and reduce overall system weight. The battery systems are incompact and have upper maintenance costs and requirements than this system. The power quality and reliability market are the base issues for developing this technology. Active Power, AFS Trinity, Beacon Power, and Pentadyne Power Corporation are parts of the development.[4]

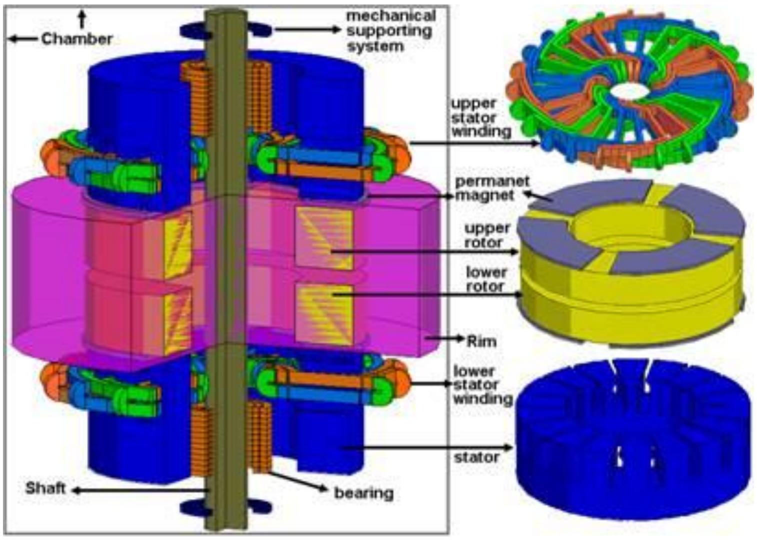

Figure 2.8 Schematic of Flywheel Technology

(http://www.pe.eee.ntu.edu.sg/Research/ResearchAreas/Pages/IEDS.aspx)

2.3.7 Thermal:

Thermal energy storage system is a high-tech energy storage technology. Ice-based for peak shaving commercial and industrial cooling are kind of thermal systems. Ices during off-peak hours are created by the ice systems. During the day, for large commercial buildings, the ice systems are used to supplement the cooling load. Operating costs of peak demand charges is allowed for smaller chillers and substantially lower air conditioning by the ice systems. The period of the sun's daylight hours is important for Thermal energy storage technique. [4]

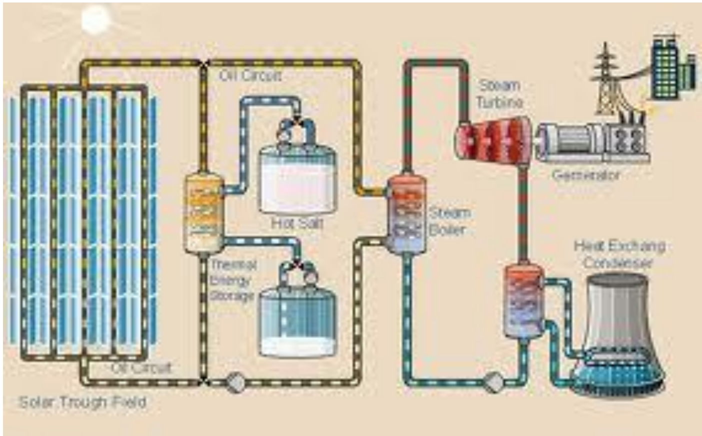

Figure 2.9 Schematic of a Thermal Energy Storage System

2.3.8 Hydrogen:

Hydrogen energy storage will be an integral component of any post-fossil energy market. The hydrogen can be stored different forms like a gas, liquid, metal hydride, or carbon-based form. Then hydrogen is released through a chemical reaction to power a fuel cell. Chemical hydrides are the preferred method for long-term stationary storage.[4]

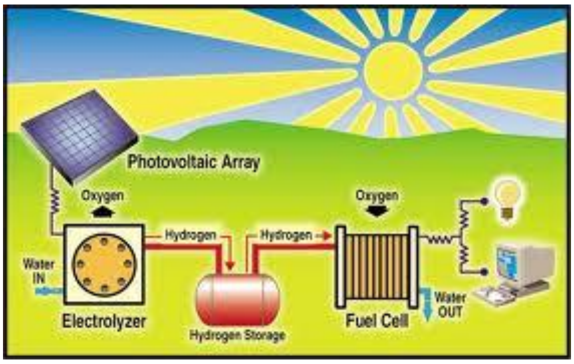

Figure 2.10 Schematic of Hydrogen Energy Storage System (http://www.oilempire.us/hydrogen.html)

2.4 Market Opportunities

Different business models have developed to take advantage of changing economic and technical market place realities according to the electric power industry evolves. The transformation will take place inside of the energy storage market. The business model is not sufficed so the system needs a functional operation to operate the system. There are four areas for multifunctional energy storage facility. They are base load arbitrage, transmission support, energy services, and renewable energy storage. First two exist is in the wholesale side of the market. The third exist is in the retail segment, and the fourth exist is depending upon the size of the renewable resource being developed in both the wholesale and retail market.[4]

- Base load Arbitrage: The largest possible revenue generating market opportunity for large-scale storage facilities is represented to arbitraging base load nuclear and coal-fired generation between off-peak and on-peak hours. The number of factors which rested on is created by the quantity of revenue.

The difference between day and night prices will be the determining factor. Reaping the additional benefits from a better performing base load facility is possible with the storage facility which is owned by the same entity that owns the coal facility that will supply the power. [4]

- Transmission Support: Long time ago, FERC has brought to light as the deregulation of the industry's center stage is transmission issues. The problem is added to simplification of additional power facilities and chronic transmission constraints for some regions. Putting off facilities and improving utilization abilities are interest to owners of transmission assets. Providing ancillary services, maintaining the grid's stability, supporting a growing power trading market and relieving of congestion are related to RTO operators in storage facilities.[4]

- Energy Services: Most of manufacturing and commercial companies installed protective gear. Their goal was minimizing impacts of outages during processes. The main reasons were avoiding from bad power quality and reliability. Enterprise energy management systems suppliers such as battery, flywheels, SMES and thermal systems producers began including storage facilities into their rollouts. [4]

- Renewables Energy Storage: Increasing renewable energy's competitiveness by selling energy and selling capacity in market by the help of contingency services. Value could be added to electricity services by prepearing contacts for storage and discharge of energy. In addition to this capacity could be sold after dispatching power's ability was sustained. [4]

2.5 What are the modeling and analysis needs?

The first generation CAES plants are necessary to quantify the emissions profile. The reserve capacities of spinning and synchronizing according to Nox, CO, and CO2 emissions are over the operating range. Providing accurate emission estimation is necessary for comprehensive life cycle analysis of first generation CAES systems. And there should be balance comparisons between other energy generation, storage options and first generation CAES systems. For CAES storage, Brine disposal has significant effect on the improving of salt formations. If it is using in the marketable products, safe disposal alternatives and options should be investigated.

Natural gas storage is completed into the CAES storage. The natural gas reservoir which is depleted is suitable for CAES. In the reservoir, the presence of natural gas should be safety. The detail analysis is necessary for this issue. Modeling of wind and solar resources activities at collaboration national labs and universities would be beneficial for integrating CAES. The CAES experiences of the European CAES community could be provided via this collaboration.

The other collaborative research is adiabatic CAES plants. The technical infrastructure is ready for adiabatic CAES. The theoretical efficiencies of this plant are not calculated. Designing of heat storage systems compression pressure, high end temperature design, selection of heat capture and selection of storage technology are some basic problems of Adiabatic CAES plants.[4]

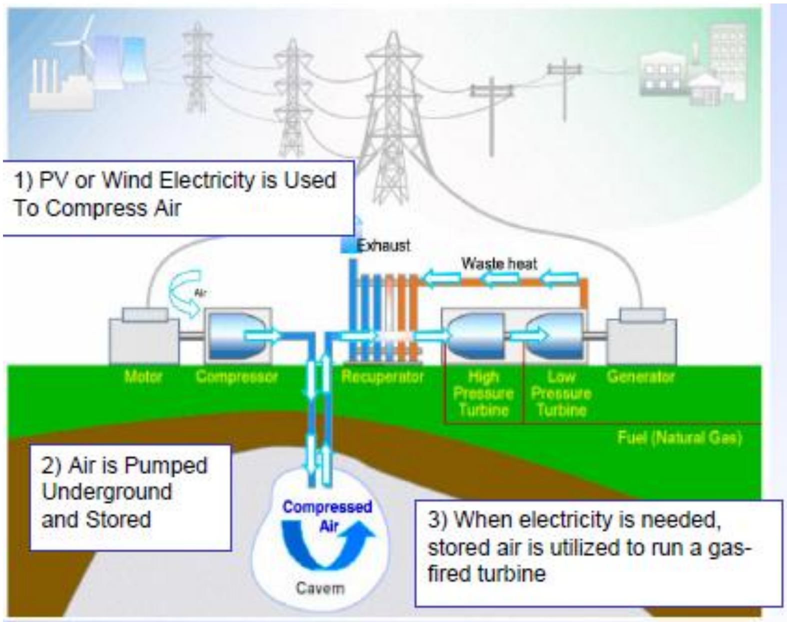

Figure 2.11 CAES System Process

2.6 What is the Turkey's Energy Policy?

Turkey is a natural bridge between the energy producer Asian countries and energy consumer European countries. Turkey's neighboring regions the Caucasus, Middle East and Central Asia are situated %70 of the known oil and gas reserves of the world. Although Turkey has the potential to play an important role over energy policies owing to its position as a transit country but it is not an energy producer country. In recent years, Turkey joins the pipeline projects and it has taken significant steps in order to have the transit country position.

On the other hand, Russia, the EU, and USA as global powers have different interests and try to benefit from the energy resources in these regions in line with their energy policy objectives. Economic and social factors affect the electrical energy demand. The demand of the Energy is impressed to the developments and growths in the industry sector.[5]

In 2008, our electricity has been realized as 198,1 billion kWh. In 2009, Turkey's gross electricity consumption decreased by 2,42%, regressing to 193,3 billion kWh.[6] Compared to the previous year (198,4 billion kWh), our country's electricity generation also decreased this year by 2,02%,regressing to 194,1 billion kWh. Our electricity generation is expected by 2020 to reach 499 TWh with an annual increase of around 8% according to the higher demand scenario, or 406 TWh with an annual increase of 6,1% according to the lower demand scenario. As of 21 July 2010, our installed power has now reached 46.126 MW after the deployment of a new power plant of 1.479 MW. This information is given from the official site of the Republic of Turkey ministry of energy and natural resources. [6]

Our electricity generation came from three main sources in 2009. The sources are natural gas by 48,6%, coal by 28,3%, hydroelectric by 18,5%, liquid fuels by 3,4%, and renewable resources by 1,1%. [6] Out of Turkey's total installed power 54,2% is in EÜAŞ, 16,4% in production companies, 13,7% in build-operate power plants, 8,1% in auto producers, 5,5% in build-operate-transfer power plants, 1,5% in transferred power plants, and 0,6% in mobile power plants as of the end of 2009.[6]

Private sector provides to Law No. 4628 for new production investments In line with the target of liberating the electricity market. Our country's installed power capacity went up from 31.750 MW to 44.600 MW between 2002 and 2009. During that period an additional capacity of 12.850 MW was deployed around 7000 MW. The privately invested power plants generate the additional capacity. [6]

A new power plant of 3.002 MW was introduced to the system in 2009. In the privately invested power plants generate the additional capacity deployed 2.810 MW. For creating a transparent and competition-driven market in the electricity sector these initiatives are necessary and thus help to improve the investment environment.[6]

In 2010, our Ministry was temporarily agreement and gave license to 64 privately owned power plants for operation. Total installed power of these power plants were 1479 MW. Of all the power plants deployed,

- 2% is Geothermal (17 MW)
- 13% is Wind Power (330 MW)
- 29% is Hydraulic (486 MW)
- 2% is Landfill gas and Bio-gas (7 MW)
- 18% is Thermal (639)

60 MW of the thermal power comes from cogeneration power plants. By the end of 2010 year, privately owned installed power is expected to exceed 2400 MW. This information is also given from the official site of the republic of Turkey ministry of energy and natural resources [6]

We can divide the policy of Turkey into terms like; between 1902 and 1923, between 1923-1933, between 1933-1950, between 1950-1960, between 1960 and 1980, between 1980 and 2001 and between 2001 to day time. The first electricity production was in Anatolia, at Tarsus. In 1902, on the Berdan River was carried out. The electricity was produced with the 2 KW power shaft belts which are connected to water mill. Then with this production a few residential and streets are illuminated. In 1913, Silahtarağa Thermal power plant is established in Istanbul by Macar Ganz

Company. This power plant has started production by 15 megawatts (MW) of power. This power plant was the first city-scale electric power plant between 1914 and 1983. In 1923, the government decided to meet the need of energy from the coal.

Kayseri and civan electric power plants are established in 11 October 1926. Then Zonguldak Çatalağzı power plant established and connected to Istanbul via power transmission line with 154kv energy. This line is the beginning of the international interconnected system. Seyhan dam and Hes, Sarıyer dam and Hes, Tunceli thermal power plant, Hirfanlı dam and HES are some of the power plants which are established between 1950- 1960.

Kuzeybatı Anadolu Elektriklendirme T.A.O., Ege Elektrik T.A.O. Çukurova Elektrik A.Ş. ve Kepez Elektrik A.Ş. are also established between 1950 and 1960. In 1974, Afşin Elbistan thermal power plant is established and in 1984 it produced the energy. And in 1974, Keban dam and the four turbines are started to produce energy at Elazığ on the Fırat River. [7]

Atatürk Dam is established in 1980-2001 at Şanlıurfa. Atatürk Dam is the biggest hydro electricity power plant in Turkey. [7] Altınkaya Dam is established in 1988 at Samsun, Oymapınar Dam is established in 1984 at Antalya, Hasanuğurlu Dam is established in 1981 at Samsun, Karakaya Dam is established in 1987 at Diyarbakır, Gökçekaya Dam is established in 1972 at Eskişehir, Mezelet Dam is established in 1989 at Kahramanmaraş, Adıgüzel Dam is established in 1992 at Denizli, Özlüce Dam is established in 2000 at Bingöl. All of those Dams are very important dams for our Energy requirements. [6]

Chapter 3

Engineering Economics and Analysis

Justification and selection of projects are important parts of engineering economy. Many engineers work on a specified activity or a problem projects. Justification of any decision about the project is important. In business environments “profit” is the most important criterion. In manufacturing environment, decisions are made at the managerial level then many engineers become managers in manufacturing environment. Methods and tools used in evaluation of projects should known by all engineers, regardless of their employment. [8]

The tools and methods which are used by individuals and non-profit organizations such as government, hospitals, and charitable entities, etc. are the sections of projects in business environment at engineering economy. Tools which used in engineering economy is aided many real life decisions. There are two criteria like monetary and nonmonetary criteria. In non-profit organizations, decisions are based on both of these criteria. If the two types of criteria are combining into one single measure, this poses will be an additional problem for evaluation of projects.

The methods which are used in evaluation of the projects are used according to engineering economy. Determining the “best” project or projects is the main objective. However, one method is discussing the benefit-cost analysis which is used for evaluation of projects in the non-profit sector. The tool is developed to know the needed variables which are named as costs, revenues, etc. [8] usually; there is a lot of possible alternatives.[9]

Each analysis must be considered, and always there should be an alternative. Both choices of the opportunity costs must be considered. [9] Color, style, public image, etc. are also noneconomic factors.[9]

In Engineering Economics; there are some terms we will often use in our project. The terms definitions are defined following; [10]

- **Cash-Flow Concepts** The inputs of the project is defined as monetary and the outputs of the project are defined as project investment.
- **Time value of money** is defined as a relationship between time and dependent value of money. [10]
- **Cash-Flow Diagrams**; Drawing a picture for showing the economical analysis is the easiest way. Three things are important at these diagrams. Firstly, a time interval should divided into an equal periods. The deposits, expenditures, etc which are defined as all cash outflows should be in each period and the withdrawals, income, etc. which are defined as all cash inflows should be in each period. If there is not any extra information, all cash flows will be considered at the end of their respective periods. [10]
- **Notation**; Economic analysis are simplified by Notation. The types of cash flows and interest factors are represented via introduced symbols.
- **Interest Calculations;** The use of borrowed money or the return on invested capital is defined as interest that means the money paid. The economic cost of money includes a factor. This factor can correctly establish the economic cost of construction, installation, ownership, or operation. [10]
- **Simple interest** principal amount is charging via interest rate.

$$F = P + (i * P) N$$

where

P=Principal amount

İ =Simple interest rate

N=Number of interest periods

F= Total amount accumulated at the end of period N

- **Discounting** The present amount is defined as inverse of compounding. This amount will yield a specified future sum. This process is named as discounting.
- **Compound interest:** Principal amount and any previously accumulated interest which has not been withdrawn is charging via interest rate. [10]

$$n=0:\ P$$
$$n=1: F_1=P\ (1+i)$$
$$n=2:\ F_2=F_1(1+i)\ =P\ (1+i)^2$$
.
.
$$n=N:\ F=P\ (1+i)^N$$

- **Present worth:** At the present or base time, future cash flows are discounting via this values. A present sum of money is converting the costs which are associated with each alternative investment and the best alternative is representing least of these values. The annual costs, future payments, and gradients should be included the present. Discounting is converting all cash flows to present worth.[10]
- **Annual Cost**: All cash flows are changed to a series of uniform payments. This is necessary to compare alternatives by annual cost. Annual cost should cover current expenditures, future costs or receipts, and gradients. The lump-sum cash flow should be converted in a two-step process when a lump-sum cash flow occurs at some time other than the beginning or end of the economic life. The first process is moving it to the present and the second process is spreading it uniformly over the life of the project. [10]
- **Payback Period Analysis**; A financial metric. This metric is an answer of "How long does it take for an investment to pay for itself?" Timing is not necessary to calculating all costs and profits. Payback period is the only result of the economic consequence. [10]

$$\text{Payback Period} = \frac{\text{The costs of Project / Investment}}{AnnualCashInflows}$$

- **Rate of return:** The interest rate of the present worth of the net cash flow is zero**.**
- **Minimum acceptable rate of return;** The project manager or company wishes the minimum rate of return acception on before starting a project. [10]

Chapter 4

Problem Formulation and Modeling for CAES

Compressed Air Energy Storage has a fairly low capital cost compared to other energy storage technologies. In a CAES facility, the natural gas is burned then the storage is heated with this energy. Then producing the electricity is happening according to expanded the combustion products in the turbine.[11]The air is added into the storage by the compressor until full capacity reached. Then the generator expands the air to produce electricity until the empty level of storage reservoir is reached. This system is shown at the Figure 4.1[11]The CAES unit can pump or generate in any hour. CAES systems operate compression and expansion operations independently and same times. [12] As can be shown at the figure, the compressor injects the air to storage from the compression operation. In the air storage, the pressure is high and the temperature is also high. Intercoolers are necessary to decrease or increase the temperature of the storage air. Then the Generation withdrawns air from the storage. In the pressurized air, natural gas is combusted.[12]

In the CAES analysis the most important issue is to decide which time is the best time for pumping the air or generating the electricity. One should know the market prices or at least can forecast the possible market prices in order to schedule a CAES system. Another important issue is the price of natural gas that is used in CAES system. That directly affects the profit and cost so it becomes an issue for scheduling. The CAES system has an air inventory that is filled while pumping and emptied while generating electricity as the air is used in turbine to generate electricity. The hourly profit is the revenue which is gained when the power is sold to the market, minus the cost which is the variable and operating cost, natural gas cost, and sum of startup costs. The sum of hourly profits over the year can give us the total profit of the corresponding year.

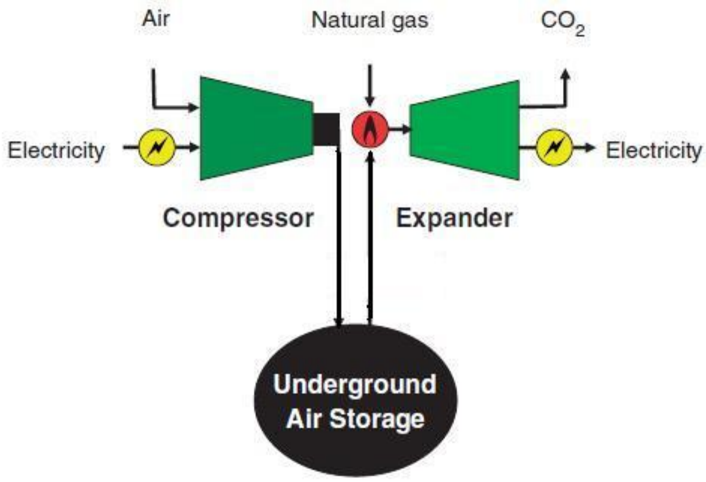

Figure 4.1: CAES schematic[11]

If the market prices and natural gas prices can be estimated for the future years, a scheduling based analysis can be provided for investors to help their decision. For this analysis, we calculated the Locational Market Prices and Gas prices for the next 30 years. The hourly data will show us which time is the best for generating or pumping. Our aim is to maximize the profit in our CAES analysis. The model is implemented at Gams and the solutions are found. Gams will solve the best generation or pumping hours for the maximum profit then will calculate the total cost for our system and the results of the data will show the investors how wise is their decision.The investors can decide to do or not to do their investment.

The capacity of the compressed air storage facility is important for CAES analysis. The capacity of the compressed air storage has different value for pumping and generating. The facility comes with a full inventory of compressed air and finishes with a full inventory of compressed air. So in our model we need to take into consideration of the capacity and inventory. The schedule of pumping and generation depends only on the relative prices and the capacity of the storage facility. The storage facility also has a system. The facility system is like that; if economics allows, the inventory of compressed air can be carried forward from one time period to another. In the CAES analysis model no fixed costs are considered.

The main objective of the model is maximization of the profit in the CAES analysis. The optimal annual operation is the other basic principle of the model. The proposed model is a mixed-integer linear programming model and formulated by the following notations.

Decision variables

$X_{t:}$ is 1 if the power generated in hour t, 0 otherwise,

$P_{t:}$ is 1 if the pumping unit pumps in hour t, 0 otherwise,

$I_{t:}$ is the compressed air inventory, in hours of generation available, in hour t,

$U_t^{c:}$ If compressor started up at hour t, (TL/Start-up)

$U_t^{g:}$ If generator is started up at hour t, (TL/Start-up)

Parameters

$I_{first:}$ is the inventory of compressed air in the first hour, (generation hours)

$I_{last:}$ is the inventory of compressed air in the last hour, (generation hours)

$P_{CAES:}$ is the MW rating of the generating unit, (MWh)

$LMP_{t:}$ is the load/gen Locational market price at the pumped air station bus, (TL/MWh)

$P_{GAS:}$ the MW rating of the gas cycle turbine, (MWh)

$HR_{GAS:}$ the heat rate of the gas CT, (mmBTU/MWh)

$MP_{GAS:}$ is the gas price in hour t, (TL/mmBTU)

$VOM_{gen:}$ the Variable operation maintenance generation cost, (TL/MWh)

S_t^c: Start- up cost of compressor, (MWh)

S_t^g: Start- up cost of generator, (Hours)

$P_{comp:}$ the MW Rating of the pumping unit, (Hours)

¥: the number of pumping hours consumed by each generating hour, (Hours)

β: the number of generating hours possible for each pumping hour, (Hours)

μ: the assumed capacity of the facility in total pumping hours, (Hours)

$\eta_{c:}$ Efficiency of compressor.

η_t: Turbine efficiency.

The model is given as follows:

$$\text{Max} \sum_{t=1}^{T} \left[\begin{array}{l} \mathrm{X_t} \left(\mathrm{P_{CAES}} (\mathrm{LMP_t} - VOM_{Gen}) - \mathrm{P_{GAS}} * \mathrm{HR_{GAS}} * \mathrm{MP_{GAS}} \right) \\ - \left(\dfrac{(\mathrm{LMP_t} + VOM_{Comp}) * \mathrm{P}_{Comp}}{\eta_t \eta_c} \right) * \mathrm{P}_t - S_t^c * U_t^c - S_t^g * U_t^g \end{array} \right] \qquad (1)$$

The problem is subject to the following constraints;

$$\mathrm{I_{(t+1)}} - \mathrm{I_t} + ¥ * \mathrm{X_{(t+1)}} - \mathrm{P_{(t+1)}} = 0 \qquad (2)$$

$$\mathrm{X_{(t+1)}} \leq \beta * \mathrm{I_t} \qquad (3)$$

$$\mathrm{X_t} \in \{0,1\} \quad \text{(Binary)} \qquad (4)$$

$$P_{\mathrm{t}} \in \{0,1\} \quad \text{(Binary)} \qquad (5)$$

$$0 \leq \mathrm{I_t} \leq \mu \qquad (6)$$

$$\mathrm{I_{first}} = \mu \qquad (7)$$

$$\mathrm{I_{last}} = \mu \qquad (8)$$

$$U_t^c \geq P_t - P_{t-1} \qquad (9)$$

$$U_t^g \geq X_t - X_{t-1} \qquad (10)$$

$$U_t^c, U_t^g \in \{0,1\} \quad \text{(Binary)} \qquad (11)$$

The objective function is the revenue minus cost of natural gas, variable operating cost and startup cost. The first parenthesis equation represents the differences between the locational market price at the pumped air station bus and the variable operational maintenance generation cost at hour t. In the first part of the equation; the net market price at hour *t* is multiplied with the MW rating of the generating unit. The revenue at hour *t* is calculated with this equation. In the next equation, we need to calculate the cost of gas at hour *t*. In this part the rating of the gas cycle turbine is multiplied with the heat rate of the gas CT and it is multiplied with the gas price in hour *t*. In this part the system calculates the gas turbine's cost at hour *t*. Then in the last parenthesis equation the function calculates the total pumping cost of the system.

The locational market price at hour *t* plus the variable operational maintenance pumping cost at hour *t* gives us the total cost of the pumping station. The efficiency of the compressor and turbine efficiency are also included. Then the pumping cost at hour *t* is multiplied with the MW Rating of the pumping unit for total pumping cost. The last part of our objective function has two binary equations. The explanation of the first binary equation is, if the compressor is started up at hour *t*, the started up cost of the compressor will affect the function at hour *t*. If the compressor is not started up at hour *t*, the started up cost of the compressor will not affect the function at hour *t*. The explanation of the next binary equation is, if the generator is started up at hour *t*, the startedup cost of the generator will affect the function at hour *t*. If the generator is not started up at hour *t*, the started up cost of the generator will not affect the function at hour *t*. The detailed GAMS formulation can be found in Appendix F.

Equation (2) represents the inventory. The differences between the inventory at *(t+1)* and at *t* should be equal to the differences between the unit pumping in hour *(t+1)* and the unit generation in hour *(t+1)*.

Equation (3) represents the relation between the inventory and generation hour. The power generated in hour *(t+1)* should be less and equal to possible number of generating hours for each pumping hour times inventory at *t*.

Equation (4) represents the binary for a generating hour. This equation means, if the system generates, X_t will be 1. If the system does not generate, X_t will be zero.

Equation (5) represents the binary for a pumping hour. This equation means, if the system pumps, P_t will be 1. If the system does not pump, P_t will be zero.

Equation (6) represents for inventory. The inventory cannot be less than zero and more than μ. In the equations (7) and (8), the first and last inventory is equal to μ.

Equation (9) represents the compressor's start up time. The differences between pumping hour at *(t)* and *(t-1)* should be less than the compressor's start up time at hour t.

Equation (10) represents the generator's start up time. The differences between generating hour at *(t)* and *(t-1)* should be less than the generator's start up time at hour *t*.

Equation (11) represents the binary equations for the compressor's and generator's start up time. If the compressor or generator starts up at hour *t*, the U_t^c and U_t^g will be 1; if the compressor or generator does not start up at hour *t*, the U_t^c and U_t^g will be zero.

To optimize the scheduling of the facility, we need to know the forward market prices, forward natural gas prices and the value of the CAES air inventory. In the next section, we provide an analysis on how to determine the market prices and natural gas prices.

Chapter 5

Market Price and Gas Price Forecasting

5.1 The Forecasting System

Forecasting is a method for estimating the value of unknown parameters with using the value of known parameters under the described conditions. Forecasts provide information to make better decisions. The designing procedure of a forecasting system is shown at Figure 5.1. [13]

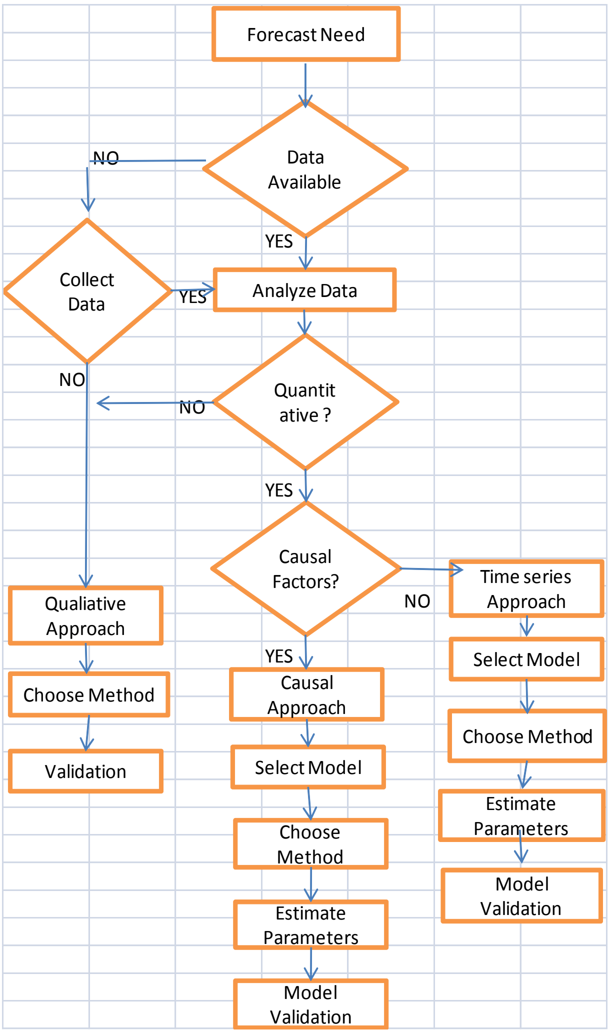

Figure 5.1: Designing a forecasting system[14]

Economical, technological and demand forecasting are types of forecasting system. Qualitative, Quantitative and Causal methods are types of methodology for forecasting system. [13]

In Qualitative method, information which is used for forecasting is based on experience, personal jurisdiction and intuition. We can investigate the qualitative methods such as Market Survey, Exper Opinion and Delphi Technique.

At Causal Methods the relationship between the variables is represented by a mathematical expression after selecting the variables that affect the measure for estimation. The measure which is researched is defined as the dependent variable and the other measure is defined as independent variable. [15]

Quantitative Methods are divided in to two parts as Time Series Analysis and Mixed Methods. In our project, we used time series analysis method to forecast next year's data. Time series analysis is based on the principle of using the information from the past to predict the future. In times series analysis, the value of the dependent variable (Y) is examined with respect to time (X). The more used type of time series analysis is Moving Average, Exponential Smoothing and Trend Analysis. The independent variables are defined with time measurements such as time, month, day, etc. The dependent variables are defined with an item such as productivity, money, number of production, and stock level etc. [15]

Mixed methods are divided into sub-headings like simple regression analysis, multiple regression analysis, econometric models, artificially intelligence and heuristic algorithms. The forecasting for the day-ahead market prices is explained below and illustrated in Fig 5.2. [16]

If you want to forecast the market price for day d, you should analysis data on day d-1. Also data for d-1 are necessary to forecast market prices on day d-2. Data may come from company records or commercial or government sources.[16]

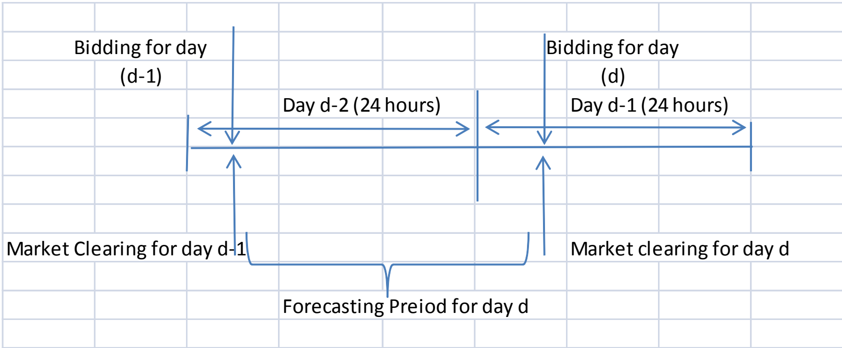

Figure 5.2: Time to forecast market prices for day d. [16]

5.2 Electricity market price forecasting models and simulation of Turkey

In the Turkey's electric sector, investors and operators are looking for some answers to the questions. The basic questions are who will buy the electric? How much energy can we sell? And how much does the electric cost?

Avoiding the price volatility is possible with bilateral agreement sales. Especially, risk of the wind and hydrogen cannot be disposed in the wind and hydro electric plants. In the spot market sales, the meeting point between the investment and operating costs and spot prices are unknown. In this case, according to market simulation and price forecasting analysis the project investment cost should return to ensure at during desired period of project. The operation cost should meet and there should improve some kinds of strategies to avoid of risks then these strategies should be implemented. [17]

The market simulation has inputs and results. Legislative and regulatory scenarios, market development scenarios, hydrological scenarios, fuel scenarios, demand-supply scenarios, etc. are some several inputs for the market simulation model.

The results of the market simulation are; system marginal costs, system marginal prices, operating hours of power plants, revenue scenarios of power plants, the possibilities of the energy gap, etc. [17]

Market simulation analyses investment environment, market conditions, the other investors and operators decisions and simulation affects the market price. EPSİM is simulation software. Model of the Turkey's electric market and forecasting the previous conditions of the market are possible via this software. There are some variables which are necessary to create "An investment needs decision analysis". Some of these variables are; Legislation and market development effects, Hydrology, Demand-Supply changes, Costs, Price Levels, Replacement capacity costs, etc. [17]

According to this information, we created six different price scenarios to see the best and worst prices of the next year. These scenarios are necessary to decide for making investment and evaluating our investment. Now we will calculate LMP and GP for next 30 years.

5.3 Market Price Forecasting

Supply and demand analysis for the sources of electricity is great important for creation of the country's energy policies. The electric energy is one of the most crucial elements of world. Electric energy cannot be stored so that we should consume energy when it is produced. Hence the production and consumption of energy shows a parallel development. [18]

Energy is one of the important inputs of industrialization, social and economic development. So the energy need is constantly increasing at industrialized and developing countries.

Electric energy is a type of clean energy. It is useful and there is no waste or smell after use. Therefore, the electric demands always increase. The demand of electricity shows regional, seasonal, daily and hourly differences. [18]

Our work was created by using time series data for the periods between May, 2010 and May, 2011 May. Electric prices were obtained from PMUS official page (http://dgpys.teias.gov.tr/dgpys/). We evaluated the price forecast for the next 30 years. We have made estimates for the next 30 years electric price using scenarios and our scenarios are based on the prices between May, 2010 and May, 2011.

We have set upper and lower limits for our estimates. If the electric price increases 10 % at year n, the scenario will be Best Price Scenario for year n. If the electric price decreases 10 % for year n, the scenario will be Worst Price Scenario for year n. Table 5.1 show the price scenarios that are used in the analysis. The simulated market price scenario is found based on the historical changes on the market price and natural gas price. The kind of forecasting scenarios are shown as follows;

Table 5.1: Forecasting Scenarios of estimations.

Worst Price Scenario	Electric Prices decrease 10%. Natural Gas Prices decrease 10%.
Low Price Scenario	Electric Prices decrease 5%. Natural Gas Prices decrease 5%.
Current Price Scenario	Electric Prices is fixed. Natural Gas Prices is fixed.
High Price Scenario	Electric Prices increase 5%. Natural Gas Prices increase 5%.
Best Price Scenario	Electric Prices increase 10%. Natural Gas Prices increase 10%.
Simulated Price Scenario	Electric Prices changes [-10%, 10%]. Natural Gas Prices changes [-5%, 5%].

In our CAES system; we need to estimate next 30 years Locational Market prices and Gas prices. I added the Microsoft Excel Tables for Locational Market Price Scenario at Appendix A and also added Gas price Scenario at Appendix B.

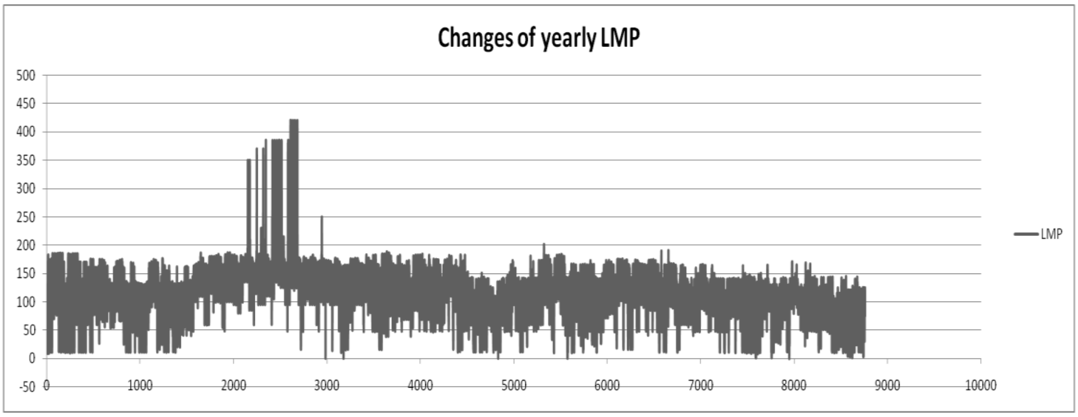

Figure 5.3: The based data of LMP

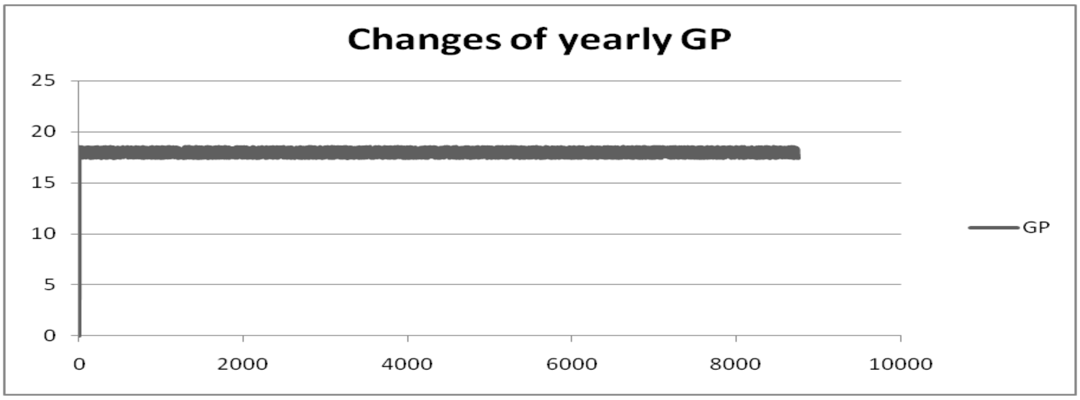

Figure 5.4: The based data of GP

As can be seen, the data of GP is in a very close range so it is difficult to see the details in the above graph. Then we graph the weekly GP data for each hour for a week. At the below table, it is shown as description the weekly changes of GP for each hour.

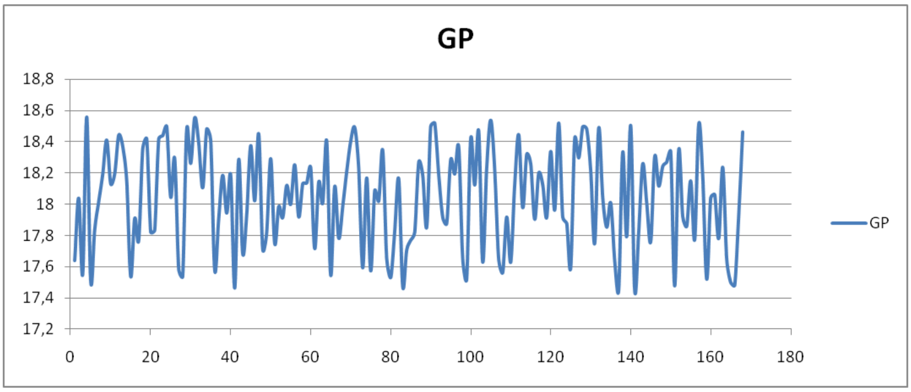

Figure 5.5 Weekly changes of GP for each hour

5.3.1 Locational Market Price Forecasting

Every day; National Load Dispatch Center (MYTM) is publishing hourly demand of electricity forecasting at Market Management System (PYS). The participants are try to guess how much electricity they need for the next day and what hours they might need electricity. They use seasonal conditions, occupancy rates of dams, rainfall, system constraints for their estimations. If demand is high at hour t; the production will increase at hour t. And if demand is low at hour t; the production will decrease at hour t. Then if offering is more than demand; the price will increase and if offering is less than demand; the price will decrease. The last offer price at hour t is determining the electricity price for hour t. The last offer price is system marginal price (SMF) for that hour. System marginal price is separately calculated for peak, daytime and nighttime. And a cumulative total price is calculated by dividing the amount then this price's name is system imbalance price (SDF). [19]

According to these calculation methods, we try to estimate next 30 years Locational Market Prices and Gas prices. The Market Management System Published prices of electricity from May 2010 to May 2011. We used this data for estimation next 30 years Market prices. We improved 6 kinds of price forecast scenarios like; Worst Locational Market Price Forecast Scenario, Low Locational Market Price Forecast Scenario, Current Locational Market Price Forecast Scenario, High Locational Market Price Forecast Scenario, Best Locational Market Price Forecast Scenario, Simulated Locational Market Price Forecast Scenario. Now I will explain how do I seperate the scenarios into 6 types.

5.3.1.1 Worst Locational Market Price Forecast Scenario

Historical data shows that power prices can change in a given interval. I estimate that power price will decrease [-10%]. The procedure to forecasting prices for 30 years is as follows;

Start;
for M years;
for T hours;
Power Price $_{M,T}$ = Price$_{M-1,T}$ * (1- 0.1)
Next hour;
Next year;
End

As shown in procedure; power price at hour T changes the previous year's price at hour T. The ratio is 10% for worst Locational Market Price forecasting. I assume that; next year the Locational Market Price will decrease regularly. The data from May 2010 to May 2011 is base data for our project. I calculated the next 30 years LMP at Excel. I used base data which were taken from the Market Management System. I produced next year's LMP with procedure format. If you accept worst

Locational market price scenario then the next year's LMP will equal to (1-0.1) times of this year's LMP. I write this function to Microsoft Excel program for Locational Market Prices forecasting. The Excel table is shown at Table 5.2 as an example. Then the Microsoft Excel produced next 30 years forecast for Worst Locational Market Price Forecast Scenario.

Table 5.2: An Example of Excel formulation about Worst LMP forecast Scenario

	Change	-0,1							
No	LMP								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
H1	130.0	117	105,3	94,77	85,293	76,7637	69,08733	62,178597	55,9607373
H2	110.0	99	89,1	80,19	72,171	64,9539	58,45851	52,612659	47,3513931
H3	115.0	103,5	93,15	83,835	75,4515	67,90635	61,115715	55,0041435	49,50372915

5.3.1.2 Low Locational Market Price Forecast Scenario

Historical data shows that power prices can change in a given interval. I estimate that power price will decrease [-5%]. The procedure to forecasting prices for 30 years is as follows;

Start;
for M years;
for T hours;
Power Price $_{M,T}$ = Price$_{M-1,T}$ * (1- 0.05)
Next hour;
Next year;
End.

As shown in procedure; power price at hour T changes the previous year's price at hour T. The ratio is 5% for Low Locational Market Price forecasting. I assume that; next year the Locational Market Price will decrease regularly. The data from May 2010 to May 2011 is base data for our project. I calculated the next 30 years LMP at Excel. I used base data which were taken from the Market Management System. I produced next year's LMP with procedure format. If you accept Low locational market price scenario then the next year's LMP will equal to (1-0.05) times of this year's LMP. I write this function to Microsoft Excel program for Locational Market Prices forecasting.

An Example of Excel formulation about Low LMP forecast Scenario is shown at Table 5.3. Then the Microsoft Excel produced next 30 years forecast for Low Locational Market Price Forecast Scenario.

Table 5.3: An Example of Excel formulation about Low LMP forecast Scenario

	Change	**-0,05**							
No	LMP								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
H1	130.0	123,5	117,325	111,45875	105,8858125	100,5915219	95,56194578	90,78384849	86,24465607
H2	110.0	104,5	99,275	94,31125	89,5956875	85,11590313	80,86010797	76,81710257	72,97624744
H3	115.0	109,25	103,7875	98,598125	93,66821875	88,98480781	84,53556742	80,30878905	76,2933496

5.3.1.3 Current Locational Market Price Forecast Scenario

Current Locational Market Price Forecast scenario takes power prices fix for all years. The next 30 years; the power prices do not change at this scenario. The procedure of Current Locational Market Price Forecast Scenario for 30 years is as follows;

Start;
for M years;
for T hours;
Power Price $_{M,T}$ = Price$_{M-1,T}$ * (1- 0)
Next hour;
Next year;
End.

As shown in procedure; power price at hour T changes the previous year's price at hour T. The price does not change so the LMP is same for all years. The data from May 2010 to May 2011 is base data for our project. I calculated the next 30 years LMP at Excel. I used base data which were taken from the Market Management System. I produced next year's LMP with procedure format. If you accept Current locational market price scenario then the next year's LMP will equal to (1-0) times of this year's LMP. Then the next year's LMP will equal this year's LMP and the LMP for next 30 years do not change. I write this function to Microsoft Excel program for Locational Market Prices forecasting.

An Example of Excel formulation about Current LMP forecast Scenario is shown at Table 5.4. Then the Microsoft Excel produced next 30 years forecast for Current Locational Market Price Forecast Scenario.

Table 5.4: An Example of Excel formulation about Current LMP forecast Scenario

	Change	0									
No	LMP										
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
H1	130.0	130	130	130	130	130	130	130	130	130	130
H2	110.0	110	110	110	110	110	110	110	110	110	110
H3	115.0	115	115	115	115	115	115	115	115	115	115

5.3.1.4 High Locational Market Price Forecast Scenario

Historical data shows that power prices can change in a given interval. I estimate that power price will increase [+5%]. The procedure to forecasting prices for 30 years is as follows;

Start;
for M years;
for T hours;
Power Price $_{M,T}$ = Price$_{M-1,T}$ * (1+0.05)
Next hour;
Next year;
End.

As shown in procedure; power price at hour T changes the previous year’s price at hour T. The ratio is 5% for High Locational Market Price forecasting. I assume that; next year the Locational Market Price will increase regularly. The data from May 2010 to May 2011 is base data for our project. I calculated the next 30 years LMP at Excel. I used base data which were taken from the Market Management System. I produced next year’s LMP with procedure format. If you accept high locational market price scenario then the next year’s LMP will equal to (1+0.05) times of this year’s LMP. I write this function to Microsoft Excel program for Locational Market Prices forecasting. An Example of Excel formulation about High LMP forecast Scenario is shown at Table 5.5. Then the Microsoft Excel produced next 30 years forecast for High Locational Market Price Forecast Scenario.

Table 5.5: An Example of Excel formulation about High LMP forecast Scenario

	Change	**0,05**							
No	LMP								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
H1	130.0	136,5	143,325	150,49125	158,0158125	165,9166031	174,2124333	182,9230549	192,0692077
H2	110.0	115,5	121,275	127,33875	133,7056875	140,3909719	147,4105205	154,7810465	162,5200988
H3	115.0	120,75	126,7875	133,126875	139,7832188	146,7723797	154,1109987	161,8165486	169,907376

5.3.1.5 Best Locational Market Price Forecast Scenario

Historical data shows that power prices can change in a given interval. I estimate that power price will increase [+10%]. The procedure to forecasting prices for 30 years is as follows;

Start;
for M years;
for T hours;
Power Price $_{M,T}$ = Price$_{M-1,T}$ * (1+ 0.1)
Next hour;
Next year;
End.

As shown in procedure; power price at hour T changes the previous year's price at hour T. The ratio is 10% for best Locational Market Price forecasting. I assume that; next year the Locational Market Price will increase regularly. The data from May 2010 to May 2011 is base data for our project. I calculated the next 30 years LMP at Excel. I used base data which were taken from the Market Management System. I produced next year's LMP with procedure format. If you accept best locational market price scenario then the next year's LMP will equal to (1+0.1) times of this year's LMP. I write this function to Microsoft Excel program for Locational Market Prices forecasting. An Example of Excel formulation about Best LMP forecast Scenario is shown at Table 5.6. Then the Microsoft Excel produced next 30 years forecast for Best Locational Market Price Forecast Scenario.

Table 5.6: An Example of Excel formulation about Best LMP forecast Scenario

	Change	0,1							
No	LMP								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
H1	130.0	143	157,3	173,03	190,333	209,3663	230,3029	253,3332	278,6665
H2	110.0	121	133,1	146,41	161,051	177,1561	194,8717	214,3589	235,7948
H3	115.0	126,5	139,15	153,065	168,3715	185,2087	203,7295	224,1025	246,5127

5.3.1.6 Simulated Locational Market Price Forecast Scenario

Historical data shows that power prices can change in a given interval. I estimate that power price can change between [-10%, +10%]. The procedure to forecasting prices for 30 years is as follows;

Start;
for M years;
for T hours;
Power Price $_{M,T}$ = Price$_{M-1,T}$ * (1- 0.1+(Rand/5))
Next hour;
Next year;
End.

As shown in procedure; power price at hour T changes the previous year's price at hour T. I accepted that; next year the Locational Market Price will change between [-10%, 10%]. The Simulation ratios of next 30 years are shown in table 8. The data from May 2010 to May 2011 is base data for our project. We calculated the next 30 years LMP at Excel. We used base data which were taken from the Market Management System. We produced next year's LMP with procedure format. If you accept best locational market price scenario then the next year's LMP will equal to (1-0.1+ (Rand/5)) times of this year's LMP. The simulation rates of LMP for each year are shown at Table 5.7 and we write this function to Microsoft Excel program for Locational Market Prices forecasting. An Example of Excel formulation about Simulated LMP forecast Scenario is shown at Table 5.8. Then the Microsoft Excel produced next 30 years forecast for Simulated Locational Market Price Forecast Scenario.

Table 5.7: Simulation rates of Locational Market Prices for each year.

Year	Simulation Rate	Year	Simulation Rate
2012	0.010417	2027	-0.00492
2013	-0.0041	2028	-0.03012
2014	-0.08605	2029	-0.00254
2015	0.094096	2030	0.28219
2016	-0.02667	2031	-0.0898
2017	-0.00061	2032	0.097054
2018	0.060449	2033	0.095131
2019	0.053563	2034	0.012113
2020	0.06433	2035	0.024576
2021	0.026954	2036	-0.04018
2022	-0.0081	2037	0.006974
2023	-0.07234	2038	0.025568
2024	0.057779	2039	-0.02095
2025	0.018903	2040	0.064278
2026	-0.06515	2041	-0.00385

Table 5.8: An Example of Excel formulation about Simulation LMP forecast Scenario

		0,010416539	-0,004104866	-0,086054544	0,094096462	-0,026670671	-0,000612798	0,060449339	0,053562748
	LMP	2012	2013	2014	2015	2016	2017	2018	2019
H1	130	131,35	130,81	119,55	130,8	127,31	127,23	134,92	142,15
H2	110	111,15	110,69	101,16	110,68	107,73	107,66	114,17	120,29
H3	115	116,2	115,72	105,76	115,71	112,62	112,55	119,35	125,74

5.3.2 Gas Price Forecasting

The BOTAŞ published prices of natural gas from May 2010 to May 2011. We used this data for estimating next 30 years gas prices. We improved 6 kinds of gas price forecast scenarios like; Worst Gas Price Forecast Scenario, Low Gas Price Forecast Scenario, Current Gas Price Forecast Scenario, High Gas Price Forecast Scenario, Best Gas Price Forecast Scenario, Simulated Gas Price Forecast Scenario. Now I will explain how we separate the scenarios into 6 types.

5.3.2.1 Worst Gas Price Forecast Scenario

Historical data shows that natural gas prices can change in a given interval. We estimate that gas price will decrease [-10%]. The procedure to forecasting prices for 30 years is as follows;

Start;

for M years;

for T hours;

Gas Price $_{M,T}$ = Gas Price$_{M-1,T}$ * (1- 0.1)

Next hour;

Next year;

End.

As shown in procedure; gas price at hour T changes the previous year's price at hour T. The ratio is 10% for worst gas price forecasting. We assume that; next year the gas price will decrease regularly. The data from May 2010 to May 2011 is base data for our project. We calculated the next 30 years GP at Excel. We used base data which were taken from the BOTAŞ Company. We produced next year's GP with procedure format. At this format if you accept worst gas price scenario then the next year's GP will equal to (1-0.1) times of this year's GP. We write this function to Microsoft Excel program for Gas Prices forecasting. Then the Microsoft Excel produced next 30 years forecast for Worst Gas Price Forecast Scenario. An Example of Excel formulation about Worst GP forecast Scenario is shown at Table 5.9.

Table 5.9: An Example of Excel formulation about Worst GP forecast Scenario

	Change	**-0,1**							
Time	GP								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
H1	17,63792357	15,87413121	14,28671809	12,85804628	11,57224166	10,41501749	9,373515741	8,436164167	7,59254775
H2	18,03863482	16,23477134	14,61129421	13,15016478	11,83514831	10,65163348	9,586470128	8,627823115	7,765040804
H3	17,5517211	15,79654899	14,21689409	12,79520468	11,51568421	10,36411579	9,32770421	8,394933789	7,55544041

5.3.2.2 Low Gas Price Forecast Scenario

Historical data shows that natural gas prices can change in a given interval. We estimate that gas price will decrease [-5%]. The procedure to forecasting prices for 30 years is as follows;

Start;

for M years;

for T hours;

Gas Price $_{M,T}$ =Gas Price$_{M-1,T}$ * (1- 0.05)

Next hour;

Next year;

End.

As shown in procedure; gas price at hour T changes the previous year's price at hour T. The ratio is 5% for Low Gas Price forecasting. We assume that; next year the Gas Price will decrease regularly. The data from May 2010 to May 2011 is base data for our project. We calculated the next 30 years LMP at Excel. We used base data which were taken from the BOTAŞ Company. We produced next year's GP with procedure format. If you accept Low gas price scenario then the next year's GP will equal to (1-0.05) times of this year's GP. We write this function to Microsoft Excel program for Gas Prices forecasting. An Example of Excel formulation about Low GP forecast Scenario is shown at Table 5.10. Then the Microsoft Excel produced next 30 years forecast for Low Gas Price Forecast Scenario.

Table 5.10: An Example of Excel formulation about Low GP forecast Scenario

	Change	**-0,05**							
No	GP								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
H1	17,63792357	16,75602739	15,91822602	15,12231472	14,36619899	13,64788904	12,96549458	12,31721986	11,70135886
H2	18,03863482	17,13670308	16,27986793	15,46587453	14,6925808	13,95795176	13,26005418	12,59705147	11,96719889
H3	17,5517211	16,67413504	15,84042829	15,04840687	14,29598653	13,5811872	12,90212784	12,25702145	11,64417038

5.3.2.3 Current Gas Price Forecast Scenario

Current Locational Gas Price Forecast scenario takes gas prices fix for all years. The next 30 years; the gas prices do not change at this scenario. The procedure of Current Gas Price Forecast Scenario for 30 years is as follows;

Start;

for M years;

for T hours;

Gas Price $_{M,T}$ = Gas Price$_{M-1,T}$ * (1- 0)

Next hour;

Next year;

End.

As shown in procedure; gas price at hour T changes the previous year's price at hour T. The price does not change so the GP is same for all years. The data from May 2010 to May 2011 is base data for our project. We calculated the next 30 years GP at Excel. We used base data which were taken from the BOTAŞ Company. We produced next year's GP with procedure format. If you accept Current gas price scenario then the next year's GP will equal to (1-0) times of this year's GP. Then the next year's GP will equal this year's GP and the GP for next 30 years do not change. We write this function to Microsoft Excel program for Gas Prices forecasting. An Example of Excel formulation about Current GP forecast Scenario is shown at Table 5.11. Then the Microsoft Excel produced next 30 years forecast for Current Gas Price Forecast Scenario.

Table 5.11: An Example of Excel formulation about Current GP forecast Scenario

	Change	**0**							
No	GP								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
H1	17,63792	17,63792	17,63792	17,63792	17,63792	17,63792	17,63792	17,63792	17,63792
H2	18,03863	18,03863	18,03863	18,03863	18,03863	18,03863	18,03863	18,03863	18,03863
H3	17,55172	17,55172	17,55172	17,55172	17,55172	17,55172	17,55172	17,55172	17,55172

5.3.2.4 High Gas Price Forecast Scenario

Historical data shows that natural gas prices can change in a given interval. We estimate that gas price will increase [+5%]. The procedure to forecasting prices for 30 years is as follows;

Start;

for M years;

for T hours;

Gas Price $_{M,T}$ = Gas Price$_{M-1,T}$ * (1+0.05)

Next hour;

Next year;

End.

As shown in procedure; gas price at hour T changes the previous year's price at hour T. The ratio is 5% for High Gas Price forecasting. We assume that; next year the Gas Price will increase regularly. The data from May 2010 to May 2011 is base data for our project. We calculated the next 30 years LMP at Excel. We used base data which were taken from the BOTAŞ Company. We produced next year's GP with procedure format. If you accept high gas price scenario then the next year's GP will equal to (1+0.05) times of this year's GP. We write this function to Microsoft Excel program for Gas Prices forecasting. An Example of Excel formulation about High GP forecast Scenario is shown at Table 5.12. Then the Microsoft Excel produced next 30 years forecast for High Gas Price Forecast Scenario.

Table 5.12: An Example of Excel formulation about High GP forecast Scenario

	Change	**0,05**							
No	GP								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
H1	17,63792	18,51982	19,44581	20,4181	21,43901	22,51096	23,6365	24,81833	26,05925
H2	18,03863	18,94057	19,88759	20,88197	21,92607	23,02238	24,1735	25,38217	26,65128
H3	17,55172	18,42931	19,35077	20,31831	21,33423	22,40094	23,52098	24,69703	25,93189

5.3.2.5 Best Gas Price Forecast Scenario

Historical data shows that natural gas prices can change in a given interval. We estimate that gas price will increase [+10%]. The procedure to forecasting prices for 30 years is as follows;

Start;

for M years;

for T hours;

Gas Price $_{M,T}$ = Gas Price$_{M-1,T}$ * (1+ 0.1)

Next hour;

Next year;

End.

As shown in procedure; gas price at hour T changes the previous year's price at hour T. The ratio is 10% for best gas Price forecasting. We assume that; next year the Gas Price will increase regularly. The data from May 2010 to May 2011 is base data for our project. We calculated the next 30 years GP at Excel. We used base data which were taken from the BOTAŞ Company. We produced next year's GP with procedure format. If you accept best gas price scenario then the next year's GP will equal to (1+0.1) times of this year's GP. We write this function to Microsoft Excel program for Gas Prices forecasting. An Example of Excel formulation about Best GP forecast Scenario is shown at Table 5.13. Then the Microsoft Excel produced next 30 years forecast for Best Gas Price Forecast Scenario.

Table 5.13: An Example of Excel formulation about Best GP forecast Scenario

	Change	**0,1**							
No	GP								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
H1	17,63792	19,40172	21,34189	23,47608	25,82368	28,40605	31,24666	34,37132	37,80846
H2	18,03863	19,8425	21,82675	24,00942	26,41037	29,0514	31,95654	35,1522	38,66742
H3	17,55172	19,30689	21,23758	23,36134	25,69747	28,26722	31,09394	34,20334	37,62367

5.3.2.6 Simulated Gas Price Forecast Scenario

Historical data shows that gas prices can change in a given interval. We estimate that gas price can change between [-5%, +5%]. The procedure to forecasting prices for 30 years is as follows;

Start;

for M years;

for T hours;

Gas Price $_{M,T}$ = Gas Price$_{M-1,T}$ * (1- 0.05+(Rand/10))

Next hour;

Next year;

End.

As shown in procedure; gas price at hour T changes the previous year's price at hour T. We assume that; next year the Gas Price will change between [-5%, 5%]. The simulation ratios of next 30 years are shown in table 8. The data from May 2010 to May 2011 is base data for our project. We calculated the next 30 years GP at Excel. We used base data which were taken from the BOTAŞ Company. We produced next year's GP with procedure format. At this format if you accept simulated gas price scenario then the next year's LMP will equal to (1-0.05+ (Rand/10)) times of this year's GP. We write this function to Microsoft Excel program for Gas Prices forecasting. The simulation rates of GP for each year are shown at Table 5.14. Then the Microsoft Excel produced next 30 years forecast for Simulated Gas Price Forecast Scenario. An Example of Excel formulation about Simulated GP forecast Scenario is shown at Table 5.15.

Table 5.14: Simulation rates of Gas Prices for each year.

Year	Simulation Rate	Year	Simulation Rate
2012	0.049111	2027	-0.00671
2013	0.020623	2028	-0.04887
2014	0.04298	2029	-0.01457
2015	-0.04354	2030	0.040519
2016	-0.04452	2031	-0.01057
2017	0.034362	2032	0.043783
2018	-0.01968	2033	0.033515
2019	-0.03494	2034	0.043933
2020	-0.01135	2035	0.008143
2021	-0.04536	2036	-0.02269
2022	0.01638	2037	0.048405
2023	0.048119	2038	0.047421
2024	-0.0089	2039	-0.0444
2025	-0.01473	2040	0.030851
2026	-0.0173	2041	0.033775

Table 5.15: An Example of Excel formulation about Simulated GP forecast Scenario

		0,049111401	0,020622761	0,042979832	-0,043537859	-0,044518781	0,034361815	-0,019683985	-0,034938299
	GP	2012	2013	2014	2015	2016	2017	2018	2019
H1	17,63792357	18,5	18,88	19,69	18,83	17,99	18,61	18,24	17,6
H2	18,03863482	18,92	19,31	20,14	19,26	18,4	19,03	18,66	18,01
H3	17,5517211	18,41	18,79	19,6	18,75	17,92	18,54	18,18	17,54

Chapter 6

Multi-year Economical Analysis of CAES

In this project, we calculate system profit assuming that we estimate the next year's power and natural gas prices. We assume that once the model is constructed and run for one year, one can use the same model to find the optimum schedule and profit of the future years given that the hourly power price and natural gas price can be estimated. To do so, we use the market price and natural gas price scenarios given in Chapter 4. These databases are necessary for our system's profit calculation. We forecasted next 30 years LMP and GP according to one year's data. Then we can decide to establish this system according to data. We can show our procedure as follows;

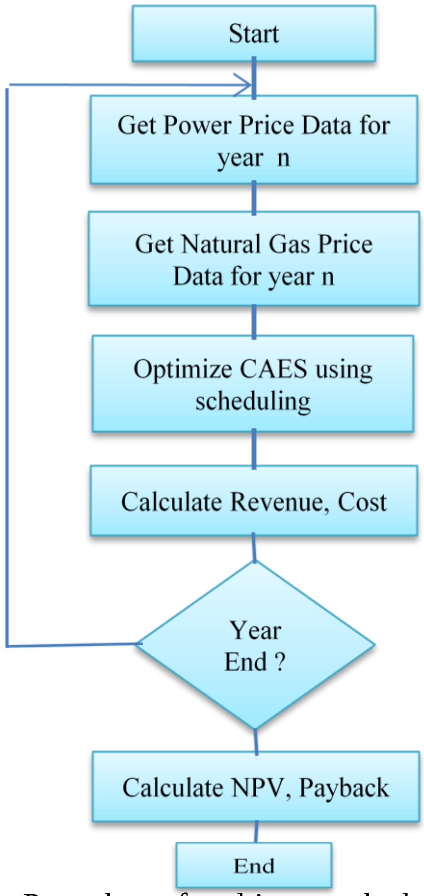

Figure 6.1: Procedure of multi-year scheduling of CAES.

As can be seen in the procedure; first of all we need Power and Gas price data for year -n then we optimize CAES using scheduling for year -n. The system calculates Revenue and cost for year n. At the end of the year we need to calculate Net Present Value, payback period for year *n* and start to get Power and gas price's data for year (n+1). We calculate 30 years net present values to decide to do or not to do our CAES project.

The model is given as follows:

$$\text{Max} \sum_{n=1}^{N}\sum_{t=1}^{T} \begin{bmatrix} \mathrm{X_t}\left(\mathrm{P_{CAES}}(\mathrm{LMP_t} - VOM_{Gen}) - \mathrm{P_{GAS}} * \mathrm{HR_{GAS}} * \mathrm{MP_{GAS}} \right) \\ - \left(\dfrac{(\mathrm{LMP_t} + VOM_{Comp}) * \mathrm{P}_{Comp}}{\eta_t \eta_c} \right) * \mathrm{P}_t - S_t^c * U_t^c - S_t^g * U_t^g \end{bmatrix} \tag{12}$$

Subject to

Equations (2)-(11).

Net Present Value is the difference between the present value of cash inflows and the present value of cash outflows. We used NPV in capital budgeting to analyze the profitability of our project. C_t is the revenue returned from the objective function in year t. And C_0 is an initial cost of investment. Annual discount rate is determined as "r". This rate is representing the interest rate of a competing investment and we determined "r" value as 8 based on previous years' rates. T defined as the number of cash flows in the list of values. We calculated our system's Net present value with the following formula; [20]

$$NPV = \sum_{t=1}^{T}\left(C_t \div (1+r)^t\right) - C_0 \tag{13}$$

An initial cost of investment for our Compressed Air Energy System is defined as $C_{0.}$ We have received our system's initial cost of investment, Technical and an economic assumption at Henrik Lund and Georges Salgi's article which's name is the role of compressed air energy storage (CAES) in future sustainable energy systems. At this article, Technical and economical data of the system is defined as follows;

Table 6.1: Technical and economical data of the CAES plant [21]

Compressor	Capacity	216 MW
	Efficiency	0.691
Storage	Capacity	1478 MW
Turbine	Capacity	360 MW
	Efficiency	2.44
	Fuel Ratio	2.15
Investment	Costs	411.750.000 TL
	Life Time	30 Years
	Interest Rate	8%
Operation Costs	Fixed Costs	10.633.104 TL/Year
	Variable Compressor	5.135.563 TL/MWh
	Variable Turbine	6.040.508 TL/MWh
Transmission Payment	Consumption (Compressor)	4.524.725 TL/MWh
	Production (Turbine)	2.199.052 TL/MWh
Availability payment on the regulating power market	Upward (Monthly)	7.533.667 TL/MWh
	Downward (Monthly)	2.420.727 TL/MWh

Table 6.2: Technical and economical data of CAES plant. [21]

Technology	Description	Annual investment and fixed operation costs (interest 8%)
CAES	360 MW Turbine 216 MW Compressor 1478 MWh Storage Life Time= 30 year	31.673.076 TL/Year

Chapter 7

Case Study

We develop a numerical analysis to validate our model. The base for the analysis is the CAES system given in Chapter 5. The investment cost of the CAES is 411.750.000 TL with a life time of 30 years. The real interest rate is 8% and it can be converted into an annual payment of 21.039.972 TL. The total annual cost is sum of the fixed operation cost and annual payment. The fixed cost is identified as 12.343.904 TL and annual payment is also identified as 21.039.972 TL then the total annual cost is identified as 36.769.076 TL plus variable fuel and operation costs.

The investment cost is 411.750.000 TL for our CAES system. The life time of our system is 30 years. First of all we run our model at Gams ide tool. The tool calculated profits of the years. We defined our gams ide files as Worst Year N, Low Year N, Current Year N, High Year N, Best Year N and Estimation Year N. The files are given at Appendix C. If we want to run the model with Best Price Scenario's data from 2016, we should write "$include Best 2016.txt". Then the tool will calculate the objective value for the Best Price Scenario of 2016. We calculated objective values for all Price Scenario between the years of 2012 to 2041. Then we created Table 7.1 for Net present value according to the results. The NPV table shows us what will be the NPV value of the profit for each corresponding year. As shown at table, we calculated the net present values until the year of 2041.

Table 7.1: Net present Value (NPV) between 2012 and 2041

Year	Worst	Low	Current	High	Best	Simulated
Cost	411.750.000	411.750.000	411.750.000	411.750.000	411.750.000	411.750.000
Base Datas2011	39.116.313	39.116.313	39.116.313	39.116.313	39.116.313	39.116.313
2012	33.368.767	36.234.604	39.116.313	42.018.462	44.935.077	33.038.944
2013	28.282.826	33.511.385	39.116.313	45.081.222	51.394.423	30.216.292
2014	23.781.458	30.948.126	39.116.313	48.313.348	58.538.561	15.316.052
2015	19.810.798	28.535.063	39.116.313	51.718.737	66.436.835	30.464.316
2016	16.334.811	26.261.993	39.116.313	55.303.893	75.177.978	31.118.411
2017	13.317.386	24.117.308	39.116.313	59.076.769	84.848.723	27.594.600
2018	10.702.786	22.099.448	39.116.313	63.047.748	95.535.758	39.116.091
2019	8.441.140	20.204.664	39.116.313	67.231.831	107.344.393	53.617.640
2020	6.488.250	18.430.259	39.116.313	71.638.926	120.386.372	69.397.180
2021	4.839.808	16.766.014	39.116.313	76.279.244	134.782.516	83.501.042
2022	3.491.324	15.213.207	39.116.313	81.166.952	150.658.601	78.768.084
2023	2.423.464	13.765.646	39.116.313	86.311.303	168.159.362	54.091.683
2024	1.620.666	12.415.484	39.116.313	91.724.889	187.443.189	68.088.368
2025	1.044.008	11.156.753	39.116.313	97.424.033	208.684.528	75.074.783
2026	681.854	9.983.602	39.116.313	103.420.774	232.078.248	61.433.687
2027	460.404	8.890.317	39.116.313	109.730.444	257.847.807	61.277.819
2028	325.029	7.871.379	39.116.313	116.370.002	286.221.985	61.425.663
2029	249.941	6.923.163	39.116.313	123.354.570	317.471.822	62.890.220
2030	195.458	6.047.692	39.116.313	130.701.138	351.876.030	63.616.869
2031	146.741	5.246.399	39.116.313	138.423.964	389.750.208	45.607.654
2032	103.142	4.512.763	39.116.313	146.544.262	431.441.568	58.765.499
2033	66.420	3.854.121	39.116.313	155.080.428	477.328.919	75.583.327
2034	35.031	3.257.491	39.116.313	164.052.479	527.831.115	71.812.746
2035	16.754	2.732.348	39.116.313	173.481.788	583.411.144	76.825.038
2036	7.630	2.269.252	39.116.313	183.390.233	644.577.337	69.937.107
2037	2.681	1.872.127	39.116.313	193.803.070	711.882.986	64.343.445
2038	0	1.521.475	39.116.313	204.742.549	785.945.659	63.279.798
2039	0	1.228.489	39.116.313	216.235.374	867.433.967	65.180.520
2040	0	990.868	39.116.313	228.311.717	957.095.734	76.160.284
2041	0	803.701	39.116.313	240.999.606	1.055.759.975	69.619.723
NPV	-283.332.223 YTL	-193.880.693 YTL	28.612.977 YTL	549.306.262 YTL	1.804.351.455 YTL	142.431.981 YTL

In this section, we give an example with using Simulated 2020 data. We saved data as “Simulated 2020” into the “projedir” file as a text. It is shown at Figure 7.1. Then we write our model at Gams ide tool as shown at Figure 7.2. After all, we run the tool then the system found optimal solution of our system. The tool shows us all of the equations and solution variables about our data. The objective function is calculated at this part and shown at Figure 7.3. The objective value is 69.397.180 for year 2020.This objective value is for the scenario of Simulated.

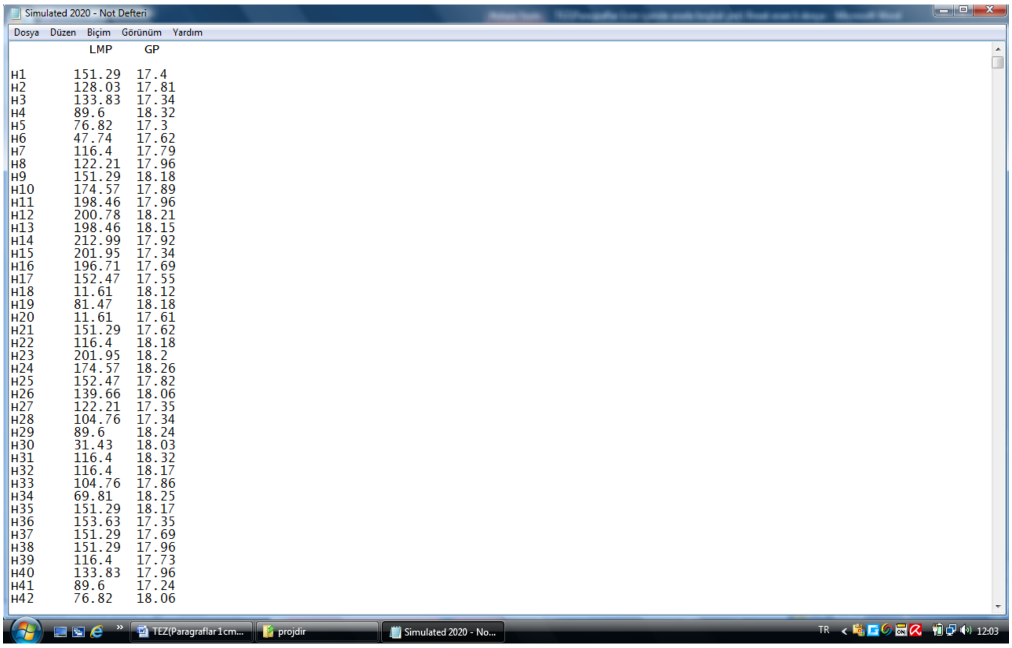

Figure 7.1: An example of Word pad document “Simulated 2020”

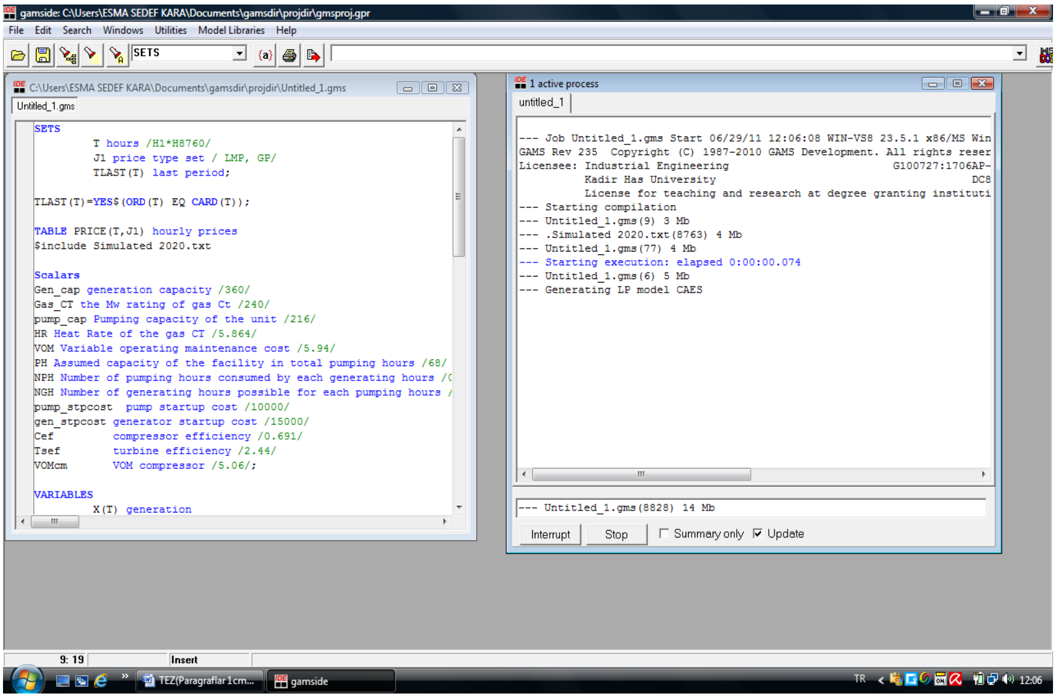

Figure 7.2: An example of CAES model at Gams ide tool description

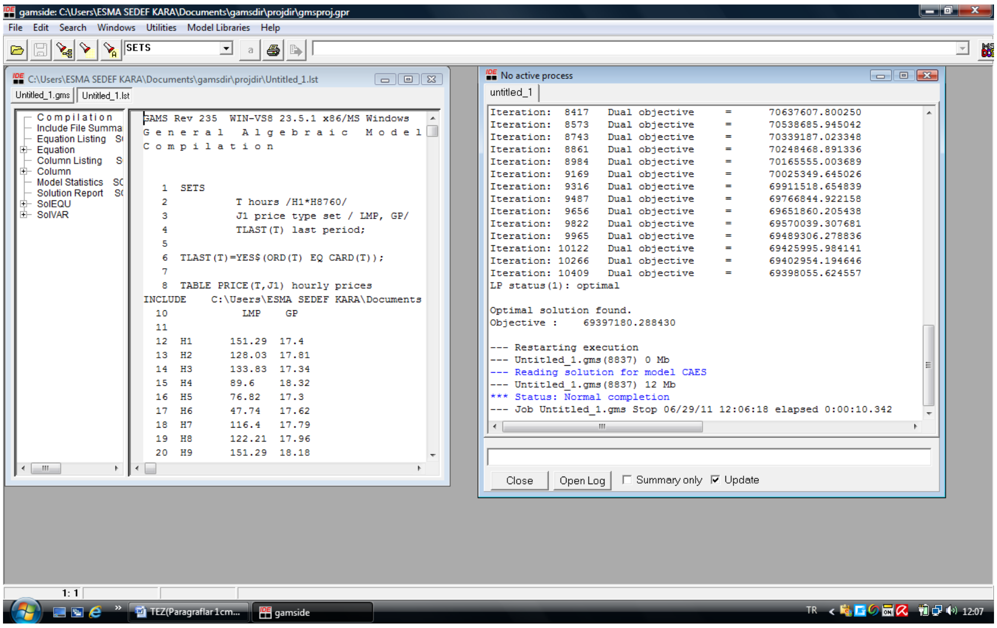

Figure 7.3: An example of Gams ide Tool after Running the Model with Simulated 2020 data

The Gams ide tool has solutions about Net Revenue, Inventory, Upper and Lower X, P, I, gs, ps. As can be seen at Figure 7.4, we can optimize the Generation, Pumping and Inventory. I will show one week's generating, pumping and inventory graphs as an example at Figure 7.5, Figure 7.6 and Figure 7.8. The relation between generating and pumping can be shown at Figure 7.7.

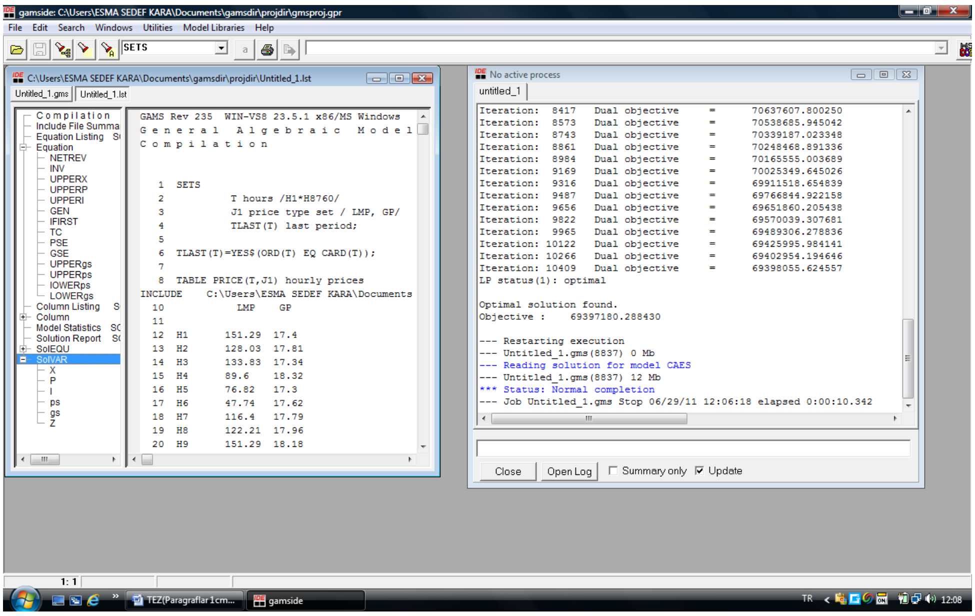

Figure 7.4: Gams ide tool solution for Simulated 2020 data.

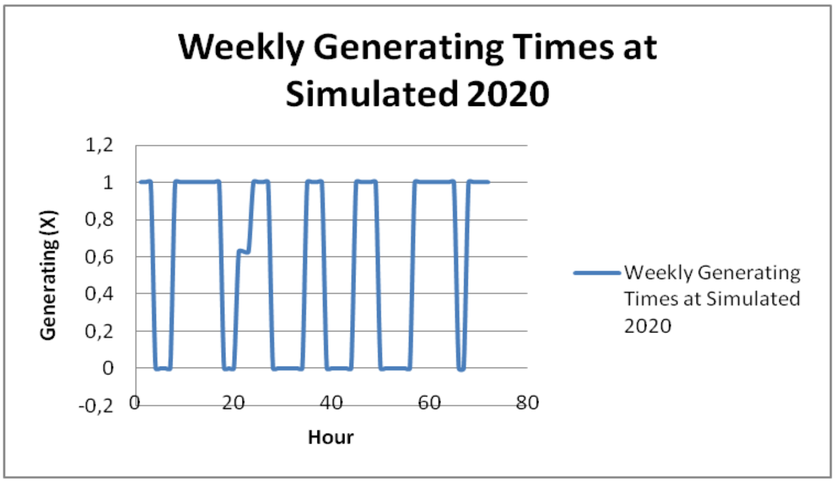

Figure 7.5: Examples of weekly Generating graph for Simulated 2020.

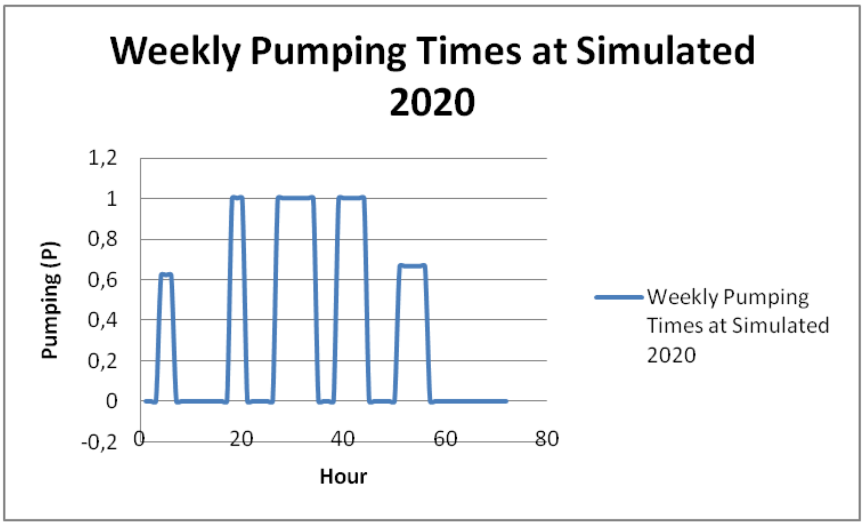

Figure 7.6: Examples of weekly Pumping graph for Simulated 2020.

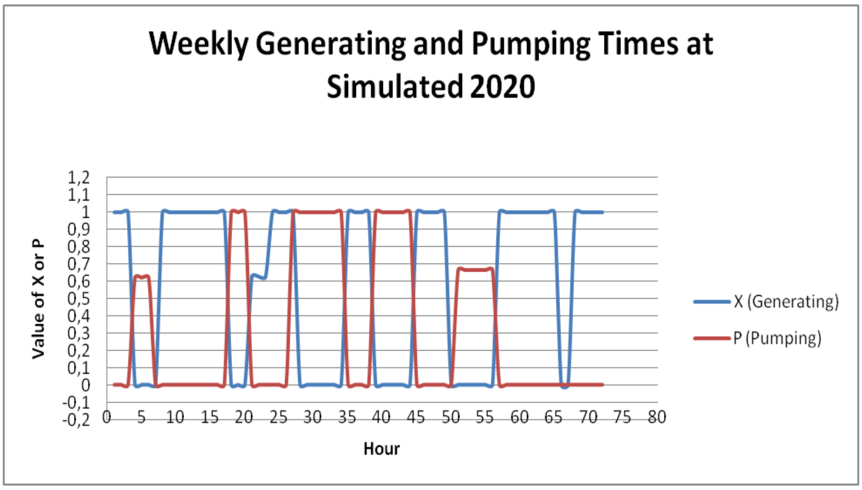

Figure 7.7: Examples of weekly relation between generating and pumping graphs for Simulated 2020.

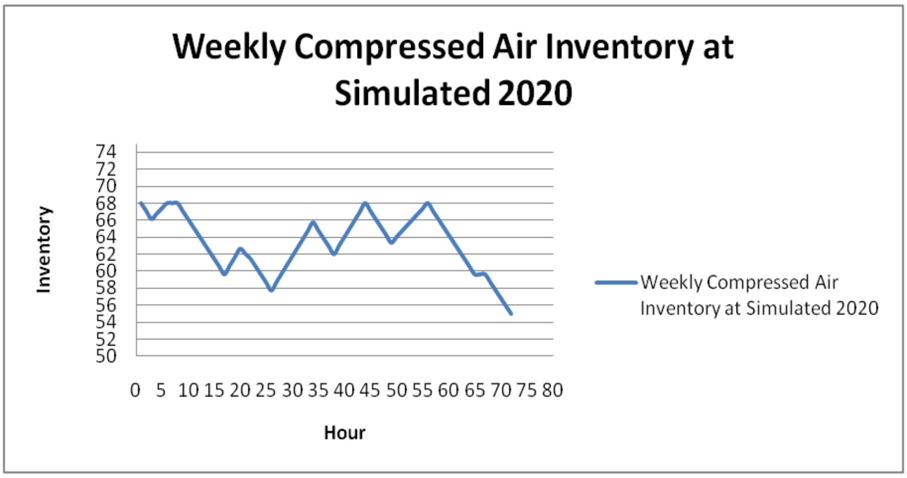

Figure 7.8: Examples of weekly Inventory graphs for Simulated 2020.

We run data from 2012 to 2041 at gams ide tool and we solve the solution for 6 scenario. Then we created net present value table for our model. The Gams ide text is given at Appendix F. NPV table is important to decide to do or not to do our CAES project. For instance, the objective value for Simulated Scenario of 2020 is 69,397,180 TL. The yearly objective values table for Simulated Scenario is at Table 7.2 Then the NPV of Simulated Scenario is calculated at Excel like 142,431,981 TL.

Table 7.2: An Example of Net Present Value for Simulated Scenario

Cost	411,750,000
Base Data	39,116,313
2012	33,038,944
2013	30,216,292
2014	15,316,052
2015	30,464,316
2016	31,118,411
2017	27,594,600
2018	39,116,091
2019	53,617,640
2020	69,397,180
2021	83,501,042
2022	78,768,084
2023	54,091,683
2024	68,088,368
2025	75,074,783
2026	61,433,687
2027	61,277,819
2028	61,425,663
2029	62,890,220
2030	63,616,869
2031	45,607,654
2032	58,765,499
2033	75,583,327
2034	71,812,746
2035	76,825,038
2036	69,937,107
2037	64,343,445
2038	63,279,798
2039	65,180,520
2040	76,160,284
2041	69,619,723
NPV	142,431,981 YTL

In this project, we calculated our system's cost according to our LMP and GP scenarios. The system calculated Net Present values for all kinds of price scenarios and NPVs are shown at Table 7.3. Net present values will help us to decide to implement our project. We can decide to establish this system according to these data. The Excel document of Net Present Value between 2012 and 2041 is added at Appendix D. If the project revenue is not sufficient to meet our needs more than 30 years, we should not invest to this project. So we need to analysis our system's cost. According to net present values; the implementation of our project is not possible with Worst and Low Price scenarios. The NPV of Current scenario provides not enough profit so we cannot implement this project with Current scenario data. The NPVs of High, Best and Simulated scenarios have enough profit to decide implementiation. The project will implement with high, best and simulated scenarios. As can be seen; the most likely revenue is given with simulated scenario.

Table 7.3: Net Present Values of Price Scenarios which includes next 30 years data

Type of Scenario :	**Worst**	**Low**	**Current**
NPV :	-283,332,223 TL	-193,880,693TL	28,612,977 TL
Type of Scenario :	**High**	**Best**	**Simulated**
NPV :	549,306,262TL	1,804,351,455TL	142,431,981TL

The positive NPV means; if we decide and implement the project, the weighted average capital cost will decrease and total market worthiness and credibility of the project will increase. [22]

The payback period is a technique. We can calculate the payback period at Excel. The Excel formulation is based on the cost of our system. The payback value of year 2012 is equal to the minus of cost plus the revenue value of the year 2012. Then the next year's payback value is equal to the previous year's payback value plus the year's revenue. Our revenues should meet our system's cost at year *n.* If the payback value is positive at year n, this means; the payback period of our system is year n. We can calculate the payback periods of our system for each kind of scenario.

Payback is important to decide to invest or not invest. The next 30 years objective revenue's are our revenue values. The investment cost is 411.750.000 TL and payback values are calculated at Excel table according to our price scenarios. I added the Payback period calculations for each scenario at Appendix E. At the worst and low scenarios, any of the payback value is not positive that means; the profit does not meet our investment at these scenarios.

As can be seen, Payback period for the Worst Scenario is shown at Table 7.4 and Payback period for the Low scenario is shown at Table 7.5. According to payback analysis, we can not do our investment if the price scenario is worst or low scenario.

Table 7.4: Payback Period for the Worst Scenario

	Payback	Year n
2012	-378.381.233	
2013	-350.098.407	
2014	-326.316.949	
2015	-306.506.151	
2016	-290.171.340	
2017	-276.853.954	
2018	-266.151.168	
2019	-257.710.028	
2020	-251.221.778	
2021	-246.381.970	
2022	-242.890.646	
2023	-240.467.182	
2024	-238.846.516	
2025	-237.802.508	
2026	-237.120.654	
2027	-236.660.250	
2028	-236.335.221	
2029	-236.085.280	
2030	-235.889.822	
2031	-235.743.081	
2032	-235.639.939	
2033	-235.573.519	
2034	-235.538.488	
2035	-235.521.734	
2036	-235.514.104	
2037	-235.511.423	
2038	-235.511.423	
2039	-235.511.423	
2040	-235.511.423	
2041	-235.511.423	

At the above table, payback value is not positive. Our investment does not generate positive return so we cannot invest if the scenario is Worst Scenario.

Table 7.5: Payback Period for the Low scenario

	Payback	**Year n**
2012	-375.515.396	
2013	-342.004.011	
2014	-311.055.885	
2015	-282.520.822	
2016	-256.258.829	
2017	-232.141.521	
2018	-210.042.073	
2019	-189.837.409	
2020	-171.407.150	
2021	-154.641.136	
2022	-139.427.929	
2023	-125.662.283	
2024	-113.246.799	
2025	-102.090.046	
2026	-92.106.444	
2027	-83.216.127	
2028	-75.344.748	
2029	-68.421.585	
2030	-62.373.893	
2031	-57.127.494	
2032	-52.614.731	
2033	-48.760.610	
2034	-45.503.119	
2035	-42.770.771	
2036	-40.501.519	
2037	-38.629.392	
2038	-37.107.917	
2039	-35.879.428	
2040	-34.888.560	
2041	-34.084.859	

At the above table, payback value is not positive. Our investment does not generate positive return so we cannot invest if the scenario is Low Scenario.

At the current scenario, payback value is positive after year 2021. That means the investment will meet the cost at year 2021, 9 years after investment. The table of payback for the Current Scenario is shown at Table 7.6.

Table 7.6: Payback period for the Current Scenario

	PAYBACK	Year n
2012	-372.633.687	
2013	-333.517.374	
2014	-294.401.061	
2015	-255.284.748	
2016	-216.168.435	
2017	-177.052.122	
2018	-137.935.809	
2019	-98.819.496	
2020	-59.703.183	
2021	-20.586.870	**2021**
2022	18.529.443	
2023	57.645.756	
2024	96.762.069	
2025	135.878.382	
2026	174.994.695	
2027	214.111.008	
2028	253.227.321	
2029	292.343.634	
2030	331.459.947	
2031	370.576.260	
2032	409.692.573	
2033	448.808.886	
2034	487.925.199	
2035	527.041.512	
2036	566.157.825	
2037	605.274.138	
2038	644.390.451	
2039	683.506.764	
2040	722.623.077	
2041	761.739.390	

At the above table, payback value is positive after year 2021. Our investment generates positive return so we can do invest if the scenario is Current Scenario.

At the High scenario, payback value is positive after year 2018. That means the investment will meet the cost at year 2018, 6 years after investment. The table of payback for the High Scenario is shown at Table 7.7.

Table 7.7: Payback period for the High Scenario

	PAYBACK	Year n
2012	-369.731.538	
2013	-324.650.316	
2014	-276.336.968	
2015	-224.618.231	
2016	-169.314.338	
2017	-110.237.569	
2018	-47.189.821	**2018**
2019	20.042.010	
2020	91.680.936	
2021	167.960.180	
2022	249.127.132	
2023	335.438.435	
2024	427.163.324	
2025	524.587.357	
2026	628.008.131	
2027	737.738.575	
2028	854.108.577	
2029	977.463.147	
2030	1.108.164.285	
2031	1.246.588.249	
2032	1.393.132.511	
2033	1.548.212.939	
2034	1.712.265.418	
2035	1.885.747.206	
2036	2.069.137.439	
2037	2.262.940.509	
2038	2.467.683.058	
2039	2.683.918.432	
2040	2.912.230.149	
2041	3.153.229.755	

At the above table, payback value is positive after year 2018. That means the investment will be meet the cost at year 2018, 6 years later of invest. So we can do invest if the scenario is High Scenario.

At the Best scenario, the payback value is positive after year 2017. That means the investment will meet the cost at year 2017, 5 years after investment. The table of payback for Best Scenario is shown at Table 7.8.

Table 7.8: Payback Period for the Best Scenario

	Payback	Year n
2012	-366.814.923	
2013	-315.420.500	
2014	-256.881.939	
2015	-190.445.104	
2016	-115.267.126	
2017	-30.418.403	**2017**
2018	65.117.355	
2019	172.461.748	
2020	292.848.120	
2021	427.630.636	
2022	578.289.237	
2023	746.448.599	
2024	933.891.788	
2025	1.142.576.316	
2026	1.374.654.564	
2027	1.632.502.371	
2028	1.918.724.356	
2029	2.236.196.178	
2030	2.588.072.208	
2031	2.977.822.416	
2032	3.409.263.984	
2033	3.886.592.903	
2034	4.414.424.018	
2035	4.997.835.162	
2036	5.642.412.499	
2037	6.354.295.485	
2038	7.140.241.144	
2039	8.007.675.111	
2040	8.964.770.845	
2041	10.020.530.820	

At the above table, payback value is positive after year 2017. That means the investment will be meet the cost at year 2017, 5 years later of invest. Our investment generates positive return so we can do invest if the scenario is Best Scenario.

At the simulated scenario, payback value is positive at year 2020. That means the investment will meet the cost at year 2022, 8 years after investment. The table of payback for the Simulated Scenario is shown at Table 7.9.

Table 7.9: Payback period for the Simulated Scenario

	Payback	Year n
2012	-378.711.056	
2013	-348.494.764	
2014	-333.178.712	
2015	-302.714.396	
2016	-271.595.985	
2017	-244.001.385	
2018	-204.885.294	
2019	-151.267.654	
2020	-81.870.474	**2020**
2021	1.630.568	
2022	80.398.652	
2023	134.490.335	
2024	202.578.703	
2025	277.653.486	
2026	339.087.173	
2027	400.364.992	
2028	461.790.655	
2029	524.680.875	
2030	588.297.744	
2031	633.905.398	
2032	692.670.897	
2033	768.254.224	
2034	840.066.970	
2035	916.892.008	
2036	986.829.115	
2037	1.051.172.560	
2038	1.114.452.358	
2039	1.179.632.878	
2040	1.255.793.162	
2041	1.325.412.885	

At the above table, payback value is positive after year 2020. That means the investment will meet the cost at year 2020, 8 years after investment. Our investment generates positive return so we can do invest if the scenario is Simulated Scenario. The most likely scenario is this scenario.

The payback period shows us if we invest this project, when we will have positive return of our investment. Then at the Figure 7.9, all of the scenarios and their payback periods are shown. In this table we can see that for the worst and low scenarios the investment is rejected. And in Figure 7.10, the payback years of the each scenario are shown as a pie. As can be seen for Worst and Low scenarios; payback period is not found so the investment is rejected but for the Current, High, Best and Simulated Scenarios; payback periods are found so the investment can be accepted.

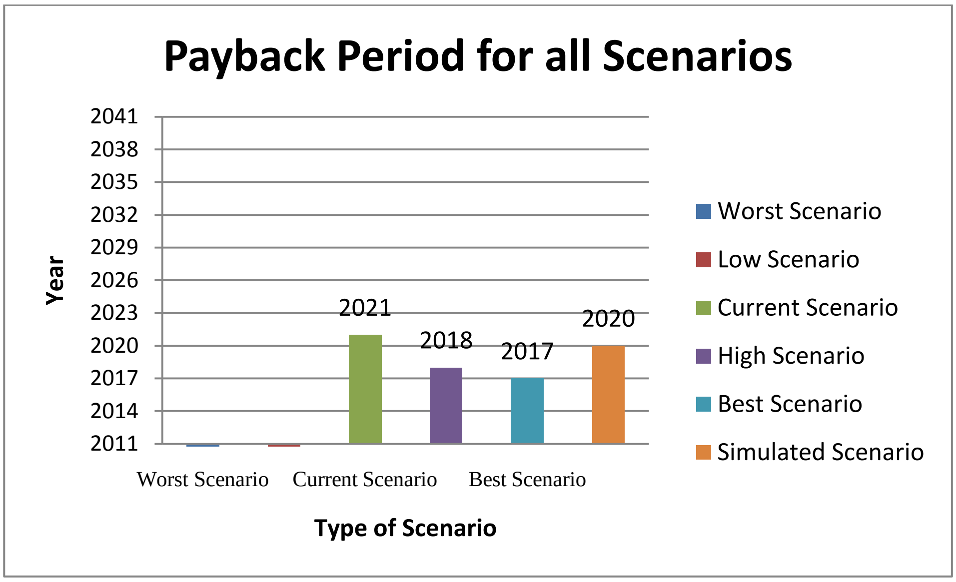

Figure 7.9: The Payback Period Graph for all Scenarios

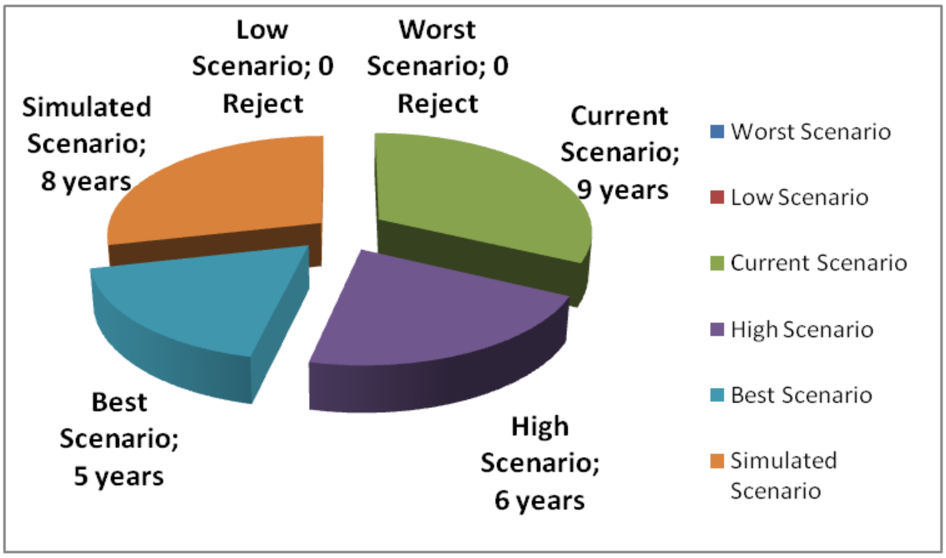

Figure 7.10: The Payback Year for all Scenarios

Chapter 8
Conclusion

Compressed Air Energy Storage (CAES) is a proven utility-scale energy storage technology that has existed for nearly 30 years. A scheduling model was implemented and analyses that include hourly prices of power and natural gas for 30 years was developed. The results show that the CAES system is economic when the price scenario is High, Best or Simulated. The financial results show that the system does not meet cost with Worst and Low Price Scenarios. Current scenario is enough to meet the cost but net present value does not make sense to invest.

For future research, the model can be expanded so that it will include the auction mechanism of the power market. The operation, capacity and scheduling of other units might be included. Another extension to this research might be to develop a stochastic based market price and natural gas price forecasting model. We have developed a model for adiabitic systems. The same model can be applied to the non-adiabiatic systems as well.

References

[1] John Gardner, Todd Hoynes, "*Overview of Compressed Air Energy Storage*", Boise State University, December 2007

[2] EPRI-DOE Handbook of *Energy Storage for Transmission and Distribution Applications*, 2003

[3] "*Compressed Air Energy Storage Scoping Workshoop"*, October 2008

[4] "*An ESC white paper"*, Published by the Energy Storage Council, May 2002

[5] *T.C Enerji Piyasası Düzenleme Kurumu*, www.epdk.gov.tr

[6] *T.C. Enerji ve Tabii Kaynaklar Bakanlığı*, www.enerji.gov.tr

[7] Serdar PAKER, "*Enerji Politikaları ve Özelleştirmeler*", Elektrrik Mühendisliği, 441.Sayı, Şubat 2011

[8] Prof. Umesh Saxena, "*Enginnering Economic Analysis Class Notes*", Industrial & Manufacturing Engineering College of engineering and Applied Sciences University of Winconsin-Milwaukee, WI 53201

[9] Sullivan Bantadelli and Wicks, "*Enginnering Economy*" 11th Ed., Prentice-Hall, New York, 2000

[10] John M.Watts, Jr. And Robert E.Chapman, "*Enginnering Economics*", Chapter 7, Section 5

[11] Jeffery B. Greenblatta, Samir Succar, David C. Denkenberger, Robert H. Williams, Robert H. Socolow., "*Baseload wind energy: modeling the competition between gas turbines and compressed air energy storage for supplemental generation*". Energy Policy 35 (2007) 1474- 1492, Available online 9 June 2006.

[12] Samir Succar and Robert H. Williams, "*Compressed Air Energy Storage: Theory, Resources, and Applications for Wind Power"*, Princeton Environmental Institute, Princeton university of Energy Systems Analysis Group, 8 April 2008.

[13] Classnotes of Prof. Dr. Şakir Esnaf about "*Logistic Management*".

[14] Danie SIPPER, Robert L., Bulfin, JR.; "*Production Planning, Control, and Integration*" International Edition 1998, Chapter 4; "Forecasting", Page: 90

[15] Prof. Dr. Müh. Bülent Koru, "*Üretim Yönetimi*", University of Massachusetts Dartmouth Charlton College of Business, 13 Th Edition, Beta publishing, Page: 90-92.

[16] Antonio J. Canejo,Fellow, Miguel A. Plazas, Rosa Espinola and Ana B. Malina, " *Day- Ahead Electricity Price Forecasting Using the Wavelet Transform and ARIMA models*"., IEE Transactions on Power Systems, Vol.20, No.2, May 2005.

[17] Bakatjan Sandalkhan, Senior Manager, Energy and Resources, "*Türkiye Elektrik Piyasası Simülasyonu ve Fiyat Tahmin Modelleri*". ICCCI 2009, 15. Uluslar arası Enerji ve Çevre Fuarı Konferansı, 13 May 2009, İstanbul.

[18] İktisadi ve idari Bilimler Dergisi, Cilt 17, Nisan 2003, Sayı: 1-2, Page: 23

[19] İsmail Özçelik, Manager of Balancing and Settlement Systems. Balancing and Settlement Code, "*Dengeleme ve Teknik Kayıp Uygulamaları*" date 04/08/2006, Financial Market Settlemet Center.

[20] "Derek Johnson, Aurora WDC, "*NPV Analysis and Applications for Competitive Intelligence*"

[21] HenrikLund, Georges Salgi, Energy Conversion and Management, "*The role of CAES in future sustainable energy systems*". Department of Development and Planning, Aalborg University, Fibigerstraede 13, Dk-9220, Denmark

[22] Brigham, Eugene F.-Gapenskı, Louis C.; "*Intermediate Financial Management"*, Fifth Edition, the Dryden Press, USA, 1996.

Appendix A: Locational Market Prices between 2012 and 2041

Appendix B: Gas Prices between 2012 and 2041

Appendix C: Yearly LMP and GP

The Excel documents of these appendixes are very big so we cannot print them. The Excel files of each appendix are saved at this CD.

Appendix D: Net Present Value between 2012 and 2041

Year	Worst	Low	Current	High	Best	Simulated
Cost	411,750,000	411,750,000	411,750,000	411,750,000	411,750,000	411,750,000
Base Data	**39,116,313**	**39,116,313**	**39,116,313**	**39,116,313**	**39,116,313**	**39,116,313**
2012	33,368,767	36,234,604	39,116,313	42,018,462	44,935,077	33,038,944
2013	28,282,826	33,511,385	39,116,313	45,081,222	51,394,423	30,216,292
2014	23,781,458	30,948,126	39,116,313	48,313,348	58,538,561	15,316,052
2015	19,810,798	28,535,063	39,116,313	51,718,737	66,436,835	30,464,316
2016	16,334,811	26,261,993	39,116,313	55,303,893	75,177,978	31,118,411
2017	13,317,386	24,117,308	39,116,313	59,076,769	84,848,723	27,594,600
2018	10,702,786	22,099,448	39,116,313	63,047,748	95,535,758	39,116,091
2019	8,441,140	20,204,664	39,116,313	67,231,831	107,344,393	53,617,640
2020	6,488,250	18,430,259	39,116,313	71,638,926	120,386,372	69,397,180
2021	4,839,808	16,766,014	39,116,313	76,279,244	134,782,516	83,501,042
2022	3,491,324	15,213,207	39,116,313	81,166,952	150,658,601	78,768,084
2023	2,423,464	13,765,646	39,116,313	86,311,303	168,159,362	54,091,683
2024	1,620,666	12,415,484	39,116,313	91,724,889	187,443,189	68,088,368
2025	1,044,008	11,156,753	39,116,313	97,424,033	208,684,528	75,074,783
2026	681,854	9,983,602	39,116,313	103,420,774	232,078,248	61,433,687
2027	460,404	8,890,317	39,116,313	109,730,444	257,847,807	61,277,819
2028	325,029	7,871,379	39,116,313	116,370,002	286,221,985	61,425,663
2029	249,941	6,923,163	39,116,313	123,354,570	317,471,822	62,890,220
2030	195,458	6,047,692	39,116,313	130,701,138	351,876,030	63,616,869
2031	146,741	5,246,399	39,116,313	138,423,964	389,750,208	45,607,654
2032	103,142	4,512,763	39,116,313	146,544,262	431,441,568	58,765,499
2033	66,420	3,854,121	39,116,313	155,080,428	477,328,919	75,583,327
2034	35,031	3,257,491	39,116,313	164,052,479	527,831,115	71,812,746
2035	16,754	2,732,348	39,116,313	173,481,788	583,411,144	76,825,038
2036	7,630	2,269,252	39,116,313	183,390,233	644,577,337	69,937,107
2037	2,681	1,872,127	39,116,313	193,803,070	711,882,986	64,343,445
2038	0	1,521,475	39,116,313	204,742,549	785,945,659	63,279,798
2039	0	1,228,489	39,116,313	216,235,374	867,433,967	65,180,520
2040	0	990,868	39,116,313	228,311,717	957,095,734	76,160,284
2041	0	803,701	39,116,313	240,999,606	1,055,759,975	69,619,723
NPV	**-283,332,223 YTL**	**-193,880,693 YTL**	**28,612,977 YTL**	**549,306,262 YTL**	**1,804,351,455 YTL**	**142,431,981 YTL**

Appendix E: Payback Period for all Scenarios

E.1 Payback period for Worst Price Scenario

	Revenue	Cost	Payback	Year
2012	33.368.767	411.750.000	-378.381.233	
2013	28.282.826		-350.098.407	
2014	23.781.458		-326.316.949	
2015	19.810.798		-306.506.151	
2016	16.334.811		-290.171.340	
2017	13.317.386		-276.853.954	
2018	10.702.786		-266.151.168	
2019	8.441.140		-257.710.028	
2020	6.488.250		-251.221.778	
2021	4.839.808		-246.381.970	
2022	3.491.324		-242.890.646	
2023	2.423.464		-240.467.182	
2024	1.620.666		-238.846.516	
2025	1.044.008		-237.802.508	
2026	681.854		-237.120.654	
2027	460.404		-236.660.250	
2028	325.029		-236.335.221	
2029	249.941		-236.085.280	
2030	195.458		-235.889.822	
2031	146.741		-235.743.081	
2032	103.142		-235.639.939	
2033	66.420		-235.573.519	
2034	35.031		-235.538.488	
2035	16.754		-235.521.734	
2036	7.630		-235.514.104	
2037	2.681		-235.511.423	
2038	0		-235.511.423	
2039	0		-235.511.423	
2040	0		-235.511.423	
2041	0		-235.511.423	

E.2 Payback period for Low Price Scenario

	Revenue	Cost	Payback	Year
2012	36.234.604	411.750.000	-375.515.396	
2013	33.511.385		-342.004.011	
2014	30.948.126		-311.055.885	
2015	28.535.063		-282.520.822	
2016	26.261.993		-256.258.829	
2017	24.117.308		-232.141.521	
2018	22.099.448		-210.042.073	
2019	20.204.664		-189.837.409	
2020	18.430.259		-171.407.150	
2021	16.766.014		-154.641.136	
2022	15.213.207		-139.427.929	
2023	13.765.646		-125.662.283	
2024	12.415.484		-113.246.799	
2025	11.156.753		-102.090.046	
2026	9.983.602		-92.106.444	
2027	8.890.317		-83.216.127	
2028	7.871.379		-75.344.748	
2029	6.923.163		-68.421.585	
2030	6.047.692		-62.373.893	
2031	5.246.399		-57.127.494	
2032	4.512.763		-52.614.731	
2033	3.854.121		-48.760.610	
2034	3.257.491		-45.503.119	
2035	2.732.348		-42.770.771	
2036	2.269.252		-40.501.519	
2037	1.872.127		-38.629.392	
2038	1.521.475		-37.107.917	
2039	1.228.489		-35.879.428	
2040	990.868		-34.888.560	
2041	803.701		-34.084.859	

E.3 Payback period for Current Price Scenario

	Revenue	Cost	PAYBACK	Year
2012	39.116.313	411.750.000	-372.633.687	
2013	39.116.313		-333.517.374	
2014	39.116.313		-294.401.061	
2015	39.116.313		-255.284.748	
2016	39.116.313		-216.168.435	
2017	39.116.313		-177.052.122	
2018	39.116.313		-137.935.809	
2019	39.116.313		-98.819.496	
2020	39.116.313		-59.703.183	
2021	39.116.313		-20.586.870	**2021**
2022	39.116.313		18.529.443	
2023	39.116.313		57.645.756	
2024	39.116.313		96.762.069	
2025	39.116.313		135.878.382	
2026	39.116.313		174.994.695	
2027	39.116.313		214.111.008	
2028	39.116.313		253.227.321	
2029	39.116.313		292.343.634	
2030	39.116.313		331.459.947	
2031	39.116.313		370.576.260	
2032	39.116.313		409.692.573	
2033	39.116.313		448.808.886	
2034	39.116.313		487.925.199	
2035	39.116.313		527.041.512	
2036	39.116.313		566.157.825	
2037	39.116.313		605.274.138	
2038	39.116.313		644.390.451	
2039	39.116.313		683.506.764	
2040	39.116.313		722.623.077	
2041	39.116.313		761.739.390	

E.4 Payback period for High Price Scenario

	Revenue	Cost	PAYBACK	Year
2012	42.018.462	411.750.000	-369.731.538	
2013	45.081.222		-324.650.316	
2014	48.313.348		-276.336.968	
2015	51.718.737		-224.618.231	
2016	55.303.893		-169.314.338	
2017	59.076.769		-110.237.569	
2018	63.047.748		-47.189.821	**2018**
2019	67.231.831		20.042.010	
2020	71.638.926		91.680.936	
2021	76.279.244		167.960.180	
2022	81.166.952		249.127.132	
2023	86.311.303		335.438.435	
2024	91.724.889		427.163.324	
2025	97.424.033		524.587.357	
2026	103.420.774		628.008.131	
2027	109.730.444		737.738.575	
2028	116.370.002		854.108.577	
2029	123.354.570		977.463.147	
2030	130.701.138		1.108.164.285	
2031	138.423.964		1.246.588.249	
2032	146.544.262		1.393.132.511	
2033	155.080.428		1.548.212.939	
2034	164.052.479		1.712.265.418	
2035	173.481.788		1.885.747.206	
2036	183.390.233		2.069.137.439	
2037	193.803.070		2.262.940.509	
2038	204.742.549		2.467.683.058	
2039	216.235.374		2.683.918.432	
2040	228.311.717		2.912.230.149	
2041	240.999.606		3.153.229.755	

E.5 Payback period for Best Price Scenario

	Revenue	Cost	Payback	Year
2012	44.935.077	411.750.000	-366.814.923	
2013	51.394.423		-315.420.500	
2014	58.538.561		-256.881.939	
2015	66.436.835		-190.445.104	
2016	75.177.978		-115.267.126	
2017	84.848.723		-30.418.403	**2017**
2018	95.535.758		65.117.355	
2019	107.344.393		172.461.748	
2020	120.386.372		292.848.120	
2021	134.782.516		427.630.636	
2022	150.658.601		578.289.237	
2023	168.159.362		746.448.599	
2024	187.443.189		933.891.788	
2025	208.684.528		1.142.576.316	
2026	232.078.248		1.374.654.564	
2027	257.847.807		1.632.502.371	
2028	286.221.985		1.918.724.356	
2029	317.471.822		2.236.196.178	
2030	351.876.030		2.588.072.208	
2031	389.750.208		2.977.822.416	
2032	431.441.568		3.409.263.984	
2033	477.328.919		3.886.592.903	
2034	527.831.115		4.414.424.018	
2035	583.411.144		4.997.835.162	
2036	644.577.337		5.642.412.499	
2037	711.882.986		6.354.295.485	
2038	785.945.659		7.140.241.144	
2039	867.433.967		8.007.675.111	
2040	957.095.734		8.964.770.845	
2041	1.055.759.975		10.020.530.820	

E.6 Payback period for Simulated Price Scenario

	Revenue	Cost	Payback	Year
2012	33.038.944	411.750.000	-378.711.056	
2013	30.216.292		-348.494.764	
2014	15.316.052		-333.178.712	
2015	30.464.316		-302.714.396	
2016	31.118.411		-271.595.985	
2017	27.594.600		-244.001.385	
2018	39.116.091		-204.885.294	
2019	53.617.640		-151.267.654	
2020	69.397.180		-81.870.474	**2020**
2021	83.501.042		1.630.568	
2022	78.768.084		80.398.652	
2023	54.091.683		134.490.335	
2024	68.088.368		202.578.703	
2025	75.074.783		277.653.486	
2026	61.433.687		339.087.173	
2027	61.277.819		400.364.992	
2028	61.425.663		461.790.655	
2029	62.890.220		524.680.875	
2030	63.616.869		588.297.744	
2031	45.607.654		633.905.398	
2032	58.765.499		692.670.897	
2033	75.583.327		768.254.224	
2034	71.812.746		840.066.970	
2035	76.825.038		916.892.008	
2036	69.937.107		986.829.115	
2037	64.343.445		1.051.172.560	
2038	63.279.798		1.114.452.358	
2039	65.180.520		1.179.632.878	
2040	76.160.284		1.255.793.162	
2041	69.619.723		1.325.412.885	

Appendix F: Gams ide Model and Solution for CAES

The GAMS IDE is a general text editor with the ability to launch and monitor the compilation or execution of GAMS models. We will use the GAMS-IDE editor to write CAES model. At our model, I need to estimate next 30 years' LMP and GP to decide to do or not to do CAES project. At Gams ide ; We defined sets of our model like T Hours, J1 price type set , TLAST (T) last period, and Table Price(T,J1) hourly prices. One day is 24 hours and one year has 365 days then there is 8760 hours in a year. So our model will analyze 8760 hours for a year. We have two types of prices like Locational Market Price (LMP) and Gas Price (GP). Our model will analyze the best time for generating or pumping according to LMP and GP data. The model will choose the best time for generating and it will also choose the best time for pumping. Then the model will calculate a cost for our system. Our historical data will show the cost for interested year. We calculated 30 years LMP and GP according to 2011 data at Excel. Then we saved our estimations into note-book. When we write the program like "$include Simulated 2026.txt"; the program calls the document of Simulated 2026 data and run the model according to this data.

At gams ide program; we also need to define the CAES scalars. At our CAES model, the generating capacity of the system is 360 and I abbreviated it like "Gen_cap" , and The MW rating of gas Cycle Turbine is 240 and I abbreviated it like "Gas_CT ". The pumping capacity is another scalar for the system and the pumping capacity is 216 and its abbreviation is "pump cap". At the cycle turbine, the gas also has a heat rate and the heat rate of the gas is 5.864. The heat rate is abbreviated like "HR". The variable operating maintenance cost which is abbreviated like "VOM" is 5.94. The assumed capacity of the facility in total pumping hours is 68 and it abbreviated like "PH". The number of pumping hours consumed by each generating hours is 0.93 and symbolized "NPH". The number of generating hours possible for each pumping hour's scalar is determined 1.072 and symbolized "NGH". In our model the start up cost of compressor/pumping or generator is also determined. The startup cost of pumping is 10000 and symbolized like "pump_stpcost". The startup cost of generator is 15000 and symbolized like "gen_stpcost". The efficiency of compressor is also important for our model, the compressor efficiency is 0.691 and I symbolized it like

"Cef". Turbine efficiency is 2.44 and it symbolized like "Tsef" .Finally, the VOM compressor is 5.06 and symbolized like "VOMcm". At gams ide; X(T) generation, P(T) pumping, I(T) compressed air inventory, ps(T) pump startup time, gs(T) generator startup time, and Z total cost are variables of the model. Then we need to calculate Total cost to decide to do or not to do CAES system.

• The total cost is symbolized like "NETREV" and the formulation of the total cost is as follows;

NETREV=SUM((T),(Gen_cap*PRICE(T,"LMP")-
Gas_CT*HR*PRICe(T,"GP")*1.2-Gen_cap*VOM)*X(T)-
(1/(Cef*Tsef))*pump_cap*(PRICE(T,"LMP")+VOMcm)*P(T)-
pump_stpcost*ps(T)-gen_stpcost*gs(T))=E= Z;

• The inventory constraint is symbolized like "INV (T)". The initial inventory is symbolized like "IFIRST". And the formulation of the Inventory constraint is as follows;

INV (T+1) = I (T+1)-I (T)+.9313*X(T+1)-P(T+1)=E=0;
IFIRST = I ("H1") =E=PH;

• The formulation of upper bound of generating, pumping and compressed air inventory are as follows;

UPPERX (T) upper bound x; UPPERX (T) = X (T) =L= 1;
UPPERP (T) upper bound p; UPPERP (T) = P (T) =L= 1;
UPPERI (T) upper bound I; UPPERI (T) = I (T) =L=PH;

• The generation constraint is symbolized like "GEN (T)" and formulated as follows;

GEN (T+1) = X (T+1)-NGH*I (T) =L=0;

• The terminal condition is symbolized like "TC (T)" and formulated as follows;

TC (TLAST) = I (TLAST) =E= PH;

• The pumping startup equation is symbolized like "PSE (T)" and formulated as follows;

PSE (T) = ps (T) =G=P (T)-P (T-1);

• The generator start up equation is symbolized like “GSE (T)” and formulated as follows;

GSE (T) =gs (T) =G=X (T)-X (T-1);

• The upper on gs and ps is symbolized like “UPPER ps (T)”, “UPPER gs (T)”. And formulated as follows;

UPPER gs (T) =gs (T) =L= 1;
UPPER ps (T) = ps (T) =L= 1;

• The Lower on gs and ps is symbolized like “Lower ps (T)”, “Lower gs (T)”. And formulated as follows;

LOWER ps (T) = ps (T) =G= 0;
LOWER gs (T) = gs (T) =G= 0;

According to above equations; the gams ide tool will solve CAES Using LP maximizing Z. The gams ide model text is written as follows;

Gams ide Text

```
SETS
    T hours /H1*H8760/
    J1 price type set / LMP, GP/
    TLAST (T) last period;
TLAST (T) =YESTL(ORD (T) EQ CARD (T));
TABLE PRICE (T, J1) hourly prices
$include simulated 2026.txt
Scalars
Gen_cap generation capacity /360/
Gas_CT the Mw rating of gas Ct /240/
Pump_cap Pumping capacity of the unit /216/
HR Heat Rate of the gas CT /5.864/
VOM Variable operating maintenance cost /5.94/
PH Assumed capacity of the facility in total pumping hours /68/
NPH Number of pumping hours consumed by each generating hours /0.93/
NGH Number of generating hours possible for each pumping hours / 1.072/
Pump_stpcost pump startup cost /10000/
Gen_stpcost generator startup cost /15000/
```

```
Cef        compressor efficiency /0.691/
Tsef       turbine efficiency /2.44/
VOMcm      VOM compressor /5.06/;
VARIABLES
        X (T) generation
        P (T) pumping
        I (T) compressed air inventory
        Ps (T) pump startup time
        Gs (T) generator startup time
        Z    total cost;
POSITIVE VARIABLE X, P;
POSITIVE VARIABLE I;
EQUATIONS
        NETREV total cost
        INV (T) Inventory constraint
        UPPERX (T) upper bound x
        UPPERP (T) upper bound p
        UPPERI (T) upper bound I
        GEN (T)    generation constraint
        IFIRST    initial inventory
        TC (T)     terminal condition
        PSE (T)    pumping startup equation
        GSE (T) generator startup equation
        UPPER gs (T) upper on gs
        UPPER ps (T) upper on ps
        LOWER ps (T) Lower on ps
        LOWER gs (T) Lower on gs;
*UPPERP1 (T) upper bound p
*NETREV....  SUM ((T), COST (T,"NrevW2")*X(T)-COST(T,"PcostW")*P(T))=E= Z;
NETREV....SUM((T),(Gen_cap*PRICE(T,"LMP")-Gas_CT*HR*PRICe(T,"GP")*1.2-
Gen_cap*VOM)*X(T)-(1/(Cef*Tsef))*pump_cap*(PRICE(T,"LMP")+VOMcm)*P(T)-
pump_stpcost*ps(T)-gen_stpcost*gs(T))=E= Z;
INV (T+1)...  I (T+1)-I (T) +.9313*X (T+1)-P (T+1) =E =0;
IFIRST    ...  I ("H1")                     =E=PH;
UPPERX (T)... X (T)   =L= 1;
UPPERP (T)... P (T)   =L= 1;
UPPERI (T)... I (T) =L=PH;
GEN (T+1)...  X (T+1)-NGH*I (T) =L=0;
TC (TLAST)... I (TLAST)   =E= PH;
```

Could minimize the use of fossil fuels.PSE (T)   ... ps (T) =G=P (T)-P (T-1);

```
GSE (T)     ...  gs (T) =G=X (T)-X (T-1);
UPPER ps (T)... Ps (T)   =L= 1;
UPPER gs (T)... gs (T)   =L= 1;
LOWER ps (T)... ps (T)   =G= 0;
LOWER gs (T)... gs (T)   =G= 0;
MODEL CAES /ALL/;
SOLVE CAES USING LP MAXIMIZING Z;
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Curriculum Vitae

Esma Sedef KARA was born on 1 January 1986, in Sapanca. She received her BS degree in Industrial Engineering in 2009 and M.S. degree in 2011 in Industrial Engineering both from Kadir University.

Thesis

- Title of Graudate Thesis: “A systematic approach to analyze the collaboration in the supply chains.” , May 2009.
  Project Supervisor: Doç. Dr. Gülçin BÜYÜKÖZKAN FEYZİOĞLU
- Title of Master’s Thesis: “Economic and operational analysis of compressed air energy storage systems (CAES)” , JULY 2011.
  Project Supervisor: Yrd.Doç.Dr. Ahmet DenizYÜCEKAYA