THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

HYDROELECTRIC POWER PLANT ENERGY OPTIMIZATION UNDER ENERGY SCARCITY

Master's Thesis

SELİM GAZEL

İSTANBUL, 2013

THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

INDUSTRIAL ENGINEERING

HYDROELECTRIC POWER PLANT ENERGY OPTIMIZATION UNDER ENERGY SCARCITY

Master's Thesis

SELİM GAZEL

Supervisor: Assoc. Prof. Barış Selçuk

İSTANBUL, 2013

THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
INDUSTRIAL ENGINEERING

Title of the Master's Thesis	:	Hydroelectric Power Plant Energy Optimization Under Energy Scarcity
Name/Last Name of the Student	:	Selim GAZEL
Date of Thesis Defense	:	03 September, 2013

The thesis has been approved by the Graduate School of Natural and Applied Sciences.

Assoc. Prof. Tunç Bozbura
Director

This is to certify that we have read this thesis and that we find it fully adequate in scope, quality and content, as a thesis for the degree of Master of Science.

Examining Commitee Members:	Signature
Assoc. Prof. Barış Selçuk (Supervisor)	: ....
Assoc. Prof. Semra Ağralı	: ....
Asst. Prof. Ahmet Beşkese	: ....

ACKNOWLEDGEMENTS

This thesis is dedicated to my family who has given me much needed support and believed in me when times were rough and tough.

I would like to thank my supervisor Assoc. Prof. Barış Selçuk for his great help and guidance. This thesis would not have been possible unless the constant support of him. It was an honor to work with him. His contributions will be very useful for my future academic research career.

I thank my jury members, Assoc. Prof. Semra Ağralı and Asst. Prof. Ahmet Beşkese for their helpful suggestions, constructive criticisms, and time. I also thank all other faculty members of Bahçeşehir University Industrial Engineering Department for their great support during my master studies and assistantship. I also thank Jbid Arsenyan for her great help. She was a mentor for me.

I would also thank all of my great colleagues, Özge Şahin, Bulut Şenel who make the days at Bahçeşehir University unforgettable.

I also would like to give thanks to my cousin Rızkullah Doğum for his great advice and assistance.

03 September 2013 SELİM GAZEL

ABSTRACT

HYDROELECTRIC POWER PLANT ENERGY OPTIMIZATION UNDER ENERGY SCARCITY

SELİM, GAZEL

INDUSTRIAL ENGINEERING
Supervisor: Assoc. Prof. Barış Selçuk

September 2013, 42 Pages

Developing efficient energy production is a significant universal engineering and sustainability objective. Scarce energy resources and high demand fluctuations motivated this thesis. In this thesis, optimal turbine usage is examined for a hydroelectric power plant considering changing energy demand, supply and cost balance. The systems fundamental working principle is to satisfy the entire demand of energy. Energy reservation is not currently a practical or viable option. If the demand for energy is over the capacity of the hydroelectric energy supply, then an energy shortage occur. This shortage is compensated by different energy resources that are more expensive than hydroelectric power plant. In this context, a nonlinear model which minimize the total cost and considers water head, turbine efficiency and water balance, is developed. We formed sample groups for different values of the parameters that we used in the model. Results were obtained by the aid of GAMS program.

Keywords: Hydroelectric Power Plant, GAMS, Design of Experiments

ÖZET

ENERJİ KITLIĞI DURUMUNDA HİDROELEKTRİK SANTRALLERİNİN EN İYİLEMESİ

SELİM, GAZEL

Endüstri Mühendisliği
Tez Danışmanı: Doç. Barış Selçuk

Eylül 2013, 42 Sayfa

Verimli enerji üretimi günümüzün en önemli problemlerinden birisidir çünkü enerji kaynakları kısıtlıdır ve talep dalgalanması oldukça yüksektir. Bu tezde bu periyodik olarak değişen enerji talep, fiyat ve arz dengesini gözetecek şekilde bir hidroelektrik santrali için en verimli türbin kullanım rejimi nedir sorusuna cevap aranmıştır. Sistemin temel çalışma prensibi bütün enerji talebini karşılamaktır, zira enerjiyi stoklamak mümkün değildir. Eğer talep edilen enerji hidro elektrik kapasitenin üstünde ise enerji açığı çıkmaktadır. Bu açık daha pahalı olan enerji kaynakları ile kapatılmaktadır. Bu kapsamda enerji satışından sağlanacak geliri en çoklayacak aynı zamanda su yüksekliği, türbin verimi, su dengesi gibi hidro elektrik santrallere özgü gerçekçi kısıtları gözetecek doğrusal olmayan bir model geliştirilmiştir. Modelde kullandığımız parametrelerin farklı değerleri için farklı zaman aralıklarında örnek gruplar oluşturduk. GAMS programı sayesinde sonuçları elde ettik.

Anahtar Kelimeler: Hidroelektrik Enerji Santrali, GAMS, Deney Tasarımı

CONTENTS

TABLES

FIGURES

ABBREVIATIONS

APSP : Alternative Power Supply System
HPP : Hydroelectric Power Plant

SYMBOLS

Reservoir Head Level in Period i : H_i
Energy Demand in Period i : D_i
Energy Demand Bought From APSP in Period i : B_i
Water Inflow to Reservoir in Period i : Q_i
Water Inflow to Turbine in Period i : q_i
Spillage Water in Period i : S_i
Selling Price of Energy in Period i : a_i
Buying Cost of Energy from APSP in Period i : b_i
Reservoir Coefficient : β
Turbine Efficiency Coefficient : θ

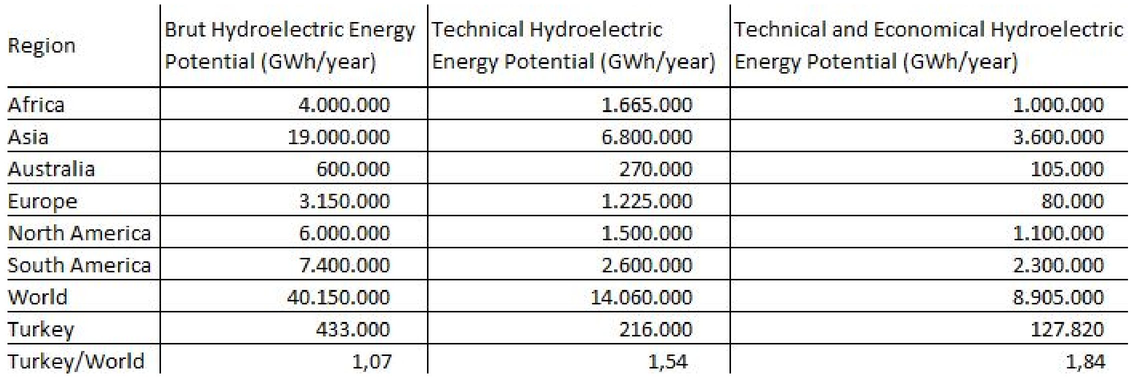
1. INTRODUCTION

1.1 INTRODUCTION

From ancient times to now people always want to control and use water in order to satisfy their needs such as agriculture and energy. Energy is considered to be a key player in the generation of wealth and also a significant component in economic development. Power generation need is increasing day by day for all countries in the world. Generating efficient energy with limited resource is considerable. This makes energy resources extremely important for societies in the world. For that reason companies and governments generate more energy with less resource consumption to reach the maximum efficiency.

Hydropower is the largest renewable resource used for electricity. As an option for clean and renewable energy, hydropower resources, once being used fully and reasonably, not only reduce the consumption of primary energy but also lessen the environmental harm caused by thermal power and other energy sources. Thus it can cut down greenhouse gases emissions. Therefore, every country attaches great importance to hydropower development shown in Table 1.1.

Table 1.1: Hydroelectric Energy Potential



Region	Brut Hydroelectric Energy Potential (GWh/year)	Technical Hydroelectric Energy Potential (GWh/year)	Technical and Economical Hydroelectric Energy Potential (GWh/year)
Africa	4.000.000	1.665.000	1.000.000
Asia	19.000.000	6.800.000	3.600.000
Australia	600.000	270.000	105.000
Europe	3.150.000	1.225.000	80.000
North America	6.000.000	1.500.000	1.100.000
South America	7.400.000	2.600.000	2.300.000
World	40.150.000	14.060.000	8.905.000
Turkey	433.000	216.000	127.820
Turkey/World	1,07	1,54	1,84

Turkey has a great and ever-intensifying need for power and water supplies and they also have the greatest remaining hydro potential. Turkey is a hydro-rich country. From north to south, from west to east, Turkey has rivers and water resources. Also Turkey does not use those resources efficiently. Turkey should make investments to build new hydroelectric power plants and make optimal operation plans for existing HPPs. Because of the social and economic development of Turkey, the demand for energy and particularly for electricity is growing rapidly.

The economically optimal design of hydro power plant by minimizing power losses and construction cost has been known for a long time, however, it is difficult to make full use of it due to the great complexity of the hydro power plant and its optimization model. The optimization model related with different parameters and the efficient utilization of hydroelectric resources play important role in the planning and operation of a power system.

In our model,we deal with a HPP for a short term planning horizon. We aimed to optimize the energy generation of HPP and APSP system which is a non-linear problem. Water inflows moves to reservoir and makes changes in reservoir head level. The power generated is proportional to the product of head level and water discharge to turbine which is related to the turbine efficiency. In bringing energy needs and energy availability into balance there are two main elements: energy demand and energy supply. If supplied energy does not meet the energy demand, APSP is used to meet the energy demand. Buying energy from APSP is cost where selling energy is revenue for our model. The flowchart of model is shown in Figure 1.1.

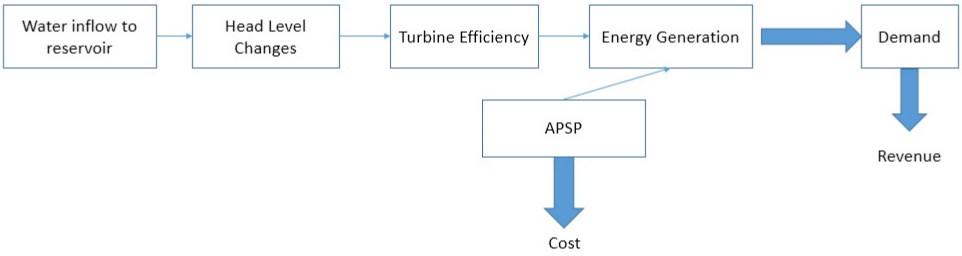


Figure 1.1: Model Flowchart

In this thesis a HPP with limited water reservoir volume is considered. In our optimization problem how much water should be sent to the turbine in one period will be decided. According to the constraints of optimization problem is defined in order to minimize the cost. The revenue is price of selling the generated energy. The cost is price of energy amount bought from APSP. We analyze the solutions according to two important parameters, which are water inflow rates to the reservoir at each period and demand at each period.

1.2 ORGANIZATION OF DISSERTATION

This thesis organized as follows;

Chapter 1, includes introduction why energy generation is important and objective of thesis.

In Chapter 2, there is a brief literature review about HPP energy generation optimization.

In Chapter 3, parts of HPPs are described.

In Chapter 4, information about Turkey’s HPP energy generation potential is given.

In Chapter 5, model is defined. Cases and solutions are also in this chapter.

In Chapter 6, the conclusion provides comments and outcomes gained throughout the thesis work process.

2. LITERATURE REVIEW

There are works done before in literature about HPPs. Energy generation function from HPP is a non-linear function. Plants generate energy in short-term, medium-term and long-term time periods. Short-term operation period deals with hourly schedule, medium-term operation period deals with daily schedule and long-term operation schedule deals with monthly schedule of HPP. Due to those time periods models become a dynamic problem. Thus there are different types of algorithms for solution methods in literature for non-linear solutions. Newton's model, Lagrangian relaxation, stochastic dynamic programming are some of those algorithmic models. These are some works that help us to improve our model.

Thermal operation costs and hydroelectrical power generation defined as non-linear function in literature. Planning schedule of a system has trade of between hydroelectric energy generation and thermal energy generation. That is hard to solve because of water flows and demand variations. Therefore in literature most of problems divided into submodels. Soares et.al (1980), Yan et.al (1993) and Kumar (2011) split their problems into two subproblems; thermal subproblem and hydroelectric submodel. However Soleymanpour et.al (2010) split their problem into three subproblems; hydroelectrical subproblem, thermal plant and electrical power system.

Another important thing for planning a schedule of HPP is time horizon. Schedule can be in short-term, medium-term and long-term. According to Karamouz et.al (2004), long-term planning as strategic, medium-term planning as both strategic and tactical, short-term planning as tactical. Also there are many different works in literature for different time horizon. Chuntian et.al (2009),describe terms as short-term means making daily operation scheduling of HPP during one-day or several days. However medium-term and long-term means making weekly,monthly or yearly scheduling programs for HPP. Soares et.al (1980) and Karamouz et.al (2004), deal with in their study short time problems in order to make assumptions for long time periods. Lo et.al (1985) and Ferrero et.al (1998), use long-term in their works. On the other hand Yan et.al (1993), Johnson et.al (1997), Mandal et.al (2007), Chuntian et.al (2009), Soleymanpour et.al (2010) and Kumar et.al (2011) deal with short-term optimization problem in their models. For the reason that, schedule of HPP is a non-linear problem there are different type solution algorithm in literature. Some algorithms used in literature are; Soares et.al (1980), use stochastic and dynamic modeling by Lagrangian technique to find optimal solution. Lo et.al (1985), use stochastic dynamic programming to plan long-term operation of a multi reservoir hydrothermal power plant. El-Hawary et.al (1992), use Newton-Raphson's iterative method to find an optimal solution. Yan et.al (1993), solve their problem by using multiplier and Newton's model. They also use Lagrangian relaxation technique for the thermal submodels to find an optimal solution for the hydrothermal system. Johnson et.al (1997), develop a model for solving the combined hydro and thermal plants, they use Lagrangian relaxation technique in both hydro and thermal parts. Ferrero et.al (1998), use dynamic programming based algorithm for long-term hydrothermal scheduling. By dynamic programming they handle the nonconvex,nonlinear and stochastic model. Mandal et.al (2007), use particle swarm optimization to determine optimal hourly schedule of power generation in a hydrothermal power system. Particle swarm optimization is comparatively new combinatorial metaheuristic technique. Particle swarm optimization is primarily based on the fact that in quest of reaching the optimum solution in a multidimensional space, a population of particles is created whose present coordinate determines the cost function to be minimized. Particle swarm optimization technique has been applied to various fields of power system optimization. Liu et.al (2009), make differential evolution technique available in order to find optimal operation for hydroelectric station. The differential evolution technique has attracted growing concern as an optimal algorithm based on swarm intelligence theory. The basic operations of differential evolution algorithm are mutation, crossover and selection. Chuntian et.al (2009), model HPP schedule by using a decision support system. The decision support system is designed to ensure more flexibility and consistency in supporting the decision-making process for operation of hydropower plants including a variety of inputs and constraints of reservoirs or hydropower plants. Soleymanpour et.al (2010), deal with daily hydrothermal generation scheduling which is nonlinear,nonconvex and nonsmooth optimization. They solve that problem with modified adaptive particle swarm optimization which is improved. Kumar et.al (2011), solve hydro submodel by genetic algorithm and thermal submodel by using lambda iteration technique. They use genetic algorithm for variables in the model for which are difficult to make simplify assumptions required by conventional techniques. Wu et.al (2011), they find optimal solution of case study by using chaotic genetic algorithm.

We build our model due to models done before in literature survey. In our model we use dynamic programming approach to analyze different case to find optimal solution which is described in model section deeply . We make an experimental design to get results for fixed planning horizon. We deal with to find short term optimal production time interval of HPP. We use GAMS computer program to find optimal solution for our nonlinear model.

3. HYDROELECTRIC POWER PLANTS

Hydroelectric power is the largest renewable resource used for electricity. Hydroelectric power plants, are generally considered renewable and therefore sustainable over the relatively long term where other energy sources such as fossil fuels are finite. The global water cycle, driven by the sun, is the renewable resource for hydro power. Basically, water's potential (or kinetic) energy is converted into electricity using water turbines and electric generators.

Hydropower continues to be the most efficient way to generate electricity. Around %20 of the electricity used in the world it comes from this source. More than 150 countries in the world are generating electricity by using hydroelectric power. Modern hydro turbines can convert as much as %90 of the available energy into electricity where the best fossil fuel plants are only about %50 efficient.

Hydropower plants are energy capacities which have negligible operation costs comparing with the high investments because of the water as natural and sustainable energy resource. On the other side comparing with the fossil fired power plants, the hydropower plants are environmentally friendly and sustainable resource of energy. The each HPP is represented with technical characteristics for hydraulic equipment;water reservoir, tunnel, penstock, turbine, water and power installed capacity.

Hydro-turbines convert water pressure into mechanical shaft power, which can be used to drive an electricity generator, or other machinery.The reservoirs of storage and pumped storage schemes, mostly in mountainous regions, are created through the optimal damming of valleys. Geological, topological and hydrological factors determine the quality of a site and the dam, which in turn defines the size of the reservoir and the electricity generation patterns of future hydropower schemes.

Dams are usually classified into two main groups: concrete and embankment dams. The choice depends on factors such as the geology and topology of the site, the local climatic and hydrological conditions, and the availability of construction resources (labor and material), as well as the appearance in the landscape.

From the reservoirs or head ponds, the water is often diverted through tunnels and penstocks in order to gain additional hydraulic head. The type of turbine used depends on the type of plant, the height of the gross head and the site characteristics. There are basically two types of hydraulic turbine: impulse and reaction turbines. The former uses only the velocity of the water and is used for high-head, low-flow applications, while the latter uses the combined effect of pressure and moving water, and is suited for lower heads and higher flows Kaplan, Francis (both reaction turbines) and Pelton (impulse turbine) are the most frequently used types of turbine.

Hydroelectric power plants capture the energy released by water falling through a vertical distance, and transform this energy into useful electricity. In general falling water through turbine which converts the water's energy into mechanical power. The rotation of the water turbine is transferred to a generator which produces electricity. The amount of electricity which can be generated at a hydroelectric plant is dependent upon two factors. These factors are the vertical distance through which the water falls, "head", and the flow rate, measured as volume per unit time. The electricity produced is proportional to the product of the head and the rate of flow. Hydro turbines are optimized for an operating point defined by speed, head and discharge.

3.1 PARTS OF HYDROELECTRIC POWER PLANTS

HPPs use many parts while generating energy. Most important ones are called as;

Dam

Reservoir

Turbine

3.1.1 Dam

Dams are an important part of HPPs. They are located between powerhouse and water resource,to create large reservoir. They are usually built in high places in order to produce more energy. All dams should accomplish two basic objectives:

To resist the push of the water

To evacuate the leftover volumes

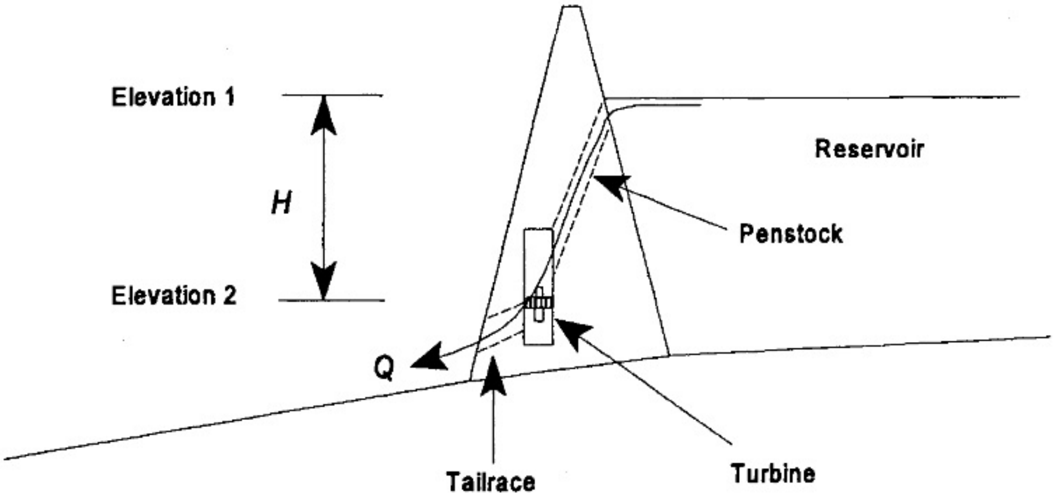


Figure 3.1: HPP Structure

3.1.2 Reservoir

Reservoir is the place where water is stored. The parameters of a reservoir impact on the amount of manufactured electric power; otherwise its depth and temperature conditions impact on ecology.The water-level changes in reservoir affects HPP operation.

3.1.3 Turbine

Turbines are parts that transform the water inflow into the electrical energy.There are different turbine types.Such as;

Pelton

Kaplan

Francis

Pelton Turbines

Common use impulse type of turbine founded by Lester Allan Pelton. The Pelton turbine is efficient and reliable when operating under large heads. Rotor occurs a large circular disc or wheel of spoon shaped buckets. The wheel is driven by jets of water being discharged.

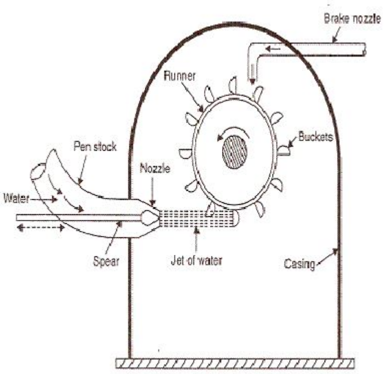


Figure 3.2: Pelton Turbine

Kaplan Turbines

Kaplan turbine is one of the reaction type turbine, which means that the fluid changes the pressure as it advances by the turbine giving his energy. It is a helix turbine in which the blades turn itself in march.Higher specific speed corresponds to a lower head. This requires that the rotor should admit a relatively large quantity of water.

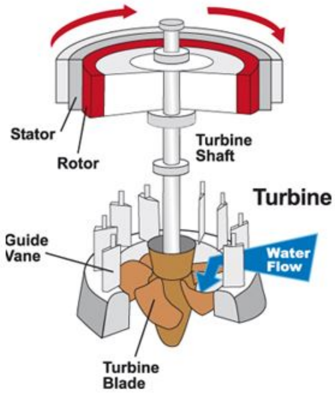


Figure 3.3: Kaplan Turbine

Francis Turbines

The Francis turbine is one of the reaction turbines. The turbine is located between the water source of high pressure and the exit of low pressure water,generally in the base of a dam. Francis turbines are best suited for sites with high flows and low to medium head.Francis turbines may be designed for a wide range of heads and flows. This,along with their high efficiency, has made them the most widely used turbine in the world.

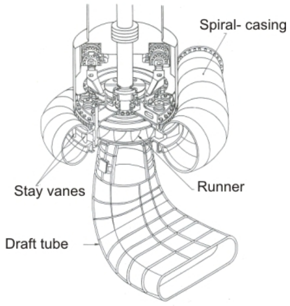


Figure 3.4: Francis Turbine

4. HYDROELECTRIC POWER PLANTS IN TURKEY

In Turkey generate electricity from hydroelectric power plants start before about 90 years ago with a 60 kW in Tarsus and it used only for providing lights for young Turkey Republic where electricity was available only in Istanbul, Izmir, Tarsus and Adapazarı.

Water projects were initiated by the Ministry of Public Works under the leadership of Atatürk in 1932.The Electrical Power Resources Planning and Survey Administration(EIE) was established in 1935 to define Turkey's energy demand, carrying out surveys and investigations to develop the hydroelectric potential of water resources and other energy resources.

Turkey has different kind of energy resources both conventional and renewable include coal types, oil, natural gas, hydro, biomass, geothermal,wind and solar in Figure 4.1.

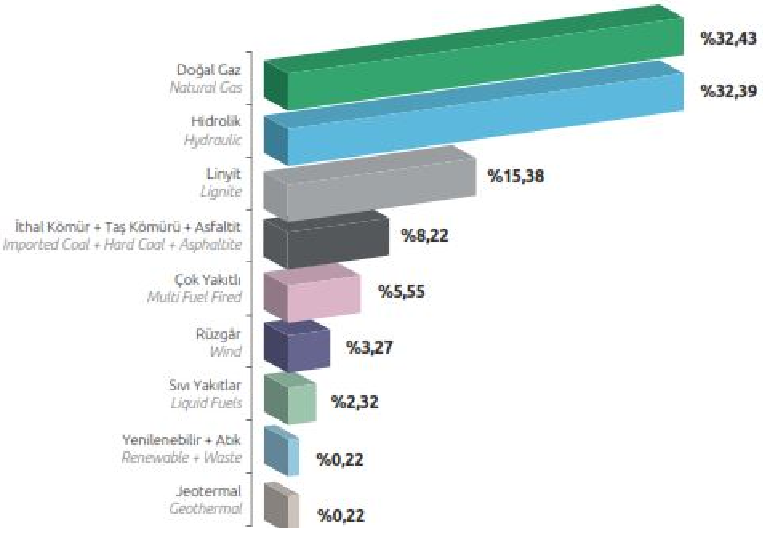


Figure 4.1: Turkey Energy Resource

Turkey has a total gross hydropower potential of 433 GWh/year but only 125 GWh/year of the total hydroelectric potential of Turkey can be economically used . By building new hydropower plants and operate them, which are under construction, %36 of the economically usable potential of country would be meet. %31 of energy generation in Turkey depends on hydroelectric power and the remaining on thermal power which are generated by (natural gas, lignite, coal, fuel oil, etc.). Alternative energy sources such as wind, solar, geothermal power are used in very small percent and also some steps have been taken in order to build and operate nuclear power plant in Turkey.

Turkey is one of the water-rich countries. However Turkey is not fully utilizing the water resources. Nowadays Turkey utilizes only 25.9 BCM of its available capacity of 110 BCM. The remains capacity also can be used in order to country needs.

In spite of generating electricity there are many benefits from hydropower and also they cause negative impacts too. Slowing down the river's velocity causes changes in sediment transport, storing huge amounts of water in reservoir changes significantly the water's quality and influences the micro-climate of the area. Irrigation itself is a great intervention in a natural system, introducing additional surface water, which throughout complex physical and chemical processes can lead to serious problems encountered nowadays in agriculture, such as soil erosion and salinization.

Energy is essential to economic and social development and improved quality of life in Turkey. Much of world's energy is currently produced and consumed in ways that could not be sustained if technology were to remain constant and if overall quantities were to increase substantially. Electricity supply infrastructures in Turkey as in many developing countries are being rapidly expanded as policymakers and investors around the world increasingly recognize electricity's pivotal role in improving living standards and sustaining economic growth. In the coming years, global environmental issues could significantly affect patterns of energy use around the world as in Turkey.

Hydropower can be adaptive and flexible. Depending on the storage capacity involved, a major advantage of hydropower is that generation can be scheduled. When water resources are not available to replenish reservoirs by natural inflow, pumped-storage schemes have been developed to assist in the storage of energy from other generation sources.

Hydropower industry is closely linked to both water management and renewable energy production, and so has a unique role to play in contributing to sustainable development in a world where billions of people lack access to safe drinking water and adequate energy supplies. Throughout history, dams and reservoirs have been used successfully in collecting, storing and managing water needed to sustain civilization. Hydropower often supports other essential water services such as irrigation, flood control and drinking water supplies.

Turkey has an adequate amount of water in general, it is not always in the right place at the right time to meet present and anticipated needs. As regards hydrology, Turkey is divided into 26 drainage basins. The rivers in general have irregular regimes, and natural flows cannot be taken directly as usable resources. The average annual precipitation, evaporation and surface runoff geographically vary greatly.

The socio-economic development, which has been progressing in parallel with fast industrial growth in Turkey, has caused living standards to rise. This has led to an increase in demand for electrical energy. The basics target of Turkey's national policy on energy is the provision of cheap electrical energy in sufficient amounts and on time, under qualified, reliable and competing conditions of the energy market. The energy policy, determined by 5-year development plans defined in Energy Ministry Annual Report (2011), is as follows:

Provision of qualified, reliable and cheap energy for sustainability in socio-economic development.

Provision of safety in energy supply.

Encouragement of private sector investments and expedition of privatization activities in the power sector.

Addition of new and renewable sources as soon as possible to the energy supply cycle.

5. PROBLEM DEFINITION AND MATHEMATICAL MODEL

5.1 PROBLEM DEFINITION

We study a hydroelectrical power plant works with alternative power plant system (APSP) in order to meet energy demand in period i. We aim to satisfy energy demand for fixed planning horizon. We assume that there is a HPP that work with Francis turbine. We selected Francis turbine because this type of the turbine is the most widely used turbine in HPPs. We assume that an additional alternative power supply plant (APSP) such as wind,solar or thermal works in our model. If the power generated from HPP does not meet the energy demand, then the APSP generate energy in order to satisfy demand. There is an additional cost of buying energy from APSP. We aim to minimize the total cost of buying APSP energy while satisfying total energy demand.

5.2 MATHEMATICAL MODEL

HPP generate energy by turbines which convert water pressure into electrical energy. The energy generated by turning turbine is the product of head level of reservoir and the water discharge to turbine in that period. Head level changes by reservoir water capacity. Reservoir head level is increased by river inflow to reservoir. β is reservoir coefficient which increase reservoir head level according to the water inflow to turbine. We assume that β is constant and equal to 0.125 according to the literature. If water capacity overreach the maximum reservoir head level (H_{max}), we should make water spillage in order to control the reservoir capacity. H_{min} is the minimum reservoir head level and if the head level is less than that level HPP is not generate energy. Head level is the difference between the heights of the turbine and the reservoir maximum.

In our model we aim to find best operation time period for different cases. We use different constant parameters such as θ where θ is turbine efficiency constant and we assume that it is equal to 0.8 according to examples in the literature. Also we use parameters that we change in every case such as a_i, b_i, Q_i and D_i. a_i is the price of selling energy in period i. b_i is the price of buying energy from APSP in period i. Q_i is the amount of water inflow to reservoir in period i. D_i is energy demand period i. By using those parameters and variables we try to find q_i, S_i and B_i, where q_i is the amount of water inflow to turbine, S_i is the amount of water spillage, B_i is the amount of energy bought from APSP in period i.

The objective function of our model is minimizing total cost of buying energy from APSP. So our objective function is;

$$Min \sum_{i=1}^{n} B_i b_i \tag{5.1}$$

Reservoir head level changing of HPP must be controlled. Head level in a period must be between levels of H_{min} and H_{max}. We assume that starting head level of reservoir H_0 is equal to H_{max}. New period H level is the summation of H level last period and β times water amount changing in reservoir. Water amount changing in reservoir is defined as $Q_i - q_i - Si$. Amount of water outgoing from reservoir is summation of water inflow to turbine and spillage water. Total of water inflow to reservoir and water outgoing from reservoir is water amount changing in reservoir.

$$H_{min} \leq H_i \leq H_{max} \tag{5.2}$$

$$H_i = H_{i-1} + \beta(Q_i - q_i - Si) \tag{5.3}$$

We aim to satisfy energy demand. In our system HPP and APSP generate energy. The HPP generate energy by water inflow to turbine. Turbine turns and convert mechanical energy to electrical energy. Turbine efficiency (θ) takes important role at energy generation. Total energy demand is summation amount of energy generated by HPP and amount of energy bought from APSP.

$$D_i = \theta q_i [H_{i-1} + \beta(Q_i - Si)] + B_i \tag{5.4}$$

After integrate all equations in one our model define as;

$$MinZ = \sum_{i=1}^{n} B_i b_i \tag{5.5}$$

$$s.t$$

$$H_i \geq H_{min} \quad i = 1, ..., n \tag{5.6}$$

$$H_i \leq H_{max} \quad i = 1, ..., n \tag{5.7}$$

$$H_i - H_{i-1} + \beta(q_i + Si) = \beta Q_i \quad i = 1, ..., n \tag{5.8}$$

$$\theta q_i(H_i + \beta q_i) + B_i = D_i \quad i = 1, ..., n \tag{5.9}$$

$$H_i, B_i, S_i, q_i \geq 0 \quad i = 1, ..., n$$

Our objective function is to minimize cost of buying energy from APSP. We sell energy generated from HPP and APSP. However there is cost of energy generation by using APSP. We deal with different cases to find optimal solution by using GAMS computer program. We build an experimental design by changing parameters D_i, Q_i and b_i for each period affect to the our model.

5.3 EXPERIMENTAL DESIGN

We try to find optimal solution for our model in different cases. For each case, we change a parameter and keep other fixed. Fixed value of parameters are average of total values in all periods. After that we change intended parameter to understand which parameter affect our objective function mostly. We build an experimental design for water inflow to reservoir in a period Q_i, energy demand in a period D_i and cost of buying energy from APSP in a period b_i. We assume our planning horizon is 12 periods with 4 value groups. Each group include 3 periods. We analyze low and high value of parameters for each cases. In each case we use fixed values for fixed parameters. That values comes from average of high and low values of parameters. We decide each case has 2 high values and 2 low values of parameters. We assume cases as;

Case 1 : High Value, High Value, Low Value, Low Value

Case 2 : High Value, Low Value, High Value, Low Value

Case 3 : High Value, Low Value, Low Value, High Value

Case 4 : Low Value, Low Value, High Value, High Value

Case 5 : Low Value, High Value, Low Value, High Value

Case 6 : Low Value, High Value, High Value, Low Value

The results of 10 replications for each parameter for each case are created by using GAMS. Furthermore, we interpret the results by graphical representation.

5.4 NUMERICAL RESULTS

5.4.1 Numerical Results for Changing Q_i Values

Water inflow to reservoir in each period is represented by Q_i. In these section we try to understand how water inflow affect to the our objective function. For each case we change the Q_i value and take other parameters steady. High value of Q_i is assumed as uniform distributed between 300-500 $m^3/s.$ and low value of Q_i is assumed as uniform distributed between 150-250 $m^3/s.$ We make 10 replications for each case and analyze results of the model objective function. We try to find how difference between water inflow to reservoir values affect to the objective function.

In Case 1, Case 2 and Case 3 we start with high value of water inflow. However the effect of those changing is not same for the objective function. In Case 1, the first two groups assigned as high value water inflow to reservoir which provide to keep the excess water in the system. That is, kept water can be used by the system to support in low value water inflow group. In Case 2, the first group is high water inflow where the second group is set as low water inflow. Surplus of water, collected in the first group, can be transferred to the second group. Likewise, the third group and the fourth group have same sequence (High,Low) and same features. In Case 3, first and last group have high water inflow. On the other hand, second group and third group have low water inflow. Moreover the surplus in the first group affects all next groups.

In Figure 5.1, it is clear that in Case 3 the high water inflow in first and forth groups is not able met energy generation requirements for second and third group. It can be inferred that the surplus of the water in first group may support energy generation for second group. However, water surplus in first group can not be accepted to support both second

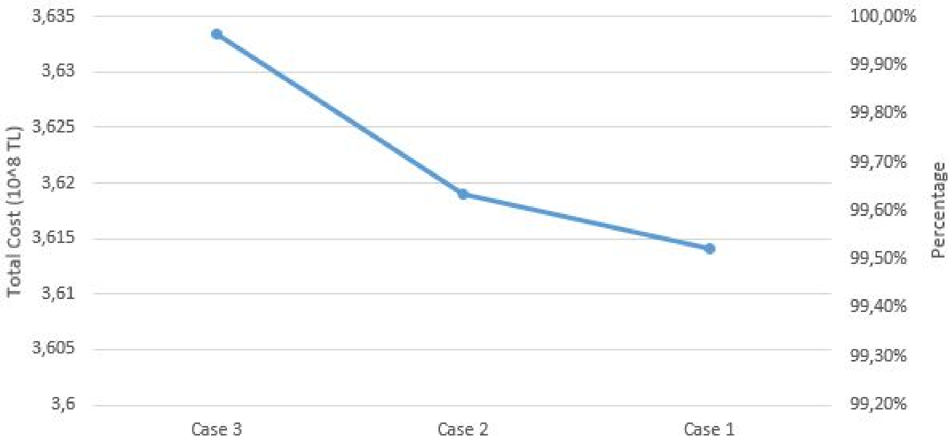


Figure 5.1: Total Cost Changes by Water Inflows For Case 1-2-3

and third group. In Case 2, the water surplus of high water inflows can balance reservoir water level in low water inflows. In Case 1 the sequential high water inflows can meet the last to sequential low water inflows. Therefore, Figure 5.1 represents that the total cost in Case 1 has the lowest value where Case 3 has the highest value.

In Case 4-5-6 we start with low value of water inflow. In Case 4, the first two groups assumed as low value water inflow to reservoir. There is no surplus water to transfer third and forth groups in Case 4. In Case 5, the first group is assigned as low water inflow where second group as high water inflow. Surplus water from second group can be kept on reservoir for next groups. In Case 6, the first group and forth group has low water inflow, second and third group has high water inflow. So surplus water from second and third groups can be kept for forth group in reservoir.

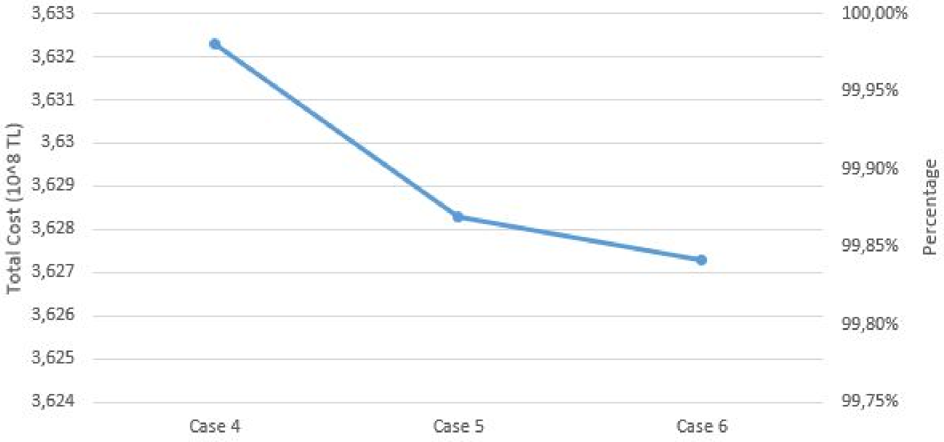


Figure 5.2: Total Cost Changes by Water Inflows For Case 4-5-6

In Figure 5.2, it is clear that in Case 4, the low water inflow in first and second groups is not able surplus water to reservoir for third and forth group to met energy generation requirements. In Case 5, the water surplus of high water inflows can balance reservoir water level in low water inflows. In Case 6, the sequential high water inflows can meet the last to sequential low water inflows. Therefore, Figure 5.2 represents that the total cost in Case 6 has the lowest value where Case 4 has the highest value.

After combining all cases in one the result we get graph as in Figure 5.3.

Figure 5.3: Total Cost Changes by Water Inflows For All Cases

5.4.2 Numerical Results for Changing D_i Values

Energy demand in each period is shown by D_i. In our model energy demand is supplied by both HPP and APSP. Amount of energy supplied from APSP is cost for our model. Therefore we try to minimize that cost in order to minimize our objective function. For each case we assume high and low value of D_i. High value of D_i is assumed as uniform distributed 200000-400000 MW and low value is assumed as uniform distributed 100000-200000 MW. We make 10 replications for each case and analyze results of the model objective function.

In Case 1, Case 2 and Case 3 energy demand start with high values. Water inflow to reservoir and buying energy cost is steady in all periods. In Case 1, energy demand is high in first two groups and then it is low in last two groups. Therefore in first two groups energy need is more than next groups. In Case 2, energy demand is changing in each group it is high in first group and third group, it is low in others. In Case 3, energy demand is high in first and last groups, low in second and third group. In low value of energy demand group we can use less water and kept remaining water for next groups. Therefore we generate more energy from HPP and by less energy from APSP.

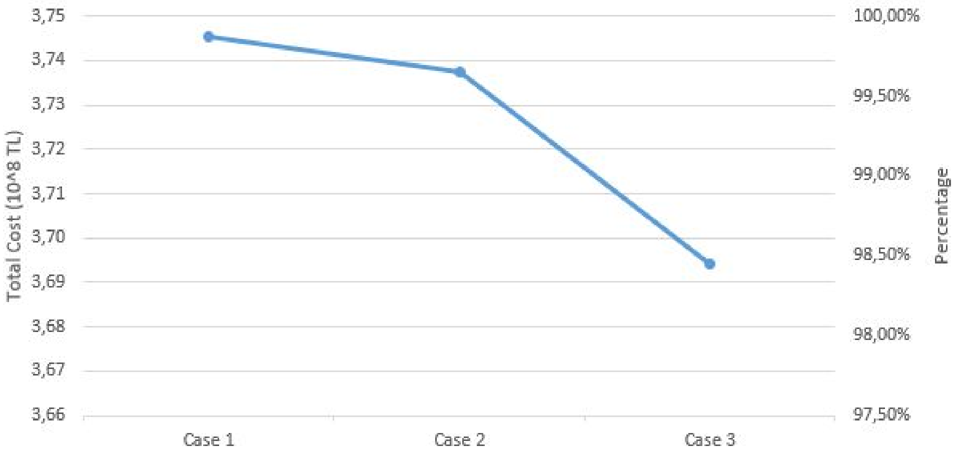


Figure 5.4: Total Cost Changes by Energy Demands For Case 1-2-3

In Figure 5.4, it is clear that in Case 1, due to the high energy demands in first and second groups is not able supply surplus water to reservoir for third and forth group to met energy generation requirements. So that, we buy more energy from APSP rather than other cases. In Case 2, the water surplus of low energy demands can balance reservoir water level for high energy demands in next stages. In Case 3, the sequential low energy demands supply more surplus water in reservoir for next stages usage. Therefore, Figure 5.4 represents that the total cost in Case 3 has the lowest value where Case 1 has the highest value.

In Case 4, Case 5 and Case 6 energy demand start with low values. In Case 4, energy demand is low in first two groups and then it is high in last two groups. Therefore in last two groups energy need is more than next groups. In Case 5, energy demand is changing in each group it is low in first group and third group, it is high in others. In Case 6, energy demand is low in first and last groups, high in second and third group. In low value of energy demand group we can use less water and kept remaining water for next groups. Therefore we generate more energy from HPP and by less energy from APSP.

In Figure 5.5, it is clear that in Case 4, energy demand is low in first two groups and it is high in last two groups. So surplus water which is not used in first two groups can be used in last two groups. In Case 5, demand is changing in each group it is low in first group and third group, high in other groups. Reservoir water level increase after the surplus water of low energy demand group enter to reservoir. In Case 6,demand is low in in first and last groups, is high in other two groups. The surplus water occurs from first period is not

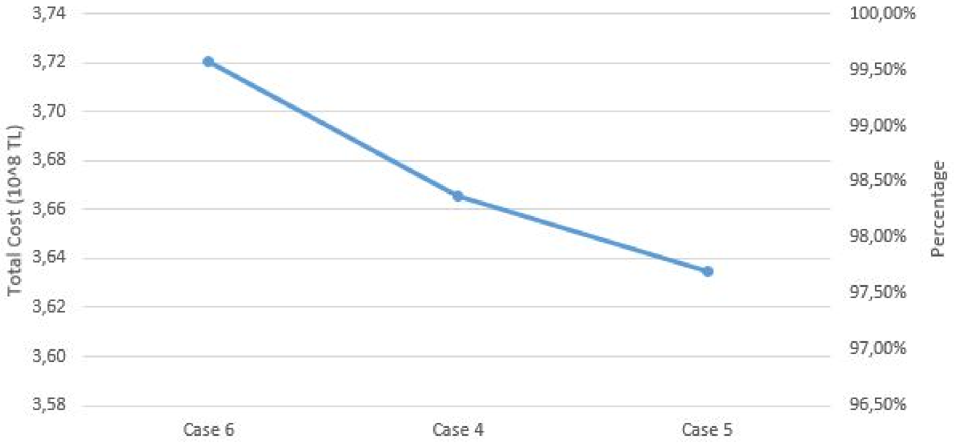


Figure 5.5: Total Cost Changes by Energy Demands For Case 4-5-6

enough for sequential two high periods in Case 6. Therefore, Figure 5.4 represents that total cost in Case 6 has the highest value where Case 1 has the lowest.

After combining all cases in one the result is in Figure 5.6. We can say that starting with high value demand makes total cost high.

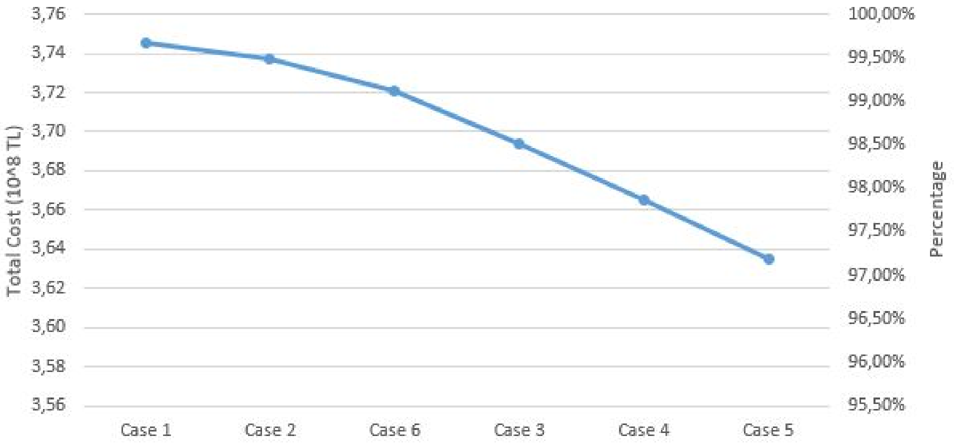
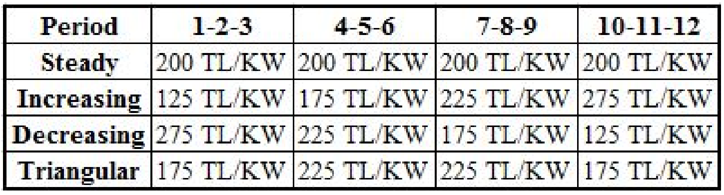


Figure 5.6: Total Cost Changes by Energy Demands For All Cases

5.4.3 Numerical Results for Changing b_i Values

Energy buying price for each period is represented by b_i. We try to minimize our cost in the objective function which is total buying energy cost from APSP. The b_i coefficient directly affects to the objective function where b_i is cost of bought energy for each period. For each case, changing in energy demand and water inflow to reservoir we assume different values of b_i. We take bi value as steady, increasing, decreasing, and first increasing then decreasing (triangular) for each period. We aim to see how our decision variable changes due to bi value changing. Steady value of bi we assume as 200 TL/KW. For other cases we keep mean of bi as 200 TL/KW and assume new values with respect that mean in Table 5.1.

Table 5.1: Cost of Buying Energy



Period	1-2-3	4-5-6	7-8-9	10-11-12
Steady	200 TL/KW	200 TL/KW	200 TL/KW	200 TL/KW
Increasing	125 TL/KW	175 TL/KW	225 TL/KW	275 TL/KW
Decreasing	275 TL/KW	225 TL/KW	175 TL/KW	125 TL/KW
Triangular	175 TL/KW	225 TL/KW	225 TL/KW	175 TL/KW

Difference of bi value directly effect to energy cost. Hence we aim to understand how power plant operation act according to the bi value. Energy demand parameter we get low energy cost in Case 5 respect to Figure 5.6. In Case 5 energy demand is different in each period. So with steady value of b_i the results of H_i, q_i and B_i are shown graphically in Figure 5.7.

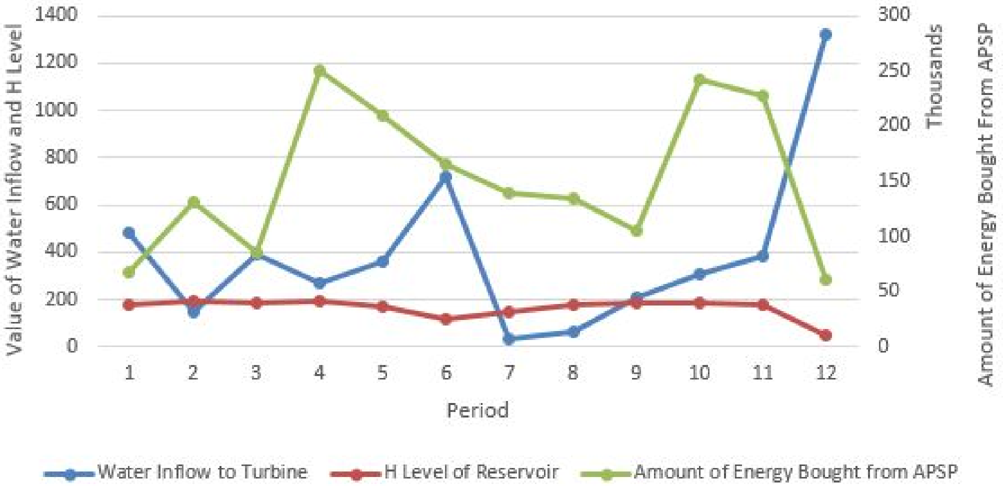


Figure 5.7: Changing in Decision Variables for Steady Cost of Energy with Different Energy Demands

Changing in b_i value also change the decision variables of the model. For each period with assume the other parameters are fixed as in Case 5, by increasing b_i our decision variables changes as in Figure 5.8. Values of decision variables for decreasing b_i are shown in Figure 5.9.

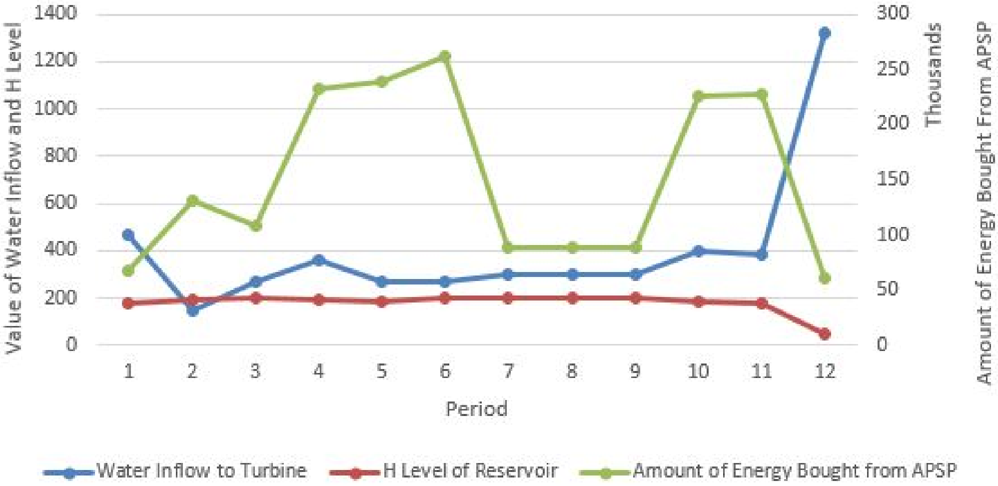


Figure 5.8: Changing in Decision Variables for Increasing Cost of Energy with Different Energy Demands

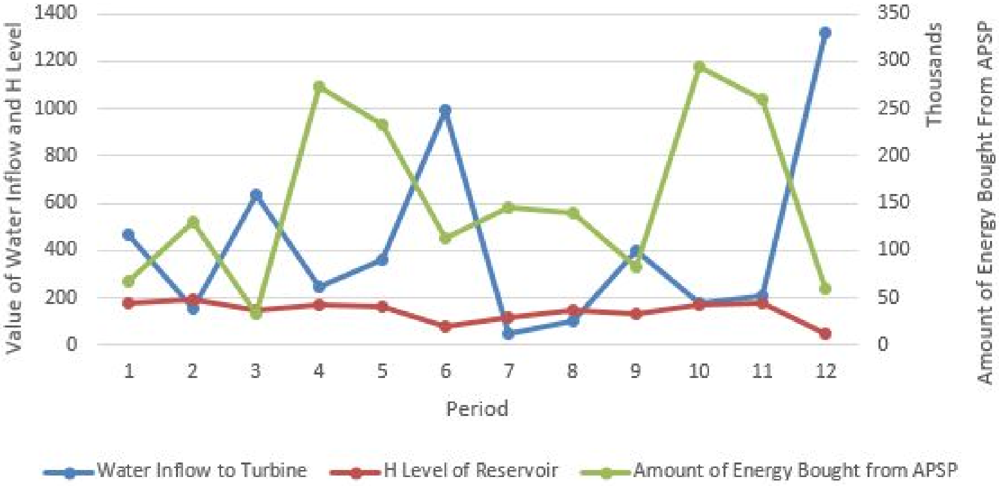


Figure 5.9: Changing in Decision Variables for Decreasing Cost of Energy with Different Energy Demands

We also analyze first increasing then decreasing (triangular) b_i values. The graphical results of these is shown in Figure 5.10.

After analyze all results for cost of buying energy from APSP change when demand change according to the Case 5. Due to graphs we can say that HPP generate more energy when high buying cost and high energy demand occur to reduce total cost.In each case

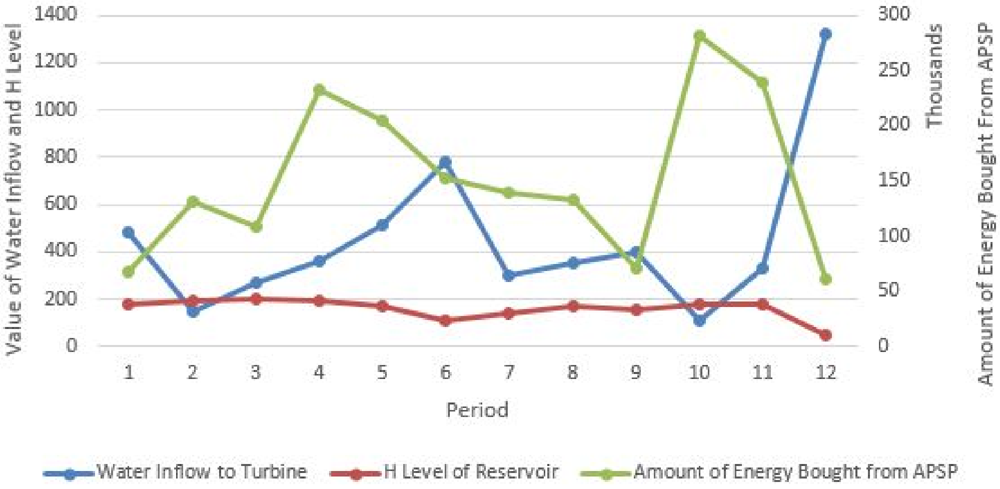


Figure 5.10: Changing in Decision Variables for Triangular Cost of Energy with Different Energy Demands

at the end of the period 11 HPP use all water in the reservoir until to H_{min} to generate enough energy for last period.

On the other hand we also analyze how water inflow to turbine paramater and cost of buying energy effect our model. We get low energy cost in Case 1 according to the Figure 5.3. We analyze the results for that cases to show HPP attribute for each bi case. For steady bi value results are shown in Figure 5.11.

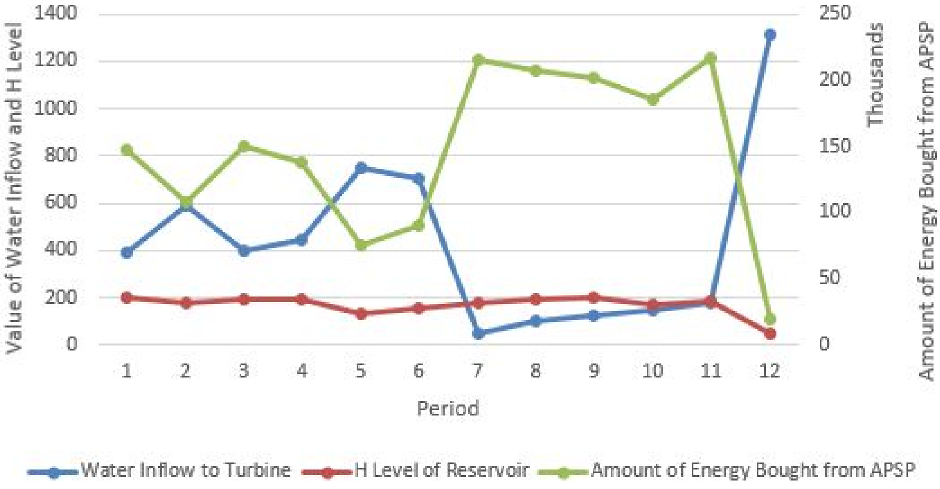


Figure 5.11: Changing in Decision Variables for Steady Cost of Energy with Different Water Inflow Values to Turbine

For increasing and decreasing b_i values the decision variable results are shown graphically in Figure 5.12 and Figure 5.13 respectively.

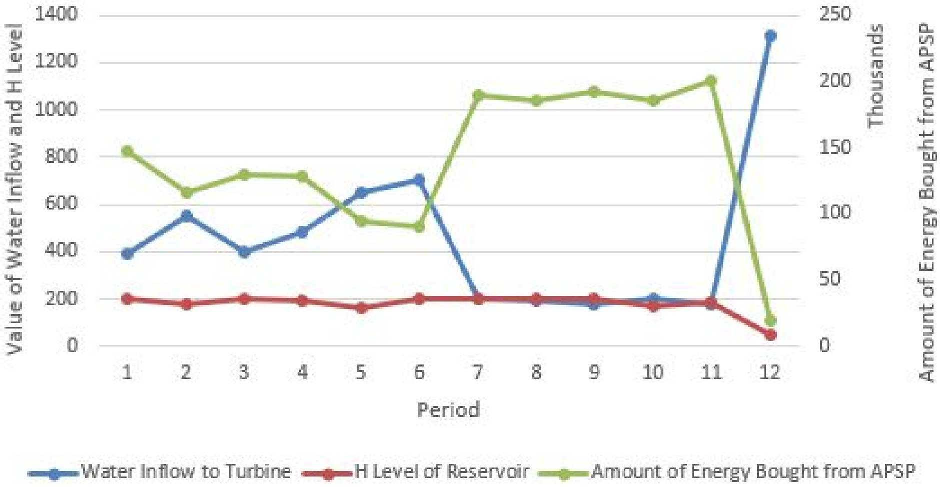


Figure 5.12: Changing in Decision Variables for Increasing Cost of Energy with Different Water Inflow Values to Turbine

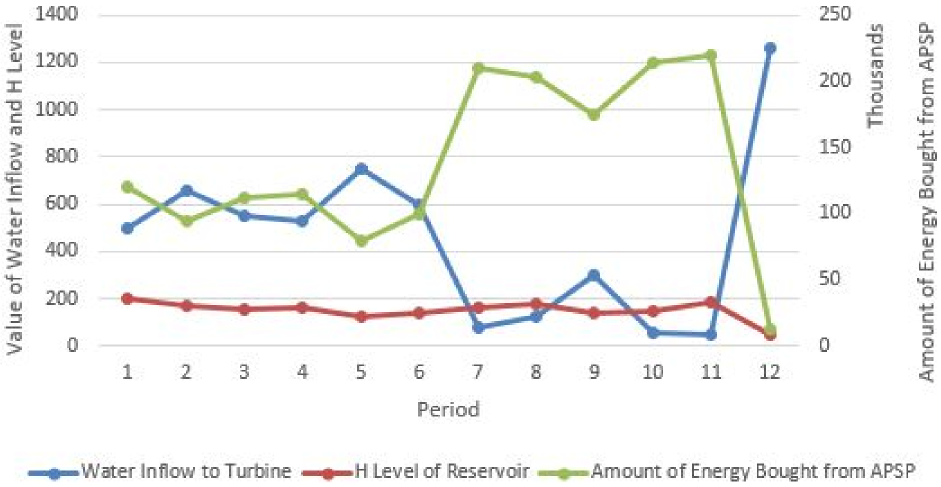


Figure 5.13: Changing in Decision Variables for Decreasing Cost of Energy with Different Water Inflow Values to Turbine

Also we analyze the triangular b_i value for Case 1. The graph of the decision variables due to that changing is shown in Figure 5.14.

We can say that HPP generates more energy when cost of buying energy is high. High water inflows to reservoir fills reservoir faster than low water inflows. Thus, HPP uses more water when water inflows to reservoir is high. In each case at the end of the period

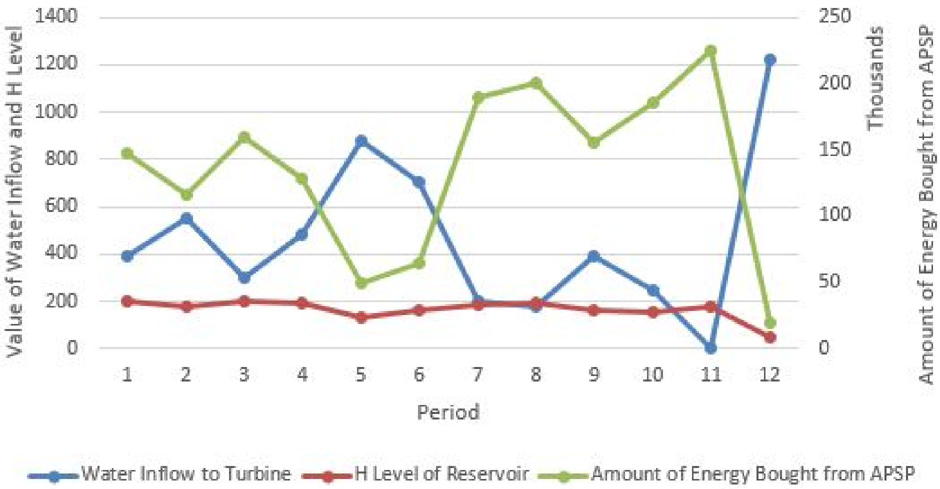


Figure 5.14: Changing in Decision Variables for Triangular Cost of Energy with Different Water Inflow Values to Turbine

11, HPP uses all water in the reservoir until to H_{min} level to generate enough energy for last period.

6. CONCLUSION

As conclude our works for model, we try to find optimal operation planning for HPPs for fixed planning horizon. We try to satisfy energy demand by generating energy from HPP. But, generated energy from HPP does not meet energy demand. Thus, we buy remaining energy from APSP and this process constructs cost for our model. Therefore, we try to minimize our total cost for all periods and we make experimental design for it.

In experimental design, we assume six cases and make experiments of those cases with three parameters: water inflow to reservoir, energy demand and cost of buying energy from APSP. According to the results, we can say that cost of buying energy from APSP parameter change our total cost for all periods. That is the reason, why cost of buying energy from APSP directly affects the total cost which is named our objective function.

Furthermore, it can be assumed that for changes in purchasing cost of energy from APSP has a direct effect on total cost of energy demand and water inflow to reservoir cases. The changes in purchasing cost value also change our H, q and B values. H, q and B changes regarding to the value of parameters in each planing horizon period. As it is mentioned in numerical results, HPP uses water in reservoir with respect to the energy demand and the water inflow to reservoir in that period; however, the energy generation decisions in a specific period affect the decision that will be made in the next periods. Hence, if the total cost is aimed to reduce, more energy should be generated from HPP. To generate more energy, it is clear that maximum amount of water should be sent to turbine with respect to reservoir head level, energy demands and water inflows to reservoir in other periods.

REFERENCES

Yuksek O. , Komurcu M.I. , Yuksel I. and Kaygusuz K.,2006. TheRole of Hydropower in Meeting Turkey's Electric Energy Demand. *EnergyPolicy*. **34**,pp.3093-3103

Rahi O.P, Chandel A.K andSharma M.G,2012. Optimization of HydroPowerPlant Design by Particle Swarm Optimization. *ProcediaEngineering*. **30**, pp.418-425

Zhao M.,Zhang X. andXu C., 2010. Assessment of Spillage of Largescale Hydropower Plant Undertaking Spinning Reserve. *IEEE*

Ibrahim Yüksel,2008. Hydropower in Turkey For a Clean and Sustainable Energy Future. *Renewable and Sustainable Energy Reviews*. **12**, pp.1622-1640

Wu X. ,Huang X. ,Fang G. and Kong F., 2011. Optimal Operation of Multi-Objective Hydropower Reservoir with Ecology Consideration. *Journal of Water Resource andProtection*. **3**, pp.904-911

B.Zahraie and M.Karamouz,2004. HydropowerReservoirsOperation:A Time Decomposition Approach. *Scientia Iranica*. **11**, pp.92-103

L.Yin and X.Liu,2009. Optimal Operation of Hydropower Station by Using an Improved DE Algorithm. *ISCSCT*. pp.71-74

S.Soares,C. Lyra and H.Tavares,1980. Optimal Generation Scheduling of Hydrothermal Power Systems. *IEEE*

IbrahimYuksel,2012. Renewable Energy Status of Electricity Generation and Future Prospect Hydropower in Turkey. *Renewable Energy*. **50**,pp.1037-1043

Chuntian C.,Shen J. ,Liao S. And Wu X.,2009. Decision Support System for Large-Scale Hydropower System Operations

Yan H.,Peter B., Guan X., and Rogan P.,1993. Scheduling of HydrothermalPowerSystems. *IEEE*,**8**

DSI Annual Report,2009.

EnergyMinistryAnnual Report,2011.

N.Amjady,H.R. Soleymanpour,2010. Daily Hydrothermal Generation Scheduling by a new Modified Adaptive Particle Swarm Optimization technique. *ElectricPowerSystems Research*.**80**,pp.723-732

M.R. Mohan,V.S Kumar,2011. A Genetic Algorithm Solution to the Optimal Short-Term Hydrothermal Scheduling.*ElectricalPowerandEnergy Systems*.**33**,pp.827-835

M.Basu,N. Chakraborty,K.K Mandal,2008.Particle Swarm Optimization Technique Based Short-Term Hydrothermal Scheduling.*AppliedSoft Computing*. **8**,pp.1392-1399

K.M. Ravindranath, M.E. El-Hawary,1992. Hydro-Thermal Power Flow Scheduling Accounting for Head Variations.*Transactions on Power Systems*.**7**

X.Guan,P.B.Luh,H.Yan and P.Rogan,1994. Optimization-Based Scheduling of Hydrothermal Power Systems with Pumped-Storage Units',*IEEE*,**9**

C.Li, E.Hsu, A.Svoboda, C.TsengandR.Johnson,1997. Hydro Unit Commitment in Hydro-Thermal Optimization. *IEEE.* **12**

R.W. Ferrero, J.F.Rivera and S.M. Shahidehpour,1998. A Dynamic Programming Two-Stage Algorithm for Long-Term Hydrothermal Scheduling of Multireservoir Systems. *IEEE.* **13**

V.R. Sherkat, R.Campo, K.Moslehi and E.O.Lo,1985. Stochastic Long-Term Hydrothermal Optimization for a Multireservoir System. *IEEE.***8**

CURRICULUM VITAE

Name Surname : Selim Gazel

Address : Bahçeşehir Üniversitesi Çırağan Caddesi 34353 Beşiktaş/İSTANBUL

Date and Place of Birth : 09.05.1988 HATAY

Languages : Turkish (native), English (fluent)

B.S. : Bahçeşehir Üniversitesi

Institute : The Graduate School of Natural and Applied Sciences

Program : Industrial Engineering

Work Experience : Bahcesehir University Industrial Engineering Department *Research and Teaching Assistant* (Istanbul, 2011 - today)