A Study on Simulation of

Istanbul Combined Cycle Power Plant

and Mathematical Model of a Gas Turbine

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Abstract

Energy is one of the significant factors that provides development and economic continuity of a country and a critical economic power therefore it is necessary for a country to use its own energy resources in order not to be dependent on foreign sources. However, the limited number of energy resources and their high costs necessitate the use of these resources at the highest efficiency. That's why various important studies on power plant are being carried out around the world.

In this thesis, a study carried out to examine modelling of Istanbul Combined Cycle Power Plant - A is mentioned. The working principles of the thermodynamic elements within this power plant, their effects on the power plant, the modelling that consists of these elements and the results will be discussed.

By modelling one of the four identical sections of the power plant in a virtual environment, the relations between the plant elements and their effects on each other will be better observed and the research will be progressed more effectively. In addition, the differences between the different models about power plant will be examined and the advantages and disadvantages of these differences will be determined. Throughout the study, more emphasis will be placed on the gas turbine, which is one of the most critical parts of the power plant.

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1 Introduction

"Obviously, if we can find a single word to represent an idea which applies to every element in our existence in a way that makes us feel we have a genuine grasp of it, we have achieved something economical and powerful. This is what has happened with the idea expressed by the word energy. No other concept has so unified our understanding of experience." (1)

"Energy is the only universal currency. It must be transformed to get anything done. Manifestations of these transformations in the physical universe range from rotating galaxies to the erosive forces of tiny raindrops.

The evolution of human societies has been dependent upon the conversion of ever larger amounts of ever more concentrated and more versatile forms of energy. From the perspective of natural science, both prehistoric human evolution and the course of history may be seen fundamentally as the quest for controlling greater energy stores and flows. This endeavour has brought about the expansion of human populations and allowed for increasingly complex social and productive arrangements. Neither the growth of technical capabilities and a deeper understanding of the surrounding world nor the effort to secure a better quality of life would have been successful without innovations in energy use." (2)

Energy is one of the most important factors contributing to the development of a country. Energy is a critical economic power, so a country must use its own energy resources in order not to be dependent on foreign sources. However, the limited number of energy resources and their high costs necessitate the use of these resources at the highest efficiency. That's why various important studies are being carried out around the world to increase the performance of power plants.

In this thesis, a study carried out to examine modelling of Istanbul Combined Cycle Power Plant - A is mentioned. The working principles of the thermodynamic elements within this power plant, their effects on the power plant, the modelling that consists of these elements and the results will be discussed. By modelling one of the four identical sections of the power plant in a virtual environment, the relations between the plant elements and their effects on each other will be better observed and the research will be progressed more effectively. In addition, the differences between the different models about power plant will be examined and the advantages and disadvantages of these differences will be determined. Throughout the study, more emphasis will be placed on the gas turbine, which is one of the critical parts of the power plant.

At the beginning of the study, the energy sources used throughout history will be mentioned and the adventure of energy will be shortly explained. Then, information will be given about actual modern energy sources and one of these energy sources, thermal power plants, will be emphasized. Subsequently, the structure and brief history of the Istanbul Combined Cycle Power Plant – A, which is examined in this thesis, will be mentioned.

Following this information, the thermodynamic approaches which about power plants will be discussed. “The Second Law of Thermodynamics” will be explained and the energy and the exergy principles will be mentioned. After that, gas, steam and combined thermodynamic cycles will be examined and explained in the study.

The main section of the study is creating model of the power plant. In this study, there will be two different models are created. One of them is mathematical model that by used the Engineering Equation Solver (EES) software and the other one is a simulation model that by used the DWSIM chemical process software. The reason of using two different approaches is aimed to comparatively obtain the mathematical data to be calculated as a result of the models and to reach more accurate results accordingly each other. Additionally, the aim is to see what kind of results the free source simulation model (DWSIM) to be used in the study can give compared to the paid and closed source simulation models used in previous academic studies. At the same time, it is wanted to see how successful an open-source chemical process software is in creating a detailed and complex simulation model by pushing the limits.

Thermal power plants are complex structures that consists of many different interconnected thermal elements, and the studies on these structures are of great importance for both today and the future. In our world, which has limited and decreasing energy resources day by day, we must do whatever we can to use these resources efficiently and hand down them to future generations, and as engineers and humans, we must protect “our Earth” and “our nature”.

1.1 Introduction to Energy

"The word energy is, as are so many abstract terms (from hypothesis to sophrosyne), a Greek compound. Aristotle (384–322 b.c.e.) created the term in his Metaphysics, by joining εν (in) and \`εργον (work) to form εν\`εργεια (energeia, "actuality, identified with movement") that he connected with entelechia, "complete reality".

According to Aristotle, every object's existence is maintained by energeia related to the object's function. The verb "energein" thus came to signify motion, action, work and change. No noteworthy intellectual breakthroughs refined these definitions for nearly two subsequent millennia, as even many founders of modern science had very faulty concepts of energy. Eventually, the term became practically indistinguishable from power and force." (3)

In physics, energy is a broad, conserved and fundamental property of a physical system that cannot be directly observed but can be calculated from its location. Energy can transform many forms and can be exist in many different situations. Energy is the capacity of a system to do work. In physics, work is defined as the effect of the component of the force in the direction of displacement multiplied by the displacement, and energy is measured in the same unit as work.

Energy has always been important to humankind since old times. The primary need of humans is energy to meet basic human needs such as heating, cooking, forging iron, producing products, etc. In the following periods, especially with the industrial revolution and the development and increase in the use of mechanical tools and machines, the concepts of energy and energy production have become more important.

The development of technology, progress of industry, increase of population and formation of crowded cities have caused the energy need to increase tremendously in the last 2 centuries. Therefore, during this period, hydroelectric power plants, coal-fired power plants, natural gas power plants, nuclear power plants, solar power plants, etc. developed, constructed and used for energy supply.

1.2 Types of Energy Resources

There are many types of energy forms like potential energy, chemical, mechanical, electrical, kinetic etc. These are out of our subject, therefore just types of energy resources that using for getting energy will be explained in this chapter.

"The world's primary energy sources are fossil fuels such as crude oil, natural gas, and coal. Despite being a non-renewable resource, fossil fuels continue to be in great demand due to their affordability and dependability. Fossil fuels play an important part in energy production and the global economy, from heating and lighting homes to fuelling automobiles. Even with tremendous technological advancements, sustainable energy has unable to supplant traditional fossil fuels." (4)

It is accepted by almost all scientific academics that the basis of the future energy source will be renewable energy sources like wind energy, solar and biomass powers, geothermal and hydrothermal energies. Despite the intense studies and investments made on renewable energy sources, conventional energy sources still constitute the majority to obtain energy. The main elements of conventional energy resources are coal, gas and oil.

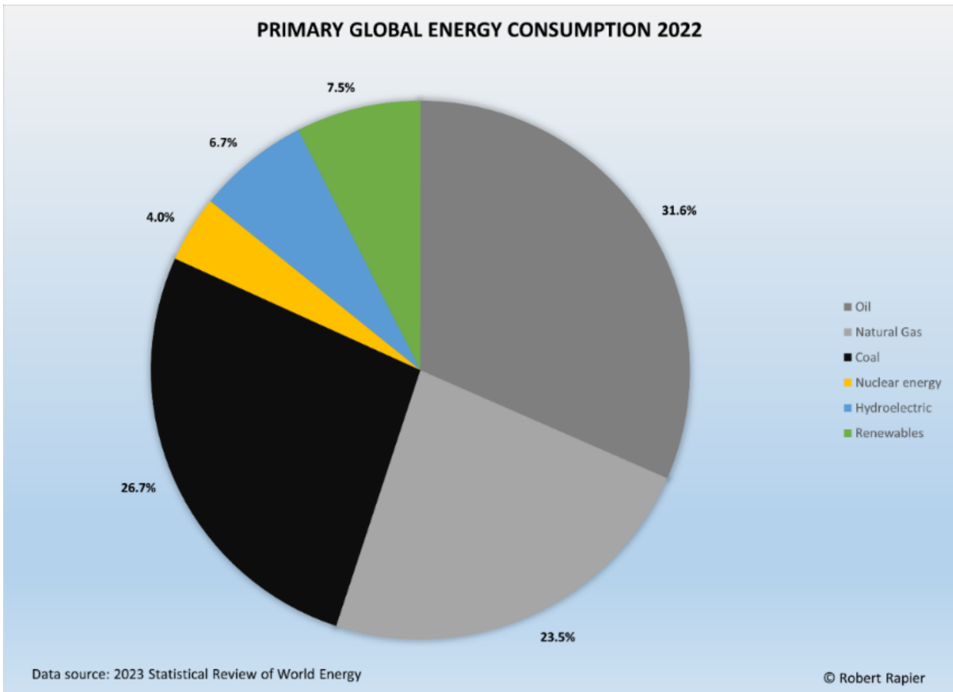

Figure 1: Primary Global Energy Consumption 2023 (5)

1.3 Electricity Generation

Electricity is another conventional source of power and it is a kind of indicator on state's economic well-being. The ease and abundance of electricity availability means unceasingly growth of production, transportation and agriculture industries.

"Electricity is indispensable to human beings comfort. Also, it is essential for productivity improvement and technological advancement without which growth is impossible. In the meantime, while the power generation industry has been responsible for a lot of damage to the environment, it has come a long way in the improvement of efficiency and the reduction of negative impacts on the environment." (6)

Gas-fired power plants, coal-fired power plants, hydro-electric power plants and nuclear power plants supply most of the electrical energy used in the world according to the 2023 Statistical Review of World Energy from Energy Institute. These four methods of producing electricity are referred to main conventional energy sources.

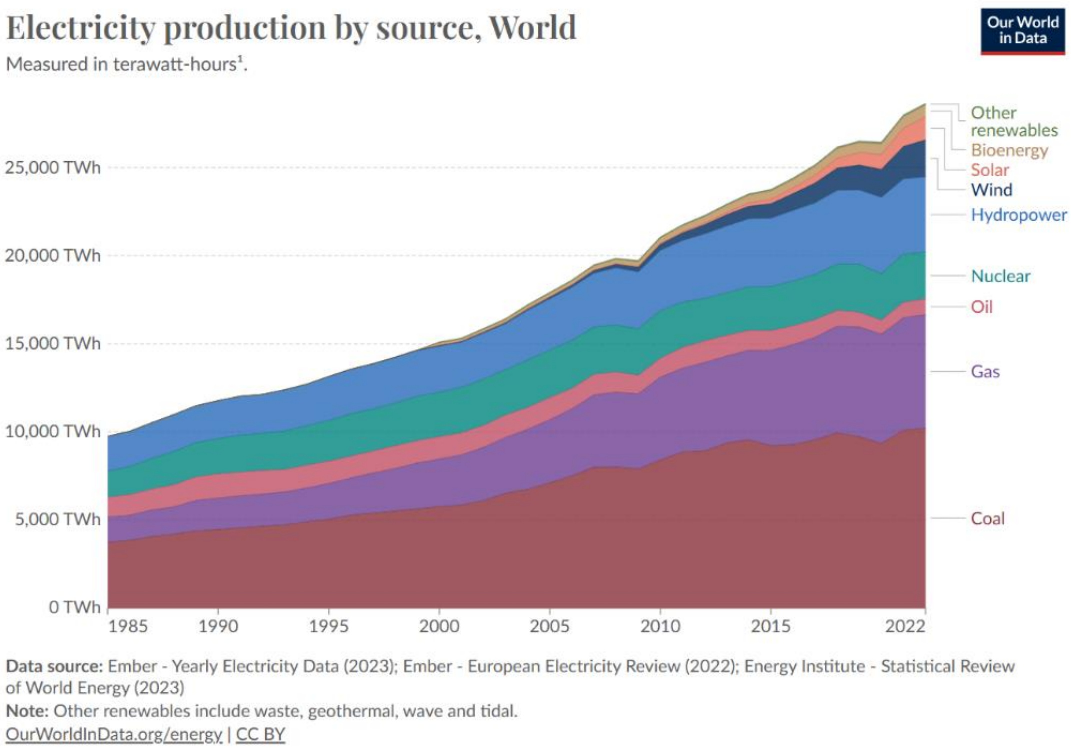

Figure 2: Electricity Production by Source in the World (7)

With all of these, considering statistical data, (Figure 3) electricity generation and consumption are expected to increase over the next 25 years.

"The figure shows the global annual electricity generation between 1980 and 2050. The solid line is based on the actual electricity generation and the dashed line is based on the projected data. The curve indicates that in the past four decades the electricity generation has tripled. It is also expected to almost double by 2050 compared to the current consumption. It should be noted that while the electricity generation and consumption are slightly different, for our analyses (which is focused on trends rather than actual values) we can use them interchangeably because increase or decrease in electricity generation and consumption is always concurrent with a few percent difference." (6)

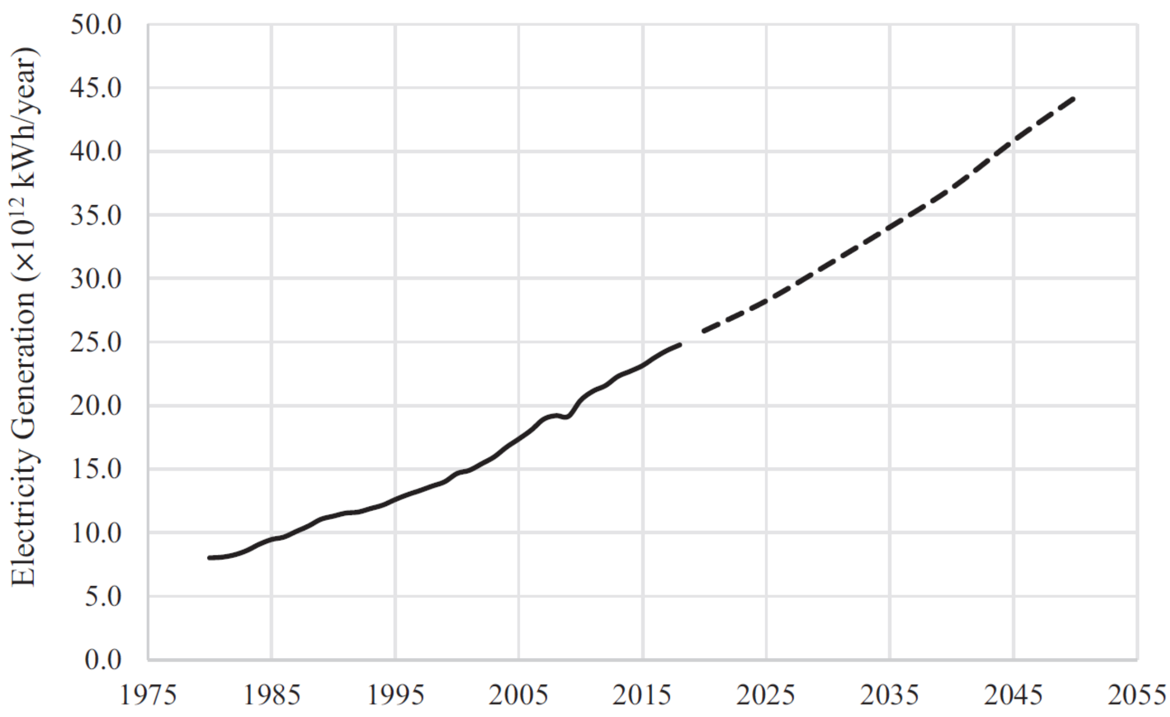

Figure 3: Global annual electricity generation between 1980 and 2050. (6)

(Based on the data provided by EIA, data before 2018 are from actual generation and beyond that are projection.)

1.4 Türkiye's Status

Türkiye needs high amount electricity that using in agriculture, transport, residential, service and industry sectors. According to Ministry of Energy and Natural Resources of Türkiye data:

"The primary energy consumption of Türkiye in 2020 was 147.2 Mtoe. The primary energy consumption will increase to 205.3 Mtoe by 2035. Primary energy consumption, which increased by an annual average of 3.1% in the 2000–2020 period, will increase by 2.2% in the 2020–2035 period. Primary energy consumption per capita, which was 1.7 toe per capita in 2020, will increase to 2.1 toe in 2035. The share of renewable energy sources in primary energy consumption, which was 16.7% in 2020, will increase to 23.7% by 2035. Nuclear energy, on the other hand, will reach a share of 5.9% by 2035. The share of fossil resources, which was 83.3% in 2020, will decline to 70.4% by 2035. The share of coal will decrease to 21.4%, and the shares of oil and natural gas will fall to 26.5% and 22.5%, respectively." (8)

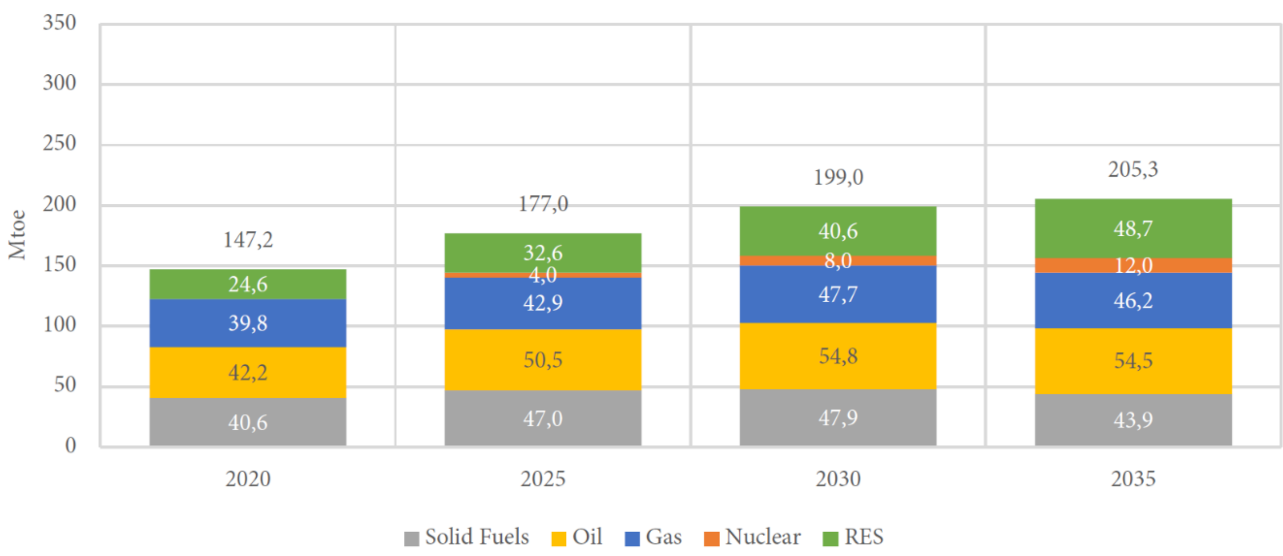

Figure 4: Primary Energy Consumption by Source (8)

If it is a needed to look at electricity consumption of Türkiye:

"Electricity consumption, which rose from 128 TWh to 306.1 TWh, with an annual average increase of 4.4%, in the 2000–2020 period, will reach 510.5 TWh by 2035 with an annual average growth of 3.5%. In the forecast period, annual average electricity consumption is expected to increase by 3.7% in the industry sector, 2.3% in the residential sector and 2.2% in the service sector. The share of electricity in final energy consumption, which was 21.8% in 2020, will reach 24.9% by 2035." (8)

For these reasons, Türkiye should increase its investment expenditures in electricity generation, intensify its R&D studies in this field and increase the production capacity and efficiency of its existing electricity generation tools.

With these data, by the end of January 2024, the electricity installed capacity of Türkiye has reached 107,271 MW. (9)

"The installed capacity, which was 95.9 GW in 2020, will increase to 189.7 GW by 2035. The share of renewable energy sources in installed capacity, which was 52.0% in 2020, will reach 64.7% by 2035. Hydroelectric power plants will reach an installed capacity of 35.1 GW in the medium to long term. Wind power installed capacity will reach 29.6 GW and solar power installed capacity will increase to 52.9 GW." (8)

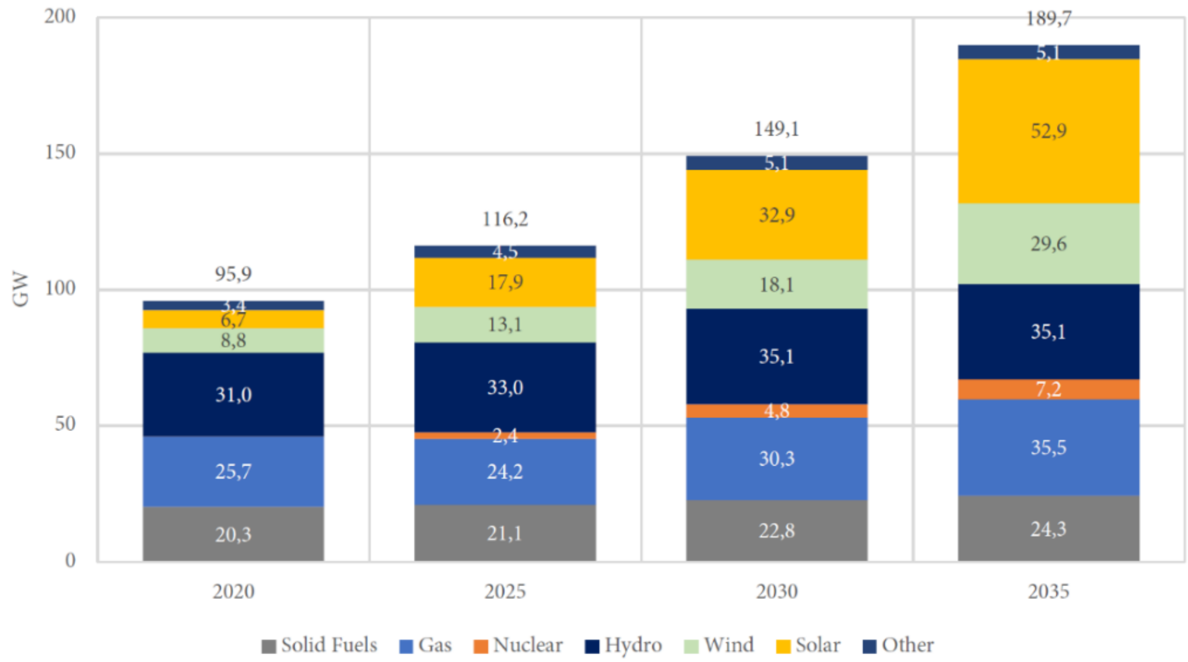

Figure 5: Electricity Installed Capacity by Source (8)

According to the information given above, Türkiye's energy production and consumption are expected to increase within the next 10-15 years period. Although the share of renewable energy sources in the resource distribution of energy production that will meet the energy consumed will increase every year, the share of traditional energy sources will still be around 35 percent.

The tables below are quoted from the report published by the Turkish Ministry of Energy and Natural Resources. Considering these data, the importance of traditional energy sources and power plants that make use of these energy sources becomes evident once again. (8)

Table 1: Electricity Power Installed Capacity (GW)

Year / Source	2025	2030	2035
Coal	21,10	22,80	24,30
Gas	24,20	30,30	35,50
Nuclear	2,40	4,80	7,20
Hydroelectric	33,00	35,10	35,10
Wind	13,10	18,10	29,60
Solar	17,90	32,90	52,90
Other	4,50	5,10	5,10
Total	116,20	149,10	189,70

Table 2: Share of Electricity Power Installed Capacity (% GW)

Source / Year	2025	2030	2035
Coal	18,16	15,29	12,81
Gas	20,83	20,32	18,71
Nuclear	2,07	3,22	3,80
Hydroelectric	28,40	23,54	18,50
Wind	11,27	12,14	15,60
Solar	15,40	22,07	27,89
Other	3,87	3,42	2,69
Total	100	100	100

If we look at the share of natural gas in electricity production, it is seen that it will have the largest share after solar energy even in 2035. According to TÜİK (Turkish Statistical Institute) estimates in the long term, the share of natural gas will continue to be around 10-11 percent in the 2050s. (8)

It is predicted that natural gas power plants will be used in at least the next 30 years. For this reason, it is necessary to increase investment and R&D studies in this field and to carry out the necessary studies to increase the efficiency of existing power plants. This is necessary to reduce or even end foreign energy imports and dependence, which are one of the most critical elements that undermine our country's independence.

2 Power Plants

The energy, energy resources and its types were explained and the statistics of consuming of these energy resources were gave in last chapter. In addition, it has been mentioned that power plants are used in the use of these energies and electricity production. In this chapter, definition of power plants, types of power plants and components of power plants will be explained. In the following, especially combined cycle power plants and their components will be mentioned.

“A power plant is assembly of systems or subsystems to generate electricity, i.e., power with economy and requirements. The power plant itself must be useful economically and environmental friendly to the society.” (10)

“The design of a power plant is a complex trade-off between thermodynamics and economic considerations, which is bounded by regulations, particularly environmental regulations.” (6)

Each power plant system has its own characteristics. The structure of power plants varies depending on their location, the fuel they will use, the operating time or life, the desired amount of energy or efficiency and the components they will consist according to all these conditions.

2.1 Types of Power Plants

The power plants are classified by two main branches. Conventional and non-conventional. conventional power plants, as the name suggests, are power plants that generate electrical energy through conventional energy sources like coil, oil, natural gas. Non-conventional power plants are, in contrast to the conventional power plants, systems that generate electricity with a renewable energy source, as opposed to a depletable one, and are cleaner and more environmentally friendly than the others. Photovoltaic power stations (solar farms), wind farms are examples of these systems.

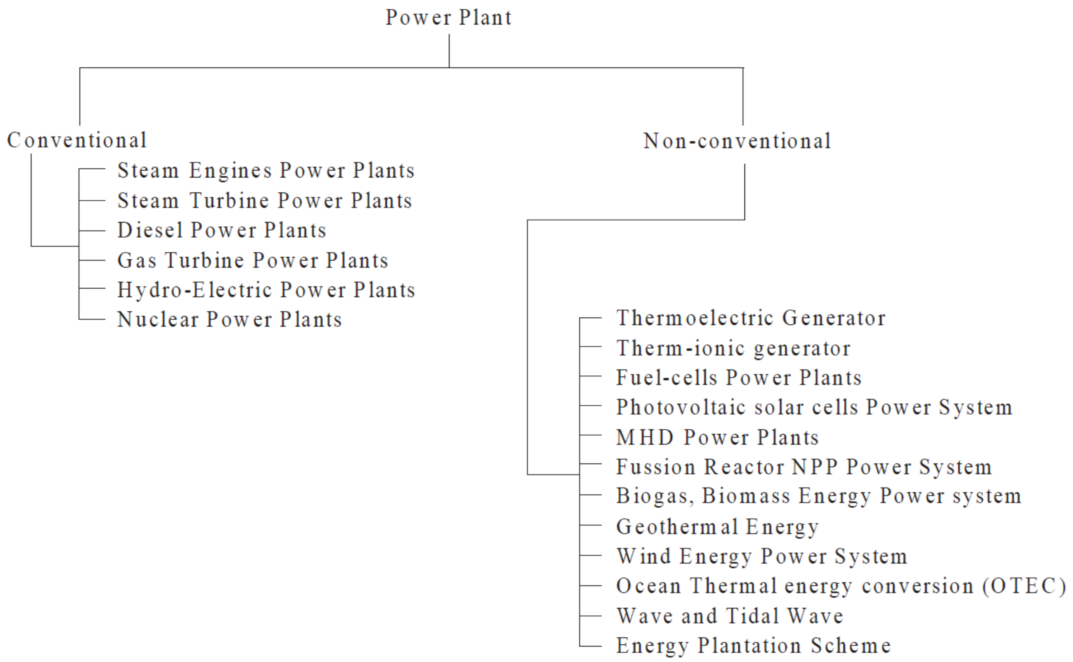

Figure 6: Classification of Power Plants (10)

2.2 Combined Cycle Power Plants (CCPP)

“Combined cycle power plants (CCPPs) can refer to any combination of two or more power generation cycles. However, in the power generation industry, the term specifically refers to when a gas turbine power unit (Brayton cycle) and a steam power plant (Rankine cycle) work together.” (6)

“Today, overall production cost is a key to their success. They must offer electricity at the lowest cost, yet still meet the requirement of flexible adjustment between demand and supply. This cost factor is of major importance for the merchant plants.… The other benefits of combined cycles are high efficiency and low environmental impact. Worldwide, levels of emissions of all kinds must meet stringent regulations acceptable to the public. It is, therefore, important for power producers to invest in plants with an inherently low level of emissions. Risk mitigation and public acceptance are paramount. Clean plants are easier to permit, build, and operate. Combined-cycle plants-especially those fired with natural gas-are a good choice with their low emissions.” (11)

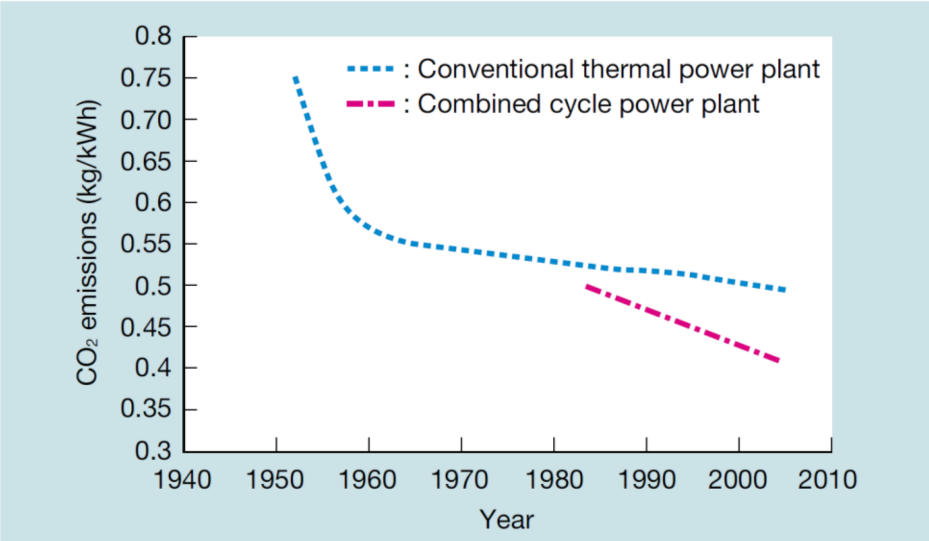

Figure 7: Transition of "CO2 emission reduction (12)

"The rapid improvement of gas turbine technology in the 1990s drove combined cycle thermal power plant efficiency to nearly 60 % with natural gas as the fuel. This efficiency is very high compared to the conventional nuclear and coal-fired power plants. As a result, combined cycle power plants, CCPP, have become the most favorite electric generation facilities as they yield both very good economic and thermodynamic performance compared to the other conventional power plants." (13)

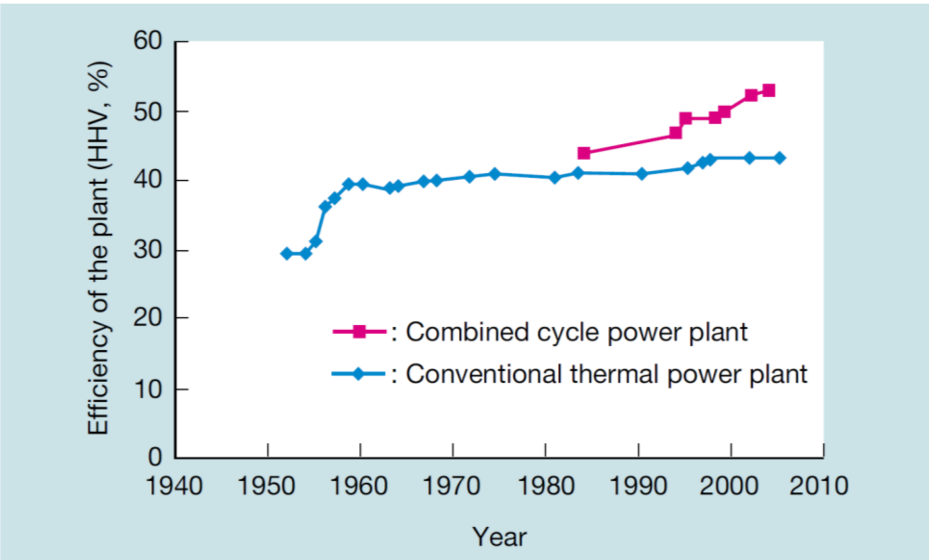

Figure 8: Transition of Plant Efficiency of Conventional Type Thermal Power Plant and Combined Cycle Power Plant (12)

The reason for this situation is due to the development of turbine, compressor and nozzle technology, as mentioned above. As a result of the studies on the structural design and materials of compressors and turbines, the manufacturers says that it has been possible to raise the hot air entering the turbines in power plants up to 1700 C. (12)

This development increased efficiency and power generation thanks to the excess heat obtained from the fuel and reduced the amount of carbon emissions.

Besides all this, it should also be said that despite these promising words, R&D studies on this technology are still continuing. Although a turbine inlet temperature of 1600 degrees Celsius has been reached, it is estimated that it will take 2025 to produce turbines with an inlet temperature of 1700 degrees. (14)

2.3 Components of CCPP

"Using a system approach, there are four major subsystems in a combined cycle power plant system:

1. Gas turbine generator (operating in Brayton cycle)

2. Steam turbine generator (operating in Rankine cycle)

3. Heat recovery boiler or, using the more common terminology, heat recovery steam generator (HRSG)

4. Heat rejection system comprising either

- A water-cooled condenser (with or without a cooling tower) or
- An air-cooled condenser (ACC).

In addition to these four major subsystems, there is a maze of condensate, cooling water and steam piping with a large number of valves along with pumps (condensate, boiler feedwater and circulating cooling water pumps) and myriad heat exchangers, which are lumped under the term "balance of plant" (BOP)." (15)

2.3.1 Gas Turbine

The industrial gas turbine is the basic component in the gas turbine, steam turbine and combined cycle power plants. The turbine works by uses pressurized and high temperature gas to spin its blades and produces electrical energy by rotating the shaft to which it is connected.

“The combined-cycle plant has been able to become a competitive thermal process only as the result of the rapid development in the direction of higher gas turbine inlet temperatures.

Parallel to this development in the turbine, there has also been an improvement in the compressor. Today the compressor can handle much larger mass flows and higher-pressure ratios, making it possible to attain considerably higher power outputs and thereby both reduce costs and improve efficiency.” (16)

Figure 9: H-Class Gas Turbine (17)

2.3.2 Steam Turbine

“The steam turbine generator is the primary power conversion component of the power plant. The function of the steam turbine generator is to convert the thermal energy of the steam from the steam generator to electrical energy. Two separate components are provided: the steam turbine to convert the thermal energy to rotating mechanical energy, and the generator to convert the mechanical energy to electrical energy. Typically, the turbine is directly coupled to the generator.” (18)

“The motive power in a steam turbine is obtained by the rate of change in moment of momentum of a high velocity jet of steam impinging on a curved blade which is free to rotate. The steam from the boiler is expanded in a passage or nozzle where due to fall in pressure of steam, thermal energy of steam is converted into kinetic energy of steam, resulting in the emission of a high velocity jet of steam which, principle of working impinges on the moving vanes or blades of turbine.

Attached on a rotor which is mounted on a shaft supported on bearings, and here steam undergoes a change in direction of motion due to curvature of blades which gives rise to a change in momentum and therefore a force. This constitutes the driving force of the turbine. This arrangement is shown. It should be realized that the blade obtains no motive force from the static pressure of the steam or from any impact of the jet, because the blade in designed such that the steam jet will glide on and off the blade without any tendency to strike it.” (10)

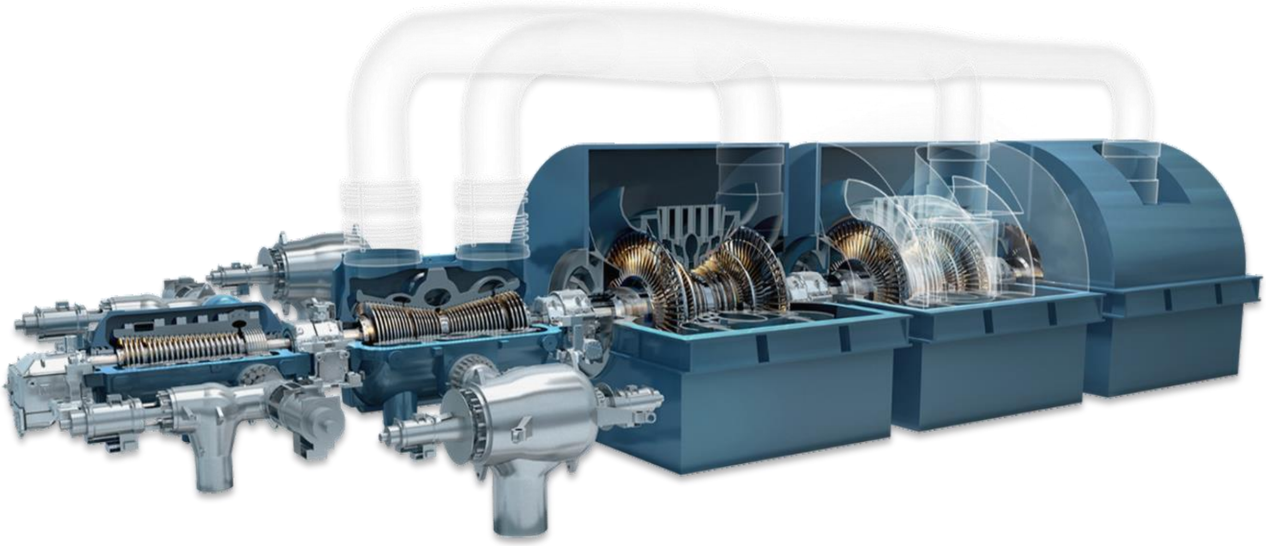

Figure 10: A Reheat Steam Turbine (19)

2.3.3 Heat Recovery Steam Generator (HRSG)

The heat recovery steam generator (HRSG) creates a connection between the gas turbine and the steam turbine. The most important purpose of HRSG is to absorb the maximum amount of thermal energy from a flue gas (exhaust) flow.

“The function of the HRSG is to convert the thermal energy in the gas turbine exhaust into steam. After heating in the economizer, water enters the drum at slightly subcooled conditions. From the drum, itis circulated to the evaporator and returns to the drum as a water steam mixture where water and steam are separated. Saturated steam leaves the drum and is forwarded to the superheater where it is exposed to the maximum heat exchange temperature of the hottest exhaust leaving the gas turbine. The heat exchange in an HRSG can take place on up to three pressure levels, depending on the desired amount of energy and exergy to be recovered. Today, steam generation at two or three pressure levels is most commonly used.” (11)

“HRSGs can be drum-type or once-through. While the former is currently more common, the latter is becoming popular due to their rapid start-up and better load-following characteristics. These steam generators can be natural or force circulation often used in horizontal and vertical configurations, respectively.” (6)

Figure 11: Heat Recovery Steam Generator (HRSG) (20)

With these basic components, the criticals are heat rejection system (air or water-cooled condenser or cooling tower) and balance of plant equipments.

Heat rejection system provides cooling the output flow of the steam turbine. This function can be fulfilled by using different methods.

"Three fundamentally different cooling configurations can be implemented in combined-cycle plants:

• Direct air cooling in an air-cooled condenser (alternatively indirect air cooling)

• Evaporative cooling with a wet or hybrid cooling tower

• Once-through water cooling using river water or seawater" (11)

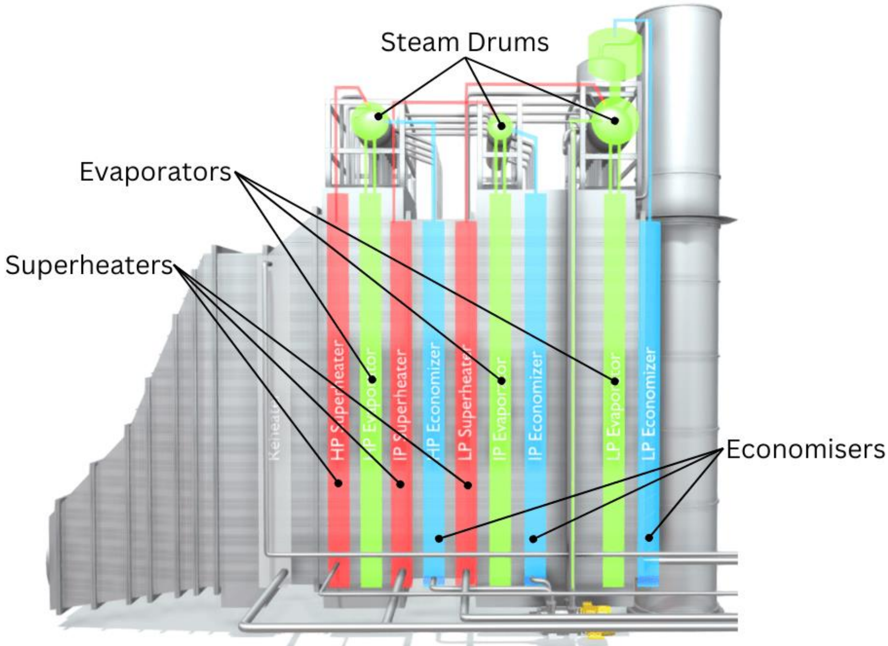

Figure 12: Components of Heat Recovery Steam Generator (21)

Balance of plant is the part that contains all the components which working with the basic parts required for the effective and efficient operation of the power plant.

"Balance of plant (BOP) considers electrical equipment, pipes and valves, condensate and feedwater pumps, tanks (water, distillate oil for backup, etc.), auxiliary boiler, fuel gas booster compressor (if necessary), fuel gas performance heater, makeup and wastewater treatment systems, miscellaneous pumps, compressors and heat exchangers." (15)

2.4 Istanbul (Ambarlı) Combined Cycle Power Plant

Ambarlı, in Avcılar, in the southwest of the Küçükçekmece Region approximately 30 km from Istanbul is one of the energy generation centers of Türkiye. There are two power plants that still in operation in the location.

The first one is Ambarlı Fuel Oil Thermic Plant that installed power (3 x 110 + 2 x 150) is 630 MW. The construction of the 1st and 2nd units started on July 17, 1964, and the first two units were put into service in February 1967, and the 3rd unit was put into service in August 1970. The 4th and 5th units of 150 MW were put into service in December 1970 and September 1971. Ambarlı Fuel Oil Thermic Plant, the largest energy production plant at the time it was established, provided approximately 46% of Turkey's total production. (22)

Figure 13: The Before Ambarlı Fuel Oil Thermic Plant (22)

The 4th and 5th units of the power plant were converted into a dual-fuel combined cycle power plant within the rehabilitation operation between 2008 and 2013, and their installed power was put into service to be increased from 300 MW to 816 MW. (23) (24)

Figure 14: Istanbul Natural Gas Combined Cycle Power Plant – B
(The Before Ambarlı Fuel-Oil Thermic Plant) (25)

The ÇED (Environmental Impact Assessment) Report was published in 2014 for the conversion of 1, 2 and 3^{rd} units into a dual-fuel combined cycle power plant, but any serious steps have not been taken yet since the specified date for the conversion of the power plant. (26)

After these studies, as of 2014, the management of the power plants was regulated and the names were changed and the before Ambarlı Fuel-Oil Thermic Plant, some of which part was converted to natural gas combine cycle with rehabilitation, was named "İstanbul Natural Gas Combined Cycle Power Plant – B".

Ambarlı Natural Gas Combined Cycle Power Plant, which was already established as a natural gas cycle power plant and has been operating since 1988, has since been named "İstanbul Natural Gas Combined Cycle Power Plant – A" as of the date mentioned above.

“İstanbul Natural Gas Combined Cycle Power Plant - A, whose first unit was commissioned on 1988 and the last unit on 1991, consists of three blocks. In each block; There are two gas turbines with a power of 138.8 MW and one steam turbine with a power of 172.7 MW. Total installed power is (3 x 450.3) = 1350.9 MW.”

“Since Istanbul CCPP-A and Istanbul CCPP-B had a serious water supply problem due to the drought in the summer months, the “Construction of Water Treatment System with Osmosis System” Project was carried out to provide treated water with from seawater between 2017 and 2019.” (27)

Figure 15: Istanbul Natural Gas Combined Cycle Power Plant – A (1990) (28)

Many problems were encountered since the technology of automation system of our power plant is from 1980s. Rehabilitation of DCS (Distrubution Control System) and Automation Project is carried out for the Power Plant – A between 2016 and 2019. (29)

“For the project of constructing new unit(s) with an installed capacity of 1800 MWe at the Istanbul Natural Gas Combined Cycle A Power Plant site, the necessity of preparing an

ÇED Report has become necessary. The final ÇED Report was submitted to Çevre, Şehircilik ve İklim Değişikliği Bakanlığı (Ministry of Environment, Urbanization and Climate Change) on 16.05.2022, and the ÇED positive certificate was received on 06.06.2022.” (30)

If the project is completed the efficiency of power plant is increases to 61% from 45% and 1800 MWe additional capacity will be available and when operates for 8,000 hours per year.

Figure 16: Istanbul Natural Gas Combined Cycle Power Plant – A (2023) (31)

3 Thermodynamics Disciplines in Power Plants

In this section, energy and exergy analysis of Istanbul CCPP – A is presented. For the equations to be given in this section, Yunus Çengel's Thermodynamics: An Engineering Approuch (32) book is referenced.

3.1 Power Plant Operation System

In this thesis, the acceptance data of Istanbul CCPP – A are used. The relevant data are not taken directly from the power plant. These data are taken from Tuğrul Başaran's article and comparisons and evaluations will be made according to these values.

Table 3: Gas Turbine Simple Cycle Acceptance Test Data

Operating Parameter	Value	Unit
Compression Ratio	10.8884	-
Compresssor Inlet Temperature	15.59	°C
Compresssor Inlet Pressure	1.0114	bar
Compressor Inlet Air Mass Flow	505.36	kg/s
Compressor Discharge Pressure	9.9	bar
Compressor Discharge Temperature	328.1	°C
Exhaust Mass Flow	514.38	kg/s
Turbine Inlet Temperature	1039.3	°C
Exhaust Temperature	535.5	°C
Gross Power	149.15	MW
Efficiency	33.46	%

Table 4: Gas Turbine Combined Cycle Acceptance Test Data

Operating Parameter	Value	Unit
Gross Power	146.09	MW
Efficiency	32.86	%
Turbine Inlet Temperature	1050	°C

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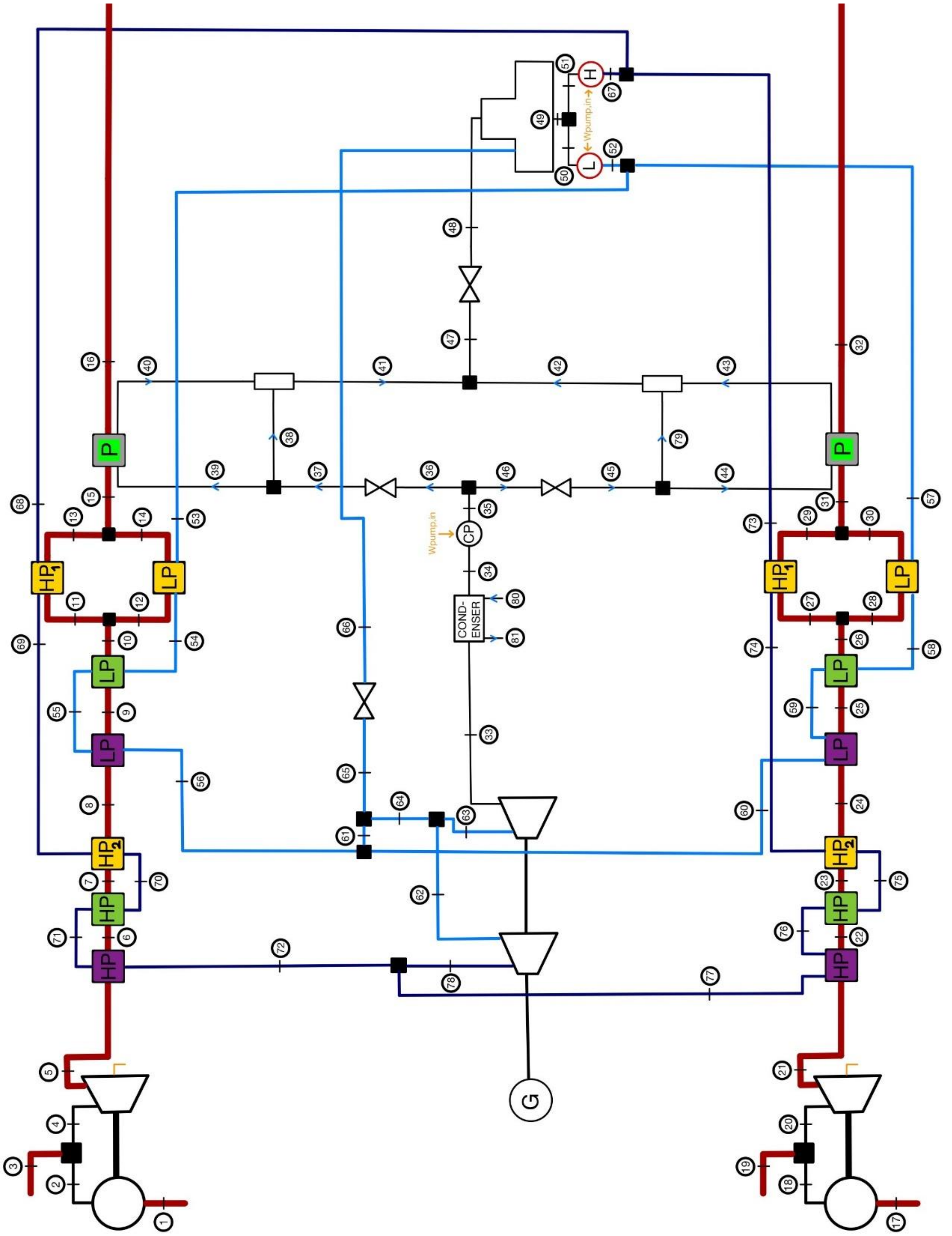

Figure 17: The Complete Model of the Ambarlı Power Plant

A flow chart of the system was drawn for necessary calculations and analyses. In the diagram, the input and output lines of the equipment are numbered and listed in (Figure 17).

Table 5: Points and Their Descriptions in Figure 17

Points	Description
1 and 17	Air inlet to the compressor
2 and 18	Air outlet from the compressor
3 and 19	Fuel inlet to Combustion Chamber
4 and 20	Gas Turbine Inlet
5 and 21	Gas Turbine Outlet
16 and 32	Gas Stack (Waste Gas)
78	Steam Inlet to High Pressure Steam Turbine
62	Steam Outlet from High Pressure Steam Turbine
63	Steam Inlet to Low Pressure Steam Turbine
33 and 34	Condenser Inlet and Outlet
80 and 81	Second Condenser Inlet and Outlet
35	Condensate Pump Outlet
48 and 49	Feed Water Heater Inlet and Outlet
50 and 52	Low Pressure Pump Inlet and Outlet
51 and 67	High Pressure Pump Inlet and Outlet
39 and 44	Preheater Inlet
40 and 43	Preheater Outlet
53 and 57	Low Pressure Water Inlet to Low Pressure Economizer
54 and 58	LP Steam Exiting the LP Economizer and Entering the LP Evaporator
55 and 59	LP Steam Exiting the LP Evaporator and Entering the LP Superheater
56 and 60	LP Steam Outlet from LP Superheater
68 and 73	HP Water Inlet to HP Economizer 1
69 and 74	HP Steam Exiting the HP Economizer 1 and Entering the HP Economizer 2
70 and 75	HP Steam Exiting the HP Economizer 2 and Entering the HP Evaporator
71 and 76	HP Steam Exiting the HP Evaporator and Entering the HP Superheater
72 and 77	HP Steam Outlet from LP Superheater

3.2 Brayton Cycle

3.2.1 Energy Analysis of Brayton Cycle

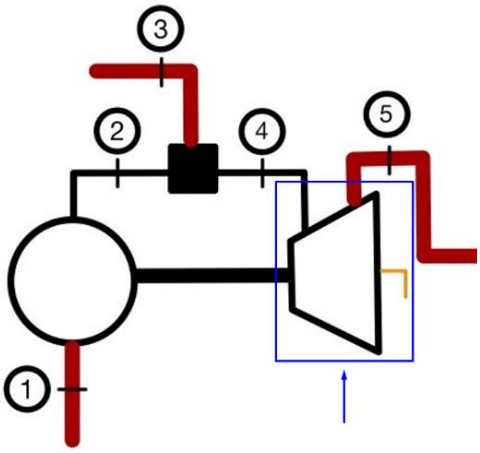

Figure 19: The Brayton Cycle Representation in Our Own Schematic

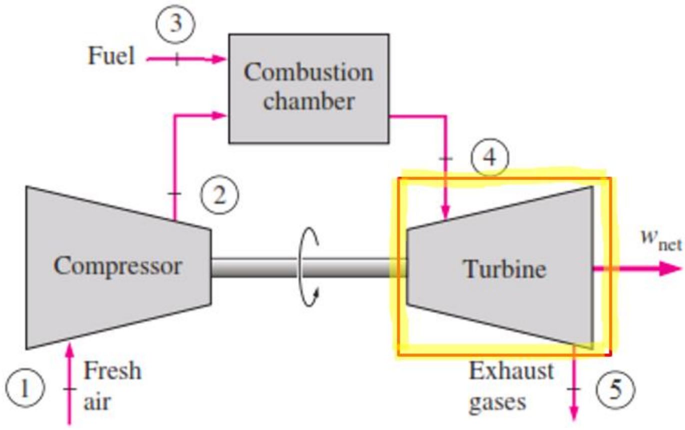

Figure 18: Thermodynamic Model of Gas Turbine Engine Cycle for Power Generation (40)

Energy analysis of a thermal power plant plays an important role in understanding, optimizing and improving the plant's energy conversion processes. Thanks to the energy analysis, the energy input and output of the gas turbine can be observed, and as a result of these observations, it is possible to detect beneficial or harmful situations for energy efficiency. In this way, energy losses can be minimized. In this section, the equations used to perform the energy analysis of Istanbul Combined Cycle Power Plant – A are presented.

The general energy and mass balance equations for gas turbines are as follows:

1. **Mass Balance**

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = \Delta\dot{m}_{system} \tag{1}$$

Since $\Delta\dot{m}_{system} = 0$

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{2}$$

2. **Energy Balance**

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} = \Delta\dot{E}_{system} \tag{3}$$

Since $\Delta\dot{E}_{system} = 0$;

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{4}$$

If the formula is explicitly written,

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \dot{m}_{in}\left(h_{in} + \frac{{V_{in}}^2}{2} + gz_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{m}_{out}\left(h_{out} + \frac{{V_{out}}^2}{2} + gz_{out}\right) \tag{5}$$

If potential and kinetic energies are neglected,

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \dot{m}_{in}\, h_{in} = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{m}_{out}\, h_{out} \tag{6}$$

For **compressors**, the energy balance, isentropic efficiency and pressure ratio are as follows:

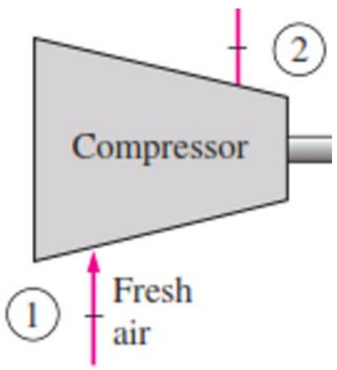

Figure 21: The Compressor Representation (40)

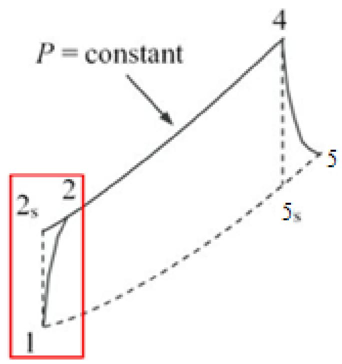

Figure 20: T-s Diagram of Actual Gas Turbine's Compressor Section (41)

1. **Energy Balance**

$$\dot{m}_{air}h_1 + \dot{W}_C = \dot{m}_{air}h_2 \tag{7}$$

$$\dot{W}_C = \dot{m}_{air}(h_2 - h_1) \tag{8}$$

2. **<u>Isentropic Efficiency</u>**

$$\eta_C = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \tag{9}$$

3. **<u>Pressure Ratio</u>**

$$r_p = \frac{P_2}{P_1} \tag{10}$$

For **turbines**, the energy balance and isentropic efficiency are as follows:

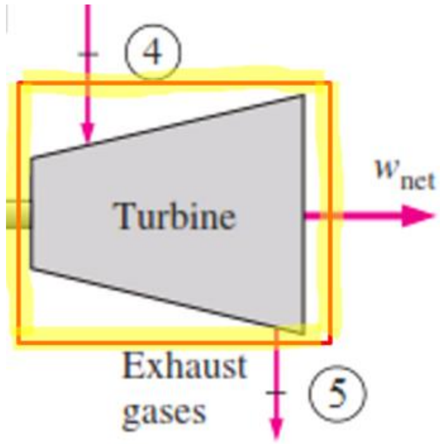

Figure 23: The Turbine Representation (40)

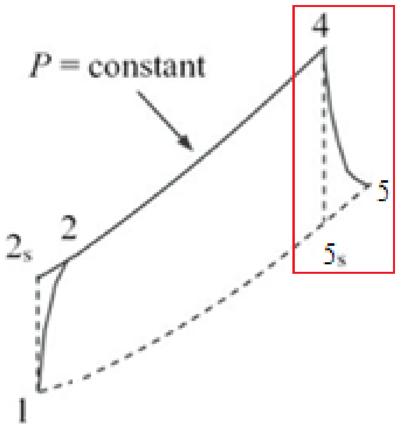

Figure 22: T-s diagram of Actual Gas Turbine's Turbine Section (41)

1. **<u>Energy Balance</u>**

$$\dot{m}_{air} h_4 = \dot{W}_T + \dot{m}_{air} h_5 \tag{11}$$

$$\dot{W}_T = \dot{m}_{air}(h_4 - h_5) \tag{12}$$

2. **<u>Isentropic Efficiency</u>**

$$\eta_T = \frac{w_a}{w_s} = \frac{h_4 - h_{5a}}{h_4 - h_{5s}} \tag{13}$$

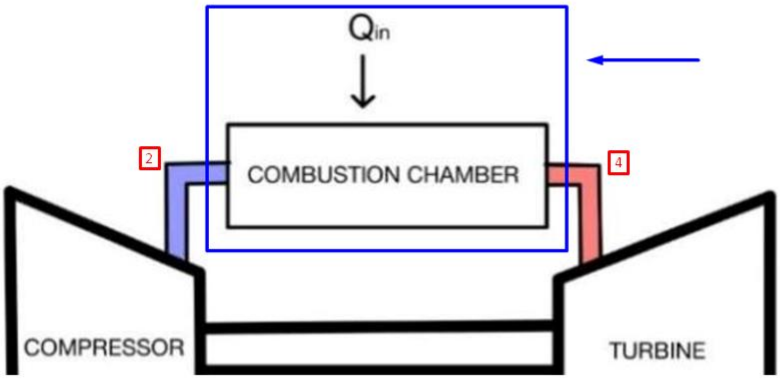

Figure 24: Combustor Chamber Representation (33)

For our system, the general energy balance equation for gas turbines are as follows,

Heat transfer rate in combustion chamber;

$$\dot{Q}_{in} = \dot{m}_4 h_4 - \dot{m}_2 h_2 \quad (14)$$

Here $\dot{m}_2$ is compressor outlet mass flow rate and $\dot{m}_4$ is turbine inlet mass flow rate. Definition of the net cycle work in MW unit.

$$\dot{W}_{net} = \dot{W}_T - \dot{W}_C \quad (15)$$

Cycle thermal efficiency is,

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \quad (16)$$

Back work ratio is

$$Bwr = \frac{\dot{W}_C}{\dot{W}_{GT}} \quad (17)$$

3.2.2 Exergy Analyses of Brayton Cycle

Another issue that is as important as how much energy is produced in thermal power plants is the availability and quality of the energy obtained. Therefore, it was found that it was necessary to perform an exergy analysis of the gas turbine. It is also very important in terms of the efficiency of energy conversion and transfer in the turbine. Examining and optimizing these energy conversion processes through exergy analysis will increase the efficiency of the turbine and have a positive impact on the efficiency of the entire cycle. The equations used in exergy analysis for Istanbul CCPP – A are given below.

For compressors, the exergy balance, exergy destruction and second isentropic efficiency are as follows:

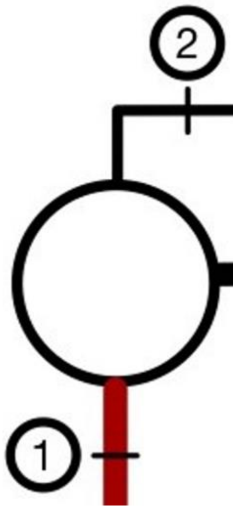

Figure 25: Compressor Representation Schematic of This Study

Exergy balance is

$$\dot{m}_a\psi_1 + \dot{W}_C = \dot{m}_a\psi_2 + \dot{X}_{dc,C} \tag{18}$$

Where ψ_1 is the compressor inlet flow exergy, ψ_2 is the compressor outlet flow exergy and $\dot{X}_{dc,C}$ is the exergy destruction in compressor.

$$\dot{X}_{dc,C} = \dot{W}_C - \dot{m}_a(\psi_1 - \psi_2) \tag{19}$$

Where $\dot{W}_C$ is the compressor power and change in exergy is,

$$\psi_1 - \psi_2 = c_{p,a}(T_2 - T_1) - T_0\left(c_{p,a}ln\frac{T_2}{T_1} - R_a ln\frac{P_2}{P_1}\right) \tag{20}$$

Where $c_{p,a}$ is the specific heat capacity of air and T_0 is the ambient temperature.

If the exergy destruction in the compressor is reorganized,

$$\dot{X}_{dc,C} = \dot{W}_C - \dot{m}_a\left[c_{p,a}(T_2 - T_1) - T_0\left(c_{p,a}ln\frac{T_2}{T_1} - R_a ln\frac{P_2}{P_1}\right)\right] \tag{21}$$

Second law efficiency of steady flow systems is,

$$\eta_{II} = \frac{obtained\ exergy}{expended\ exergy} \tag{22}$$

Second law efficiency of compressors is,

$$\eta_{II,comp} = \frac{\dot{W}_C - \dot{X}_{dc,C}}{\dot{W}_C} \tag{23}$$

For turbines, the exergy balance, exergy destruction and second isentropic efficiency are as follows:

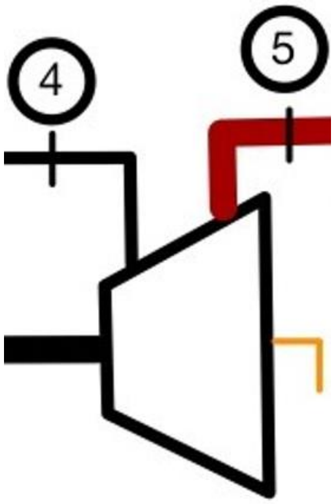

Figure 26: Turbine Representation Schematic of This Study

Exergy balance is,

$$\dot{m}_g\psi_4 = \dot{W}_T + \dot{m}_g\psi_5 + \dot{X}_{dc,T} \tag{24}$$

Where ψ_4 is the turbine inlet flow exergy, ψ_5 is the turbine outlet flow exergy and $\dot{X}_{dc,T}$ is the exergy destruction.

$$\dot{X}_{dc,T} = \dot{m}_g(\psi_4 - \psi_5) - \dot{W}_T \tag{25}$$

Where $\dot{W}_T$ is the turbine power and change in exergy is,

$$\psi_4 - \psi_5 = c_{p,g}(T_4 - T_5) - T_0\left(c_{p,g} ln\frac{T_4}{T_5} - R_g ln\frac{P_4}{P_5}\right) \tag{26}$$

Where $c_{p,g}$ is the specific heat capacity of the gas and T_0 is the ambient temperature.

If the exergy destruction in the turbine is re-organized,

$$\dot{X}_{dc,T} = \dot{m}_g \left[c_{p,g}(T_4 - T_5) - T_0 \left(c_{p,g} ln \frac{T_4}{T_5} - R_g ln \frac{P_4}{P_5} \right) \right] - \dot{W}_T \tag{27}$$

Second law efficiency of turbines is,

$$\eta_{II,turb} = \frac{\dot{W}_T}{\dot{W}_T + \dot{X}_{dc,T}} = \frac{\dot{W}_T}{\dot{m}_g(\psi_4 - \psi_5)} = \frac{\dot{m}_g(\psi_4 - \psi_5) - \dot{X}_{dc,T}}{\dot{m}_g(\psi_4 - \psi_5)} = 1 - \frac{\dot{X}_{dc,T}}{\dot{m}_g(\psi_4 - \psi_5)} \tag{28}$$

4 Simulation and Modelling

In this section, the modelling in engineering, modelling of power plant, simulation programs about power plant modelling will be mentioned. After that, the work done by our team, the models of the Istanbul Natural Gas Power Plant – A we made with two different software, and the comparison and evaluation of the values obtained as a result of these models with the design and actual data will be discussed.

At the beginning of this section, we would like to point out that throughout these studies, we have carried out these studies and made analyses using the power plant data provided to us by Dr. Tuğrul Başaran. We thank him for his contributions.

4.1 Introduction to Modelling

In engineering, design process of a vehicle, machine or more complex machine system or any kind of product has many complicated details and calculations. Engineers who from different engineering branches can work at the projects according to the level of complexity of the project. No matter how professional the engineers and employees working on the project are, they may make mistakes on the project due to internal and external factors. Therefore, before the production process, creating model of the project is important for less mistake products.

In addition, the modelling provides a cost-efficiency assessment for power plant process management.

"Furthermore, degraded component performance may affect quality. Costs for producing subquality product can be included in the analysis if a model can be determined for component degradation as a function of time, if quality can be modeled as a function of component performance, and if revenue can be modeled as a function of quality." (34)

"Costs for operation at a derated state can be included in the analysis if a model can be determined for component degradation as a function of time, if quality can be modeled as a function of component performance, and if revenue can be modeled as a function of quality." (35)

Modelling is an engineering method that creating a mathematical or computer-based or different scale physical representation of a system. This technique used for different purposes such as working process learning, observing mistakes on the systems and make design decisions. The modelling method is preferred, especially in high-cost engineering projects, to identify and solve the deficiencies and problems in the design of these incomplete systems by creating low-cost models before the production phase, through tests and trials carried out on these models.

There are many types of modelling in engineering world. Some main types of these are:

1. Physical Modelling: This model is based on the principle of designing and producing the desired model on a different scale and producing this model before the prototype.
2. Simulation Modelling: This model is based on a computer base simulation model that consists of identical or representative appearance of product and mathematical values.
3. Mathematical Modelling: The mathematical model is a representation of a physical or non-physical product by using mathematical equations, assumptions and calculations. The method is developed for to describe, analyse, and predict the behaviour of engineering systems in framework of mathematics. Mathematical models are widely used across various engineering disciplines for a range of purposes, including design, analysis, simulation, and optimization.

With all of these, another modelling types can be considered for different projects and engineering disciplines. However, it can be said that the modelling has significant role in the machine design and mechanical system design processes due to its advantages such as easy problem detection, faster problem solving and economical.

4.2 Modelling of Power Plant

Design and development of power plant are so complex, compelling, long-term and costly processes. The power plant structure has many different types of components such as turbine, compressor, heat exchanger, pump, condenser and has much more than electronic instruments within. Therefore, the possibility of mistake can be high and causes expensive cost when the physical models are developed. For these reasons, computer-based simulation models are developed for the power plant systems.

The power plant simulation programs are used for many different reasons such as:

Design: Creating virtual models of power plant, design of different configurations and define the errors and mistakes before construction

Performance: Observing of physical and chemical processes, assessing performance in different working conditions, analysing and comparing of the performance of actual and desired power and work with efficiency

With these reasons, the power plant models are developed for academical research and studies for advance to power plant industry. The energy and engineering academia use these models for their research and try to discover new concepts or increase the efficiency of these existing systems. All the factors mentioned above are beneficial in reducing and minimizing design and production costs and increasing the overall efficiency of energy investments.

There are many types of simulation software that used for power plant modelling. Some of these are:

- Aspen Plus & HYSYS
- Matlab Simulink
- Siemens Simcenter Amesim
- GE's GateCycle (Deprecated)
- DWSIM & DWSIM Pro
- CHEMCAD
- ProSim & ProSim Plus
- Coco Simulator
- Engineering Equation Solver (EES)

All of these programs have different advantages and disadvantages according to each other because of they are developed for different power systems like wind power plant, thermal plant or combined power plant etc.

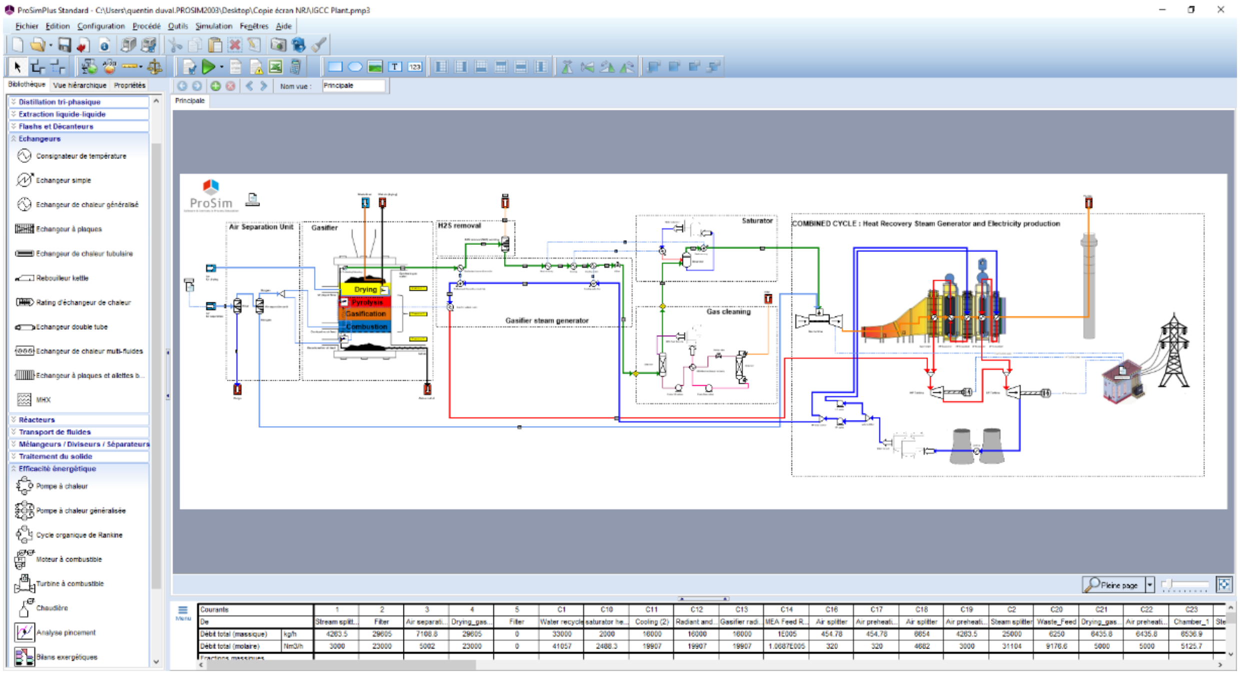

Figure 27: A Sample View Interface of ProSim Simulation Software (36)

4.3 Power Plant Simulation Model on DWSIM Software

The modelling of power plant and the softwares which using in this area is mentioned above section. Actually, many simulation models had been developed before this study however we want to advance these studies at one step. Many simulation models have been developed by paid and closed-source programs. Therefore, it was decided to use an unpaid and free-source program in order to see the abilities of these programs to simulate power plants and to observe the differences between other known programs in this study.

In this study, the DWSIM process simulator software is used for creating for simulation model of power plant.

4.3.1 DWSIM Software

DWSIM is an open-source process simulator that developed in framework of CAPE-OPEN Interface Standard that an industry standard developed for the simulation and design of chemical processes by providing integration and interaction between chemical processes and process simulation technologies.

“DWSIM features a high-quality graphical user interface (GUI), advanced thermodynamics calculations, reactions support and petroleum characterization / hypothetical component generation tools. DWSIM is able to simulate steady–state, vapor–liquid, vapor–liquid–liquid, solid–liquid and aqueous electrolyte equilibrium processes.” (37)

“At the same time the program serves many kinds of thermodynamic models such as SRK (Soave-Redlich-Kwong), Raoult’s Law, GERG-2008, Lee-Kesler, CoolProp, IAPWS-IF97 (Steam Tables), Peng-Robinson and its derivatives. In addition, the program consists of many kinds of operation units that using in thermodynamic processes such as turbine, compressor, heat exchanger, mixer, splitter, valve, reactor etc.” (38)

4.3.2 Simulation of Istanbul CCPP on DWSIM

Operation of the Istanbul Natural Gas Combined Cycle Power Plant – A, which has an installed capacity of 1350 MW, started in 1990. This power plant had such remarkable results in terms of efficiency that it earned the title of the world's most efficient combined cycle power plant in those years. Siemens AG produced steam turbines and gas turbines for this power plant.

In a block in the power plant, there are two heat recovery steam generators feeding one steam turbine, one steam turbine, one condenser and two gas turbines. Since there are three blocks with exactly the same elements as this block, as a result, there are six heat recovery steam generators, three steam turbines, three condensers and six gas turbines feeding a total of three steam turbines in the power plant. Apart from these, there are also many auxiliary elements such as valves, fittings and pumps.

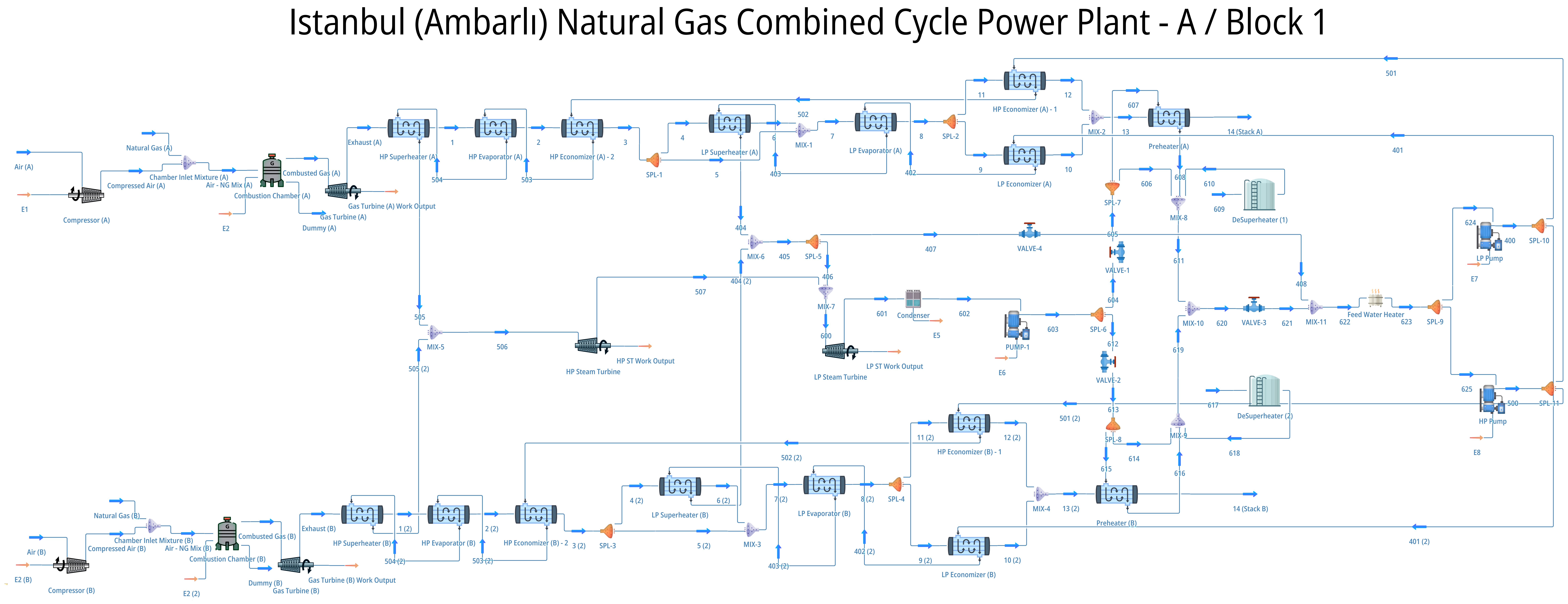

Figure 28: The Simulation of Istanbul CCPP – A in DWSIM

Figure 29: Istanbul CCPP – A, Siemens V94.2 Gas Turbines (39)

In this study, the simulation has been developed for just one block, so there are two gas turbines, compressors and HRSG systems and one steam turbine in the simulation. All necessary data has been provided from **Dr. Tuğrul Başaran** who made his degree of master's thesis on the performance analysis of the power plant to realize the performance analysis and to compare the design, actual and result values of simulation with each other.

GateCycle software had been used in the Tuğrul Başaran's study. GateCycle is very effective, compact and professional simulation program that developed by General Electric that well-known global energy company.

In this study, DWSIM has been used for creating of a simulation model as mentioned before. The thermodynamic models have been selected as IAPWS-IF97 (Steam Tables) for steam turbine and cooling water system (water-vapor) and Peng Robinson (PR) for gas turbine and HRSG system (natural gas and exhaust). The input values of each component are determined and apply on the simulation model.

After all of the system had been completed, heat, temperature, mass flow and other parameters were optimized and try to determine possible errors and mistakes. In the next step, the low possible result values were examined and the design or actual data were implemented when it is necessary. Hereby the calibration of the simulation of power plant was realized.

"In order to achieve a successful and complete plant model, every component has been modeled, customized and connected to each other. Using actual plant specific component design data the local heat and mass balance equations have been solved foreach component. Every system component in the model should be in mass and energy balance. Otherwise, the analysis would not converge. Therefore, great effort has been spent to model the power plant. Once a comprehensive model that includes all components down to small pumps has been constructed, the overall heat and mass balance equations have been solved to calculate the overall power plant performance." (39)

Along the developing of simulation, the compressor and combustion chamber systems were simulated, the gas turbine was integrated this system after that the HRSG system was created, respectively. The same steps had been done for second gas turbine system and lastly the steam turbine and cooling systems were simulated on the model. While the simulation was developing, the flow order and process steps were taken into account for each step.

4.3.3 Analysis of the Simulation Model

When the power plant model is building, a heterogeneous dataset is created for simulation model by using the simulation values of GateCycle and acceptance data that obtained from power plant's related department. In this way, it is aimed to create a model that more precise and closer than to ideal. The data has been obtained from the Tuğrul Başaran's thesis.

In the gas turbine section (Figure 30: The Gas Turbine Section), the properties of inlet air, natural gas and combustion chamber output temperature are entered as same as the GateCycle values because of the structure of the DWSIM software. Many properties are similar to the GC results and factory acceptance data such as mass flow rate, pressure. However, the compressor outlet temperature is 268.658 °C that has 50-60 °C lower than the GC and acceptance data. The combustion chamber outlet temperature is 1090 °C. According to many times of manual tests on the software, it was concluded that this situation provides to more efficient turbine work and more optimized turbine outlet temperature. The result of these test, the gas turbine generates ideally 190,21 MW net power that more than the value of 146,5 MW in the GC results. (39) This value is 148,261 MW in design performance table. (39) Naturally, this situation is related about the difference between ideal and actual cases.

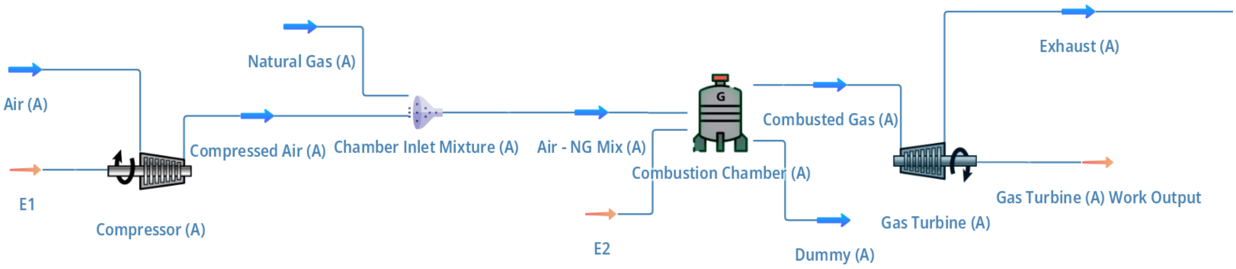

Figure 30: The Gas Turbine Section

If it is needed to mention that the Gas Turbine (B), the turbine is more efficient than the Gas Turbine (A). The work output and the output temperature are bigger than according to Gas Turbine (A)'s values. The Gas Turbine (B) contributes to steam turbine because of the high output temperature.

In the HRSG section (Figure 31), the exhaust and the stack properties are so similar to GC results. However, some minor differences occur in intermediate stages. There are negative temperature differences of 2-10 °C at the exhaust outputs of the superheaters, evaporators and economizers according to GC. The exhaust stack of HRSG (A) is 90,26 °C in the DWSIM software, this value was 99,06 °C in the GC. However, there are no big difference on HRSG (B). When look at the water and steam flow, there are obvious pressure differences of 14-16% for both low- and high-pressure flows. If a comparison is made between the two software results, it is agreed that the DWSIM results are more precise according to GC for HRSG section.

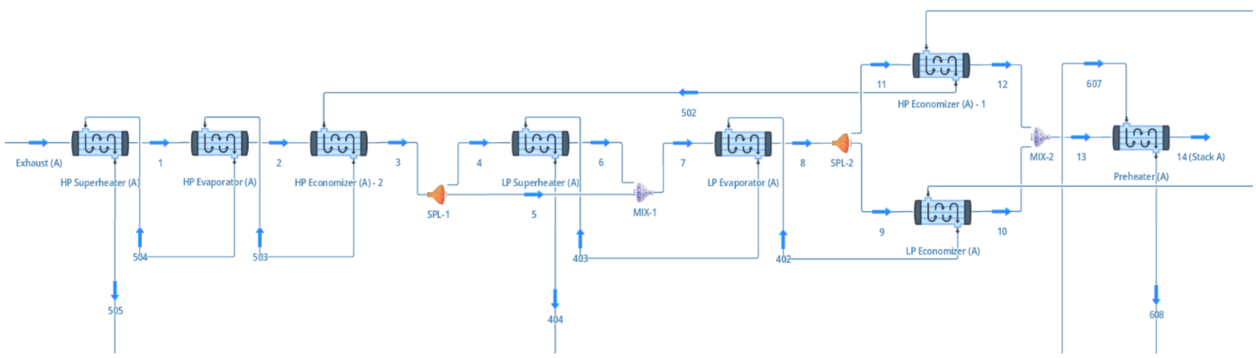

Figure 31: The HRSG Section

In the steam turbine section (Figure 32), the initial values are entered according to GC and acceptance data however the output values are different from the GC. The output temperature of high-pressure section of steam turbine is 193,91 °C in the DWSIM, this value was 208,39 °C in the GC. This case effects the LP steam performance because of the outlet steam is joined to the inlet flow that comes from the LP Superheater. Therefore, the inlet temperature of the LP steam turbine is lower than according to GC. The result of these test, the steam turbine generates ideally 186,4 MW net power that more than the value of 171,685 MW in the GC results. This value is 175,16 MW in design performance table. (39)

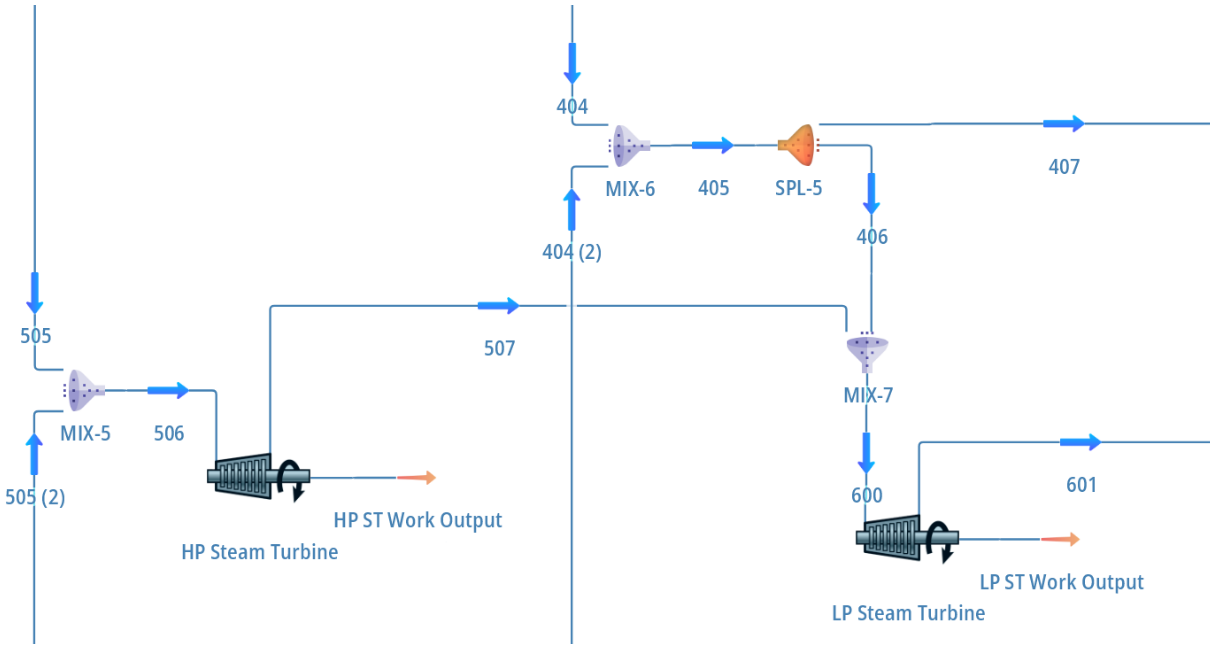

Figure 32: The Steam Turbine Section

In the feed water system (Figure 33), the outlet temperature value is entered for condenser, the pressure value and molar fraction are equal to GC values however the mass flow, which is increasing according to GC, remains constant according to DWSIM. This difference is removed using by "Sea Water" and "Desuperheater Tank" in the DWSIM so the flows are joined in "MIX-10" the mass flow values are equal each other for both DWSIM and GC. There is a big temperature difference for flow "408". In DWSIM, the temperature of this flow is 231,26 °C and its phase is vapor although its phase is liquid in GC. Despite of these differences, the properties of output flow of feed water heater match correctly. The pump's total power spend is 0,93 MW. This value is accepted zero on the GC. The condenser duty is 312,842 MW on the GC. The value is 299,95 MW on the DWSIM.

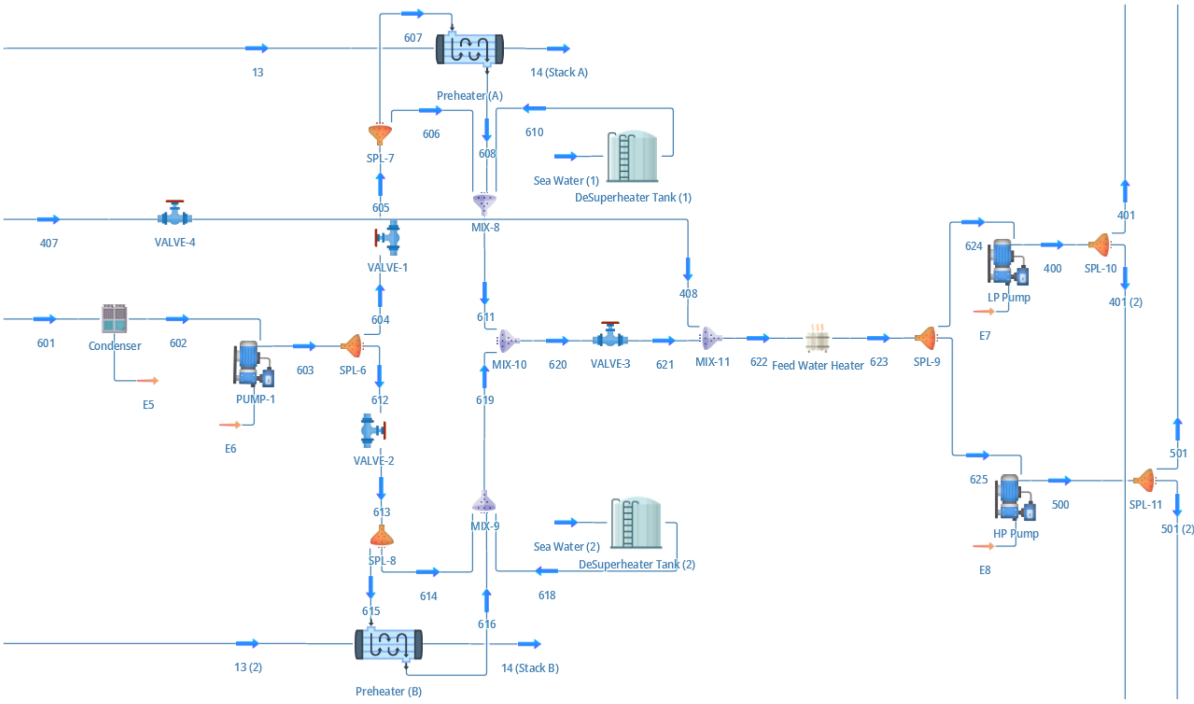

Figure 33: The Feed Water System

When the entire system is totally considered, the overall power plant power is 562,2 MW in DWSIM, 466,7 MW in GC and 471,56 MW in design acceptance data.

As a result of, the DWSIM is very effectively simulation program and help to demonstrate the before studies about power plant simulation. At the same time, it is very instructive for giving information about working principle of power plants and their components. Additionally, the ability to choosing different solution methods (property packages) and wide material options make powerful the program. However, there are some differences occurs according to GC results and it is predicted to the GC values are more accurate than the DWSIM results. In addition, the efficiency options of the components might not work effectively. However, this study is showed up the free-source simulation programs are so useful when using effectively and practically for creating power plant simulations.

5 Mathematical Model on EES

In this section, we will use the EES program to create a mathematical model of the gas turbines at Istanbul CCPP - A with the help of the thermodynamic equations presented in Chapter 3. Then, by iterating some values in the system, it will be observed how other values change and related graphs will be obtained. What these values are will be explained later.

5.1 Energy Analysis on EES Program

5.1.1 Codes of the Energy Analysis Equations of Brayton Cycle

The equations of the gas turbine cycle were written in EES (Engineering Equation Solver) and a mathematical model was created for energy analysis. EES codes of the mathematical model will be given in the appendix of the thesis. Here, screenshots and usage of the interface used in the program while writing these codes will be presented.

Function Information

When modeling a gas turbine, some values of the air are needed. Thanks to the Function Information section, these values were quickly obtained. For example, to find the enthalpy of the air, one property (Figure 35) is enough, while to find the pressure of the air, two properties (Figure 34) are needed. These were concluded by entering the acceptance data into the program.

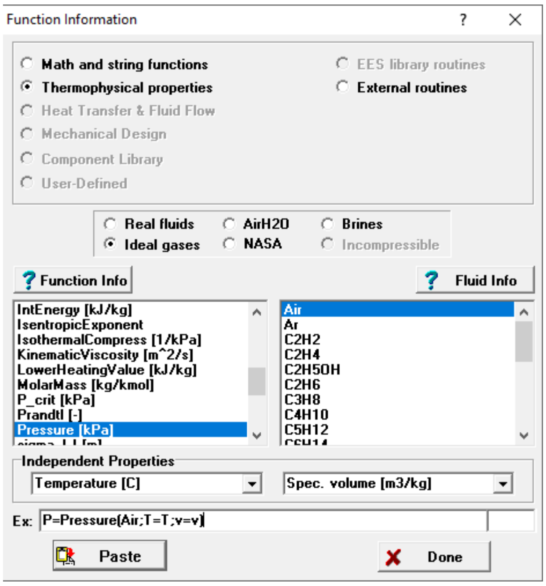

Figure 35: One Independent Property

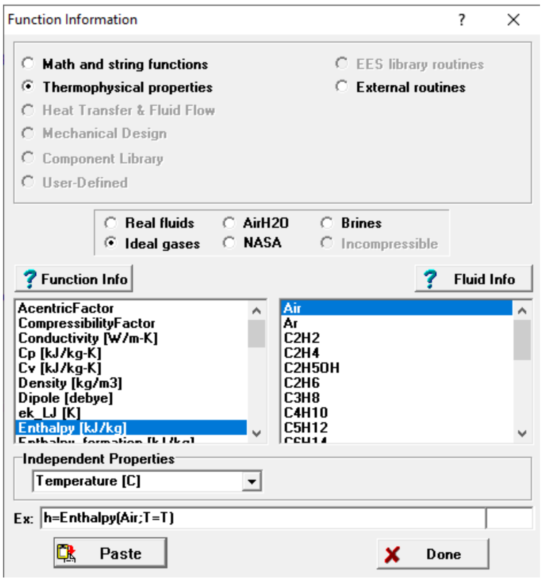

Figure 34: Two Independent Properties

Equation Window

Equations are written in this section. Next to the equations, comments related to that equation are indicated in blue. In addition, for iteration in the parametric table section, the isentropic efficiencies of the turbine and compressor are not written in the equations and are set as input, as shown in Appendix 1.

Parametric Table Window

A parametric table was created using the data from the Equation Screen. In this table, the isentropic efficiencies of the turbine and compressor were iterated and the following values were obtained:

- Compressor Output Temperature
- Compressor Input Power
- Turbine Output Temperature
- Turbine Output Power
- Cycle Efficiency
- Gross Power
- Back work Ratio

1..10	1 $\eta_{ise;C}$	2 T_2 [Celcius]	3 $\dot{W}_C$ [kW]	4 $\eta_{ise;GT}$	5 T_5 [Celcius]	6 $\dot{W}_{GT}$ [kW]	7 η_{th}	8 $\dot{W}_{net}$ [kW]	9 Bwr
Run 1	0,8			0,8					
Run 2	0,8111			0,8111					
Run 3	0,8222			0,8222					
Run 4	0,8333			0,8333					
Run 5	0,8444			0,8444					
Run 6	0,8556			0,8556					
Run 7	0,8667			0,8667					
Run 8	0,8778			0,8778					
Run 9	0,8889			0,8889					
Run 10	0,9			0,9					

Figure 36: Parametric Table of Energy Analysis

As shown in (Figure 37), the isentropic efficiencies of the compressor and turbine are set to be between 80 percent and 90 percent and the results according to these values are observed.

1..10	$\eta_{ise;C}$	T_2 [Celcius]	$\dot{W}_C$ [kW]	$\eta_{ise;GT}$	T_5 [Celcius]	$\dot{W}_{GT}$ [kW]	η_{th}	$\dot{W}_{net}$ [kW]	Bwr
Run 1	0,8	361	178994	0,8	568,3	287149	0,2699	108155	0,6233
Run 2	0,8111	356,4	176542	0,8111	561,4	290960	0,2838	114418	0,6068
Run 3	0,8222	351,9	174156	0,8222	554,6	294772	0,2974	120615	0,5908
Run 4	0,8333	347,6	171834	0,8333	547,8	298583	0,3108	126749	0,5755
Run 5	0,8444	343,3	169573	0,8444	541	302395	0,3239	132821	0,5608
Run 6	0,8556	339,2	167371	0,8556	534,1	306206	0,3367	138835	0,5466
Run 7	0,8667	335,2	165225	0,8667	527,2	310017	0,3494	144792	0,533
Run 8	0,8778	331,2	163134	0,8778	520,4	313829	0,3618	150695	0,5198
Run 9	0,8889	327,4	161095	0,8889	513,5	317640	0,374	156546	0,5072
Run 10	0,9	323,6	159106	0,9	506,6	321452	0,386	162346	0,495

Figure 37: Results After Start-Up

5.1.2 Graphs

<u>Plot Window (Results for isentropic efficiency between %80 and %90)</u>

In this section, graphs of the values obtained from the parametric table of energy analysis were created and the changes in the graphs were observed.

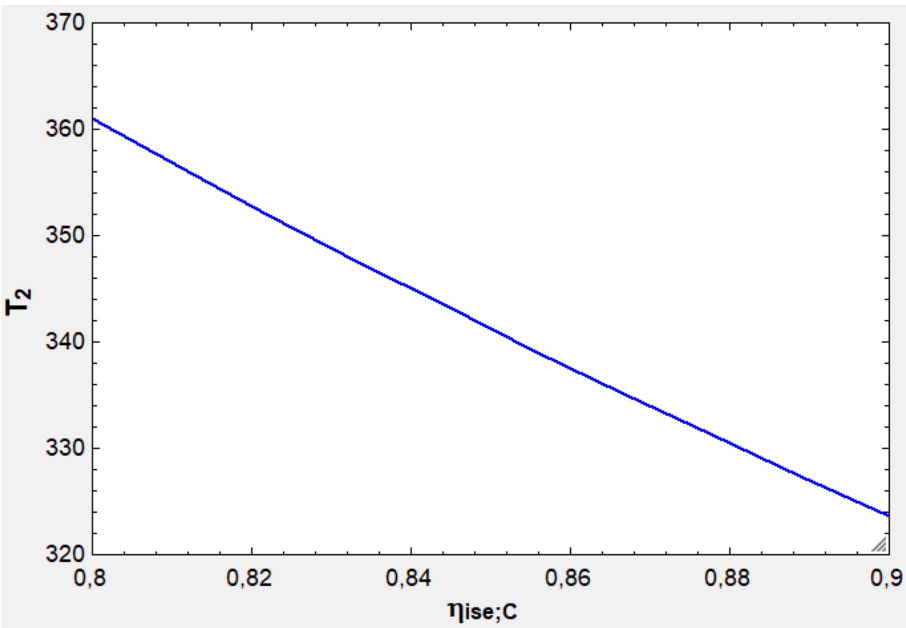

Figure 38: Isentropic Efficiency of Compressor vs Compressor Outlet Temperature

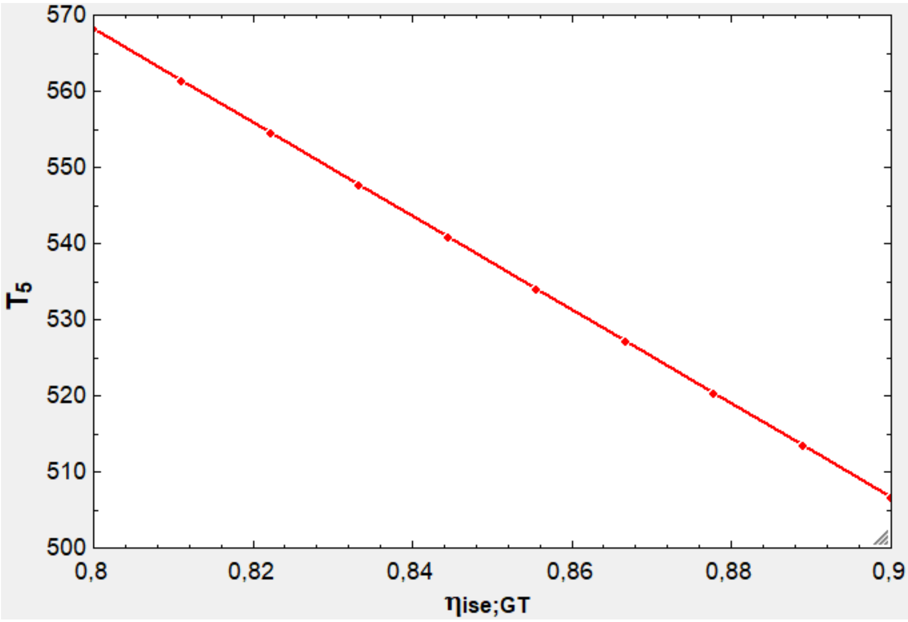

Figure 39: Isentropic Efficiency of Turbine vs Turbine Outlet Temperature

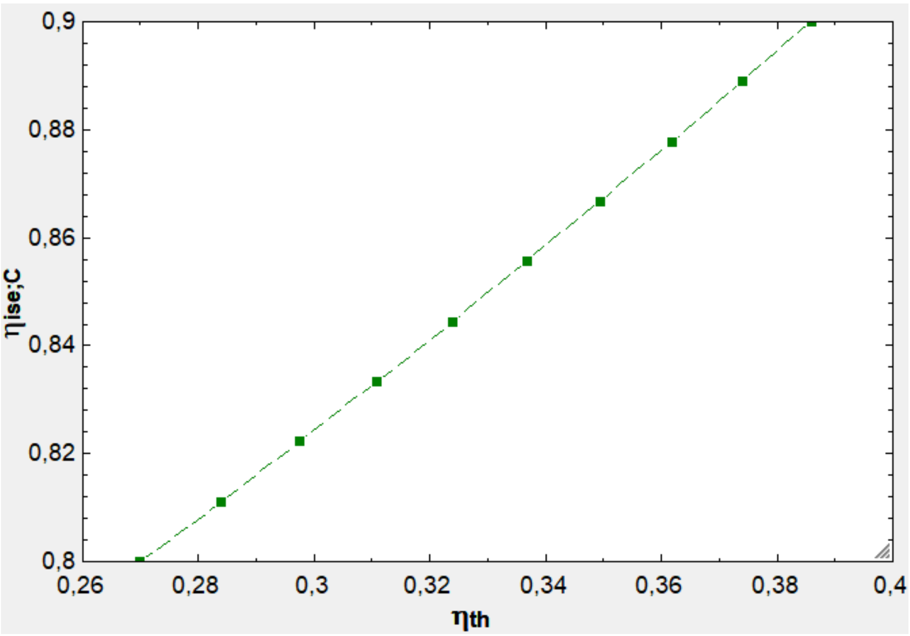

Figure 40: Isentropic Efficiency of Compressor vs Isentropic Efficiency of Cycle

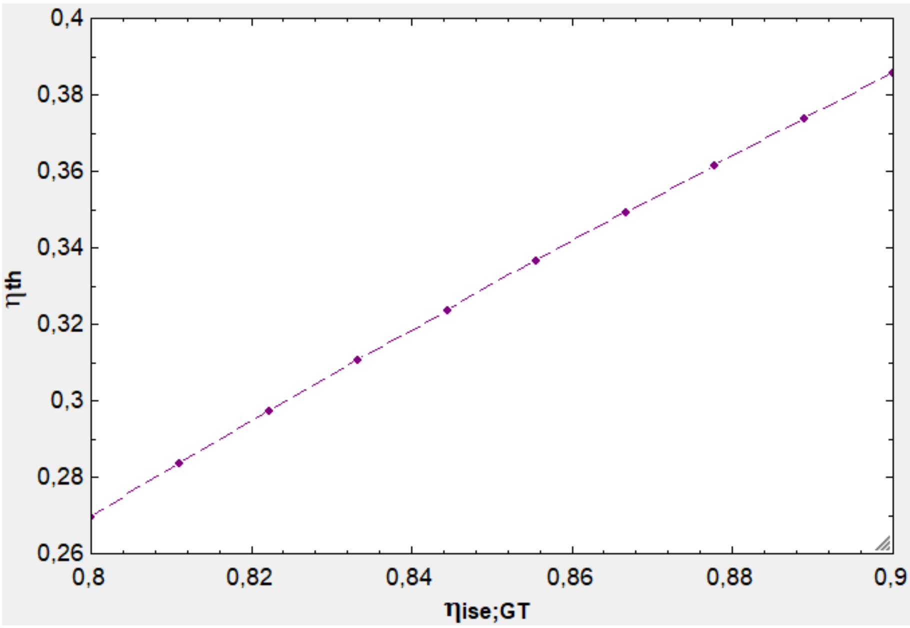

Figure 41: Isentropic Efficiency of Turbine vs Isentropic Efficiency of Cycle

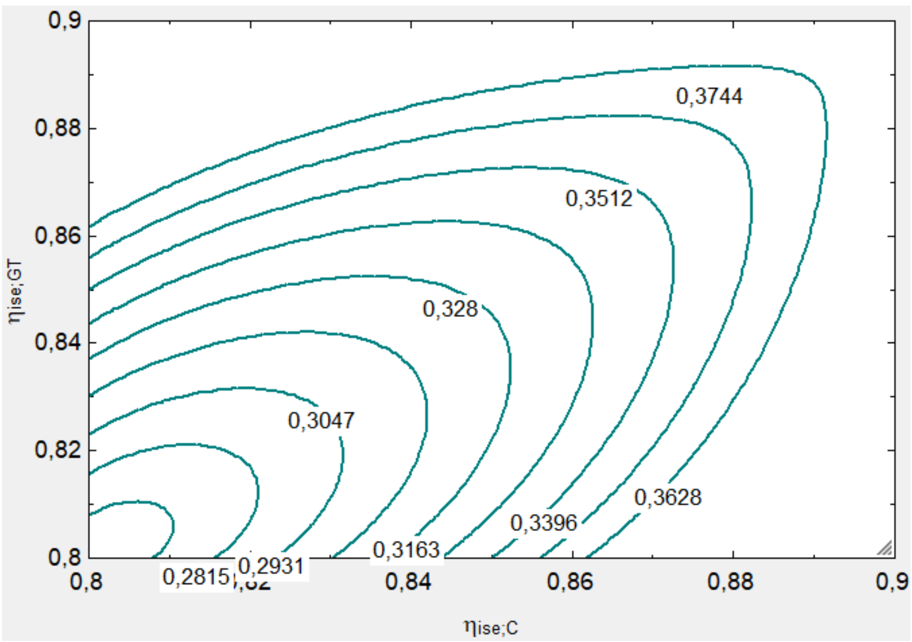

Figure 42: Isentropic Efficiency of Turbine vs Isentropic Efficiency of Compressor vs Isentropic Efficiency of Cycle

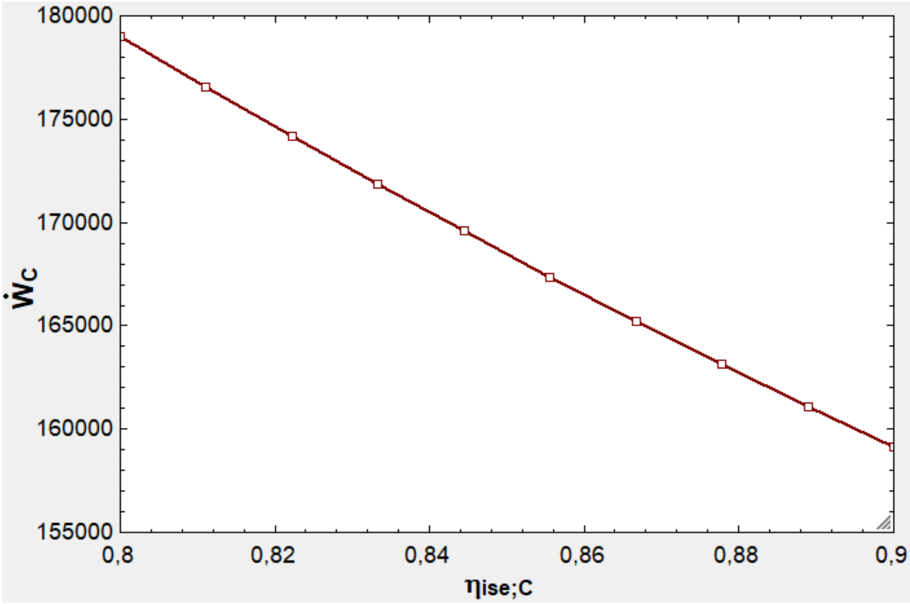

Figure 43: Isentropic Efficiency of Compressor vs Compressor Input Power

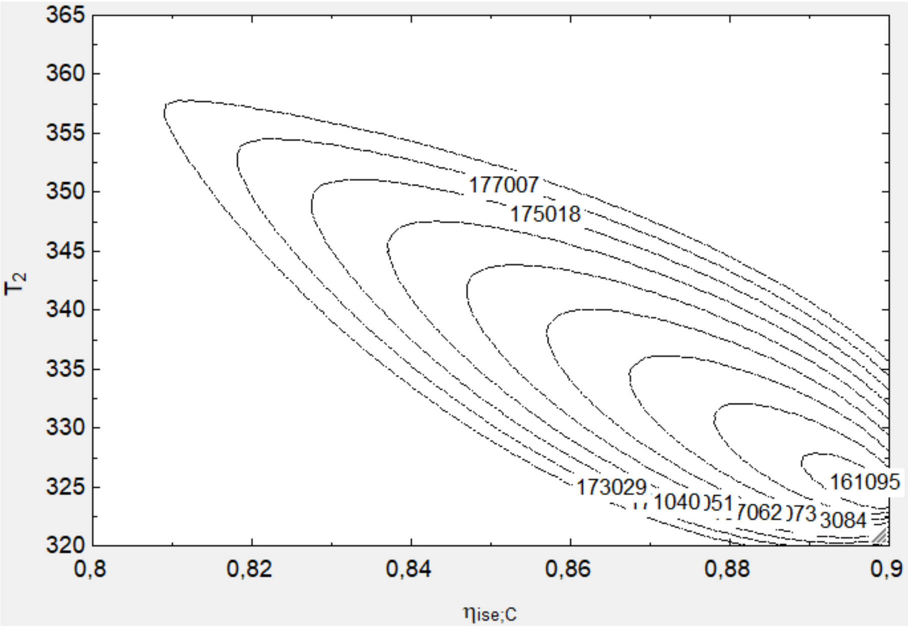

Figure 44: Compressor's Isentropic Efficiency vs Outlet Temperature vs Input Power

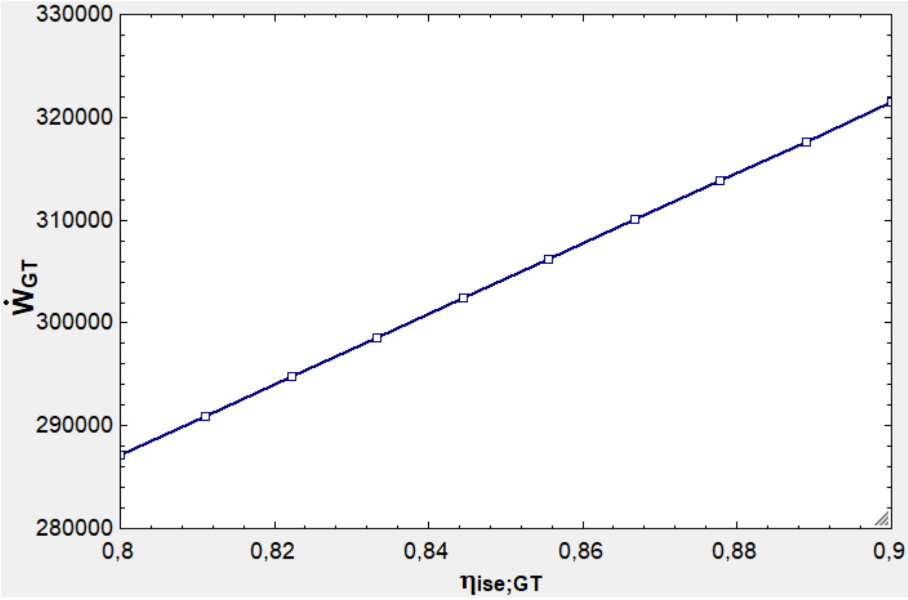

Figure 45: Isentropic Efficiency of Turbine vs Turbine Output Power

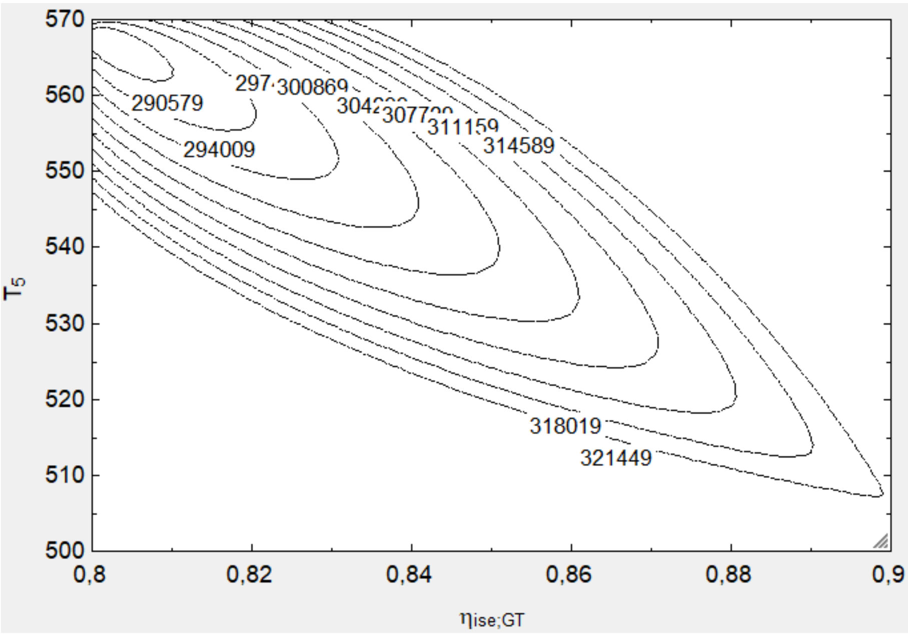

Figure 46: Turbine's Isentropic Efficiency vs Outlet Temperature vs Output Power

5.1.3 Results

Table 6: Gas Turbine Combined Cycle Acceptance Test Data of Ambarlı Power Plant (39)

Operating Parameter	Value	Unit
Compressor Outlet Temperature	328.1	°C
Turbine Outlet Temperature	535.5	°C
Cycle Efficiency	32.86	%
Gross Power	146.09	MW

In the parametric table the isentropic efficiencies of the compressor and turbine are iterated. Acceptance data were taken into account while performing these iterations. The first test range of 80 percent to 90 percent efficiency was examined and the range was narrowed for more accurate results. After many iteration trials, the values of the acceptance data in the following ranges were reached:

Compressor Isentropic Efficiency = between 0.88 and 0.89

Turbine Isentropic Efficiency = between 0.84 and 0.87

1..10	$\eta_{ise;C}$	T_2 [Celcius]	$\dot{W}_C$ [kW]	$\eta_{ise;GT}$	T_5 [Celcius]	$\dot{W}_{GT}$ [kW]	η_{th}	$\dot{W}_{net}$ [kW]	Bwr
Run 1	0,88	330,4	162722	0,84	543,7	300870	0,3313	138148	0,5408
Run 2	0,8811	330,1	162517	0,8433	541,6	302013	0,3344	139497	0,5381
Run 3	0,8822	329,7	162312	0,8467	539,6	303157	0,3375	140845	0,5354
Run 4	0,8833	329,3	162108	0,85	537,5	304300	0,3405	142192	0,5327
Run 5	0,8844	328,9	161904	0,8533	535,5	305444	0,3436	143540	0,5301
Run 6	0,8856	328,5	161701	0,8567	533,4	306587	0,3466	144886	0,5274
Run 7	0,8867	328,1	161498	0,86	531,4	307731	0,3497	146232	0,5248
Run 8	0,8878	327,8	161296	0,8633	529,3	308874	0,3527	147578	0,5222
Run 9	0,8889	327,4	161095	0,8667	527,2	310017	0,3558	148923	0,5196
Run 10	0,89	327	160893	0,87	525,2	311161	0,3588	150267	0,5171

Figure 47: The Results Obtained by Repeating Isentropic Efficiencies

The compressor input power required for the compressor outlet temperature of 328.1 °C is **161498 kW**

The turbine output power for the turbine inlet temperature of 535.5 °C is **305444 kW**

Net Power = Turbine Output Power - Compressor Input Power

Net Power = **305444 kW - 161498 kW = 143946 kW ≈ 143.95 MW**

$$\text{Error of Power} = \left|\frac{143.95 - 146.09}{146.09}\right| \times 100 = \mathbf{1.46}\ \%$$

The compressor isentropic efficiency that must be achieved is **88.67 %**.

The turbine isentropic efficiency that must be achieved is **85.33 %**.

Cycle efficiency was found to be approximately **34.67 %.**

$$\text{Error of Efficiency} = \left|\frac{0.3467 - 0.3286}{0.3286}\right| \times 100 = \mathbf{5.51}\ \%$$

Table 7: Comparison of EES results and acceptance data

Operating Parameter	Acceptance Data	EES	Error (%)
Compressor Outlet Temperature (°C)	328.1	328.1	0
Turbine Outlet Temperature (°C)	535.5	535.5	0
Cycle Efficiency (%)	32.86	34.67	5.51
Gross Power (MW)	146.09	143.95	1.46

All these results show that repetitions can be made for the desired values according to the needs of the thermal power plant and the results have high accuracy.

5.1.4 Analyses of the Result Graphs

In (Figure 38), it is observed that by increasing the isentropic efficiency of the compressor, the outlet temperature of the compressor decreases. Increasing isentropic efficiency allows the compressor to compress air more effectively. While air is compressed in the compressor, energy is lost. If the pressure increase is more effective, this energy loss decreases, resulting in a lower outlet temperature.

In (Figure 39), it is observed that by increasing the isentropic efficiency of the turbine, the outlet temperature of the turbine decreases. Increasing isentropic efficiency enables the gas in the turbine to be converted into mechanical energy more effectively. In this case, it is observed that the turbine exhaust temperature decreases, as the more effective conversion of mechanical energy means more use of heat in the turbine.

In (Figure 40), it is observed that as the isentropic efficiency of the compressor increases, the efficiency of the cycle also increases.

In (Figure 41), it is observed that as the isentropic efficiency of the turbine increases, the efficiency of the cycle also increases because the more efficient the turbine, the more power output increases. This means an increase in the efficiency of the cycle.

In (Figure 42), the effect of changing the isentropic efficiencies of the compressor and turbine on the overall efficiency of the cycle was examined. It has been observed that the overall efficiency of the cycle increases with the increase of both isentropic efficiency.

In (Figure 43), if the isentropic efficiency of the compressor increases, less input power must be supplied to the system. Therefore, as the isentropic efficiency of the compressor increases, the compressor input power decreases.

In (Figure 44), compressor input power values were observed by changing the isentropic efficiency of the compressor and the compressor outlet temperature.

In (Figure 45), it has been observed that as the isentropic efficiency of the turbine increases, the power output from the turbine increases.

In (Figure 46), Turbine output power values were observed by changing the isentropic efficiency of the turbine and the turbine outlet temperature.

5.2 Exergy Analysis

5.2.1 Codes of the Exergy Analysis Equations of Brayton Cycle

Since the EES program sections used in energy analysis are used here as well, interface images and functions are not included again. The codes can be achieved on Appendix 2. An important point should be mentioned here that the exergy destruction expression in the equations is stated as I, not $\dot{X}_{dc}$ in the equation in Chapter 3.

Parametric Table Window

A parametric table was created using the data from the Equation Screen. In this table, the pressure ratio of air and turbine inlet temperature were iterated and the following values were obtained:

- Exergy Destruction in Compressor
- Second Law Efficiency of Compressor
- Exergy Destruction in Turbine
- Second Law Efficiency of Turbine

1..10	1 P_{ratio}	2 I_C	3 $\eta_{II;C}$	4 T_4	5 I_T	6 $\eta_{II;T}$
Run 1	8			1400		
Run 2	9,333			1422		
Run 3	10,67			1444		
Run 4	12			1467		
Run 5	13,33			1489		
Run 6	14,67			1511		
Run 7	16			1533		
Run 8	17,33			1556		
Run 9	18,67			1578		
Run 10	20			1600		

Figure 48: Parametric Table of Exergy Analysis

As shown in (Figure 48), the pressure ratio of the air was set between 8 and 20 and the inlet temperature of the turbine was set between 1400 °C and 1600 °C and the first results were observed according to these values.

1..10	P_{ratio}	I_C	$\eta_{II;C}$	T_4	I_T	$\eta_{II;T}$
Run 1	8	22189	0,8626	1400	139083	0,6871
Run 2	9,333	21840	0,8648	1422	150444	0,67
Run 3	10,67	21538	0,8666	1444	161806	0,6537
Run 4	12	21272	0,8683	1467	173171	0,6382
Run 5	13,33	21034	0,8698	1489	184538	0,6234
Run 6	14,67	20818	0,8711	1511	195906	0,6092
Run 7	16	20621	0,8723	1533	207276	0,5957
Run 8	17,33	20440	0,8734	1556	218648	0,5828
Run 9	18,67	20273	0,8745	1578	230022	0,5704
Run 10	20	20117	0,8754	1600	241397	0,5586

Figure 49: Results After Start-Up

5.2.2 Graphs

Plot Window

(Results for P ratio between 8 and 20, for turbine inlet temperature between 1400 and 1600)

In this section, graphs of the values obtained from the parametric table of exergy analysis were created and the changes in the graphs were observed.

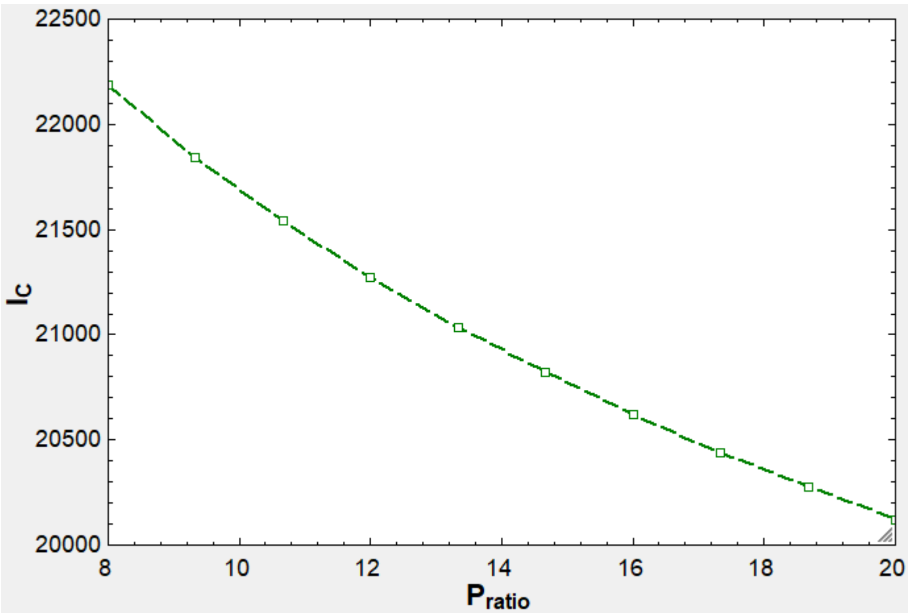

Figure 50: Pressure Ratio of Air vs Exergy Destruction in Compressor

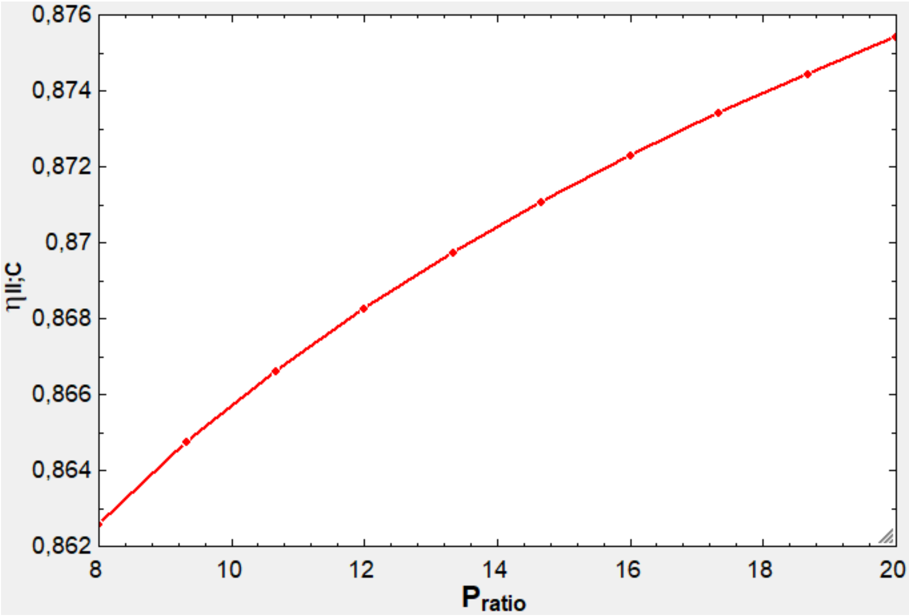

Figure 51: Pressure Ratio of Air vs Second Law Efficiency of Compressor

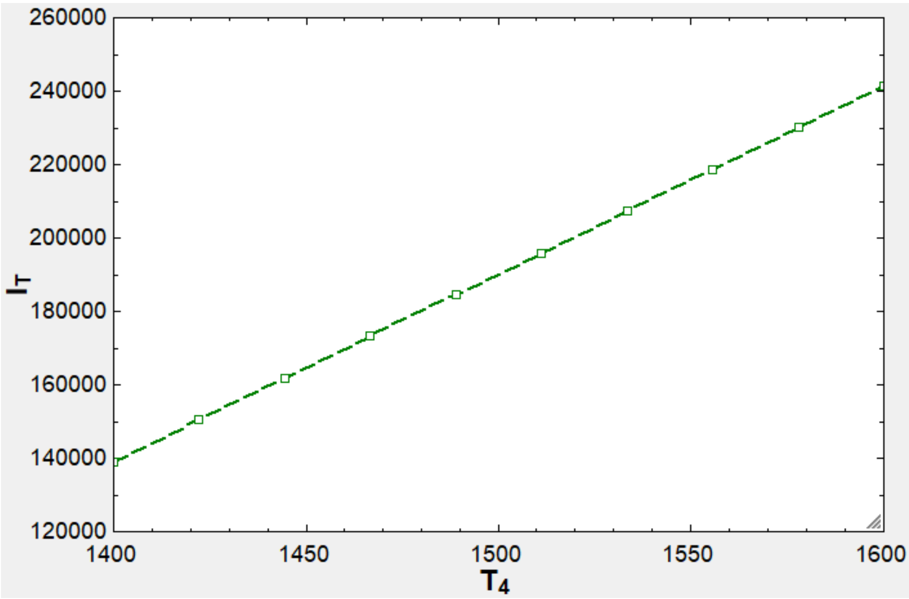

Figure 52: Turbine Inlet Temperature vs Exergy Destruction in Turbine

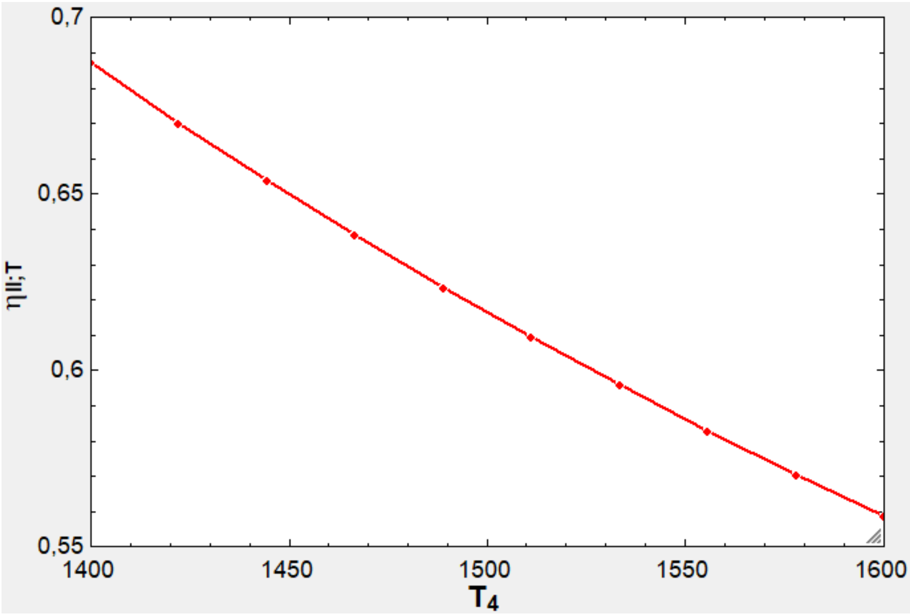

Figure 53: Turbine Inlet Temperature vs Second Law Efficiency of Turbine

5.2.3 Results

Table 8: Gas Turbine Combined Cycle Acceptance Test Data of Ambarlı Power Plant

Operating Parameter	Value	Unit
Pressure Ratio of Air	10.8884	-
Design Turbine Inlet Temperature	1221.298	°C

**For the design turbine inlet temperature value, the data obtained from Tuğrul Başaran's GateCycle program results were used.*

In the parametric table, the pressure ratio of the air and the inlet temperature of the turbine were iterated. Acceptance data was taken into account when performing these iterations. The test ranges in (Table 8: Gas Turbine Combined Cycle Acceptance Test Data of Ambarlı Power Plant) were examined and the range was narrowed for more accurate results. After a few iterations, the following ranges of the acceptance data were obtained:

Pressure Ratio of Air = between 10 and 11

Design Turbine Inlet Temperature = between 1210 – 1230

1..10	P_{ratio}	I_C [kW]	$\eta_{II;C}$	T_4 [Celcius]	I_T [kW]	$\eta_{II;T}$
Run 1	10	21684	0,8657	1210	42037	0,879
Run 2	10,11	21659	0,8659	1212	43171	0,8762
Run 3	10,22	21635	0,866	1214	44305	0,8733
Run 4	10,33	21610	0,8662	1217	45439	0,8705
Run 5	10,44	21586	0,8663	1219	46573	0,8677
Run 6	10,56	21562	0,8665	1221	47708	0,8649
Run 7	10,67	21538	0,8666	1223	48842	0,8621
Run 8	10,78	21515	0,8668	1226	49976	0,8594
Run 9	10,89	21492	0,8669	1228	51110	0,8567
Run 10	11	21469	0,8671	1230	52244	0,8539

Figure 54: The Results that obtained by repeating the pressure ratio of the air in the compressor and the turbine inlet temperature

When the pressure ratio of air is set to 10,89 and the exergy destruction and second law efficiency of compressor are as follows.

Table 9: The Results That Obtained According to The Acceptance Data of The Pressure Ratio of The Air

Pressure Ratio of Air	Exergy Destruction (kW)	Second Law Efficiency (%)
10,89	21492	86,69

When the turbine inlet temperature is set to 1221, the exergy destruction and second law efficiency of turbine are as follows.

Table 10: The Results That Obtained According to Acceptance Data of Design Turbine Inlet Temperature

Design Turbine Inlet Temperature (°C)	Exergy Destruction (kW)	Second Law Efficiency (%)
1221	47708	86,49

5.2.4 Analyses the Result Graphs

In (Figure 50), it is observed that as the pressure ratio of the air entering the compressor increases, the exergy destruction in the compressor decreases.

In (Figure 51), it is observed that the second law efficiency of the compressor increases as the pressure ratio of the air entering the compressor increases.

In (Figure 52), it is observed that as the turbine inlet temperature increases, the exergy destruction in the turbine increases.

In (Figure 53), it is observed that the second law efficiency of the compressor decreases as the turbine inlet temperature increases.

6 Cost Analysis of Simulation Results

The power and efficiency values of simulation results that developed on EES and DWSIM softwares are observed with other significant thermodynamic variables such as temperature, pressure, flow rate etc. until this analysis. In this section, the cost analysis will be realized about power plant simulation results.

The cost analysis will consist of natural consumption cost and electricity price values for each model results that developed on DWSIM and GateCycle. At the same time, these values will be compared with actual data of power plant.

This analysis will show that cost precision level between simulation programs and actual case. Additionally, this study shows that the reliability grade of the simulation programs about cost analysis of power plants.

"It has been assumed that average electricity whole sale price is 100 \$/MWh, and natural gas cost is 5 \$/GJ. It has been assumed that the power plant is operating 8000 hours per year at base load. These are typical current values." (39)

If these typical values are accepted, the cost of the natural gas is 18 \$/MWh.

Table 11: The Comparing Power Results of Simulations and Actual Case

	Actual Case (39)	GateCycle	DWSIM
Gross Power of per Block (MWh)	410,41	466,70	562,20
Gross Power of All Plant (MWh)	1231,23	1400,10	1686,60
Gross Power of All Plant (MWy)	$9{,}85 * 10^6$	$11{,}20 * 10^6$	$13{,}49 * 10^6$

Table 12: The Natural Gas Cost, Electricity Price and Net Cost According to Gross Power of All Power Plant per Year (Million $)

	Actual Case	GateCycle	DWSIM
Natural Gas Cost	-177,30	-201,60	-242,82
Electricity Price	+985	+1120	+1349
Net Cost	+807,70	+918,4	+1106,18

When examine the net cost values, it can be seen that there is a important error between the actual case and the simulation results. The minimum error corresponds to an annual deviation of 110.7 million dollars, or an error rate of 13.41%. The error value corresponds to a deviation of 298.48 million dollars in DWSIM, or in other words, an error rate of 36.95%, which is unacceptable.

Considering that DWSIM's component efficiencies are considered ideal, it can be easily decided that this data cannot be taken into account in any cost analysis. However, if taken into consideration that the GateCycle simulation values are very close to the acceptance data, it will be seen that the obtained data is not at all reliable and consistent for cost analysis because of the difference between the reference values and the actual case values. Therefore, for a consistent, precise and accurate cost analysis, it is necessary to take into account real situations including exergy destruction, real operation cases, degradation effects, fuel quality, etc.

7 Conclusion

In this study, it was aimed to develop a simulation of a combined cycle power plant by using open-source and high capability software and made a mathematical model of a gas turbine that consisted of the power plant by using Engineering Equation Solver (EES) software. The power plant on which simulation and modelling are based in this study is Istanbul Natural Gas Combined Cycle Power Plant – A.

It is well-established fact that electricity demand and consequently electricity supply are constantly increasing around the World. The renewable energy resources are getting popular last 20 years however the conventional energy resources still hold significant value for electricity supply. Especially, natural gas that among of the resources will be a major source of electricity generation in our country, Türkiye, both today and within the next 30 years according to studies and plans. Therefore, the studies on the natural gas and combined cycle power plants that using natural gas as source are important for development and advancement.

The simulation was created with an open-source program called DWSIM, which can simulate the results of chemical and physical processes of substances in many different phases and has the ability to optimize with different solution methods. After the determination of solution methods, materials and substances and creating of simulation model, the results were observed and compared another simulation study that done on same power plant. Simulation results for each section of power plant, including gas turbine, steam turbine, HRSG, feed water system, were examined in itself and then analysed as a whole system.

The result of DWSIM simulation shows that the compression, combustion and turbine sections have various differences between DWSIM, GateCycle and design values, especially compression part. The power generation is another important factor for analyses of these programs and DWSIM results are more ideal than the GC and design value. The same situation is valid for steam turbine section. When examined the HRSG section, properties of each output of the heat exchangers, the DWSIM results are more consistent and precise than the GC values. There is not any information about these outputs for design values. Additionally, the final exhaust gas (stack) in DWSIM is cooler than according to GC.

These analyses show the free-source simulation programs are so useful when create simulation models of power plants. However, the efficiency options for components in DWSIM are not working optimally. Therefore, the paid and closed-source simulation programs show more closer to design values and more consistent and logical results than free-source programs at naturally. Nonetheless, this study highlights that free-source simulation programs can be extremely useful for creating power plant simulations when used effectively and practically.

A mathematical model of the energy and exergy analysis of Istanbul CCPP – A was derived. This mathematical model was prepared using the EES program. Then, the parametric tables of the mathematical model were extracted. Considering the acceptance data in these parametric tables, it was observed how other variables in the system changed by iterating some data. As a result of the parametric analysis, it was observed that the model was very similar to the actual data of the power plant and had an error rate of only 1.46% in determining the net power of the gas turbine. This showed that the model is a reliable mathematical model to be used for retrofitting the turbines or regulating their operating conditions. In addition, the data obtained from the parametric table were plotted and the changes were observed.

The fact that the graphs obtained from the parametric tables support the thermodynamic equations and are compatible with these equations can be said as an indicator of the accuracy of the graphs.

The main important conclusions drawn from the parametric tables and graphs are:

- ✓ If the isentropic efficiency of a gas turbine is increased, the turbine output power increases and accordingly the turbine exhaust temperature decreases. In addition, increasing the isentropic efficiency causes the entire cycle efficiency to increase.
- ✓ If we increase the temperature of the flow entering the turbine, this will cause the exergy destruction in the turbine to increase and observed that the second law efficiency decreases.
- ✓ These findings are guiding in terms of improving and optimizing the turbine and detecting possible damage situations.
- ✓ Thanks to the prepared EES program, power plant conditions can be rearranged according to the desired turbine values and a general improvement can be seen thanks to these regulations.

8 References

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9 Appendix


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```
" ******************** GAS TURBINE (BRAYTON CYCLE) ********************* "

"ACCEPTANCE DATAS"
"Eta_ise_GT=input"   " Isentropic efficiency of Gas Turbine "
"Eta_ise_C=input"    " Isentropic efficiency of Compressor "
P_ratio=10,8884
m_dot_air=505,36
m_dot_2=m_dot_air
m_dot_4=514,38
m_dot_5=514,38
P_1=1,0114
T_1=15,59
T_4=1039,3


"Point 1"
h_1=enthalpy(Air;T=T_1)
s_1=entropy(Air;P=P_1;T=T_1)
s_s_2=s_1   "For the ideal case the entropies are constant across the compressor"


"Point 2"
P_ratio=P_2/P_1
T_s_2=temperature(Air;s=s_s_2;P=P_2)
h_s_2=enthalpy(Air;T=T_s_2)

Eta_ise_C=(h_s_2-h_1)/(h_2-h_1)   "Compressor adiabatic efficiency; Eta_c = W_dot_c_ideal/W_dot_c_actual."

T_2=temperature(Air;h=h_2)

m_dot_air*h_1+W_dot_C=m_dot_air*h_2  "SSSF First Law for the actual compressor, assuming: adiabatic, ke=pe=0"   "Steady State Steady Flow (SSSF)"


"Point 4"
P_4=P_2  "process 2-4 is SSSF constant pressure"
h_4=enthalpy(Air;T=T_4)
s_4=entropy(Air;T=T_4;P=P_4)
s_s_5=s_4  "For the ideal case the entropies are constant across the turbine"


"Point 5"
P_ratio=P_4/P_5
T_s_5=temperature(Air;s=s_s_5;P=P_5)  "Ts[4] is the isentropic value of T[4] at turbine exit"
h_s_5=enthalpy(Air;T=T_s_5)   "Eta_t = W_dot_t /Wts_dot turbine adiabatic efficiency, Wts_dot > W_dot_t"

h_5=h_4-Eta_ise_GT*(h_4-h_s_5)


T_5=temperature(Air;h=h_5)

m_dot_4*h_4=W_dot_GT+m_dot_air*h_5   "SSSF First Law for the actual turbine, assuming: adiabatic, ke=pe=0"


"Cycle analysis"

Q_dot_in=m_dot_4*h_4-m_dot_2*h_2

W_dot_net=W_dot_GT-W_dot_C   "Definition of the net cycle work, MW"

Eta_th=W_dot_net/Q_dot_in  "Cycle thermal efficiency"

Bwr=W_dot_C/W_dot_GT   "Back work ratio"


"Ideal expansion power in the Turbine A"
Power_ideal_GT=h_4-h_s_5

"Actual expansion power in the Turbine A"
Power_actual_GT=h_4-h_5
```

Appendix 1: Screenshot of the Section Where the Codes are Written

```
" For Compressor Acceptance Datas "

c_pa=1,005
T_0=15,59
R_a=0,287
T_2=328,1
T_1=15,59
m_dot_air=505,4
W_dot_C=161498
"P_ratio=10,8884"

" Exergy Destruction (I_C) = Irreversibility "

I_C=W_dot_C-m_dot_air*(c_pa*(T_2-T_1)-T_0*(c_pa*ln(T_2/T_1)-R_a*ln(P_ratio)))

" Exergy Efficiency of Comprressor "

ETA_II_C=(W_dot_C-I_C)/W_dot_C


" For Turbin Acceptance Datas "

c_pg=1,005
R_g=0,287
"T_4=1039,3"
T_5=535,5
m_dot_gas=514,38
W_dot_T=305444
P_4=1069,03
P_5=103,81

" Tubine Exergy Destruction (I_T) "

I_T=m_dot_gas*(c_pg*(T_4-T_5)-T_0*(c_pg*ln(T_4/T_5)-R_g*ln(P_4/P_5)))-W_dot_T


" Exergy Efficiency of Turbine "

ETA_II_T=(W_dot_T)/(W_dot_T+I_T)
```

Appendix 2: Screenshot of the Section Where the Codes are Written