ENERGY NETWORK OPTIMIZATION OF AN OIL REFINERY

by

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,
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ABSTRACT

Energy consumption is a critical factor in refinery operations, having a significant impact on production costs. The effective management of the energy system in the refinery can improve the economic performance significantly.

Energy demand in refineries does not stay constant due to change in crude oil properties, operation conditions of process units and cost of fuels. TUPRAS Izmit Refinery operates a complex utility system to satisfy its energy demand in the form of steam and electricity. The design of the utility plants allows multiple operational configurations to secure the continuity and flexibility of refinery processes in different operating conditions.

The main objective of the work is developing a decision support system to manage the complex energy network of the refinery by determining the optimum operational combinations of the equipment for achieving a global minimum in terms of energy costs. In the scope of the work, first of all, the steam and power production equipment in the refinery are analyzed, thermodynamically to determine the variables which have an impact on the equipment efficiency. The determined variables are evaluated by regression analysis and the efficiency models of the equipment are developed. In the second part of the work, the optimization problem is formulated as mixed integer linear programming model. The model contains all operational constraints, efficiency models, mass balances, operational status of the equipment and demand satisfaction constraints of the refinery.

The developed approach is analyzed and tested with a real case of the refinery. MILP model scenarios are solved by using GAMS CPLEX solver. In scenario analysis, the economic impact of optimization is evaluated by comparing the optimal solutions with online refinery operations. As a result, up to 3.5 % cost reduction is achieved without making an investment.

ÖZET

Üretim maliyetleri üzerinde önemli bir paya sahip olan enerji, rafineri operasyonları için kritik bir faktördür. Rafinerideki enerji sisteminin etkin yönetimi, ekonomik performansı önemli ölçüde arttırma potansiyeline sahiptir.

Rafinerilerdeki enerji talebi, ham petrol özelliklerinde, proses ünitelerinin çalışma koşullarında ve yakıt maliyetlerinde meydana gelen değişimlerden dolayı sabit kalmamaktadır. TÜPRAŞ İzmit Rafinerisi, enerji talebini buhar ve elektrik şeklinde karşılamak için 3 tane yardımcı tesis işletmektedir. Yardımcı tesislerinin tasarımı, farklı çalışma koşullarında rafineri proseslerinin sürekliliğini ve esnekliğini güvence altına almak için çoklu işletme konfigürasyonlarına olanak tanımaktadır.

Çalışmanın temel amacı, enerji maliyetleri açısından global minimuma ulaşmak için ekipmanın optimum işletme kombinasyonlarını belirleyerek rafinerinin karmaşık enerji ağını yönetecek bir karar destek sistemi geliştirmektir. Çalışma kapsamında öncelikle rafinerideki buhar ve güç üretim ekipmanları, termodinamik olarak analiz edilerek ekipman verimliliği üzerinde etkili olan değişkenler belirlenmiştir. Belirlenen değişkenler regresyon analizi ile değerlendirilmiş ve ekipmanın verimlilik modelleri geliştirilmiştir. Çalışmanın ikinci bölümünde optimizasyon problemi karışık tam sayılı doğrusal programlama modeli ile formüle edilmiştir. Model, tüm operasyonel kısıtlamaları, verimlilik modellerini, kütle dengelerini, ekipmanın çalışma durumunu ve rafinerinin talep karşılama kısıtlamalarını içermektedir.

Geliştirilen yaklaşım, rafinerinin gerçekleşmiş bir durumu üzerinden senaryo analizi çalışmaları yapılarak test edilmiştir. MILP modeli, GAMS CPLEX çözücüsü kullanılarak çözülür. Gerçekleştirilen senaryo analizleri ile, baz durum ve optimum çözümünün karşılaştırıldığı çıktılar elde edilmiştir. Çalışma sonucunda operasyonel maliyette % 3,5’ a varan mali avantaj sağlanmıştır.

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NOMENCLATURE

C	Set of parameters
$Cost_{Cs,t}$	Cost of stream *Cs* in period *t*
Cs	Subset of streams (S) that is used in operational cost calculation
E	Set of all utility headers, equipment and transfer operations in the energy system
EQ	Subset of E that involves all equipment in the energy system
EG_{COGEN}	Subset of EQ that involves cogeneration systems
EQ_{B}	Subset of EQ that involves boilers
EQ_{D}	Subset of EQ that involves rolling drives
EQ_{EM}	Subset of EQ that involves electric motors
EQ_{FU}	Subset of EQ that involves furnaces
EQ_{HEX}	Subset of EQ that involves heat exchangers
EQ_{M}	Subset of EQ that involves the equipment that have different operation modes
EQ_{PRS}	Subset of EQ that involves PRS's
EQ_{STG}	Subset of EQ that involves steam turbines
EQ_{T}	Subset of EQ that involves turbines
EQ_{WHB}	Subset of EQ that involves WHB's
F	Set of flow direction of streams
G	Set of equipment and header types in the energy system
M	Set of modes
opt	Set of optimization status of streams
$P_{eq,c}$	Parameter *c* of the equipment *eq*
plt	Set of plants in the refinery
$rMode_{eqM,m,t}$	Online operational mode of the equipment in period *t*

$rV_{s,t}$	Online flow rate of the stream *s* in period *t*
S	Set of streams
SH	Subset of EQ that involves common shaft operations of rotating drives
t	Set of time periods
TO	Transfer operations of the Refinery performed by rotating drives
UH	Subset of E that involves utility headers in the energy system
$V_{Cs,t}$	flow rate of the stream *Cs* in period *t*
V_{plt}	flow rate of the stream s from/to the equipment *eq* of type *g* in period t
$V_{plt,HEADER,uh,f,opt,s,t}$	flow rate of the stream s from/to the header *uh* in period t
$V_{plt,POWER,to,f,s,t}$	Required power of the stream s for transfer operation "*to*"
$Mode_{eqM,m,t}$	mode *m* of equipment eq_M in period *t*

ABBREVIATIONS

APHin	Air Pre Heating Steam Inlet Flow
APHout	Air Pre Heating Condensate Outlet Flow
ATOMin	Atomizing Steam Inlet Flow
BDout	Blow Down Steam Outlet Flow
BFW	Boiler Feed Water
BFWin	Boiling Feed Water Inlet
BFWout	Boiling Feed Water Outlet Flow
BFW-RUP	Boiler Feed Water in RUP
BWFin	Boiling Feed Water Inlet Flow
CC	Clean Condensate
CCin	Clean Condensate Inlet Flow
CC-RUP	Clean Condensate in RUP
CHN	Unburnt Hydrocarbons
Cin	Cold Stream at heat Exchanger Inlet
Cout	Cold Stream at heat Exchanger Outlet
DSH1	Spray Water Injection for Desuperheating of 1st Stage Extraction Steam
DSH2	Spray Water Injection for Desuperheating of 2nd Stage Extraction Steam
DSH3	Spray Water Injection for Desuperheating of 3rd Stage Extraction Steam
DW	Demineralized Water

DWin	Demineralized Water Inlet Flow
DW-RUP	Demineralized Water in RUP
FA	Fresh Air Operating Mode of the Heat Recovery Steam Generator
FG	Fuel Gas
FGin	Fuel Gas Inlet Flow
FG-RUP	Fuel Gas in RUP
FO	Fuel Oil
FOin	Fuel Oil Inlet Flow
HHV	Higher Heating Value
Hin	Heating stream at heat Exchanger Inlet
Hout	Heating stream at heat Exchanger Outlet
HP	High Pressure Steam
HP-RUP	High Pressure Steam in RUP
HRSG	Heat recovery Steam Generators
IN	Entering Flow to the Header
LHV	Lower Heating Value
LP	Low Pressure Steam
LPG	Liquefied Petroleum Gas
LP-RUP	Low Pressure Steam in RUP
MILP	Mixed Integer Linear Programming
MP	Medium Pressure Steam
MP-RUP	Medium Pressure Steam in RUP

NG	Natural Gas
NG-RUP	Natural Gas in RUP
OUT	Leaving Flow from the Header
Pout	Power for Rotating Drive
PRS	Pressure Reducing Stations
PWout	Electricity Outlet
RUP	Residuum Upgrade Project
SBin	Steam Inlet Flow in Standby Mode of turbine
SBout	Steam Outlet in Standby Modes
SF	Supplementary Fired Operating Mode of the HRSG
STout	Steam Outlet Flow
STout1	1^{st} Stage Extraction Steam Flow in Steam Turbine
STout2	2nd Stage Extraction Steam Flow in Steam Turbine
STout3	3rd Stage Extraction Steam Flow in Steam Turbine
SWin	Spray Water Inlet
TEG	Turbine Exhaust Gas Operating Mode of the HRSG
TEIAS	Turkish Electricity Transmission Corporation
TUPRAS	Turkish Petroleum Refineries Corporation
UHP-RUP	Ultra-High Pressure Steam in RUP
VENTout	Steam Loss by Vent
VHP	Very High Pressure Steam
WHB	Waste Heat Boilers

Chapter 1

INTRODUCTION

An oil refinery is a complex production facility, refining crude oil into the finished products. Modern refineries involve blending, process heating, distillation, cracking, reforming, absorption, evaporation and cooling processes to convert crude oil into a wide variety of products, such as liquefied petroleum gas (LPG), gasoline, kerosene, jet fuel, diesel, and fuel oil [1].

The production of refined petroleum products is highly energy intensive. Although refinery processes involve both energy generating and consuming operations, extra energy is required to keep operational stability. Most of the refineries operate its own utility system to satisfy the energy demand. Refinery energy production expenses comprise a significant portion of the refinery budget. Effective energy management is essential to improve the effectiveness while minimizing the operational costs in a very competitive environment. However, because of the complexity of energy network, the decision-making process is a very problematic task. In addition, the energy demand for refining operations changes time due to varying crude oil properties and operating conditions. Optimization in the energy network system minimizes the operation cost and allows to get the most value from the existing system.

The study is about developing a decision support system to manage the complex energy network of the refinery. Optimization in refinery energy network is important in terms of selecting optimum operational combinations, operation modes and production rate of the equipment. Different operation modes of equipment have different capacities and efficiency parameters. Therefore, determining the efficiency parameters of the equipment is important.

In the scope of the study, power production equipment in the refinery is analyzed, thermodynamically to determine the variables which have an impact on the equipment efficiency. A mathematical programming model is utilized to satisfy the energy demand of the refinery with the minimum production cost of energy. The model is formulated as MILP and it includes all operational constraints, mass and energy balances, demand satisfaction constraints, efficiency models and operational status of the equipment. All energy consuming/producing equipment in the refinery are defined in the model. Thus, the interactions between production and utility plants are taken into consideration.

The model is applied to the energy network of Turkish Petroleum Refineries Corp (TUPRAS) Izmit Refinery. Optimum cases are generated with real data of the refinery. The computational study shows that an effective management of the energy network can yield as much as 3.5% savings. Additionally, sensitivity analysis considering the electricity trade with national grid is also studied to determine the breakeven point.

Chapter 2

LITERATURE REVIEW

Important researches and contributions have been addressed for the problem of utility system optimization. The first important study on this field have been published by Papoulias and Grossmann [29]. A MILP model is proposed in their study to the synthesis of utility systems with fixed steam and electricity demands. Hui and Natori [30] claims that LP an NLP models are commonly used for optimization of utility system operations. However, LP and NLP models are not suitable to make discrete decisions like equipment shutdown. The problem is resolved by using mixed integer programming methodology in optimization model.

Bruno et al. [31] states a MINLP approach for structural and parameter optimization in utility systems. The model is developed and extended based on the work of Papoulias and Grossmann [29]. The optimization algorithm decides the configurations and loads of the equipment but also the operating conditions like enthalpies and efficiencies.

In the study of Iyer & Grossmann [32], a MILP mathematical model is developed to determine the optimum operational combinations of the equipment at minimum cost of operation. The objective function takes into account changeover costs for units. In solution, a shortest path algorithm is preferred instead of branch and bound to shorten the computation time. The study of Velasco-Garcia et al. [34] accounts the cost of shut-downs and start-ups of utility operating units, as well. A SMILP model approach is proposed for varying utility demand of process.

Zhang et al. [25] presents an overall optimization model for process and utility operation. In the traditional approach for oil refinery-wide production planning, utility system and process system are optimized, separately. LP models of the process units are developed first to obtain a planning strategy. Production planning model determines crude oil selection, product and allocation of utilities. Secondly, the utility system is optimized to meet the energy demean at minimum operational cost. The production planning model is much more complicated than the utility optimization model. By separating these two models, the interrelationship between them is simplified and the global optimum result may not be achieved. Therefore, the utility model and process model are composed together to increase the optimization model efficiency.

Micheletto et al. [28] develops a MILP model for utility plant optimization of RACAP Refinery (Sao Paulo, Brazil). The objective function is minimization of operation cost of the overall plant. The mathematical model can be simplified from MINLP to MILP, because each header temperature and pressure are taken as constant. Micheletto et al. states that MILP modelling gives pretty accurate optimization result.

Chapter 3

DESCRIPTION OF THE REFINERY ENERGY NETWORK

3.1 TUPRAS Izmit Refinery

TUPRAS, Turkey’s sole oil refiner, operates 4 refineries in Izmit, Izmir, Kırıkkale and Batman, with a total annual crude oil processing capacity of 28.1 million tons. As Europe’s 7th largest refining company, TUPRAS ranks among the most complex refiners in the Mediterranean region, with an average Nelson Complexity Index of 9.5 [2].

TUPRAS Izmit Refinery started refining operations in 1961 with a processing capacity of one million crude oil processing. TUPRAS has initiated several expansions at the Izmit Refinery, the latest of which is the Residuum Upgrade Project (RUP). The project started up full scale production in May 2015. As a result of significant capacity augmentation and investments over the years, its design capacity reached 11.5 million tons/year and the Nelson Complexity Index of the Izmit Refinery increased to 14.5 [3].

The main products of the Izmit Refinery are LPG, naphtha, kerosene, diesel, fuel oil, asphalt and coke. Total petroleum products production is about 8.7 million tons with a utilized capacity of 85.2 percent in year 2013.

3.2 TUPRAS Izmit Refinery Energy Network

TUPRAS Izmit Refinery consists two facilities: Facility 1 and Facility 2 which contains Residuum Upgrade Facility (RUP). Figure 3.1 represents the simplified flow diagram of the energy network system in Facility 1 and Facility 2

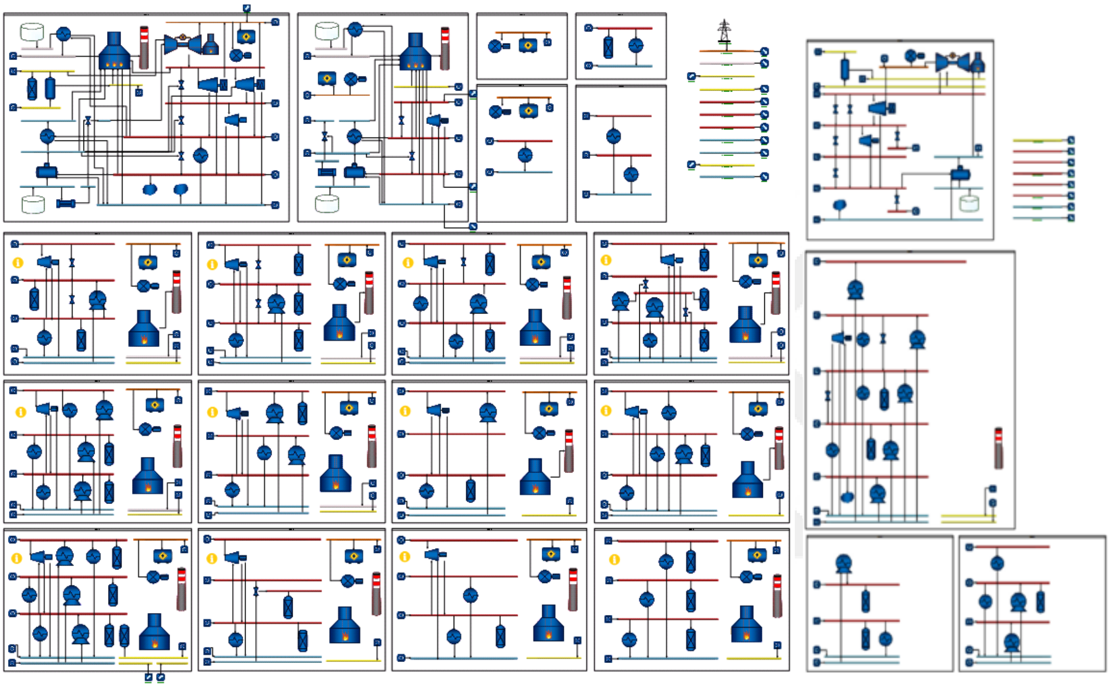

Figure 3.1. Flow Diagram of the Energy Network

The plants in the facilities are bounded within boxes. All equipment in energy network system are placed in related plants. 10 different types of equipment are defined in the system:

- Boilers
- Gas turbines
- Heat recovery Steam Generators(HRSG)
- Steam turbines

- Heat Exchangers
- Deaerators
- Pressure Reducing Stations (PRS)
- Furnaces
- Waste Heat Boilers (WHB)
- Turbine driven pumps
- Motor driven pumps

The system contains each equipment in the energy system of the refinery. All equipment are connected to the refinery headers to collect or distribute on or multiple types of fuel and/or utilities. The produced utilities are sent from equipment to the corresponding refinery headers. Similarly, consumed utilities are sent from corresponding headers to the related equipment. Refinery headers in the facilities are classified in types of steam, fuel, electricity and water and denoted as below:

Table 3.1. Utility and fuel headers in the refinery

Steam Headers	
Very High Pressure Steam (VHP)	Ultra High Pressure Steam RUP (UHP-RUP)
High Pressure Steam (HP)	High Pressure Steam RUP (HP-RUP)
Medium Pressure Steam (MP)	Medium Pressure Steam RUP (MP-RUP)
Low Pressure Steam (LP)	Low Pressure Steam RUP (LP-RUP)

Fuel Headers	
Fuel Gas (FG)	Fuel Gas RUP (FG-RUP)
Natural Gas (NG)	Natural Gas RUP (NG-RUP)
Fuel Oil (FO)	

Water Headers	
Clean Condensate (CC)	Clean Condensate RUP (CC-RUP)
Boiler Feed Water (BFW)	Boiler Feed Water RUP (BFW-RUP)
Demineralized Water (DW)	Demineralized Water RUP (DW-RUP)
Power Header	
Electricity (PW)	Electricity RUP (PW-RUP)

The production process involves in not only energy consuming but also energy generating operations (for example, steam generation from waste heat boilers in crude oil process). Production system cannot meet itself demand and the extra energy must be transported from the utility system in order to keep operational stability. In Facility 1, there are 2 utility plants, Plant A and Plant B, whereas Facility 2 contains one utility plant, Plant C. For power production, additionally, refinery is connected to the national grid, so exchange of electricity with the national grid, TEIAS, is also one of the options to meet the power demand of the refinery.

In Plant A there are 4 very high pressurized steam (VHP) producing boilers which have different efficiencies. All VHP steam produced is consumed by 4 different steam turbines to generate electricity. VHP steam is expanded throughout the steam turbines and discharged at lower pressures. In plant A, there is also a cogeneration system, which includes a gas turbine to generate electricity and an attached heat recovery units (HRSG) to raise steam from the waste heat found in exhaust gases from gas turbines. In Plant B, there are 4 more conventional boilers which produce HP steam. Produced HP steam is used in back pressure turbines to drive rolling equipment like pumps, compressors etc. [4].

Plant C in Facility 2 contains two cogeneration systems. Both of the cogeneration systems consist one gas turbine to produce electricity and an attached HRSG to generate UHP steam. The produced UHP steam is fed to the steam generator for electricity generation. Additionally, each utility plant has deaerators to remove the oxygen contaminant in the water to prepare BFW, heat exchangers to preheat the water and fuel streams before the boiler operations, PRS's to produce low-pressure steam and rolling equipment like pumps and compressors to transfer and pressurize the fluids.

Facility B can transfer the excess steam of HP and LP to Facility A. Additionally, electricity can be transmitted in two directions between facilities. Transfer options increase the production combination of the equipment to satisfy the of energy demand.

3.3 Refinery Utility and Fuel System

3.3.1 Steam

Steam is a flexible and widely used source of energy in the refinery. In Facility 1, steam is distributed at four pressures—very high, high, medium and low.

- Very-High-Pressure steam (VHP) is generated in the utility boilers and in the HRSG of the gas turbines typically at about 70 bar-g pressure. Very high pressurized steam is not distributed to the refinery, instead, it is used as a source to steam turbines to generate electricity.
- High-pressure (HP) steam, at 42 bar-g is provided to the refinery from utility boilers, from pressure reduction of VHP steam and from steam turbines. Additionally, HP steam can be transferred from Facility 2. It is used as a power for pumps, compressors and other machinery.
- Medium-pressure (MP) steam is produced at 13 bar-g pressure. MP steam is typically used in process heat exchangers and stripping equipment. It is also provided to the ejectors, used for maintaining the vacuum in vacuum distillation units. MP steam is produced principally from steam turbines, and from direct pressure reduction of HP steam.

- Low-pressure (LP) steam is generated at 6 bar-g. LP steam is consumed for heating services, including process exchangers, tank heating, line tracing, and miscellaneous services and heating steam for the boiler feed water (BFW) deaerators. It can be also transferred from Facility 2 [4].

Facility 2 has four main steam headers—ultra high, high, medium and low.

- Ultra-High-Pressure RUP steam (UHP-RUP) is provided at 98 bar-g pressure by two HRSG's attached to the gas turbines. Produced UHP is transferred to the steam generator for electricity production or to the PRS's for pressure reduction.
- High-Pressure RUP steam (HP-RUP) is generated at 42 bar-g from steam turbine extraction or from pressure reduction of VHP-RUP steam. HP-RUP steam is used to drive the rolling equipment in Facility 2.
- Medium-Pressure RUP steam (MP-RUP) is produced only by pressure reduction of UHP-RUP and HP-RUP steam. It is provided to the refinery at 13 bar-g as heating steam in heat exchangers and as stripping steam in column operations.
- Low-Pressure RUP steam (LP-RUP) is produced at 6 bar-g as an extract of the steam turbine and back-pressure turbines in Facility 2. Additionally, it can be generated by steam reduction of higher-pressure steam. LP-RUP is used in heating services of Facility 2, like LP steam.

3.3.2 Electricity

Petroleum refineries are the biggest users of electricity. It is widely used as power for major compressors, pumps and fans in air coolers with electric motors. TUPRAS Izmit Refinery provides required electricity of the refinery,

- from steam turbines by converting thermal energy from pressurized steam into mechanical energy to drive the electric generators

- from gas turbines by turning the chemical energy from the fuel into mechanical energy using the gaseous energy of the working fluid (air) to drive the electric generators
- from TEIAS (Turkish Electricity Transmission Corporation).

3.3.3 Water

Boiler feed water is water that undergoes purification and preheating and before fed to the boilers and HRSG's. Water treatment is important to prevent corrosion and keep the operation continuity. BFW is prepared in the deaerators by mixing demineralized water and condensate recovered from refinery operations.

3.3.4 Fuel

Fuel gas, natural gas and fuel oil are used as fuel in TUPRAS Izmit Refinery. Natural gas is purchased from outside suppliers, while refinery gas and fuel oil are by-products of the refining processes. Refinery gas is mixed with natural gas to enrich its heating value. The mixture fuel is named as fuel gas.

Fuel oil consists of complex mixtures of aliphatic and aromatic hydrocarbons. The aliphatic alkanes (paraffins) and cycloalkanes (naphthenic) are saturated by hydrogen and compose approximately 80-90% of its content. Aromatics (e.g., benzene) and olefins (e.g., styrene and indene) compose 10-20% and l%, respectively, of the fuel oil content. The fuel oil used in the refinery contains also sulfur impurity. Fuel oil is consumed in the boilers and in the furnaces [5].

Natural gas contains primarily methane, but also ethane, propane and heavier hydrocarbons. It also contains small amounts of nitrogen, carbon dioxide, hydrogen sulfide and trace amounts of water. Natural gas is used as fuel in some furnaces and in cogeneration of heat and power.

Fuel gas is a gaseous mixture of methane, light hydrocarbons, hydrogen, and other miscellaneous species like nitrogen, hydrogen and water. Fuel gas is consumed in the boilers, in supplementary firing burners of two HRSG's and in the furnaces.

3.4 Energy Network Equipment

3.4.1 Cogeneration

Cogeneration system contains a heat engine or power station to produce electricity and thermal power.

Cogeneration system has significantly higher yield than traditional power plants, due to the combined generation of electricity and thermal power. Greenhouse gas emissions and energy savings are other advantages of the cogeneration systems. There are different applications of cogeneration systems in the industry. In TUPRAS Izmit Refinery, the cogeneration system includes gas turbines to generate electricity and heat recovery units (HRSG) to raise steam from the waste heat found in exhaust gases from gas turbines. By the utilization of waste heat contained in the high-temperature exhaust gas of gas turbines, the conversion efficiency of the fuel energy into electric energy increases to 50 % approximately. On the other hand, the efficiency of steam turbine plants is only around 40% and 35% for gas turbine plants [6].

There are 3 gas turbines in TUPRAS Izmit Refinery, one of them located in Facility 1 and the others in Facility 2.

Table 3.2. List of cogeneration systems in the refinery

Cogeneration	Location	Gas Turbine	HRSG
COGEN1	Facility 1	GT1	HRSG1
COGEN2	Facility 2	GT2	HRSG2
COGEN3	Facility 3	GT3	HRSG3

Each gas turbine has an attached HRSG unit to recover the waste heat at the end of the turbine. The HRSG units in TUPRAS Izmit Refinery have additional supplementary firing burners, which increase the efficiency of the steam production. The operational and thermodynamic details of the gas turbines and HRSG units are explained in Chapter 4: BACKGROUND OF MODELING

3.4.2 Steam Turbines

A steam turbine converts a part of thermal energy from pressurized steam to mechanical work, in turn electrical power. According to heat drop processes, steam turbines are classified. In back pressure turbines, steam is extracted from turbine at lower pressure levels. In condensing turbines, the extract left the turbine at almost vacuum conditions and directed to a condenser

In TUPRAS Izmit Refinery, there are 4 back-pressure steam turbines and one condensing turbine with two stage extractions. The steam turbines of the refinery is listed below:

Table 3.3. List of steam turbines in refinery

Steam Turbine	Location	Inlet Steam	Extractions
STG1	Facility 1	VHP	MP & LP
STG2	Facility 1	VHP	MP & LP
STG3	Facility 1	VHP	HP & MP & CC
STG4	Facility 2	UHP-RUP	HP-RUP & LP-RUP

3.4.3 Boiler

A boiler can be defined as a closed vessel in which water or other fluid is heated. Heated fluid, most commonly steam, is then circulated out of the boiler for use in various processes, heating or power generation. In industry, mainly two types of boiler are available:

- Fire tube boiler, in which hot gases are passed through the tubes and water surrounds these tubes.

- Water tube boiler, in which water is inside the tubes and the hot gases pass around the outside of the tubes.

In TUPRAS Izmit Refinery, there are 8 water- tube boilers. 4 of them are located in utility Plant A in Facility 1 and produce VHP steam. The other 4 are in utility Plant B and generate HP steam. The boilers can use fuel oil and fuel gas as fuel.

Table 3.4. List of boiler in refinery

Boiler	Location	Produced Steam	Fuel Types
BOILER1	Facility 1	VHP	Fuel oil & Fuel Gas
BOILER2	Facility 1	VHP	Fuel oil & Fuel Gas
BOILER3	Facility 1	VHP	Fuel oil & Fuel Gas
BOILER4	Facility 1	VHP	Fuel oil & Fuel Gas
BOILER5	Facility 1	HP	Fuel oil & Fuel Gas
BOILER6	Facility 1	HP	Fuel oil & Fuel Gas
BOILER7	Facility 1	HP	Fuel oil & Fuel Gas
BOILER8	Facility 1	HP	Fuel oil & Fuel Gas

3.4.4 Deaerators

In utility plants, deaerators are used to remove oxygen and other dissolved gases from BFW before boiler operations. Oxygen and other dissolved gasses cause corrosion during steam generation and lowering their concentration protect production continuity. In deaerators, BFW is heated until the saturation temperature by LP steam. Thus, the dissolved gasses are removed from BFW and corrosion damage is minimized.

3.4.5 Turbines and Electric Motors

In refinery plants, there are a large number of rotating drives like coolers, pumps, fans, and compressors to transfer fluids. These drives are powered by steam turbines and/or electric motors. In the past, steam turbines are the best technology to meet the speed and power requirements. However, nowadays the steam turbines are not advantageous due to high operational and maintenance costs. Therefore, some of the steam turbines replaced or spared by electric motors.

3.4.6 Pressure Reducing Stations

Pressure reducing stations reduces high-pressure steam to a lower pressure. The high pressure steam passes through a control valve. After control valve, the steam pressure decreases due to increasing volume. Water temperature is controlled via spray water injection. In refinery operations low-pressure steam is required for various operations:

- Heating steam
- Atomizing steam at fuel oil
- Ejection steam to vacuum column

- Soot blower steam

3.4.7 Heat Exchangers

A heat exchanger is a device that allows thermal energy (enthalpy) transfer between two or more fluid. In refinery processes, heat exchangers are used in various operations:

- Heating/ cooling of reactants
- Heating/ cooling of intermediate/ final products
- Heating of reactors and production containers
- Heating/ cooling of water circuit
- Heating of refinery fuel system

3.4.8 Furnaces

A furnace is a closed vessel which provides heat to the refinery reactions by burning fuel. Fuel gas and fuel oil can be used in furnaces as the fuel sources. Furnace operations are considered as fixed operations, so each furnace in the refinery must have same level fuel consumption.

3.4.9 Waste Heat Boilers (WHB)

Waste Heat Boilers (WHB) recover the heat of waste gasses from refinery operations to produce steam. WHB operations are dependent on the process conditions. Therefore, WHB's in the refinery have same steam production in optimum case.

Chapter 4

BACKGROUND AND MODELLING

4.1 Cogeneration

4.1.1 Gas Turbine

A gas turbine, also called a combustion turbine, is a type of combustion engine which is used to transform fuel energy to mechanical energy. This mechanical energy drives a generator to produce electricity. According to driving methods, there are different types of gas turbines. In a single-shaft gas turbine, all the rotating elements including an air compressor, compressor turbine and power turbine have a common shaft. A simple diagram for single shaft gas turbine is shown in Figure 4.1.

There are 3 main parts in a gas turbine. First of all, the incoming air is compressed to a higher pressure in the compressor section. During compression, the temperature of the air increases as well, so the air is discharged from compressor both at a higher temperature and pressure. Then, the air enters to a combustor in order to burn the fuel and produce high pressure, high-velocity gas. In the turbine part, the high-pressure gas is expanded to produce work which is used to drive the generator [7].

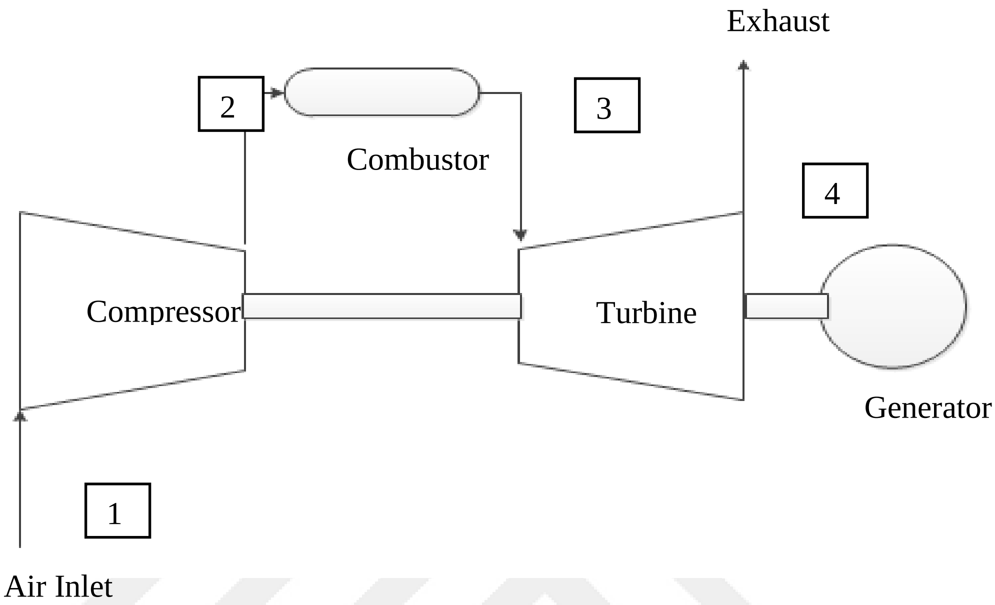

Figure 4.1. Simple Diagram for Single Shaft Gas Turbine [8]

4.1.1.1 Thermodynamic Analysis of Gas Turbine

The Brayton cycle explains the working principle of the gas turbines. The thermodynamic cycle is named after George Bailey Brayton.An ideal Brayton Cycle contains four internally reversible processes explained below:

- 1-2 isentropic compression in compressor
- 2-3 isobaric process in combustion chambers
- 3-4 isentropic expansion in turbine
- 4-1 isobaric process in exhaust gas

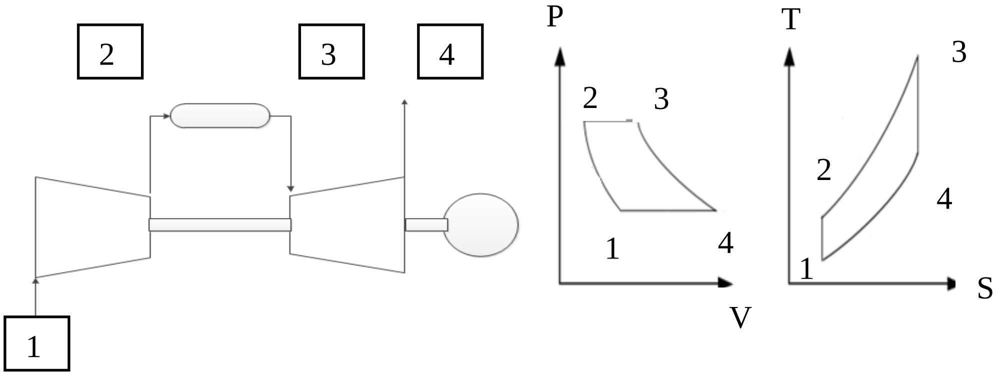

Figure 4.2. Ideal Brayton Cycle T-S and PV Diagram [9]

Actual Cycle is different than the ideal one. In actual gas turbines, compression and expansion do not perform isentropic processes due to the losses. Additionally, mechanical friction causes the pressure drop at heat addition. Therefore, in an Actual Brayton Cycle processes, compressor and turbine are considered to perform adiabatic processes:

- 1-2 adiabatic compression in compressor
- 2-3 isobaric process in combustion chambers
- 3-4 adiabatic expansion in turbine
- 4-1 isobaric process in exhaust gas rejection

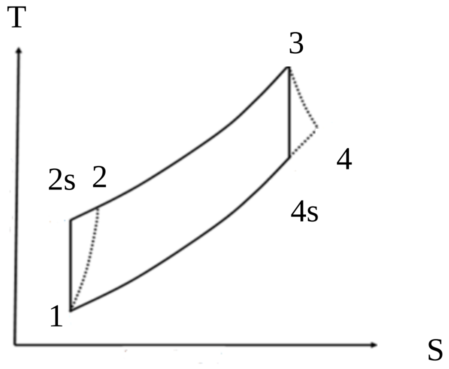

Figure 4.3. Actual Brayton Cycle [10]

Through the compression process the compression ratio is calculated as:

$$r_p = \frac{Pr_2}{Pr_1} \tag{1}$$

Where Pr_1 and Pr_2 are the inlet and outlet pressures at the compressor respectively. Isentropic efficiency of compressor (n_c) is estimated as:

$$n_c = \frac{T_{2s} - T_1}{T_2 - T_1} \tag{2}$$

T_1 : Compressor inlet temperature

T_2 : Compressor outlet temperature

T_{2s} : Isentropic compressor outlet temperature

The work of compressor (W_c) is expressed as:

$$W_c = \frac{c_{pa}\, T_1 \quad r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{n_m\ n_c} \tag{3}$$

where,

$$Rpa = \frac{r_p^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{n_c} \tag{4}$$

$$Rpg = 1 - \frac{1}{r_p^{\frac{\gamma_g - 1}{\gamma_g}}} \tag{5}$$

T_1 : Compressor inlet temperature

C_{pa} : Specific heat of air

n_m : Mechanical efficiency of the compressor

n_c : Isentropic efficiency of the compressor

γ_a : 1.4, constant

γ_g : 1.33, constant

In the combustion chamber, pressurized air and fuel are ignited. The energy balance in the combustion chamber is calculated from the equation:

$$m_a C_{pa} T_2 + m_f LHV_f + m_f C_{pf} T_f = m_a + m_f \quad TIT \tag{6}$$

m_a : Air mass flow

C_{pa} : Specific heat of air

m_f : Fuel mass flow

LHV_f : Low heating value of fuel

C_{pf} : Specific heat of fuel

T_f : Temperature of fuel

C_{pf} : Specific heat of flue gas

TIT: Turbine inlet temperature

After combustion, flue gas is expanded in the turbine section to produce work. The shaft work is expressed as follow:

$$W_t = C_{pf}\ TIT\ n_t\ Rpg/n_m \quad (7)$$

The net work (W_{net}) of gas turbine is the difference of turbine shaft work (W_t) and compressor shaft work (W_c):

$$W_{net} = W_t - W_c \quad (8)$$

The power production of the gas turbine is calculated by the multiplying the air mass flow (m_a) and net work (W_{net}):

$$Power = m_a W_{net} \quad (9)$$

4.1.1.2 Variables of Power Production in Gas Turbine

4.1.1.2.1 Air Temperature at Compressor Inlet

The efficiency of the gas turbines is directly affected by the ambient air condition. Although gas turbines are capable to take a constant volume of the air at a given shaft speed, the mass of air compressed by the compressor determines the power performance (Equation 9). As inlet air gets cooler, it gets denser as well. Therefore, the air flow through the turbine and power output increase proportionately.

4.1.1.2.2 Humidity

Humidity is the amount of gaseous water in the air. According to the measurement types, it can be divided into three. Absolute humidity is the total mass of water vapor present in a given volume of air. Relative humidity, expressed as a percent, the amount of atmospheric moisture present, divided by the amount of moisture that would be present if the air were completely saturated. Specific humidity is the weight of water vapor in the air.

Al-Fahed, S. F. et al. [11] performed a study on the relative humidity effect on cogeneration system. Dry air is denser than the air with a high content of water. Less air enters to the gas turbine at high relative humidity rate. On contrary, due to the high specific enthalpy drop, the specific turbine work increases with high relative humidity rate. Al-Fahed, S. F. et al. [11] reported that increasing relative humidity had a small positive impact on increasing gas turbine cycle net power.

Additionally, humid air decreases NOx emissions through the combustion process, by this way the water injection rate for NOx emission is also reduced.

4.1.1.2.3 Fuel

The combustion of the pressurized air and fuel takes place in the combustor part of the gas turbine. Fuel supply is an important factor to control the reliability and operability of the gas turbine.

Both liquid and gaseous fuels can be consumed as the fuel supply. Common gaseous fuels used in the gas turbines are natural gas, LNG, LPG, Refinery gas, coke oven gas, coal gas, hydrogen. Common liquid fuels are diesel, kerosene, jet a, naphtha, ethanol, methanol, heavy residual grade oil. From Equation 6 and Equation 9, the work of gas turbine affected by the total mass flow of air and fuel, the specific heat of flue gas and temperature difference across the turbine. The specific heating value of the flue gas depends on the products of the fuel combustion. According to the fuel content, the combustion products and ratios change. Natural gas is one of the most common combustion fuels used in the gas turbines. Natural gas consists primarily of methane, other higher alkanes like ethane, propane, butane and pentane and a small percentage of impurities like carbon dioxide, nitrogen, helium, hydrogen sulphide, or water. Natural gas has higher hydrogen to carbon ratio compared to distilled oil. Therefore, the combustion of the natural gas includes higher vapor amount. The high water amount increases the specific heat of flue gas, so gas turbines with natural gas have 2-3% higher efficiency than the ones with distilled oil [12].

When a fuel is completely combusted, the total amount of energy produced is defined as heating value of the fuel. The heating value of fuels is expressed in two ways:

- The higher heating value (also known gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products.
- The lower heating value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered [13].

LHV value shows the useful energy amount in the fuel. According fuel content the LHV value is calculated by the following expression:

$$LHV = \sum_{i}^{n} y_i \; LHV_i \qquad (10)$$

y_i: Volume or mole fraction of combustible gas component

LHV_i: Lower heating value of combustible gas component

Methane and other heavier alkenes has high heating value of the natural gas, while the inerts tend to decrease. From Equation 6, the shaft work of the turbine depends both on LHV and mass of the fuel. If fuel has only hydrocarbon content, the shaft work increases as the LHV of the fuel increases. The network of the gas turbine increases as well because turbine work remains the same. Therefore, the gas turbine provides more power output.

On the other hand, an increase in the amount of inert gases in the fuel results lower LHV value. The mass has a higher impact on the than shaft work than LHV value, so gas turbine provides more power.

4.1.1.2.4 Steam and Water Injection

During the combustion, gas turbine produces smoke, unburnt hydrocarbons (CHN), CO, CO_2, sulfur oxides and nitrogen oxides as pollutants. Smoke is formed mainly during start-ups. Sulphur in the fuel and air is converted to Sulphur oxides through combustion. The unburnt hydrocarbons and CO are formed as a result of incomplete combustion, while complete combustion of hydrocarbons produces CO_2.

Nitrogen oxides are environmentally the most harmful products of gas turbines. Nitrogen oxides are produced mainly in the form of NO and NO through combustion. These gases contribute to the formation of harmful particulate matter, ground level ozone and acid rain.

Three mechanisms cause NO_x emission in the gas turbine:

1) Thermal NO_x oxidation atmospheric nitrogen ,N_2, at high temperature
2) fuel bound NO_x, oxidation of bounded nitrogen in fuel
3) Prompt, reaction of atmospheric nitrogen, N_2, with radicals such as C, CH, and CH_2 fragments derived from fuel.

Fuel combustion is the main reason for fuel bound NO_x emission. Therefore, it is feasible to reduce the NO_x level from other mechanisms than fuel bound. For other NO_x mechanisms, high combustion temperature increases the NO_x formation. Steam or water injection is one efficient way to decrease the flame temperature. Additionally, the mass flow through the engine increases, so the power production increases as well.

4.1.1.3 Regression Analysis of Power Production

Multiple regression analysis is a powerful technique used to learn about the relationship between several independent and dependent variables. From thermodynamic analysis, the independent variables of power production ($m_{COGEN,PWout}$) in a gas turbine, are determined as air temperature at compressor inlet ($T_{COGEN,AIRin-GT}$), humidity at compressor inlet($\mathrm{RH}_{COGEN,AIRin-GT}$), flow of fuel ($\mathrm{m}_{COGEN,\mathrm{NGin-GT}}$), LHV of fuel ($\mathrm{LHV}_{COGEN,NGin-GT}$) and steam injection flow in combustion chamber ($m_{COGEN,,STin-inj}$).

The process data of the dependent and independent variables were collected to perform multiple regression analysis. The data were analyzed by using SPSS Statistics (Statistical Package for the Social Sciences). Backward elimination method is used to determine which independent variables contribute significantly to explaining the variability in the dependent variable. In backward elimination method, all variables are entered into the equation then sequentially removed. At each step, the largest probability of F is removed. After checking the collinearity, ANOVA (F-test), t-test and adjusted R^2, the regression model is built by using B- coefficients.

Power production model of the gas turbine:

$$PW_{COGEN,PWout} = m_{COGEN,NGin-GT}\, P_{c_{PW-NGin-GT}} + (T_{COGEN,AIRin-GT}\, P_{eq_{CO},c_{PW-AIRin-GT-T}} + P_{eq_{CO},c_{0-PW}}) \tag{11}$$

There is a positive correlation between steam injection and fuel flow of gas turbine. Therefore, steam injection is not included in the model.

The relative humidity has a very small coefficient in the model, as it is claimed in thermodynamic analysis. Therefore, the effect of relative humidity is neglected in the model.

The natural gas is used in gas turbines in TUPRAS Izmit Refinery. Natural gas is supplied by outsources. The composition and heating value of the natural gas is almost constant. Therefore, LHV of the natural gas has no impact on the power production.

The developed regression model for power production is compared to the real data of each gas turbine in the refinery. Maximum error percentage in the models for power generation is found 4.2 %. In Figure 4.4., the regression model and real data is shared to show the efficiency.

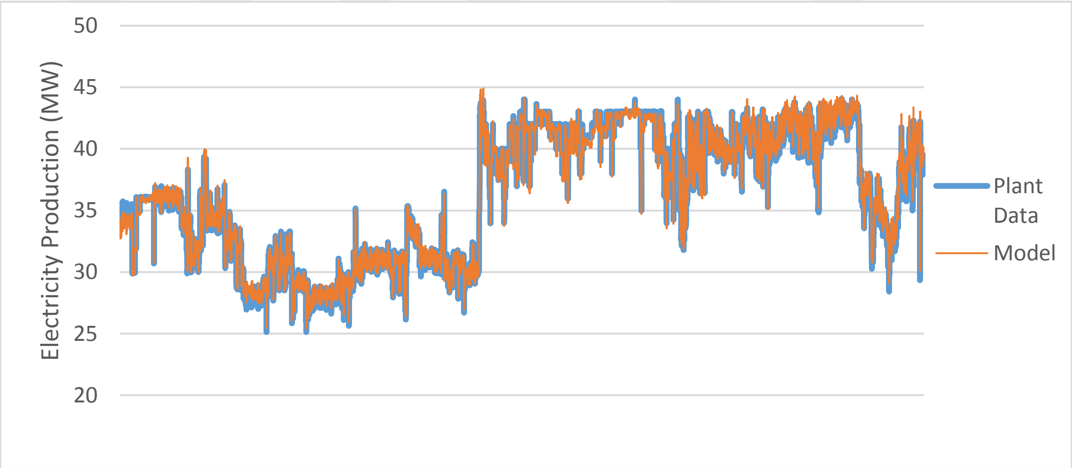

Figure 4.4. Comparison of the regression model and plant data for power generation in a gas turbine G1

4.1.2 Heat Recovery Steam Generator (HRSG)

Heat Recovery Steam Generator (HRSG) transform the useful energy in the gas turbine exhaust gas into the steam energy. Generated steam can be used either in process applications or/and in a steam turbine to produce electricity. There are different configurations for HRSG units. Generally, HRSG consists of 3 main sections:

1. Economizer, where the water is preheated to its saturation temperature.
2. Evaporator, where the saturated water is converted saturated vapor.
3. Super heater, where the pressurized steam is heated to saturation temperature.

According to design, HRSG units can operate single or multi pressure steam. In a single pressure HRSG, gas turbine exhaust gas passes through super heater, evaporator and economizer respectively. By this way, useful thermal energy in the exhaust is transferred to circulating water via heating surfaces to produce high-pressure steam. In multi pressure HRSG, there are economizer, evaporator and super heater sections for each pressure level. Heat recovery continues in sections of lower pressure steam. Therefore, a lower stack temperature is achieved.

With suitable configurations, HRSG units can be operated in different modes like turbine exhaust gas (TEG), fresh air (FA), supplementary fired (SF). These modes enable production flexibility for power plants without interrupting steam supply conditions. In TEG mode, the HRSG produces steam by recovering the thermal energy in the exhaust of the gas turbine. For FA and SF modes, an additional firing equipment must be installed across the inlet transition duct of HRSG. With this firing equipment, the HRSG capable to generate steam in FA mode, even the gas turbine is shut down. An additional air draft fan is used to provide fresh air to the HRSG for the combustion reaction. A bypass damper is installed between a gas turbine and HRSG to prevent leakage of hot gases, when maintenance is performed on the gas turbine and the HRSG is operated in FA mode. Since the flue gas at the exhaust of a gas turbine has high oxygen content, additional air is not required for combustion.

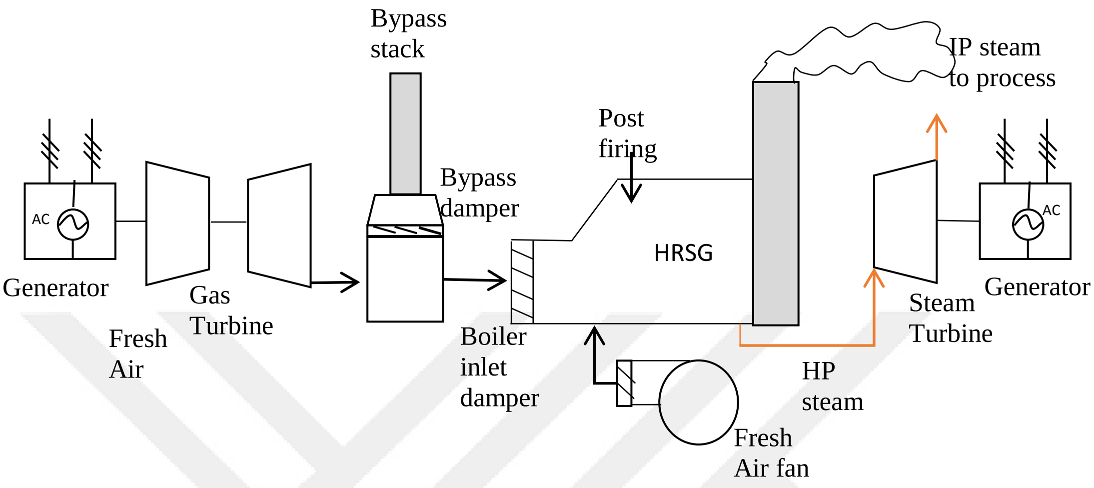

Figure 4.5. Cogeneration installation with a steam turbine, bypass stack, FA fan, post firing burners and a flying take-over assembly [14]

4.1.2.1 Thermodynamic Analysis of HRSG

Figure 4.6, represents a single pressure HRSG with a supplementary firing unit like in TUPRAS Izmit Refinery. The diagram shows that the flue gas coming from gas turbine is heated by supplementary firing burners. Afterward, heated flue gas reduces its temperature in superheater, evaporator and economizer, respectively.

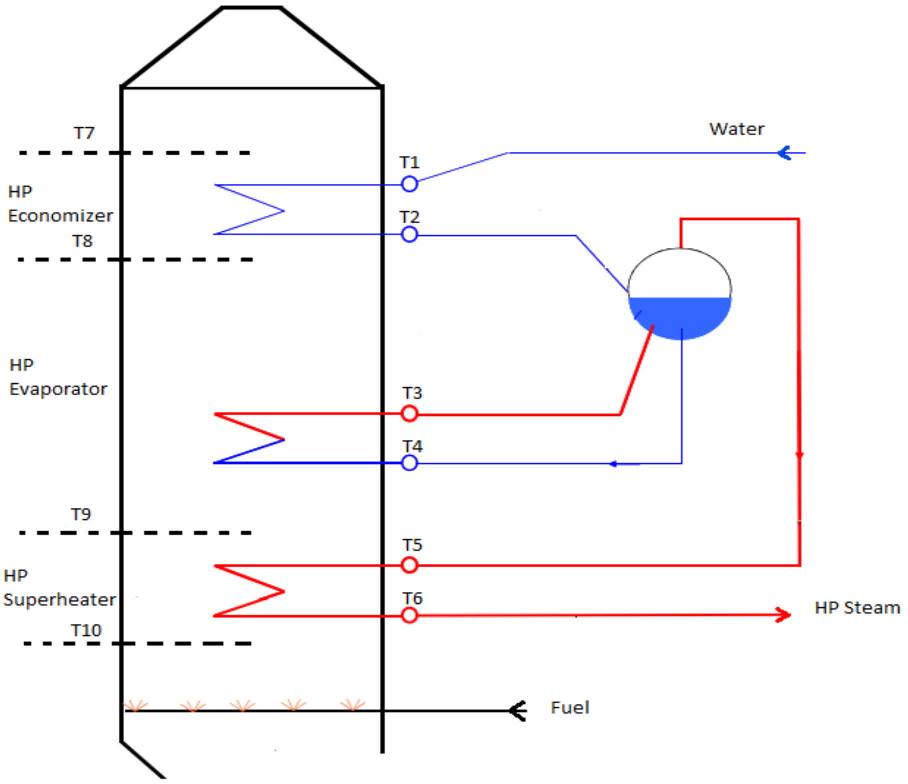

Figure 4.6. Single pressure HRSG with supplementary firing burners

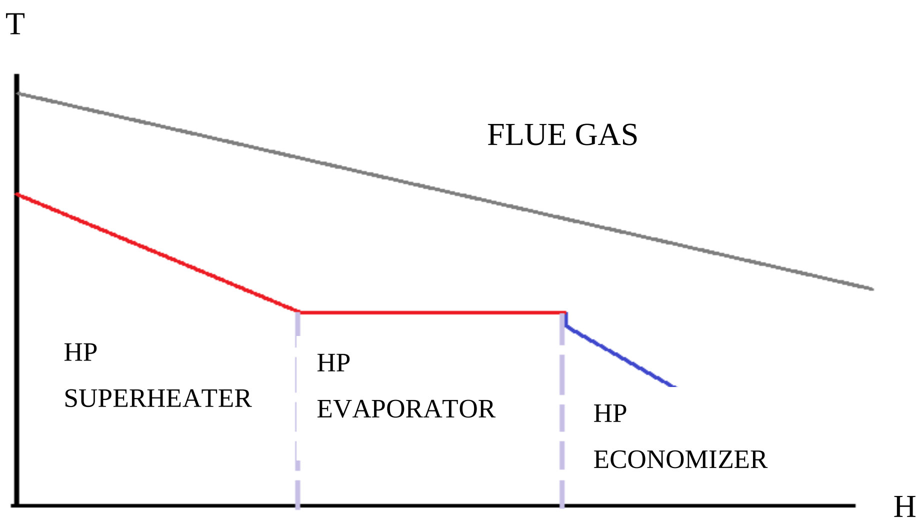

Figure 4.7. T-H diagram of a single pressure HRSG

Figure 4.7 shows T-H Diagram of a single pressure HRSG. The below line illustrates the heating of water, vaporizing and becoming a superheated steam in three steps, while the upper line represents the cooling of flue gas from inlet to outlet in the HRSG. The area between water-steam and flue gas line shows the heat loss in the HRSG. As the area increases, lower heat recovery takes place and higher stack temperature is observed. Another important parameter of HRSG efficiency is the pinch point temperature difference which is the temperature difference between water evaporation and flue gas at the evaporator outlet. Water vaporizes at a constant temperature, so for a lower pinch point temperature difference, more heat is transferred from flue gas to water vaporization process. Additionally, in order to avoid evaporation in the economizer, water temperature at the economizer outlet is kept less than the saturation point. This difference is defined as approach point. In this system, it is assumed that there is no approach temperature.

The energy balance in the supplementary firing:

$$m_{GT,EG}\ h_{11} + n_{SF}\ m_{HRSG,f}\ LHV_{HRSG,f} \ = \ m_{HRSG,f} + m_{GT,EG})\ h_{10} \qquad (12)$$

$m_{GT,EG}$: Gas turbine exhaust gas flow to HRSG

h_{11}: Gas turbine exhaust gas enthalpy

$m_{HRSG,f}$: Fuel flow in suplementary firing

h_{10}: Flue gas enthalpy at superheater inlet.

n_{SF}: Supplementary firing efficiency

Energy balance for gas and water in each part of the HRSG the gas temperature and water is calculated as following:

- At economizer

$$Q_{HRSG,ECO} = m_{HRSG,EG}\, c_{pHRSG,EG}\ \ T_8 - T_7\ \ = m_{HRSG,W}\ (h_2 - h_1 \qquad (13)$$

$m_{HRSG,EG}$: Flue gas flow through HRSG

$c_{pHRSG,EG}$: Specific heat of flue gas

T_8: Flue gas temperature at economizer inlet

T_7: Flue gas temperature at economizer outlet

$m_{HRSG,W}$: Water flow through HRSG

h_2: Enthalpy of water at economizer outlet

h_1: Enthalpy of water at economizer inlet

- At evaporator

$$Q_{HRSG,EVAP} = m_{HRSG,EG}\, c_{pHRSG,EG}\ \ T_9 - T_8\ \ = m_{HRSG,S}(h_4 - h_3) \qquad (14)$$

T_9: Flue gas temperature at evaporator inlet

T_8: Flue gas temperature at evaporator outlet

$m_{HRSG,S}$: Steam flow through evaporator at HRSG

h_4: Enthalpy of saturated steam at evaporator outlet

h_3: Enthalpy of saturated water at evaporator inlet

- At superheater

$$Q_{HRSG,SUPHEATER} = m_{HRSG,EG}\ c_{pHRSG,EG}\ \ T_{10} - T_{9} \qquad (15)$$
$$= m_{HRSG,S}(h_6 - h_5)$$

T_{10}: Flue gas temperature at superheater inlet

T_9: Flue gas temperature at superheater outlet

h_6: Enthalpy of superheated steam at superheater outlet

h_5: Enthalpy of saturated steam at evaporator inlet

$$m_{HRSG,S} = m_{HRSG,W} \qquad (16)$$
$$h_2 = h_3 \qquad (17)$$
$$h_4 = h_5 \qquad (18)$$

Total energy balance across HRSG

$$Q_{HRSG,T} = Q_{HRSG,ECO} + Q_{HRSG,EVAP} + Q_{HRSG,SUPERHEATER} \qquad (19)$$

$$Q_{HRSG,T} = \ m_{HRSG,EG}\ c_{pHRSG,EG}\ \ T_{10} - T_{7}\ \ = m_{HRSG,S}\ \ h_6 - h_1 \qquad (20)$$

Steam generation model from total energy balance

$$m_{HRSG,S} = m_{HRSG,EG}\ c_{pHRSG,EG}\ \frac{T_{10} - T_7}{h_6 - h_1} \qquad (21)$$

4.1.2.2 Variables of Steam Production in HRSG

From HRSG steam generation model [Equation 21], flue gas amount, specific heat and superheater inlet temperature affects the steam production rate. In TEG mode operations, the HRSG produces steam by recovering the thermal energy in the exhaust of the gas turbine. Gas turbine exhaust gas conditions are highly dependent on the gas turbine operation, so the gas turbine performance factors (humidity, air inlet temperature, gas turbine fuel load etc.) affect steam production, as well. In SF mode, the exhaust gas turbine is heated by firing fuel in HRSG. This additional energy from fuel combustion increases the steam production rate of HRSG. From Equation 12, the additional energy of fuel combustion is affected by the LHV and load of the fuel used in fired heaters.

In FA mode operations, the HRSG capable to generate steam by supplementary firing burners even the gas turbine is shut-down. In FA mode, HRSG operates like conventional boilers. However, steam generation efficiency is lower than in conventional due to low inlet air temperature. From regression analysis, steam generation in FA mode is affected by fuel burned in supplementary firing burners, stack temperature and air inlet temperature of HRSG.

Flue gas temperature at economizer outlet (stack temperature) is another determinant of steam production rate. In a single pressure HRSG, flue gas temperature at economizer outlet (stack temperature) temperature is also a function of the steam pressure and temperature. At higher pressure, steam has higher saturation temperature. Therefore, from Equation 13, the stack gas leaves the evaporator at a higher temperature. In process operations, due to the production stability, steam drum pressure level is kept almost constant. Therefore, reducing stack temperature just means increasing exhaust heat recovery and increasing the steam production rate.

Boiler feed water temperature and pressure at the economizer inlet affects steam production, as well. In Equation 21, steam production increases with increasing enthalpy of water at the economizer inlet.

4.1.2.3 Regression Analysis of Steam Production in Cogeneration System

There are 3 operation modes for steam generation in HRSG. Each mode has different operation dynamics. Therefore, the independent variables of each operation mode are determined separately. The data sets of variables are analyzed in SPSS by using backward elimination method.

In TEG mode, only the gas turbine operates and the thermal energy in exhaust of the gas turbine is recovered to produce steam. In TEG mode, the independent variables of steam production are:

- $T_{COGEN,STout}$: Steam temperature at superheater outlet
- $Pr_{COGEN,STout}$: Steam pressure at superheater outlet
- $T_{COGEN,BFWin}$: BFW temperature at economizer inlet
- $Pr_{COGEN,BFWin}$: BFW pressure at economizer inlet
- $T_{COGEN,GASout-STACK}$: Flue gas temperature at economizer outlet (stack temperature)
- $T_{COGEN,AIRin-GT}$: Air temperature at compressor inlet.
- $RH_{COGEN,AIRin-GT}$: Air humidity at compressor inlet.
- $m_{COGEN,NGin-GT}$: Fuel flow to the combustion chamber of gas turbine
- $LHV_{COGEN,NGin-GT}$: LHV of the Fuel burned in the combustion chamber of gas turbine

By using backward elimination method via SPSS Statistic, the steam production model equation of cogeneration system in TEG mode is built as following:

$$
\begin{aligned}
m_{COGEN,STout-TEG} &= m_{COGEN,NGin-GT}\ P_{,c_{ST-TEG-NGin-GT}} \\
&+ T_{COGEN,STout}\ P_{c_{ST-TEG-STout-T}} \\
&+ T_{COGEN,GASout-STACK}\ P_{c_{ST-TEG-GASout-STACK-T}} \\
&+ P_{c_{0-ST-TEG}}
\end{aligned} \qquad (22)
$$

The regression analysis shows that, compressor inlet temperature is correlated with stack temperature. Therefore, the model does not include compressor inlet temperature. The relative humidity has a small impact on steam production, it is neglected. The inlet water temperature and outlet steam temperatures are correlated with their pressure, therefore the pressure variables are not included in the model.

For SF mode operations, flow rate and LHV of the fuel in the supplementary firing burners are added to the model equation as independent variables. In supplementary firing, fuel gas is burned. Fuel gas is by-product of the refinery, so the composition changes affect the heating value. Therefore, impact of LHV fuel gas is included in the model.

$$\begin{aligned} m_{COGEN,STout-SF} \\ &= m_{COGEN,NGin-SF}\, P_{,ST-SF-NGin-SF} \\ &+ m_{COGEN,NGin-GT}\, P_{ST-SF-NGin-GT} \\ &+ (\mathrm{LHV}_{COGEN,NGin-SF}\, P_{c_{ST-SF-NGin-SF-LHV}} \\ &+ T_{COGEN,GASout-STACK}\, P_{c_{ST-SF-GASout-STACK-T}} \\ &+ P_{eq_{CO},c_{0-ST-SF}}) \end{aligned} \tag{23}$$

In FA mode, the gas turbine does not operate. Steam is generating by fuel-fresh air combustion in supplementary burners.

- $T_{COGEN,STout}$: Steam temperature at superheater outlet
- $Pr_{COGEN,STout}$:: Steam pressure at superheater outlet
- $T_{COGEN,BFWin}$: BFW temperature at economizer inlet
- $Pr_{COGEN,BFWin}$: BFW pressure at economizer inlet
- $\mathrm{T}_{COGEN,GASout-STACK}$: Flue gas temperature at economizer outlet (stack temperature)
- $m_{COGEN,NGin-SF}$:Fuel flow to the supplementary firing burners of HRSG
- $\mathrm{LHV}_{COGEN,NGin-SF}$: LHV of the fuel burned in supplementary firing burners

- $T_{COGEN,AIRin-SF}$: Air temperature at HRSG inlet

  The regression model for FA operation mode is determined as below:

$$m_{COGEN,STout-FA} = m_{COGEN,NGin-SF}\, P_{,ST-FA-NGin-ST} + (\mathrm{LHV}_{COGEN,NGin-SF}\, P_{c_{ST-FA-NGin-SF-LHV}} + T_{COGEN,eq_{CO},AIRin-SF}\, P_{,c_{ST-FA-AIRin-SF}} + \mathrm{T}_{COGEN,GASout-STACK}\, P_{,c_{ST-FA-GASout-STACK-T}} + P_{,c_{0-ST-FA}}) \quad (24)$$

The accuracy of the regression model is controlled by comparing real plant data and model result. Maximum 4.76 % error is calculated. Comparison of the regression model and plant data for steam generation in HRSG 1 is illustrated below:

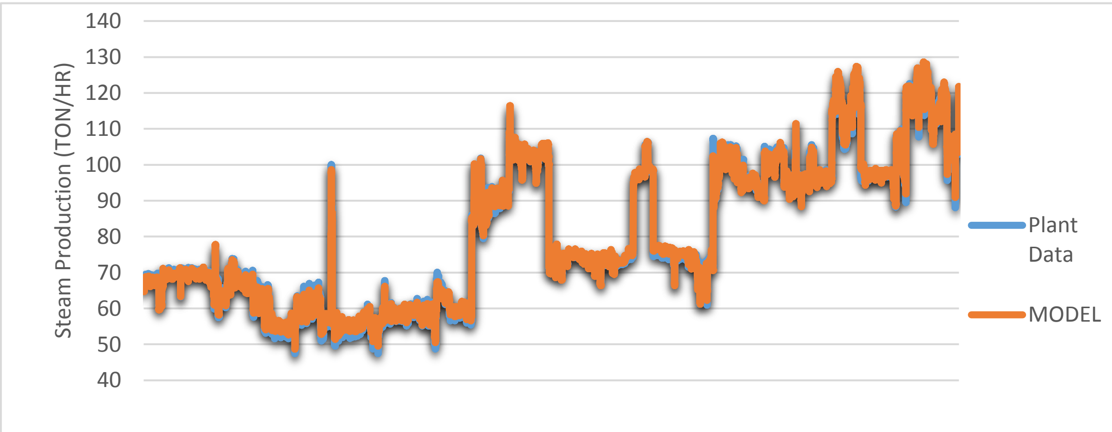

Figure 4.8. Comparison of the regression model and plant data for steam generation in HRSG 1.

4.2 Steam Turbines

A steam turbine converts a part of the thermal energy from pressurized steam to mechanical work, in turn, electrical power. In power plants, high-pressure steam provided by boilers or HRSG's is expanded in the nozzles of steam turbines to create a fast speed steam jet, thus the thermal energy is transformed into kinetic energy. Then, the steam jet strikes and rotates the blades or vanes mounted on a rotor. The turbine rotor drives the attached generator rotor to produce electricity [15].

4.2.1 Thermodynamic Analysis of Steam Turbine

A steam turbine is a form of heat engine that converts the thermal energy of the fluid into mechanical energy. The high-pressure steam expands through the turbine to produce work and is discharged at lower pressure. In order to predict the performance of steam turbine systems, the Rankine cycle model is used. The Rankine cycle is an idealized thermodynamic model of the power plant where an operating fluid is continuously evaporated and condensed [16].

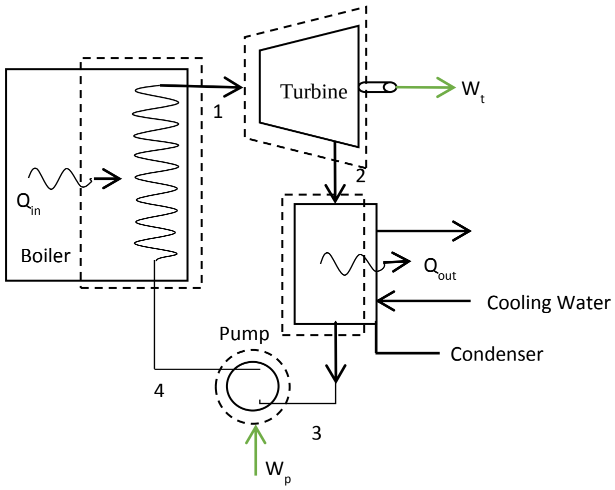

Figure 4.9. Typical work and heat transfers of a power plant [17]

The heat and work transfer of a typical power plant is represented in Figure 4.10. The water is heated up in the boiler and converted to superheated steam and sent to the turbine. The exhaust from the turbine is converted to the liquid in the condenser and is pumped back to the boiler for heating up again. Temperature-entropy (T-S) diagram of this cycle is given in Figure 4.10

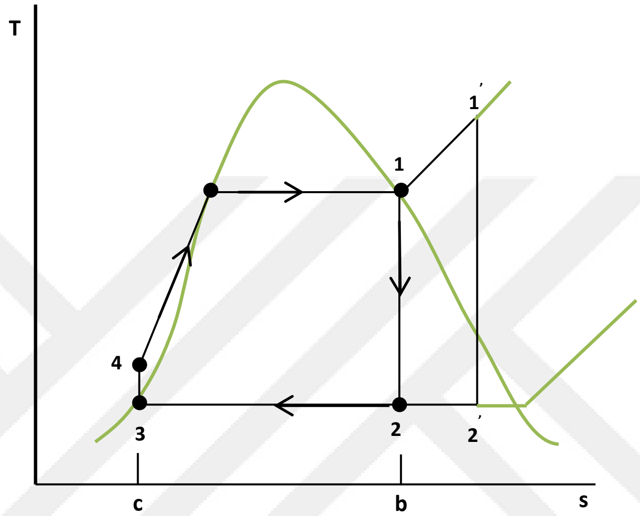

Figure 4.10. Temperature–entropy diagram of the ideal Rankine cycle[18]

The Rankine cycle operates in the following steps:

Process 1–2: Isentropic expansion of the working fluid through the turbine

Process 2–3: Constant pressure heat rejection in the condenser

Process 3–4: Isentropic compression in the pump

Process 4–1: Constant pressure heat addition in the boiler.

The superheated vapor produced in the boiler expands through turbine from state 1 to state 2. Mass balance for a control volume around steam turbine at steady state is defined in Equation 25.

$$0 = Q_{TURBINE} - W_{TURBINE} + m_{\mathrm{Wf}}\ h_1 - h_2 + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2) \quad (25)$$

$W_{TURBINE}$: Turbine power

$Q_{TURBINE}$: Heat transfer through turbine

h_1, h_2: Enthalpy of working fluid at turbine inlet and outlet

m_{Wf}: mass of working fluid flow through turbine

V_1, V_2: Velocity of working fluid

g: Gravity

z_1, z_2: elevation at turbine inlet and outlet

Heat transfer with surroundings, kinetic and potential energy changes are neglected through the expansion process in the turbine. Thus, the equation is reduced as follows:

$$W_{TURBINE} = m_{\mathrm{Wf}}\ h_1 - h_2 \quad (26)$$

In real plants, each stage of the Rankine cycle is associated with irreversible processes, which reduces the overall efficiency. In turbine operations, actual adiabatic expansion causes irreversibility. Due to the adiabatic expansion, entropy increases and work produced per unit of mass decreases compare to the ideal cycle.

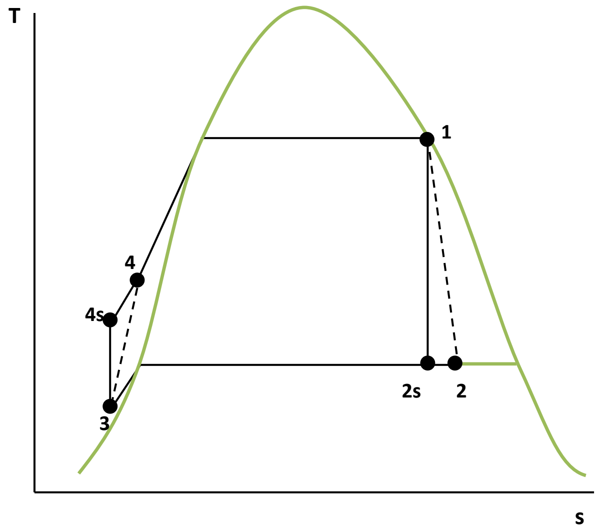

Figure 4.11. Temperature–entropy diagram showing the effects of turbine and pump irreversibility. [19]

The isentropic efficiency of the turbine is calculated below:

$$\mu_t = \frac{(W_{TURBINE}\quad m_{Wf})}{(W_{TURBINE}\quad m_{Wf})_s} = \frac{h_1 - h_2}{(h_1 - h_{2s})} \tag{27}$$

μ_t**:** The isentropic efficiency of the turbine

h_{2s}: Enthalpy of working fluid after isentropic expansion in the turbine

The turbine output formula becomes:

$$\frac{W_{TURBINE}}{\mu_t} = m_{Wf}\,(h_1 - h_{2s}) \tag{28}$$

In TUPRAS Izmit Refinery, steam turbines have multi-stage extractions. Figure 4.12, inlet steam is extracted at three different stages.

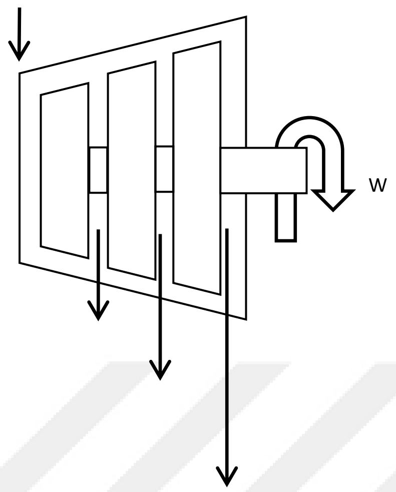

Figure 4.12. Multi-stage steam turbine diagram

For a control volume of the turbine enclosing all the extraction stages, the mass balance equation is expressed as below:

$$m_0 = m_1 + m_2 + m_3 \quad (29)$$

m_0, m_1, m_2, m_3: Mass flow rate of working fluid at inlet, 1st stage, 2nd stage and 3rd stage of turbine

The total work of the turbine is the sum of the work developed by each turbine stage. Neglecting kinetic and potential energy effects and assuming no heat transfer with the surroundings, total turbine work is calculated as following:

$$W_{TURBINE} = m_0 \quad h_0 - h_1 \ + \ m_0 - m_1 \quad h_1 - h_2 \\ + \ m_0 - m_1 - m_2 \quad h_2 - h_3 \qquad (30)$$

m_0, m_1, m_2, m_3: Mass flow rate of working fluid at inlet, 1st stage, 2nd stage and 3rd stage of turbine

h_0, h_1, h_2, h_3: Enthalpy of working fluid at inlet, 1st stage, 2nd stage and 3rd stage of turbine

By substituting equation 30 into, the turbine work calculation is reduced to :

$$W_{TURBINE} = (m_1) \quad h_0 - h_1 \ + \ m_2 \quad h_0 - h_2 \ + \ m_3 \quad h_0 - h_3 \qquad (31)$$

4.2.2 Variables of Power Production in Steam Turbines

The work of steam turbine depends on enthalpy of inlet steam, enthalpy of extractions and flow rates of extractions. In Equation 31, the work of steam turbine increases with increasing extraction rates. Additionally, as the difference between inlet steam and extraction enthalpies rises, more power is generated by the steam turbine. Therefore, the enthalpy of inlet steam is directly proportional to the work output of the steam turbine, while enthalpies of extractions are inversely proportional.

4.2.3 Regression Analysis of Power Production in Steam Turbines

The model equation of steam turbine for power production was determined by multi regression analysis. The data sets of independent variables were analyzed by using back regression method.

The independent variables of power production in a steam turbine with three extractions are:

- $T_{STG,STin}$: Steam temperature at steam turbine inlet
- $Pr_{STG,STin}$: Steam pressure at steam turbine inlet
- $T_{STG,ST1}$: Temperature of the extraction steam at 1st stage
- Pr_{STGST1}: Pressure of the extraction steam at 1st stage
- $m_{STG,ST1out}$: Flow of the extraction steam at 1st stage
- $T_{STG,ST2}$: Temperature of the extraction steam at 2nd stage
- $Pr_{STG\ ,ST2}$: Pressure of the extraction steam at 2nd stage
- $m_{STG,ST2out}$: Flow of the extraction steam at 2nd stage
- $T_{STG,ST3}$: Temperature of the extraction steam at 3rd stage
- $Pr_{STG,ST3}$: Pressure of the extraction steam at 3rd stage
- $m_{STG,ST3out}$: Flow of the extraction steam at 3rd stage

The power production model equation of steam turbine:

$$\begin{aligned} PW_{STG,eq_{STG},PWout} &= m_{STG,,ST1out}\ P_{,c_{PW-ST1}} + m_{STG,eq_{STG},ST2out}\ P_{,c_{PW-ST2}} \\ &+ m_{STG,ST3out}\ P_{c_{PW-ST3}} + (T_{STG,,ST1}\ P_{,c_{PW-ST1-T}} \\ &+ T_{STG,ST2}\ P_{,c_{PW-ST2-T}} + T_{STG,,ST3}\ P_{,c_{PW-ST3-T}} \\ &+ P_{c_{PW-0}}) \end{aligned} \quad (32)$$

The power production model depends on the steam extraction rates and their temperatures. The inlet steam is fed to the steam turbine almost at constant temperature. Therefore, steam inlet temperature has no impact on the power production. Additionally, pressure of the extractions are correlated with their temperatures, so they are not included in the model.

The developed power model is compared to real data of each steam turbine in the refinery. Maximum %4.86 error is achieved.

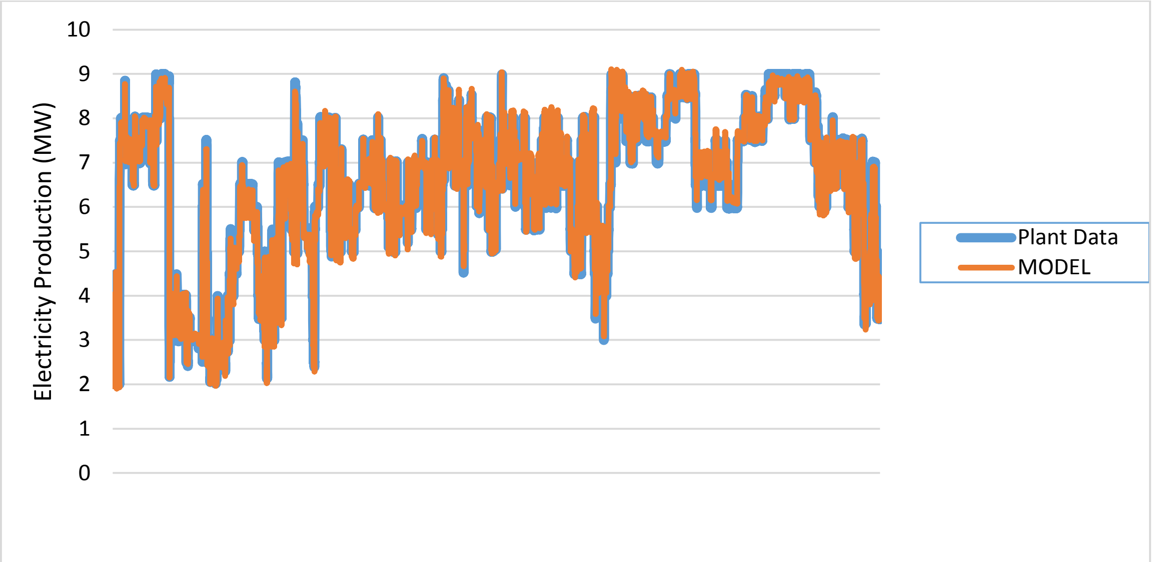

Figure 4.13 Comparison of the regression model and plant data for power generation in STG 1.

4.3 Boiler

In boiler processes, fuel is mixed with air and burnt in the combustion chamber. Generated hot gases come in contact with the drum and make water evaporate. Produced steam is piped from drum to the utility system. At the same time, boiling feed water is continuously pumped to the drum in the boiler to replace transferred steam.

In TUPRAS Izmit Refinery, there are 8 water tube boilers in the utility system. In order to increase the efficiency, some arrangements are made in boiler system:

- Air preheater is designed to heat air by steam. Raising temperature of combustion air increases thermal efficiency and flame stability
- The economizer is located at the very cold end of the stack gas. In economizer, the water is preheated by heat taken from stack gas.
- The superheater is a section of the boiler where saturated steam is converted into superheated steam by adding heat in order to improve the efficiency of the steam cycle.
- Blow down is a process of high impurity concentrated water removal from the boiler. During steam generation, the impurities of water remain in the boiler. Precipitation of the impurities causes corrosion and decreases operational safety. Therefore, water is intentionally taken from a boiler to avoid concentration of impurities during continuing evaporation of steam
- Fuel Oil Atomizer breaks the oil into fine droplets to achieve efficient combustion

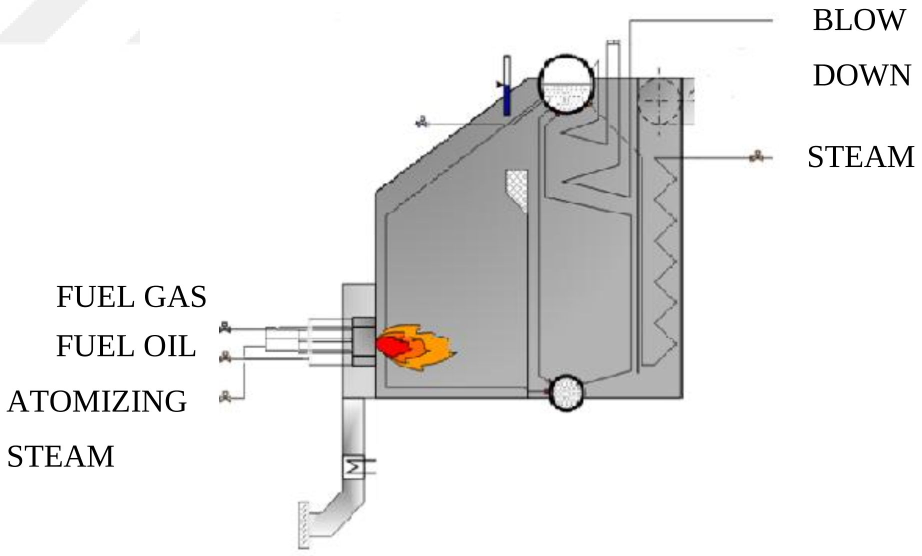

Figure 4.14. Boiler diagram. [2]

4.3.1 Thermodynamic Analysis of Boiler

Efficiency is a parameter which is used to determine boiler fuel utilization. There are several efficiency definitions that are commonly used for boiler systems.

- Combustion efficiency indicates is a measurement of how well the fuel being burned is being utilized in the combustion process. Unburnt fuel quantities and excess air in exhaust assess the combustion efficiency
- Thermal efficiency is the ability of heat exchanger in the boiler to transfer heat from the combustion process to the water or steam. The thermal efficiency does not take radiation or convection losses into account. It is highly affected by scale formation on the boiler tubes.
- Fuel-to-Steam Efficiency The fuel-to-steam efficiency is a measurement of the overall efficiency of a boiler. It accounts for the effectiveness of both the combustion process and the heat exchanger as well as the losses due to radiation and convection [21].

The German DIN 1942 and the American ASME standards are generally used to determine boiler efficiency [22]. While efficiency calculation of German DIN 1942 standard is based on lower heating value (LHV) of the fuel, the American ASME standard uses higher heating value (HHV). In this section, boiler efficiency is calculated via German DIN 1942 standard [23].

Total heat balance of boiler:

$$Q_{HTOT,BOILER} = Q_{HUTOT,BOILER} + Q_{LOSS,BOILER} \tag{33}$$

$Q_{HTOT,BOILER}$: Total heat input of the boiler

$Q_{HUTOT,BOILER}$: Total utilized heat of the boiler

$Q_{LOSS,BOILER}$: Total heat losses of boiler

The total heat input depends on heat in fuel, heat in combustion air:

$$Q_{HTOT,BOILER} = \mathrm{m}_{BOILER,\mathrm{FUEL}}\ LHV_{BOILER,\mathrm{FUEL}} + \mathrm{m}_{BOILER,\mathrm{AIR}}\ \ h_{BOILER\ ,\mathrm{AIRout-APH}} - h_{BOILER\ ,\mathrm{AIRin-APH}} \tag{34}$$

$\mathrm{m}_{BOILER,\mathrm{FUEL}}$: Fuel flow to boiler burner

$LHV_{BOILER,\mathrm{FUEL}}$: Lower heating value (LHV) of fuel

$\mathrm{m}_{BOILER,\mathrm{AIR}}$: Air flow to boiler burner

$h_{BOILER\ ,\mathrm{AIRout-APH}}$: Enthalpy of air at air preheater outlet

$h_{BOILER\ ,\mathrm{AIRin-APH}}$Enthalpy of air at air preheater inlet

Total utilized heat of the boiler indicates the total heat transferred to water to generate steam.

$$Q_{HUTOT,BOILER} = Q_{ST,BOILER} + Q_{RH,BOILER} + Q_{BD,BOILER} \tag{35}$$

$Q_{ST,BOILER}$: The heat transferred to main steam

$Q_{RH,BOILER}$: The heat transferred to reheat steam

$Q_{BD,BOILER}$: The heat transferred to blow down steam.

There is no reheating in boiler process of the refinery, so utilized heat consists of heat transfer to main steam and blow down.

$$Q_{HUTOT,BOILER} = \mathrm{m}_{BOILER,\mathrm{ST}}\ \ h_{BOILER,\mathrm{ST}} - h_{\ BOILER,\mathrm{BFW}} + \mathrm{m}_{BOILER,\mathrm{BD}}\ \ h_{BOILER,\mathrm{BD}} - h_{\ BOILER,\mathrm{BFW}} \tag{36}$$

$m_{BOILER,ST}$: Main steam flow from boiler

$h_{BOILER,ST}$: Enthalpy of main steam at boiler outlet

$h_{BOILER,BFW}$: Enthalpy of boiler feed water at boiler inlet

$m_{BOILER,BD}$: Blow down steam flow from boiler

$h_{BOILER,BD}$: Enthalpy of blow down steam at boiler outlet

There are some heat losses which reduce the efficiency of boiler. The heat losses can be classified into three:

$$Q_{LOSS,BOILER} = Q_{SG\ LOSS,BOILER} + Q_{CO\ LOSS,BOILER} + Q_{RD\ LOSS,BOILER} \quad (37)$$

$Q_{STC\ LOSS,BOILER}$: Flue gas losses

$Q_{CO\ LOSS,BOILER}$: Unburned combustible losses

$Q_{RD\ LOSS,BOILER}$: Radiation and convection losses

In boiler, heat of combustion process is transferred to the water or steam. Heat of flue gas leaving boiler stack indicates the energy that did not transfer from the fuel to the steam or hot water. Heat loss of flue gas ($Q_{STC\ LOSS,BOILER}$) depends on the enthalpy of flue gas at stack temperature $T_{BOILER,GASout-STACK}$ and the amount of flue gas mass flow:

$Q_{STC\ LOSS,BOILER}$: $m_{BOILER,GAS} \quad h_{BOILER,GASout-STACK} - h_{BOILER,GASout-REF}$

$m_{BOILER,GAS}$: The amount of flue gas mass flow

$h_{BOILER,\text{GASout-STACK}}$: The enthalpy of flue gas at stack temperature ($T_{BOILER,\text{GASout-STACK}}$)

$h_{BOILER,\text{GASout-REF}}$: The enthalpy of flue gas at reference temperature ($T_{BOILER,\text{GASout-REF}}$)

Incomplete combustion occurs when there is insufficient oxygen for fuel to react completely. It produces highly toxic carbon monoxide and releases less energy compare to the complete combustion. The heat loss caused by incomplete combustion is defined as unburned combustible losses ($Q_{CO\ LOSS,BOILER}$). For oil and gas, almost complete combustion is performed. Therefore, it is assumed that there are no unburned combustible losses in the boilers.

The outer surface of an operating boiler is hotter than its surroundings. Therefore, boiler loses heat by both radiation and convection. Radiation and convection losses are independent of the fuel type being burnt, instead, they rely mainly on the size and type of the boiler. For industrial water tube boilers, radiation and convection losses ($Q_{RD\ LOSS,BOILER}$) are between 2 to 3% [24].

4.3.2 Boiler Efficiency Calculation Methods

4.3.2.1 The Direct Method

In the direct method, the boiler efficiency (η_{BOILER}) is calculated by the ratio of utilized heat output ($Q_{HUTOT,BOILER}$) to the total heat input ($Q_{HTOT,BOILER}$) [21]:

$$\eta_{BOILER} = \frac{Q_{HUTOT,BOILER}}{Q_{HTOT,BOILER}} \tag{38}$$

4.3.2.2 The Indirect Method

The indirect method defines efficiency as the difference between heat losses and energy input:

$$\eta_{BOILER} = 1 - \frac{Q_{HUTOT,BOILER}}{Q_{HTOT,BOILER}} \tag{39}$$

where the efficiency is the difference between the losses and the energy input. The indirect method is based on accounting for all heat losses of a boiler. The total stack, radiation and convection losses in percent are subtracted from 100 % and the resulting value is the fuel-to-steam efficiency of the boiler. [24]

4.3.3 Model Analysis of a Boiler

In TUPRAS Izmit Refinery, there are 8 boilers. 4 of them produce VHP steam, while the others produce HP steam. Steam can be generated in 3 operation modes according to the fuel types used in boilers: Fuel gas, fuel oil, combined fuel (fuel gas and fuel oil). Boiler efficiency depends on the boiler type and process conditions, so it does not remain fixed during the course of operations. In order to increase the sensitivity of the steam production model equation, real time efficiency of a conventional boiler, is used. The steam production model of a boiler is stated as below:

$$\mathrm{m}_{BOILER,\mathrm{STout}} = \frac{LHV_{BOILER,\mathrm{Fuel}}}{(h_{BOILER,\mathrm{STout}} - h_{BOILER,\mathrm{BFWin}})} \, \eta_{BOILER,Fuel} \tag{40}$$

The online values of LHV of fuel types and enthalpy of steam and boiler feed water are taken from data acquisition system of the refinery. According to operating conditions and fuel types, boiler efficiency and model parameters are updated. Thus, the steam generation model becomes a linear function of the fuel consumption [25].

The developed model is compared to the real data of each boiler. The maximum error is estimated as 5.213%. The comparison of real data and model for steam production in BOILER 6 is represented in Figure 4.15.

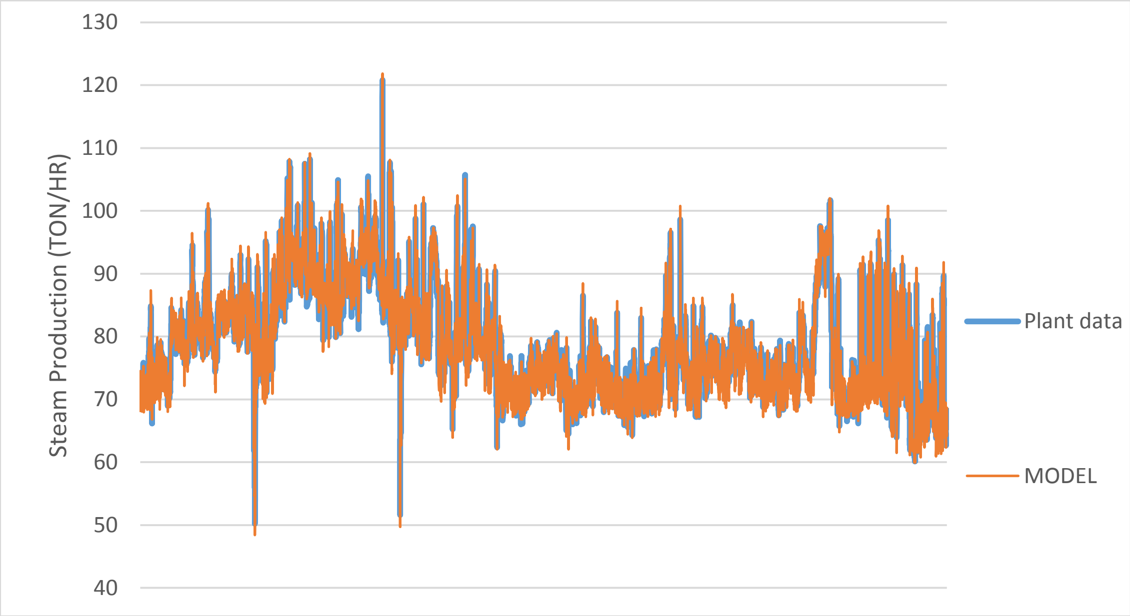

Figure 4.15 Comparison of the model and plant data for steam generation in BOILER 6.

4.4 Pressure Reducing Station

Pressure reducing stations (PRS) decrease the pressure of steam generated by steam boilers to levels required in process operations by water injection.

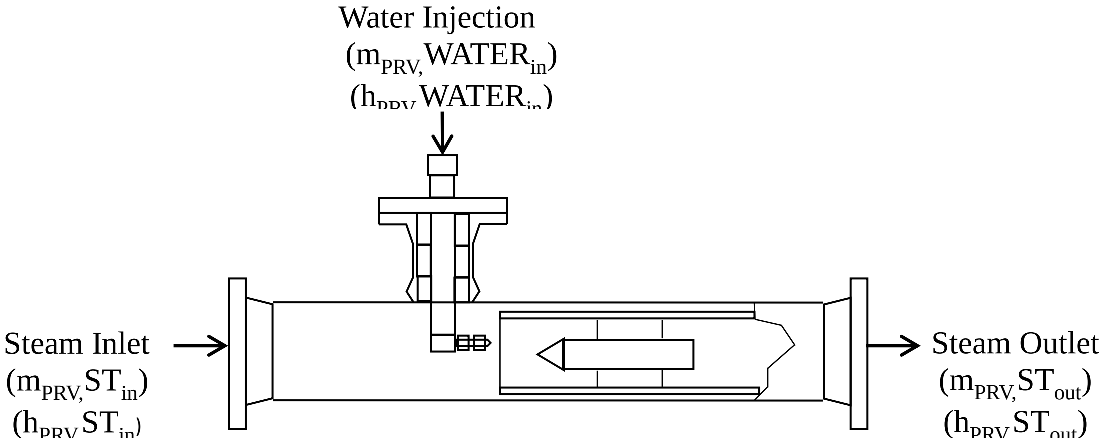

Figure 4.16 Diagram of a pressure reducing station (PRS).

The mass balance equation over pressure reducing valve:

$$m_{PRS,STin} + m_{PRS,WATERin} = m_{PRS,STout} \tag{41}$$

The energy balance equation over pressure reducing valve:

$$0 = Q - W + m_{PRS,STin}\, h_{PRS,STin} + m_{PRS,WATERin}\, h_{PRS,WATERin} - m_{PRS,STout}\, h_{PRS,STout} \tag{42}$$

When the heat transfer (Q) and work transfer (W) is ignored, the energy balance equation becomes:

$$m_{PRS,STin}\, h_{PRS,STin} + m_{PRS,WATERin}\, h_{PRS,WATERin} = m_{PRS,STout}\, h_{PRS,STout} \tag{43}$$

$m_{PRS,STin} + m_{PRS,WATERin}$ is substituted for $m_{PRS,STout}$ in Equation 43:

$$m_{PRS,STin}\, h_{PRS,STin} + m_{PRS,WATERin}\, h_{PRS,WATERin} = (m_{PRS,STin} + m_{PRS,WATERin})\, h_{PRS,STout} \tag{44}$$

The amount of water must be injected to decrease the pressure of the steam is calculated as below:

$$m_{PRS,WATERin} = m_{PRS,STin}\, \frac{h_{PRS,STin} - h_{PRS,STout}}{h_{PRS,STout} - h_{PRS,WATERin}} \tag{45}$$

If steam and water enthalpies are assumed to stay constant, the water injection flow becomes a linear function of the steam inlet flow.

4.5 Deaerators

In utility plants, deaerators are used to remove oxygen and various other dissolved gases from BFW before boiler operations. Oxygen and other dissolved gasses cause corrosion during steam generation and lowering their concentrations protect production continuity. In deaerators, recovered condensate and demineralized water are mixed to prepare BFW. BFW is heated until the saturation temperature by LP steam. Thus, the dissolved gasses are removed from BFW and corrosion damage is minimized.

Mass balance equation over the deaerator:

$$m_{DEA,CCin} + m_{DEA,DWin} + m_{DEA,STin} = m_{DEA,BFWout} + m_{DEA,VENTout} \tag{46}$$

Energy balance equation over the deaerator:

$$m_{DEA,CCin}h_{DEA,CCin} + m_{DEA,DWin}h_{DEA,DWin} + m_{DEA,STin}h_{DEA,STin} = m_{DEA,BFWout}h_{DEA,BFWout} + m_{DEA,VENTout}h_{DEA,VENTout} \quad (47)$$

The model equation of deaerator for steam consumption was determined by multi regression analysis. The variables in the mass and energy balance equations are analyzed by using back regression method. Steam consumption model in the deaerator is built as following:

$$m_{DEA,STin} = m_{DEA,DWin}\, P_{c_{STin-DW}} + m_{DEA,CCin}\, P_{c_{STin-CC}} + P_{c_{STin-0}} \quad (48)$$

4.6 Heat Exchanger

A heat exchanger is a device that allows thermal energy (enthalpy) transfer between two or more fluid. The fluids are at different temperatures and separated by a solid wall. Heat exchangers are classified according to the flow arrangement and type of construction [26].

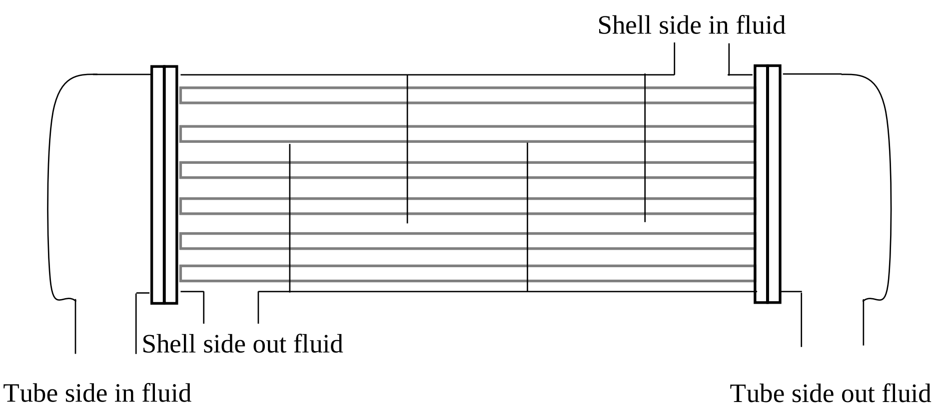

Figure 4.17. Flow arrangement of shell and tube heat exchanger. [27]

Figure 4.17 represents a shell and tube heat exchanger with counter-current flow. The hot fluid flows in opposite direction of the cold fluid. The thermal energy in the hot fluid is transferred to the cold fluid. This energy transfer process decreases the temperature of the hot fluid and increases the temperature of the cold fluid. If the energy loss and work transfer is ignored, the energy balance for hot and cold fluids are equal to:

$$Q_{HEX,COLD=} - Q_{HEX,HOT} \tag{49}$$

$$\Delta H_{HEX,COLD=} - \Delta H_{HEX,HOT} \tag{50}$$

For heating process of a cold stream with steam, the energy balance equation becomes:

$$m_{HEX,COLD}\, c_{p\,HEX,COLD} \quad T_{HEX,COLDout} - T_{HEX,COLDin} = m_{HEX,HOT}(h_{HEX,HOTin} - h_{HEX,HOTout}) \tag{51}$$

$$m_{HEX,HOT} = m_{HEX,COLD} \frac{c_{p\,HEX,COLD} \quad T_{HEX,COLDout} - T_{HEX,COLDin}}{(h_{HEX,HOTin} - h_{HEX,HOTout})} \tag{52}$$

For constant operating conditions, the steam flow is linearly proportionate to cold flow.

Chapter 5

OPTIMIZATION MODELLING

In this section, a mathematical programming model has been developed to solve optimization algorithm for energy system of TUPRAS Izmit Refinery (Kocaeli, Turkey) and satisfy its utility demand at minimum operational cost. The online utility demand of the refinery is determined by receiving live plant data for steam, fuel, condensate, BFW, and electric system metering devices via plant information system. Additionally, for the purpose of planning, pressure and temperature in each network can be assumed constant and with values that are the same as those obtained from data acquisition systems. Therefore, the system is formulated as mixed integer linear programming model (MILP) [28]. The MILP models are solved in GAMS optimization package by CPLEX 12 solver.

5.1 NETWORK STRUCTURE

Equipment operations are optimized to satisfy the utility demand at optimum working criteria and combination. In order to get an accurate optimization result, first of all, dynamic utility demand of refinery must be estimated. Plant data is taken from electrical measuring devices via plant information system. By using plant data, equipment-based flow rates are determined. In order to specify the utilities consumed or produced by the equipment, primarily, a network matrix is created. Network matrix contains each stream between an equipment and a header in the energy system of the refinery.

Table 5.1 contains an example that shows the amount of steam produced from BOILER1. The amount of steam produced by “BOILER1” is taken from actual plant data and paired with stream name “VHP-BOILER1”. The streams produced or consumed by the equipment are specified in the column named “FLOW”. The streams of produced steam sent from boilers are classified as “STout”. The utility headers are defined as type “HEADER” in the matrix. "IN" and "OUT" describe whether the stream is entering or leaving the header, respectively. The steam produced in the BOILER1 feeds VHP header, therefore the same "VHP-BOILER1" stream is entered in the matrix for VHP header as "in". By this way, the utility flow between a unit and its corresponding header is balanced.

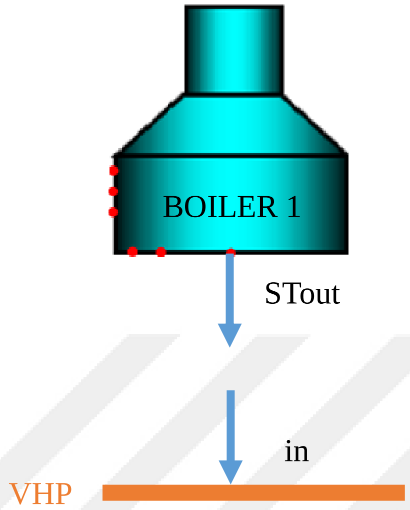

Figure 5.1. Steam flow diagram from a boiler to related header.

Table 5.1. Energy network matrix

PLT (PLANT)	TYPE	EQUPMENT/UTILITY	FLOW	STREAM	VALUE	OPT
PLANT-1	BOILER	BOILER1	STout	VHP-BOILER1	40	YES
PLANT-1	HEADER	VHP	IN	VHP-BOILER1	40	YES

Each equipment in the energy system presents fixed or variable operation. Variable operations can be optimized, however, the fixed operations (for example, steam generation from waste heat boilers in crude oil process) must have same level utility consumption or production. The optimizable streams are indicated as “YES” in “OPT” column.

The matrix contains all in and out utility connections to headers in the same time period. Total utility demand is calculated by mass balance for each steam level and by energy balance for electricity. Table 5.2 contains an example that shows the refinery utility demand of VHP steam. The optimum operational configuration must also satisfy the same demand target for different stream levels and electricity, therefore calculated demand streams are classified as fixed operations in the system.

Table 5.2. HP demand in energy network matrix

PLT (PLANT)	TYPE	EQUPMENT/UTILITY	FLOW	STREAM	VALUE	OPT
PLANT-1	HEADER	HP	out	HP-DEMAND	110	NO

After attaining the utility demands, the system is optimized to operate not only to meet the different demands of the processing plants but also to minimize the operational cost of the system

5.2 Mathematical Model

5.2.1 Set & Indices

C Set of parameters

Cs Subset of streams (S) that is used in operational cost calculation

E	Set of all utility headers, equipment and transfer operations in the energy system
EQ	Subset of E that involves all equipment in the energy system
EG_{COGEN}	Subset of EQ that involves cogeneration systems
EQ_B	Subset of EQ that involves boilers
EQ_D	Subset of EQ that involves rolling drives
EQ_{EM}	Subset of EQ that involves electiric motors
EQ_{FU}	Subset of EQ that involves furnaces
EQ_{HEX}	Subset of EQ that involves heat exchangers
EQ_M	Subset of EQ that involves the equipment that have different operation modes
EQ_{PRS}	Subset of EQ that involves PRS's
EQ_{STG}	Subset of EQ that involves steam turbines
EQ_T	Subset of EQ that involves turbines
EQ_{WHB}	Subset of EQ that involves WHB's
F	Set of flow direction of streams/ APHin ,ATOMin ,BFWin ,CCin ,Cin,DWin ,FGin ,FOin ,Hin ,SBin,SWin ,APHout ,BDout,BFWout ,Cout ,Hout ,Pout,PWout ,SBout,STout,STout1,STout2,STout3 ,VENTout/
G	Set of equipment and header types in the energy system /BOILER, STG, COGEN, HEADER, GRID, MOTOR, TURBINE, LETDOWN, POWER, DEA, HEX, WHB, FURNACE/
M	Set of modes
opt	Set of optimization status of streams
plt	Set of plants in the refinery
S	Set of streams
SH	Subset of EQ that involves common shaft operations of rotating drives
t	Set of time periods
TO	Transfer operations of the refinery performed by rotating drives

UH	Subset of E that involves utility headers in the energy system /PW, VHP, HP, MP, LP, UVHP-RUP, HP-RUP, MP-RUP, LP-RUP, CC, CC-RUP, BFW, BFW-RUP, DW, DW-RUP, FG, FG-RUP, NG, NG-RUP, FO, FO-RUP/

5.2.2 Decision Variables

A decision variable, also known as a controllable input variable, is a quantity that the decision-maker controls. In energy network optimization algorithm, continuous and discrete variables are defined.

A continuous variable is a variable which can take on any value within variable limits. Selection of how much electricity to produce and/or trade, selection of steam amount to produce or consume and selection of how much fuel to consume are the continuous variables of energy network.

Variables that can only take on a finite number of values are called discrete variables. Binary variables are a type of discrete variables that can only take two values, 1 and 0. In energy network optimization, binary variables are used to determine the operational mode and on/off status of units.

Table 5.3. Decision Variables

Continuous Variables	$V_{plt,g,eq,f,,s,t}$	flow rate of the stream s from/to the equipment *eq* of type *g* in period t

Continuous Variables	$V_{plt,HEADER,uh,f,opt,s,t}$	flow rate of the stream s from/to the header *uh* in pertiod t
Continuous Variables	$V_{plt,POWER,to,f,s,t}$	Required power of the stream s for transfer operation "*to*"
Continuous Variables	$V_{Cs,t}$	flow rate of the stream *Cs* in pertiod *t*
Binary Variables	$Mode_{eq_M,m,t}$	mode *m* of equipment eq_M in period *t*

5.2.3 Parameters

The parameters defined in the optimization algorithm is listed in Table 5.4.

Table 5.4. Parameters

$rV_{s,t}$	Online flow rate of the stream *s* in period *t*
$Cost_{Cs,t}$	Cost of stream *Cs* in period *t*
$rMode_{eq_M,m,t}$	Online operational mode of the equipment in period *t*
$P_{eq,c}$	Parameter *c* of the equipment *eq*

rV and rMode parameters are online refinery values and estimated by data acquisition. rV values show online flow rate between equipment and headers. It also includes utility demand values of the refinery. rMode contains the online operational mode and on/off status of the equipment in the field. Cost parameters (Cost) are the cost values of fuels and electricity trade prices.

The parameters of the equipment, P, are defined to determine the operational design limits and regression model coefficients of the equipment. Design limits usually remain constant if no investment is made. Some regression model coefficients are calculated by formulas which use the header properties like temperature and pressure. In the operation of utility plants, these properties are considered constant and equal to the values obtained from the data acquisition system.

5.2.4 Objective Function

The objective function is formulated to achieve a minimum operational cost of energy production. Operational cost consists of demineralized water production cost and fuel cost consumed in conventional boilers, gas turbines and supplementary firing systems of HRSG's. In a case of electricity trade with the market, operational cost is increased by the electric acquisition or decreased by electric sales.

$$\min z = Cost_{Cs,t}\, V_{Cs,t} \tag{53}$$

5.2.5 General Constraints

5.2.5.1 Mass Balance

The individual utility and fuel components of the refinery are connected to their associated headers by the piping network. The set of "uh" includes types of refinery headers in energy network system. "IN" and "OUT" describe whether the stream is entering or leaving the header, respectively. Mass balance of headers are defined by Equation 54.

$$\sum_{s} V_{plt,HEADER,uh,in,opt,s,t} - \sum_{s} V_{plt,HEADER,\mathrm{uh},out,\mathrm{opt},s,t} = 0 \tag{54}$$

5.2.5.2 Utility Demand and Fixed Operations Constraints

The optimum working combination of the energy system must satisfy hourly energy demand of the refining processes. Additionally, process-related fixed operations cannot be changed for optimization. The set of “opt” shows optimization status of streams. “YES” and “NO” describe whether the stream is a variable or fixed operation in the energy system, respectively. The following constraint expresses that the fixed streams including refinery demand must have the same level of utility production or consumption in period t.

$$\underset{s}{} V_{plt,g,e,f,NO,s,t} = rV_{s,t} \tag{55}$$

5.2.5.3 Mode Constraint

The set of “eq_M” includes the equipment that have different operation modes “m”. In an hourly period, only one mode can be active. The modes of equipment are listed as below:

Table 5.5. Modes of Equipment

	m1	m2	m3
BOILER	Fuel Gas	Fuel Oil	Fuel Gas + Fuel Oil
COGENARATION	TEG	FA	SF
STEAM TURBINES	ON	-	-
GRID	BUY	SELL	-
TURBINE	ON	ROLL	
MOTOR	ON	-	-
DEA	ON	-	-

The binary variable, $\mathrm{Mode}_{\mathrm{eq_U,m,t}}$, describes mode m of equipment in period t. The active mode is described with constraint 1. The following constraint forces equipment to activate only one operational mode.

$$\sum_{m} Mode_{eq_M,m,t} \leq 1 \quad \forall\, u_M \tag{56}$$

5.2.5.4 Electricity exchange with the power grid

For process continuity, most of the refineries prefer to generate the electricity in their own utility plants. Exchange of electricity with the national grid, TEIAS, is also one of the options to meet the demand. However, any trouble in exchanging process might cause power outage and process shutdown. Therefore, the electricity transfer from or to the refinery is represented by streams s as PW-SELL and PW-BUY, respectively. Limits of transfer are expressed as follow:

$$V_{plt,GRID,eq,out,PW-BUY,t} \leq P_{GRID,BUY\_MAX} \tag{57}$$

$$V_{plt,GRID,eq,in,PW-SELL,t} \leq P_{GRID,SELL\_MAX} \tag{58}$$

5.2.6 Equipment Based Constraints and Models

5.2.6.1 Boiler

Boiler is a closed vessel where water is boiled by fuel combustion. In Figure 5.2, inlet and outlet flows of the boiler are represented

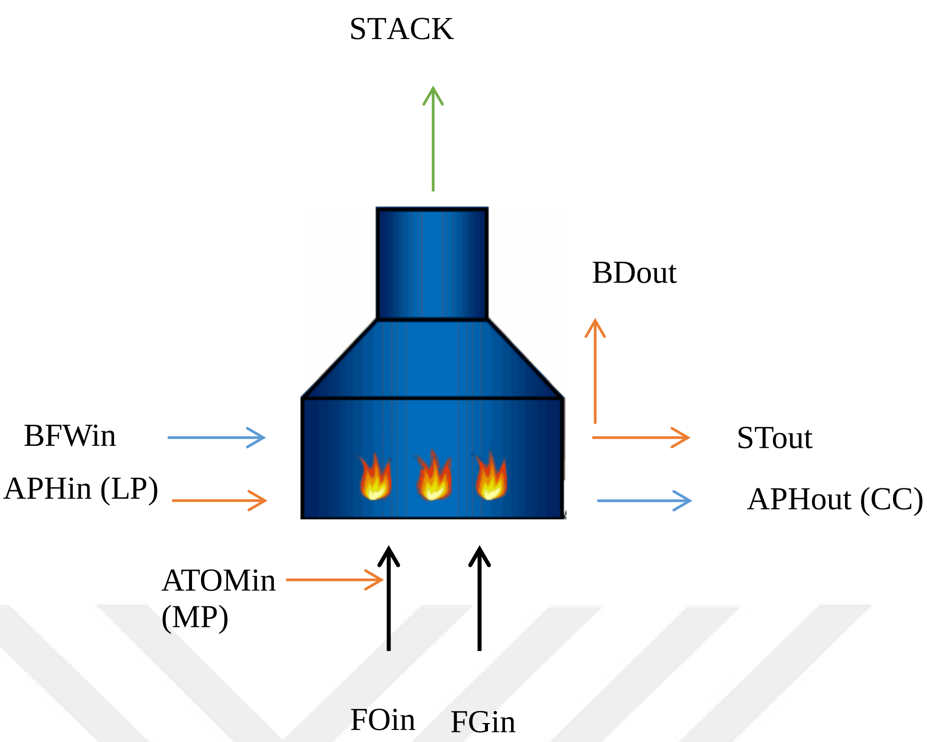

Figure 5.2 Inlet and outlet flows of a boiler

BFWin:	Boiling Feed Water Inlet
STout:	Steam Outlet
FOin:	Fuel Oil Inlet
FGin:	Fuel Gas Inlet
ATOMin:	Atomizing Steam (MP)
APHin:	Air Pre Heating Steam Inlet (LP)
APHout:	Air Pre Heating Condensate Outlet (CC)
BDout:	Blow Down Steam Outlet

The conventional boilers in TUPRAS Izmit Refinery have 3 operation modes according to the fuel types used in boilers. Mode selection is restricted by following equation:

$$\sum_{m} Mode_{eq_B,m,t} \leq 1 \quad \forall\, eq_B \tag{59}$$

In boilers, fuel oil and/or fuel gas is burned for combustion.

Fuel gas consumption limits:

$$V_{plt,BOILER,eq_B,FGin,s,t} \leq (Mode_{eq_B,m1,t} + Mode_{eq_B,m3,t})\; P_{eq_B,FGMAX} \tag{60}$$

$$V_{plt,BOILER,eq_B,FGin,s,t} \geq \; (Mode_{eq_B,m1,t} + Mode_{eq_B,m3,t})\; P_{eq_B,FGMIN} \tag{61}$$

Fuel oil consumption limits:

$$V_{plt,BOILER,eq_B,FOin,s,t} \leq (Mode_{eq_B,m2,t} + Mode_{eq_B,m3,t})\; P_{eq_B,FOMAX} \tag{62}$$

$$V_{plt,BOILER,eq_B,FOin,s,t} \geq \; (Mode_{eq_B,m2,t} + Mode_{eq_B,m3,t})\; P_{eq_B,FOMIN} \tag{63}$$

Steam production limits of boilers:

$$V_{plt,BOILER,eq_B,STout,s,t} \leq \sum_{m} Mode_{eq_B,m,t}\; P_{eq_B,SToutMAX} \tag{64}$$

$$V_{plt,BOILER,eq_B,STout,s,t} \geq \sum_{m} Mode_{eq_B,m,t}\; P_{eq_B,SToutMIN} \tag{65}$$

In a boiler, boiling feed water is heated by fuel combustion to get high-pressure steam. The amount of water entering the boiler must be equal to the amount of generated steam due to mass balance. During water evaporation, the concentration of dissolved solids increases in the boiler drum. The solids may be carried by steam to boiler tubes and cause tube overheating. Therefore, a rate of generated steam is wasted by blowdown $(P_{eq_B,c_{BD}})$ to remove impurities. The blowdown steam is also considered in mass balance calculation of boiler:

$$V_{plt,BOILER,eq_B,BFWin,s,t} = V_{plt,BOILER,eq_B,STout,s,t}\,(1 + P_{eq_B,c_{BD}}) \tag{66}$$

Steam production model coefficients of boilers are dependent on the consumed fuel type and calculated from the indirect efficiency of boiler:

$$\begin{aligned} &V_{plt,BOILER,eq_B,BFWin,s,t} \\ &= V_{plt,BOILER,eq_B,FGin,s,t}\,\frac{LHV_{BOILER,\mathrm{eq_B},\mathrm{FG}}}{(h_{BOILER,\mathrm{eq_B},\mathrm{STout}} - h_{BOILER,\mathrm{eq_B},\mathrm{BFWin}})}\,\eta_{BOILER,eq_B,FGin} \\ &+ V_{plt,BOILER,eq_B,FOin,s,t}\,\frac{LHV_{BOILER,\mathrm{eq_B},\mathrm{FO}}}{h_{BOILER,\mathrm{eq_B},\mathrm{STout}} - h_{BOILER,\mathrm{eq_B},\mathrm{BFWin}})}\,\eta_{BOILER,eq_B,FOin} \end{aligned} \tag{67}$$

In the case of fuel oil combustion, oil is broken into fine droplets by atomizing steam, MP, to achieve efficient combustion. Atomizing MP steam injected into fuel oil is calculated as below:

$$V_{plt,BOILER,eq_B,ATOMin,s,t} = V_{plt,BOILER,eq_B,FOin,s,t}\,P_{eq_B,c_{ATOM}} \tag{68}$$

In order to increase thermal efficiency, the air supplied to the burners is heated before combustion process. LP steam is used for pre heating process. Amount LP steam used in air pre-heating process is estimated in Equation 69.

$$\begin{aligned} &V_{plt,BOILER,eq_B,APHin,s,t} \\ &= V_{plt,BOILER,eq_B,STout,s,t}\,P_{eq_B,c_{APH}} \\ &+ \sum_{m} Mode_{eq_B,m,t}\;P_{eq_B,c_{APHc0}} \end{aligned} \tag{69}$$

As LP steam gives up heat energy, it condenses. The amount of condensate at the air-preheater outlet is equal to amount of LP steam at air-preheater inlet due to mass balance:

$$V_{plt,BOILER,eq_B,APHin,s,t} = V_{plt,BOILER,eq_B,APHout,s,t} \tag{70}$$

5.2.6.2 Steam Turbine

Steam turbines convert a part of the thermal energy from pressurized steam to mechanical work, in turn, electrical power. Figure 5.3 demonstrates the inlet and outlet flows of a steam turbine with 3 steam extractions

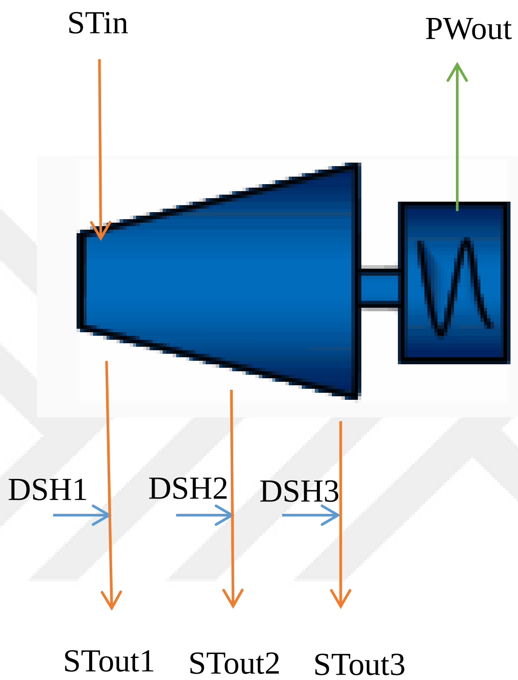

Figure 5.3. Inlet and outlet flows of a steam turbine

STin: Steam Inlet

STout1: 1^{st} Stage Extraction Steam

STout2: 2^{nd} Stage Extraction Steam

STout3: 3^{rd} Stage Extraction Steam

PWout: Electricty Outlet

DSH1: Spray Water Injection for Desuperheating of 1^{st} Stage Extraction Steam

DSH2: Spray Water Injection for Desuperheating of 2^{nd} Stage Extraction Steam

DSH3: Spray Water Injection for Desuperheating of 3^{rd} Stage Extraction Steam

For steam turbines, on/off operation modes are defined. The mode limitation is expressed as below:

$$\sum_{m} Mode_{eq_{STG},m,t} \leq 1 \quad \forall\, eq_{STG} \tag{71}$$

In back pressure turbines, high-pressure steam is extracted at lower pressure level to generate electricity. The mass balance of steam turbine and operational limits are expressed as below:

Mass balance of steam turbine:

$$V_{plt,STG,eq_{STG},STin,s,t} = V_{plt,STG,eq_{STG},ST1out,s,t} + V_{plt,STG,eq_{STG},ST2out,s,t} + V_{plt,STG,eq_{STG},ST3out,s,t} \tag{72}$$

Electricity production limits:

$$V_{plt,STG,eq_{STG},PWout,s,t} \leq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq_{STG},PWMAX} \tag{73}$$

$$V_{plt,STG,eq_{STG},PWout,s,t} \geq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq_{STG},PWMIN} \tag{74}$$

Entering steam limits:

$$V_{plt,STG,eq_{STG},STin,s,t} \leq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq_{STG},STinMAX} \tag{75}$$

$$V_{plt,STG,eq_{STG},STin,s,t} \geq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq,STinMIN} \tag{76}$$

Limits for 1st , 2nd and 3rd steam extractions, respectively:

$$V_{plt,STG,eq_{STG},ST1out,s,t} \leq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq_{STG},ST1MAX} \tag{77}$$

$$V_{plt,STG,eq_{STG},ST1out,s,t} \geq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq_{STG},ST1MIN} \tag{78}$$

$$V_{plt,STG,eq_{STG},ST2out,s,t} \leq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq_{STG},ST2MAX} \tag{79}$$

$$V_{plt,STG,eq_{STG},ST2out,s,t} \geq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq_{STG},ST2MIN} \tag{80}$$

$$V_{plt,STG,eq_{STG},ST3out,s,t} \leq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq_{STG},ST3MAX} \tag{81}$$

$$V_{plt,STG,eq_{STG},ST3out,s,t} \geq \sum_{m} Mode_{eq_{STG},m,t} \; P_{eq_{STG},ST3MIN} \tag{82}$$

According to the regression analysis of steam turbines, the power generation depends on the amount of and temperature of inlet and extracted steam levels. Steam temperatures are assumed to stay constant after optimization, therefore online data of temperatures are used in the optimization model in time t:

$$\begin{aligned} V_{plt,STG,eq_{STG},PWout,s,t} & \\ &= V_{plt,STG,eq_{STG},ST1out,s,t} \, P_{eq_{STG},c_{PW-ST1}} \\ &+ V_{plt,STG,eq_{STG},ST2out,s,t} \, P_{eq_{STG},c_{PW-ST2}} \\ &+ V_{plt,STG,eq_{STG},ST2out,s,t} \, P_{eq_{STG},c_{PW-ST3}} \\ &+ \sum_{m} Mode_{eq_{STG},m,t} \, (T_{STG,eq_{STG},ST1} \, P_{eq_{STG},c_{PW-ST1-T}} \\ &+ T_{STG,eq_{STG},ST2} \, P_{eq_{STG},c_{PW-ST2-T}} \\ &+ T_{STG,eq_{STG},ST3} \, P_{eq_{STG},c_{PW-ST3-T}} + P_{eq_{STG},cP_{PW-0}}) \end{aligned} \tag{83}$$

Desuperheater reduces the temperature of generated steam to the levels in process operations. Water is injected into the superheated steam. As water comes into direct contact with the superheated steam, it starts to vaporize. The heat required to vaporize water reduces the steam temperature at the outlet. Desuperheaters are used to control the temperatures of extractions at the turbine outlet. The amount of water required for each extraction is calculated by following equations:

$$V_{plt,STG,eq_{STG},DSH1,s,t} = V_{plt,STG,eq_{STG},ST1out,s,t} \frac{h_{STG,eq_{STG},ST1out} - h_{STG,eq_{STG},ST1-Satureted}}{h_{STG,eq_{STG},ST1-Saturated} - h_{STG,eq_{STG},Waterin}} \tag{84}$$

$$V_{plt,STG,eq_{STG},DSH2,s,t} = V_{plt,STG,eq_{STG},ST2out,s,t} \frac{h_{STG,eq_{STG},ST2out} - h_{STG,eq_{STG},ST2-Satureted}}{h_{STG,eq_{STG},ST2-Saturated} - h_{STG,eq_{STG},Waterin}} \tag{85}$$

$$V_{plt,STG,eq_{STG},DSH3,s,t} = V_{plt,STG,eq_{STG},ST3out,s,t} \frac{h_{STG,eq_{STG},ST3out} - h_{STG,eq_{STG},ST3-Satureted}}{h_{STG,eq_{STG},ST3-Saturated} - h_{STG,eq_{STG},Waterin}} \tag{86}$$

5.2.6.3 Cogeneration

Cogeneration or combined heat and power (CHP) is the use of a gas turbine to generate electricity and its useful heat at the same time. The supply of high-temperature heat first drives a gas turbine-powered generator and the resulting high-temperature exhaust heat is then used for water heating.

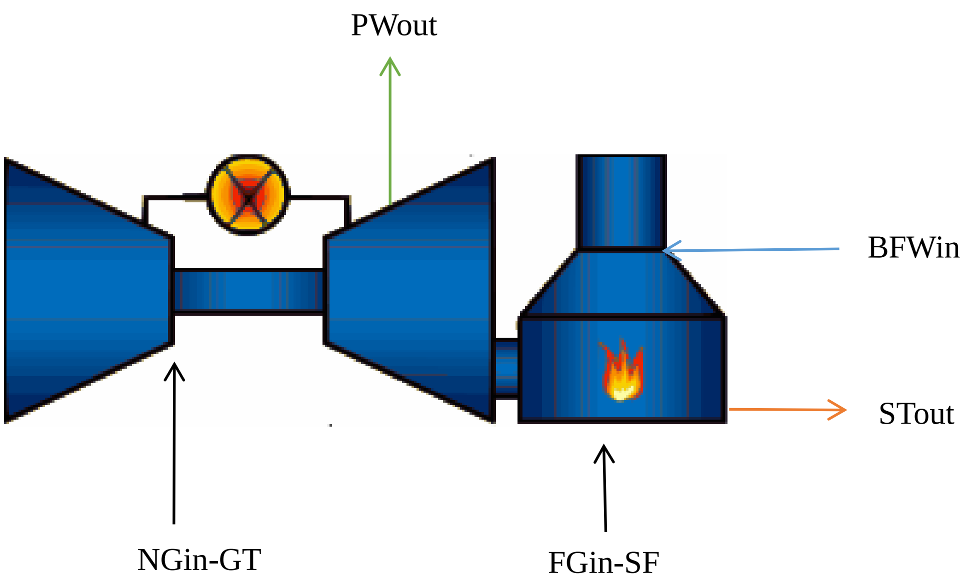

Figure 5.4. Inlet and outlet flows of a cogeneration system

BFWin: Boiling Feed Water Inlet

PWout: Electricity Outlet

NGin-GT: Fuel Inlet at Gas Turbine (NG)

FGin-SF: Fuel Inlet at HRSG (FG)

STout: Steam Outlet

The cogeneration system of TUPRAS Izmit Refinery have 3 operation modes. The mode restriction equation is defined as below:

$$\sum_{m} Mode_{eq_{CO},m,t} \leq 1 \quad \forall\, eq_{CO} \tag{87}$$

Gas turbine is a combustion engine in which expanding gases from the combustion chamber drive the blades of a turbine to generate electricity. Operational limits of the gas turbine is expressed as following:

Fuel consumption limits of the gas turbine:

$$V_{plt,COGEN,eq_{CO},NGin-GT,s,t} \leq (Mode_{eq_{CO},m1,t} + Mode_{eq_{CO},m3,t})\, P_{eq_{CO},NGin-GTMAX} \tag{88}$$

$$V_{plt,COGEN,eq_{CO},NGin-GT,s,t} \geq (Mode_{eq_{CO},m1,t} + Mode_{eq_{CO},m3,t})\, P_{eq_{CO},NGin-GTMIN} \tag{89}$$

Power production limits of the gas turbine:

$$V_{plt,COGEN,eq_{CO},PWout,s,t} \leq (Mode_{eq_{CO},m1,t} + Mode_{eq_{CO},m3,t})\, P_{eq_{CO},PWMAX} \tag{90}$$

$$V_{plt,COGEN,eq_{CO},PWout,s,t} \geq (Mode_{eq_{CO},m1,t} + Mode_{eq_{CO},m3,t})\, P_{eq_{CO},PWMIN} \quad (91)$$

HRSG generates steam from the waste heat in the exhaust gases of the gas turbine. The HRSG boilers in TUPRAS Izmit Refinery have supplementary firing burners. The fuel consumption limits in supplementary firing burners are stated in Equation 92 and 93.

$$V_{plt,COGEN,eq_{CO},FGin-SF,s,t} \leq (Mode_{eq_{CO},m2,t} + Mode_{eq_{CO},m3,t})\, P_{eq_{CO},FGin-SFMAX} \quad (92)$$

$$V_{plt,COGEN,eq_{CO},FGin-SF,s,t} \geq (Mode_{eq_{CO},m2,t} + Mode_{eq_{CO},m3,t})\, P_{eq_{CO},FGin-SFMIN} \quad (93)$$

Additional burners enable different modes for HRSG operations like turbine exhaust gas (TEG), fresh air (FA), supplementary fired (SF). Each operation mode has different steam production limits.

Steam production limits for TEG mode

$$V_{plt,COGEN,eq_{CO},STout,-TEGs,t} \leq Mode_{eq_{CO},m1,t}\; P_{eq_{CO},ST-TEGMAX} \quad (94)$$

$$V_{plt,COGEN,eq_{CO},STout-TEG,s,t} \geq Mode_{eq_{CO},m1,t}\; P_{eq_{CO},ST-TEGMIN} \quad (95)$$

Steam production limits for FA mode

$$V_{plt,COGEN,eq_{CO},STout-FA,s,t} \leq Mode_{eq_{CO},m2,t}\; P_{eq_{CO},ST-FAMAX} \quad (96)$$

$$V_{plt,COGEN,eq_{CO},STout-FA,s,t} \geq Mode_{eq_{CO},m2,t}\; P_{eq_{CO},ST-FAMIN} \quad (97)$$

Steam production limits for SF mode

$$V_{plt,COGEN,eq_{CO},STout-SF,s,t} \leq Mode_{eq_{CO},m3,t}\ P_{eq_{CO},ST-SFMAX} \tag{98}$$

$$V_{plt,COGEN,eq_{CO},STout-SF,s,t} \geq Mode_{eq_{CO},m3,t}\ P_{eq_{CO},ST-SFMIN} \tag{99}$$

According to the regression analysis of gas turbines, the power generation depends on the amount of fuel burned in combustion chamber, compressor inlet temperature and compressor inlet humidity. The gas turbine operates in TEG and SF modes, thus the model is valid for $\mathrm{Mode}_{\mathrm{eq_{CO}},\mathrm{m1},\mathrm{t}}$ and $\mathrm{Mode}_{\mathrm{eq_{CO}},\mathrm{m3},\mathrm{t}}$

$$\begin{aligned} V_{plt,COGEN,eq_{CO},PWout,s,t} & \\ &= V_{plt,COGEN,eq_{CO},NGin-GT,s,t}\ P_{eq_{CO},c_{PW-NGin-GT}} \\ &+ (T_{COGEN,eq_{CO},AIRin-GT}\ P_{eq_{CO},c_{PW-AIRin-GT-T}} \\ &+ P_{eq_{CO},c_{0-PW}})(Mode_{eq_{CO},m1,t} + Mode_{eq_{CO},m3,t}) \end{aligned} \tag{100}$$

The regression analysis shows that performance parameters of steam production are changed according to the operation modes. In TEG mode, the HRSG produces steam only by recovering the thermal energy in the exhaust of the gas turbine. The performance parameters include the fuel burned in the combustion chamber, compressor inlet temperature and stack gas temperature of HRSG.

$$\begin{aligned} & V_{plt,COGEN,eq_{CO},STout-TEG,s,t} \\ & = V_{plt,COGEN,eq_{CO},NGin-GT,s,t}\ P_{eq_{CO},c_{ST-TEG-NGin-GT}} \\ & + \ T_{COGEN,eq_{CO},STout}\ \ P_{eq_{CO},c_{ST-TEG-STout-T}} \\ & + T_{COGEN,eq_{CO},GASout-STACK}\ P_{eq_{CO},c_{ST-TEG-GASout-STACK-T}} \\ & + P_{eq_{CO},c_{0-ST-TEG}}\ \ (Mode_{eq_{CO},m1,t}) \end{aligned} \tag{101}$$

Steam is generated by additional firing burners in HRSG in FA mode, even the gas turbine is shut-down. In FA mode, HRSG operates like conventional boilers. However, steam generation efficiency is lower than in conventional due to low inlet air temperature. From regression analysis, steam generation in FA mode is affected by fuel burned in supplementary firing burners, stack temperature and air inlet temperature of HRSG.

$$\begin{aligned} &V_{plt,COGEN,eq_{CO},STout-FA,s,t} \\ &\quad = V_{plt,COGEN,eq_{CO},FGin-SF,s,t}\, P_{eq_{CO},ST-FA-FGin-SF} \\ &\quad + \; T_{COGEN,eq_{CO},AIRin-SF}\, P_{eq_{CO},c_{ST-FA-AIRin-SF}} \\ &\quad + LHV_{COGEN,eq_{CO},FGin-SF}\, P_{eq_{CO},c_{ST-SF-FGin-SF-LHV}} \\ &\quad + \mathrm{T}_{COGEN,eq_{CO},GASout-STACK}\, P_{eq_{CO},c_{ST-FA-GASout-STACK-T}} \\ &\quad + P_{eq_{CO},c_{0-ST-FA}} \; (Mode_{eq_{CO},m2,t}) \end{aligned} \tag{102}$$

In SF mode, the exhaust gas turbine is heated by firing fuel in HRSG. This additional energy from fuel combustion increases the steam production rate of HRSG. Steam generation in SF mode depends on fuel burned both in gas turbines and supplementary firing burners, stack temperature and air inlet temperature of gas turbine.

$$\begin{aligned} &V_{plt,COGEN,eq_{CO},STout-SF,s,t} \\ &\quad = V_{plt,COGEN,eq_{CO},FGin-SF,s,t}\, P_{eq_{CO},ST-SF-FGin-SF} \\ &\quad + V_{plt,COGEN,eq_{CO},NGin-GT,s,t}\, P_{eq_{CO},ST-SF-NGin-GT} \\ &\quad + (\mathrm{LHV}_{COGEN,eq_{CO},FGin-SF}\, P_{eq_{CO},c_{ST-SF-FGin-SF-LHV}} \\ &\quad + T_{COGEN,eq_{CO},GASout-STACK}\, P_{eq_{CO},c_{ST-SF-GASout-STACK-T}} \\ &\quad + P_{eq_{CO},c_{0-ST-SF}}) \; (Mode_{eq_{CO},m3,t}) \end{aligned} \tag{103}$$

Total steam production in HRSG is equal to the sum of steam production in each operation mode.

$$\begin{aligned} &V_{plt,COGEN,eq_{CO},STout,s,t} \\ &\quad = V_{plt,COGEN,eq_{CO},STout-TEG,s,t} \\ &\quad + V_{plt,COGEN,eq_{CO},STout-FA,s,t} \\ &\quad + V_{plt,COGEN,eq_{CO},STout-SF,s,t} \end{aligned} \tag{104}$$

5.2.6.4 Turbines and Electric Motor

Inlet and outlet flows of a turbine and electric motor are given in Figure 5.5 and Figure 5.6, respectively.

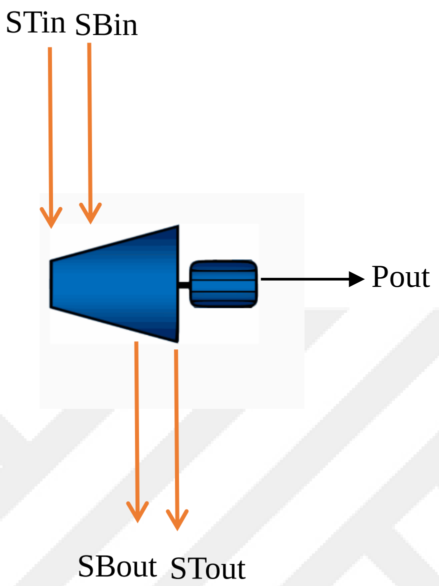

Figure 5.5. Inlet and outlet flows of rolling equipment driven by steam

STin: Steam Inlet

STout: Steam Outlet

SBin: Steam Inlet in Standby Mode

Pout: Power for rotating drive

SBout: Steam Outlet in Standby Mode

The turbine transforms the thermal energy of steam into mechanical work to drive rotating drive. Turbines in TUPRAS Izmit Refinery are operated in 3 different modes: “ON”, “STANDBY” and “OFF” (0). The mode restriction equation is defined as below:

$$\sum_{m} Mode_{eq_T,m,t} \leq 1 \quad \forall\, eq_T \qquad (105)$$

The steam consumption of the turbine at full load is equal to its design performance in Equation 106. In a turbine, high-pressure steam is extracted to lower pressure steam. The amount of low-pressure steam at the turbine outlet is equal to the amount of high-pressure steam at turbine inlet due to mass balance in Equation 107.

$$V_{plt,TURBINE,u_T,STin,s,t} = Mode_{u_T,m1,t}\, P_{u_T,D} \quad (106)$$

$$V_{plt,TURBINE,u_T,STout,s,t} = V_{plt,TURBINE,u_T,STin,s,t} \quad (107)$$

To ensure rapid automatic starting of the standby turbines, they are kept warm by high-pressure steam flow circulation. The amount of steam consumed by turbine in stand-by mode is equal to a percentage of its design performance at full load.

$$V_{plt,TURBINE,eq_T,SBin,s,t} = Mode_{eq_T,m2,t}\ P_{eq_T,D}\ P_{eq_T,p-SB} \quad (108)$$

$$V_{plt,TURBINE,eq_T,SBout,s,t} = V_{plt,TURBINE,eq_T,SBin,s,t} \quad (109)$$

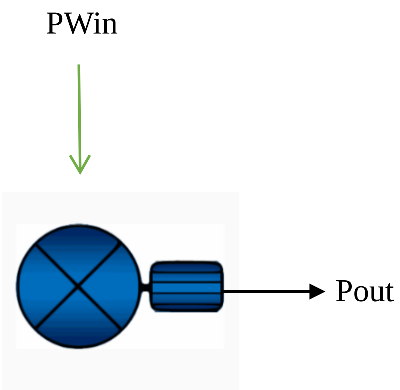

Figure 5.6. Inlet and outlet flows of rolling equipment driven by electricity

PWin: Electricity Inlet

Pout: Power for rotating drive

Electric motors transform electric energy into mechanical energy to rotate drives. There are two operation modes for electric turbines: “ON” (1) and “OFF” (0). Electricity consumption of an operating electric motor is equal to its field consumption or design performance. The mode restriction and electricity consumption model of the motors are described in following equations:

$$Mode_{eq_{EM},m,t} \leq 1 \quad \forall\, eq_{EM} \tag{110}$$

m

$$V_{plt,MOTOR,eq_{EM},PWin,s,t} = Mode_{eq_{EM},m1,t}\; P_{eq_{EM},D} \tag{111}$$

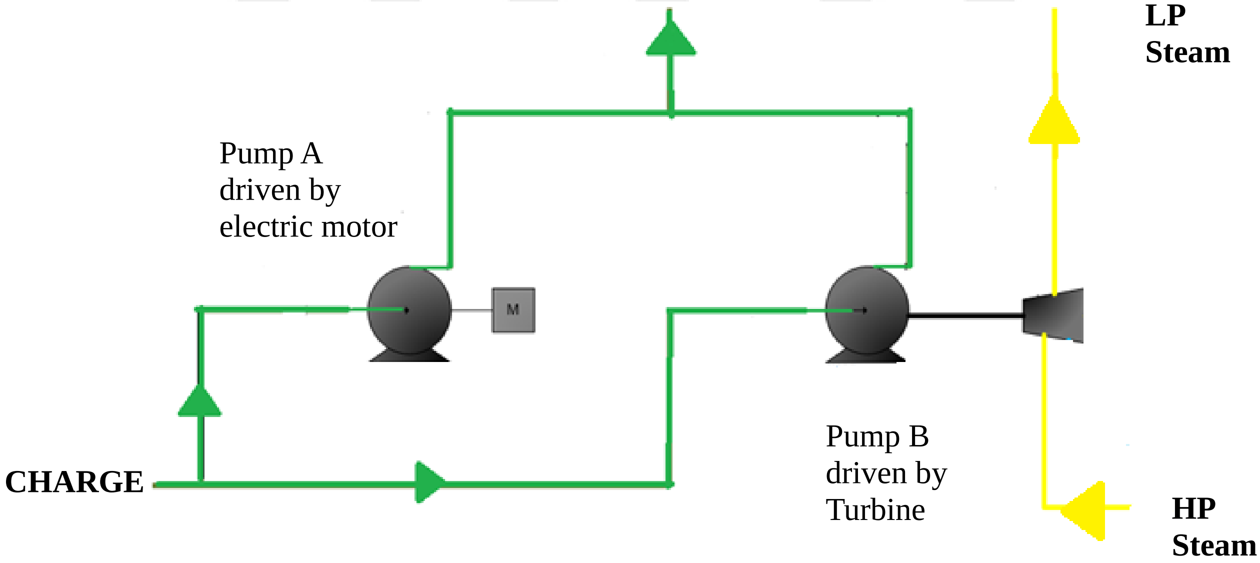

Figure 5.7. Operation of spared pumps

In figure 5.7, transfer operation can be powered by two spared drives, Pump A and Pump B. Pump A is driven by an electric motor, whereas Pump B is driven by a steam turbine. The power rates transferred to the transfer operation “s” by a turbine and an electric motor are stated, respectively:

$$V_{plt,TURBINE,eq_T,Pout,s,t} = Mode_{eq_T,m1,t}\ P_{eq_T,c-P} \tag{112}$$

$$V_{plt,MOTOR,eq_{EM},Pout,s,t} = Mode_{eq_{EM},m1,t}\ P_{eq_{EM},c-P} \tag{113}$$

Sparing drives allows multiple operational configurations for a shared process. For the least cost operation, it is important to choose the optimal set of drives to operate. The power demand of the transfer operation must also be satisfied in optimum working combination. Therefore the power demand of transfer operation “s” must be fixed as the equation below:

$$V_{plt,POWER,to,out,s,t} = rV_{s,t} \tag{114}$$

In the optimum scenario, the drives which can perform the same transfer operation “s” must at least satisfy its power demand:

$$\underset{s}{} V_{plt,g,eq_D,Pout,s,t} \geq V_{plt,POWER,to,out,s,t} \qquad \forall\ eq_D \tag{115}$$

5.2.6.5 Deaerator

Deaerators are used to remove oxygen and various other dissolved gases from BFW before boiler operations by consuming LP steam.

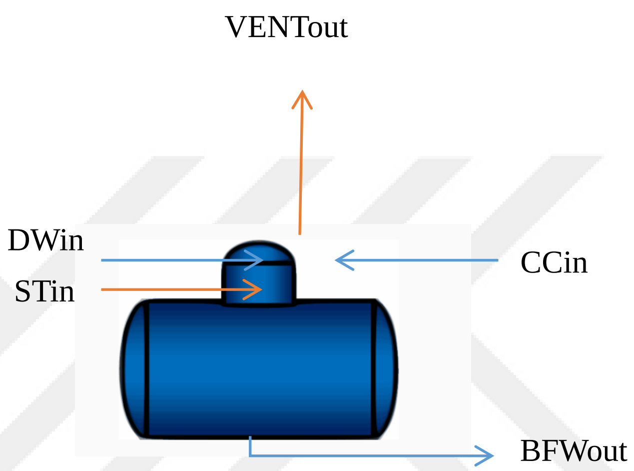

Figure 5.8. Inlet and outlet flows of a deaerator

STin:	Steam Inlet
DWin:	Demineralized Water (DW) Inlet
CCin:	Clean Condensate (CC) Inlet
BFWout:	BFW Outlet
VENTout:	Steam Loss by Vent

Deaerators in TUPRAS Izmit Refinery are operated in 2 different modes: “ON” (1) and “OFF” (0). The mode restriction equation for deaerator eq_{DEA} is defined as below:

$$\sum_{m} Mode_{eq_{DEA},m,t} \leq 1 \quad \forall\, eq_{DEA} \tag{116}$$

LP steam removes oxygen and dissolved gasses in BFW. The gasses passed into the steam is vented to the atmosphere. The ratio between vent steam and inlet LP steam is taken as constant ($P_{eq_{DEA},c-VENT}$). The mass balance equation over the deaerator is stated as follows:

$$\begin{aligned} V_{plt,DEA,eq_{DEA},DWin,s,t} + V_{plt,DEA,eq_{DEA},CCin,s,t} + V_{plt,DEA,eq_{DEA},STin,s,t} \\ = V_{plt,DEA,eq_{DEA},STin,s,t}\ P_{eq_{DEA},c-VENT} \\ +\ V_{plt,DEA,eq_{DEA},BFWout,s,t} \end{aligned} \tag{117}$$

The BFW production in the deaerator is limited by the equation below:

$$V_{plt,DEA,eq_{DEA},BFWout,s,t} = \sum_{m} Mode_{eq_{DEA},m,t}\ P_{eq_{DEA},BFWMAX} \tag{118}$$

Steam consumption model in the deaerator is stated in the following equation:

$$\begin{aligned} V_{plt,DEA,eq_{DEA},STin,s,t} \\ = V_{plt,DEA,eq_{DEA},DWin,s,t}\ P_{eq_{DEA},c_{STin-DW}} \\ + V_{plt,DEA,eq_{DEA},CCin,s,t}\ P_{eq_{DEA},c_{STin-CC}} \\ + \sum_{m} Mode_{eq_{DEA},m,t}\ P_{eq_{DEA},c_{STin-0}} \end{aligned} \tag{119}$$

5.2.6.6 Pressure Reducing Stations

Pressure reducing stations (PRS) decrease the pressure of steam generated by steam boilers to levels required in process operations.

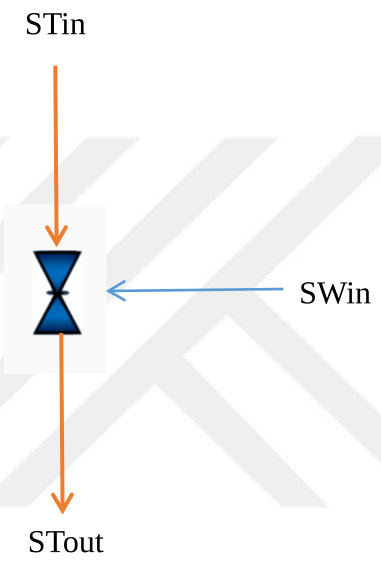

Figure 5.9. Inlet and outlet flows of a PRS

STin: Steam Inlet

STout: Steam Out

SWin: Spray Water Inlet

Steam passing through the PRS is limited in Equation 120:

$$V_{plt,PRS,eq_{PRS},STin,s,t} \leq P_{eq_{PRS},STin-MAX} \quad (120)$$

The outlet steam temperature is controlled by spray water. Evaporation of the water reduces the steam temperature, as they are brought in direct contact. The spray water injection is modelled in Equation 121:

$$V_{plt,PRS,eq_{PRS},SWin,s,t} = V_{plt,PRS,eq_{PRS},STin,s,t} \frac{h_{PRS,eq_{PRS},STin} - h_{PRS,eq_{PRS},STout}}{h_{PRS,eq_{PRS},STout} - h_{PRS,eq_{PRS},WATERin}} \quad (121)$$

5.2.6.7 Heat Exchangers

In utility operations, fuel and BFW streams are heated in heat exchangers by thermal energy of steam before boiler and HRSG operations. By increasing fuel temperature, an efficient combustion reaction is obtained. Additionally, for fuel oil combustion, preheating prevents freezing oil in the pipes. Preheating the BFW increases efficiency as well since less energy is required to heat water to steam.

As a result of optimization in energy network, refinery utility demand is satisfied in different equipment combinations, which changes the BFW and fuel consumption. Therefore, steam used in preheating of fuel and BFW changes as well. To determine steam production in optimum case, heat exchanger models are included in the optimization algorithm.

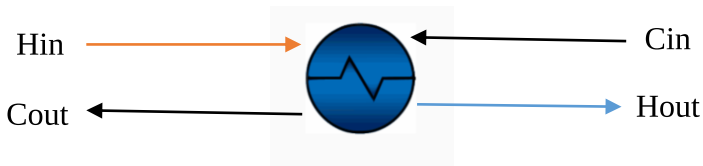

Figure 5.10. Inlet and outlet flows of a heat exchanger

Hin: Heating stream at heat exchanger inlet

Hout: Heating stream at heat exchanger outlet

Cin: Cold stream at heat exchanger inlet

Cout: Cold stream at heat exchanger outlet

The amount of steam required to heat the cold stream from $T_{HEX,eq_{HEX}COLDin}$ to $T_{HEX,eq_{HEX},COLDout}$ is calculated as below:

$$V_{plt,HEX,eq_{HEX},Hin,s,t} = V_{plt,HEX,eq_{HEX},Cin,s,t} \frac{c_{p\ HEX,eq_{HEX},C} \quad T_{HEX,eq_{HEX},COLDout} - T_{HEX,eq_{HEX}COLDin}}{(h_{HEX,eq_{HEX},HOTin} - h_{HEX,eq_{HEX},HOTout})} \tag{122}$$

From mass balance, the amount of cold and hot streams at the heat inlet are equal to the amounts at the outlet:

$$V_{plt,HEX,eq_{HEX},Hin,s,t} = V_{plt,HEX,eq_{HEX},Hout,s,t} \tag{123}$$

$$V_{plt,HEX,eq_{HEX},Cin,s,t} = V_{plt,HEX,eq_{HEX},Cout,s,t} \tag{124}$$

5.2.6.8 Furnaces

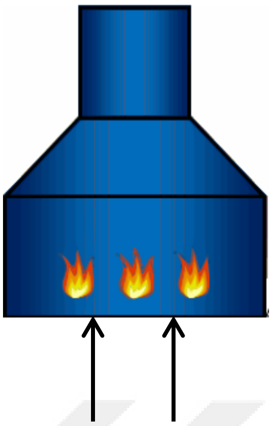

Figure 5.11. Inlet flows of a furnace

FOin: Fuel Oil Inlet

FGin: Fuel Gas Inlet

Furnace operations are taken as fixed operations in optimization algorithm. Therefore, fuel consumption level of each furnace stays constant in optimum case.

$$V_{plt,FURNACE,eq_{FU},FGin,s,t} = rV_{,s,t} \tag{125}$$

$$V_{plt,FURNACE,eq_{FU},FOin,s,t} = rV_{,s,t} \tag{126}$$

5.2.6.9 Waste Heat Boilers (WHB)

Figure 5.12 Outlet flow of a WHB

STout: Steam Outlet

WHB operations are dependent on the process conditions. Therefore, WHB's in the refinery have same steam production in optimum case.

Chapter 6

COMPUTATIONAL RESULTS

In this section, the developed approach is analyzed and tested on real case scenarios of the TUPRAS Izmit Refinery. MILP model scenarios are solved by using GAMS CPLEX solver. The optimization results are compared with the real data of the Refinery. The MILP model contains 10656 equations and 28104 variables.

6.1 Scenario Analysis

In the scope of scenario analysis, 3 different cases are studied. The base case is selected as an hourly real-plant data of the refinery. The online utility demand of the refinery is determined by receiving live plant data for steam, fuel, condensate, BFW, and electric system metering devices via plant information system. The day ahead electricity prices are taken from the web site of EPIAS (Market & Financial Settlement Centre), whereas the fuel prices from the Energy Management Department of TUPRAS. Because of the company y confidentiality, fuel prices and operating costs are not explained in the results. The effect of optimization on the results are given as percentage decrease.

In selected base case, the refinery operates under normal operating conditions, without any process upset. The details of refinery base case for scenarios are listed in Appendix A.

6.1.1 1st Scenario

In the first scenario, the optimized case is generated by fixing the rolling drives and electricity trade. By this way, the steam and electricity demand of the refinery kept fixed and the equipment models are validated. The detailed comparison between the base case and first optimum case scenario (OPT1) is listed in Table A.1 in Appendix A.

Table 6.1 is a summary table containing the equipment whose load vary in OPT1. In OPT1, the BOILER 2, one of the VHP producer, is removed from the operation. The produced VHP is used in steam turbines to generate electricity or in PRS's to produce lower pressure steam. In the base case, all of the VHP steam generated by the BOILER 2 is converted to HP steam in PRS. By shutting down of BOILER 2, the amount of HP steam produced in the PRS is reduced. For electricity generation, the gas turbines in Facility 2 are found more efficient. Therefore load of the gas turbine in Facility1 (G1) is shifted to the gas turbines in Facility 2 (G2 and G3). Additionally, steam productions in the attached HRSG's are also risen due to the increase in loads of the gas turbines in Facility 2. The excess UHP production in Facility 2 is used to generate electricity in STG 4.

Table 6.1 Equipment loads in base case and Opt1

	FACILITY	EQUIPMENT	UNIT	BASE CASE	OPT1	Delta
STEAM	1	**BOILER2**	VHP TON/HR	42.57	0.00	-42.57
		HRSG1	VHP TON/HR	106.76	110.00	3.24
		BOILER6	HP TON/HR	50.38	64.48	14.10
		VHP/HP PRS	HP TON/HR	49.92	8.30	-41.62
		HP/LP PRS	LP TON/HR	0.20	0.00	-0.20
	2	**HRSG-2**	UVHP-RUP TON/HR	103.32	111.90	8.58
		HRSG-3	UVHP-RUP TON/HR	100.68	111.90	11.21

		HP Steam Transfer to Facility 1	HP-RUP TON/HR	30.02	50.00	19.98
		LP Steam Transfer to Facility 1	LP-RUP TON/HR	91.71	92.00	0.29
	1 & 2	**Back Pressure Turbines**	HP TON/HR	291.44	281.64	-9.80
ELECTRICITY	1	**STG1**	MW	7.00	7.65	0.66
		G1	MW	42.03	28.06	-13.97
	2	**G2**	MW	31.94	38.74	6.79
		G3	MW	34.02	38.74	4.72
		STG4	MW	18.99	20.79	1.80

In OPT1, total fuel gas consumption in the utility plants is decreased, while total natural gas consumption is increased. In Opt1, fuel oil is not burnt in the boilers of utility plants. Table 6.2 summarizes total fuel consumptions in the utility plants for the base case and Opt1. Furnace operations in the refinery are taken as the fixed operations in optimization algorithm, so the fuel consumption level of each furnace remains constant.

Table 6.2. Total fuel consumption in base case and Opt1

	UNIT	**BASE CASE**	**OPT1**	**Delta**
Total FG Consumption in Utility Plants	TON/HR	9.57	8.29	-1.28
Total NG Consumption in Utility Plants	TON/HR	27.20	27.76	0.56
Total FO Consumption in Utility Plants	TON/HR	0	0	0

Greenhouse gases are formed by combustion of the fossil fuels. These gasses (CO_2 ,SO_2 and $NO_{x)}$ absorb radiation and cause climate change. There are some regulations and limits determined by government to control the green gas emissions of industrial facilities. Refineries and utility plants are one of the main sources of green gas emissions.

The composition of each fuel type consumed for utility production is determined by the laboratory analysis in the refinery. The online laboratory analysis report in the data acquisition system gives the information of volumetric ratio of each component in the fuel. The volumetric sulphur (S) and carbon (C) ratio are represented by $\boldsymbol{vol}\%_{\boldsymbol{S,FUEL}}$ and $\boldsymbol{vol}\%_{\boldsymbol{C,FUEL}}$ respectively. Based on the combustion reaction the SO_2 and CO_2 production and fuel ratios are calculated as following:

$$\frac{m_{SO_2}}{m_{FUEL}} = vol\%_{S,FUEL} \frac{1}{1} \frac{MW_{SO_2}}{MW_S} \tag{127}$$

$$\frac{m_{CO_2}}{m_{FUEL}} = vol\%_{C,FUEL} \frac{1}{1} \frac{MW_{CO_2}}{MW_S} \tag{128}$$

By optimizing the energy operations, less fuel is used to satisfy the energy demand of the refinery. The total energy of consumed fuel in the utility plants is decreased from 427.53 Gcal/HR to 418.97 Gcal/HR. The decrease in the fuel consumption level reduces CO2 and SO2 emissions as well. The emission rates are calculated by using $\left(\frac{m_{SO_2}}{m_{FUEL}}\right)$ and $\left(\frac{m_{CO_2}}{m_{FUEL}}\right)$ for each type of fuel. In the base case, the FG does not have any sulfur content. Additionally, FO is not burnt in the boilers in the base case and in Opt1. Therefore, there is no SO2 emission from utility plants. CO_2 emission level is reduced from 101.1 TON/HR to 99.1 TON/HR by optimization study.

The objective of the optimization model is operational cost minimization in energy production. Operational cost consists of demineralized water production cost and fuel cost consumed in the energy production. In the first scenario, the overall saving is achieved as 2.512 %.

6.1.2 2nd Scenario

For process continuity, most of the refineries prefer to generate the electricity in their own utility plants. Exchange of electricity with the national grid, TEIAS, is also one of the options to meet the demand. The second scenario is studied to determine the impact of electricity trade. The optimized case (Opt 2) is generated by just fixing the rolling drives. The electricity trade price at the time of base case is taken from the web site of EPIAS. In Appendix A, Table A.2 represents the detailed configuration of the base case and second optimum case scenario (Opt 2).

In table 6.3, load variations of the equipment are listed. The utility demand of the refinery is the same, however, depending on the electricity price, the optimization algorithm decides how much electricity to buy or sell. Combinations and loads of the equipment for electricity production are changed in case of purchase or sales. For scenario 2, the electricity trade price is determined as 110 TL. In Opt 2, the steam production equipment have the same level of production, like in Opt 1. Since the steam demand of the refinery stays constant. As it is mentioned in the first scenario, G2 and G3 are more efficient than G1. In the optimum case, electricity sales to the national grid are increased by 2.5 MW. G2 and G3 are loaded fully to provide this excess 2.5 MW. G1 and steam turbines in the refinery have the same level of production.

	FACILITY	EQUIPMENT	UNIT	BASE CASE	OPT2	Delta
STEAM	1	**BOILER2**	VHP TON/HR	42,57	0,00	-42,57
		HRSG1	VHP TON/HR	106,76	110,00	3,24
		BOILER6	HP TON/HR	50,38	64,48	14,10
		VHP/HP PRS	HP TON/HR	49,92	8,30	-41,62
		HP/LP PRS	LP TON/HR	0,20	0,00	-0,20
	2	**HRSG-2**	UVHP-RUP TON/HR	103,32	111,90	8,58
		HRSG-3	UVHP-RUP TON/HR	100,68	111,90	11,21
		HP Steam Transfer to Facility 1	HP-RUP TON/HR	30,02	50,00	19,98
		LP Steam Transfer to Facility 1	LP-RUP TON/HR	91,71	92,00	0,29
	1 & 2	**Back Pressure Turbines**	HP TON/HR	291,44	281,64	-9,80
ELECTRICITY	1	**STG1**	MW	7,00	7,65	0,66
		G1	MW	42,03	28,06	-13,97
	2	**G2**	MW	31,94	40,00	8,06
		G3	MW	34,02	40,00	5,98
		STG4	MW	18,99	20,79	1,80
	GRID	**ELECTRICITY SELL**	MW	10,98	13,50	2,50

Table 6.3. Equipment loads in base case and Opt2

Total fuel load variations in the utility plants are listed in Table 6.4. G2 and G3 are fully loaded to provide electricity, so the natural gas consumptions of these gas turbines increase. Therefore, more natural gas is consumed in Opt 2 compared to Opt1. However, the HRSG's attached to G2 and G3 produce the same level of steam in Opt 1 and Opt 2. Therefore, in Opt2 less FG is consumed at the supplementary firing burners of HRSG's to keep the steam production level.

Table 6.4. Total fuel consumption in base case and Opt2

	UNIT	BASE CASE	OPT2	Delta
Total FG Consumption in Utility Plants	TON/HR	9.57	8.16	-1.41
Total NG Consumption in Utility Plants	TON/HR	27.20	28.15	0.95
Total FO Consumption in Utility Plants	TON/HR	0	0	0

The total energy of consumed fuel in the utility plants is 427.53 Gcal/HR in the base case. It is decreased to 421.8 Gcal/HR in Opt 2. Additionally, CO2 emission level is reduced from 101.1 TON/HR to 99.9 TON/HR. Total operating cost of the energy production is decreased by 2.75 %.

A sensitivity analysis study is carried out to examine the effect of the electricity price on the electricity trade in more detail. The maximum electricity trade limits for buying and selling are determined as 15 MW. The optimization model is utilized for electricity prices between 80 and 135 TL/MW.

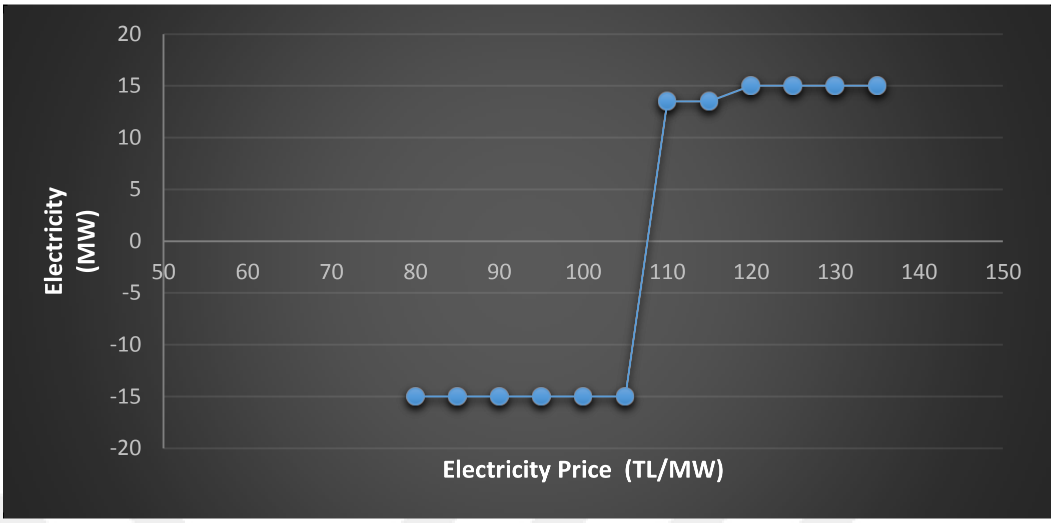

Figure 6.1 Electricity Trade vs Electricity Price

Figure 6.1 shows the optimum amount of electricity purchased or sold at the corresponding electricity price. It is more profitable to buy electricity from the national grid for the prices under the approx. 105 TL/MW.

G2 and G3 generate electricity more efficiently than G1. For this reason, the amount of purchasing electricity is profitable up to a level between the prices 105 TL/MW and 115 TL/MW. For prices over 120 TL/MW, it is profitable to receive maximum amount of electricity from the national grid.

6.1.3 3rd Scenario

In the third scenario, the rolling equipment are involved in the optimization algorithm. Sparing rolling drives allows multiple operational configurations. For the least cost operation, it is important to choose the optimal set of drives to operate. Switching sparing drives for optimization changes the steam and electricity demand of the refinery. Additionally, the electricity trade is not fixed in the 3rd scenario, either. The detailed comparison between the base case and third optimum case scenario (OPT3) is listed in Table A.3 in Appendix A.

Table 6.5 is a summary table including the equipment whose load change in OPT3. In the optimum case, the VHP steam production rate in BOILER 2 is increased. Most of the excess VHP steam is used in STG1 to increase the electricity production. BOILER 6, one of the HP producer, is removed from the operation. Additionally, 9 rolling drives powered by steam are switched by the ones powered by electricity. Thus, The electricity demand of the refinery increased by 0.49 MW, while HP steam demand decrease by 44.88 TON/HR. The switched turbines are kept on STANDBY mode in OPT3 to be started fast in case of emergency. Since BOILER 6 is not operated in the optimization, the air fan of the Boiler 6 (M-10) is removed from the operation, as well. The detailed list of the switched rolling drives are given in Table A.4 in Appendix A. Additionally, in the optimum case, electricity sales to the national grid are increased by 2.5 MW.

Table 6.5 Total fuel consumption in base case and Opt3

	FACILITY	EQUIPMENT	UNIT	BASE CASE	OPT3	Delta
STEAM	1	**BOILER2**	VHP TON/HR	42.57	57.54	15.00
		HRSG1	VHP TON/HR	106.76	110.00	3.24
		BOILER6	HP TON/HR	50.38	0.00	-50.38
		VHP/MP PRS	HP TON/HR	49.9	58.0	8.1
		HP/MP PRS	MP TON/HR	0.00	1.00	1.00
		HP/LP PRS	LP TON/HR	0.20	20.61	20.41
	2	**HRSG-2**	UVHP-RUP TON/HR	103.32	111.90	8.58

		HRSG-3	UVHP-RUP TON/HR	100.68	111.90	11.21
		HP Steam Transfer to Facility 1	HP-RUP TON/HR	30.02	50.00	19.98
		LP Steam Transfer to Facility 1	LP-RUP TON/HR	91.71	92.00	0.29
	1 & 2	**Back Pressure Turbines**	HP TON/HR	291.44	248.19	-43.25
ELECTRICITY	1 & 2	**Electric Motors**	MW	28.39	28.87	0.49
	1	**STG1**	MW	7.00	9.00	2.00
		G1	MW	42.03	27.20	-14.83
	2	**G2**	MW	31.94	40.00	8.06
		G3	MW	34.02	40.00	5.98
		STG4	MW	18.99	20.79	1.80
	GRID	**ELECTRICITY SELL**	MW	10.98	13.50	2.52

In OPT3, total fuel gas consumption in the utility plants is decreased, while total natural gas consumption is increased. CO2 emission level is reduced from 101.1 TON/HR to 98.9 TON/HR by optimization study. Additionally, in the third scenario, the overall saving is achieved as 3.451 %.

Table 6.6 Total fuel consumption in base case and Opt3

	UNIT	**BASE CASE**	**OPT3**	**Delta**
Total FG Consumption in Utility Plants	TON/HR	9.57	7.9	-1.67
Total NG Consumption in Utility Plants	TON/HR	27.20	28.06	0.86
Total FO Consumption in Utility Plants	TON/HR	0	0	0

Chapter 7

CONCLUSION

The main aim of this study is developing a mathematical model for optimization the operations of the complex energy network in the refinery. The problem is formulated as a mixed-integer linear program with the objective function of minimizing the energy production cost. The mathematical model includes all operational constraints, mass and energy balances, demand satisfaction constraints, efficiency models and operational modes of the equipment in the energy network.

The developed approach is analyzed and tested on real plant data of the TUPRAS Izmit Refinery. The online utility demand of the refinery is determined by receiving live plant data for steam, fuel, condensate, BFW, and electric system metering devices via plant information system. The problem is modeled in GAMS software and solved by CPLEX solver.

In scenario analyses, three optimization studies are completed for a stable base case of the refinery. The main objective of these optimization studies is to validate the accuracy of the developed model and to evaluate the economic impact of the optimization. In addition, a detailed sensitivity analysis study is carried out to examine the effect of the electricity price on the electricity trade. Up to 3.5 % cost reduction is achieved compere to base cases.

BIBLIOGRAPHY

1. Worrell, E. and C. Galitsky, *Energy Efficiency Improvement and Cost Saving Opportunities For Petroleum Refineries.* Ernest Orlando Lawrence Berkeley National Laboratory, 2005. p. 9-17.
2. KOC. *General Information*. 2015; Available from: http://www.koc.com.tr/en-us/activity-fields/sectors/energy/TUPRAS.
3. 22WPC. *Daily Technical Visit- Izmit Crude Oil Refinery*. 2017; Available from: http://www.22wpc.com/files/TUPRAS%20Daily.pdf.
4. Acar, E., *Multi-period MILP Optimization of Utility Plant in a Refinery,* (Unpublished master's thesis) Koc University,Istanbul,Turkey ,2014. p.3-4.
5. ATSDR. *Chemical and Physical Information*, Available from: https://www.atsdr.cdc.gov/toxprofiles/tp75-c3.pdf
6. Ordys A. W, et al., *Modelling and Simulation of Power Generation Plants* 1994, London: Springer-Verlag. p.1-10.
7. Ordys A. W, et al., *Modelling and Simulation of Power Generation Plants* 1994, London: Springer-Verlag. p.144-160.
8. Darwish, M. (2013) *Towards Energy Conservation in Qatar*. Open Journal of Energy Efficiency, **2**, 2013 :p. 180.
9. Narasimharao, V. and R. Kumar, *Thermodynamic Analysis of Triple Pressure Heat Recovery Steam Generator*, International Journal for Innovative Research in Science & Technology , 2015. **30**(2): p. 191.
10. Rahman, M. M., et al., *Thermodynamic performance analysis of gas-turbine power-plant*, International Journal of the Physical Sciences, 2011. **14**(6): p. 3541-3542
11. Al-Fahed, S. F. et al., *The effect of elevated inlet air temperature and relative humidity on cogeneration system.*International Journal of Energy Research, 2009. **33**: p.257-258.

12. Gas Turbine Fuels System Design, Combustion and Operability, Cycrus B Meher- Homji SteadieSeifi, M., et al.,
13. PNL. Lower and Higher Heating Values, Available from: http://hydrogen.pnl.gov/tools/lower-and-higher-heating-values-fuels
14. Decentralized Energy. Optimized solutions for industrial cogen units, Available from: http://www.decentralized-energy.com/articles/print/volume-15/issue-1/features/optimized-solutions-for-industrial-cogen-units.html
15. Steam Turbines Compatibility Mode, Available from: https://tr.scribd.com/document/314230649/13-Steam-Turbines-Compatibility-Mode
16. Thermopedia. Rankine Cycle. 2011; Available from: http://www.thermopedia.com/content/1072/Croxton
17. Moran, M. J., and Shapio, N. M, *Fundamentals Of Engineering Thermodynamics*. 2006: Wiley. p. 327.
18. Moran, M. J., and Shapio, N. M, *Fundamentals Of Engineering Thermodynamics*. 2006: Wiley. p. 330.
19. Moran, M. J., and Shapio, N. M, *Fundamentals Of Engineering Thermodynamics*. 2006: Wiley. p. 336.
20. Kahya, T., *Fault Detection And Data Validation In Refinery Power Production*, (Unpublished master's thesis) METU,Ankara,Turkey, 2014. p.10.
21. HEB, Combustion Analysis, Available from: http://energetika.cvut.cz/files/HEB%20l7.pdf
22. Din Deutsches, Institut Fur Normung E.V.,Acceptance Testing of Steam Generators, DIN 1942: February 1994,; the German standard.
23. Budapest University of Technology and Economics Department of Energy Engineering, *Determination of higher and lower heating value of natural gas*. 2013; Available: ftp://ftp.energia.bme.hu/pub/Measurement_at_Energy_and_Env._Protection_ BMEGEENAG51/Heating%20value.pdf.

24. Bureau of Energy Efficiency, Energy Performance Assessment of Boilers, Available from: https://www.beeindia.gov.in/sites/default/files/4Ch1.pdf

25. Zhang, B. J. and B. Hua, *Effective MILP model for oil Refinery-wide production planning and better energy utilization.* Journal of Cleaner Production, 2007.European Journal of Operational Research, 2008. **15**(5): p. 446.

26. Theodore, L., *Heat transfer applications for the practicing engineer*, Wiley, New Jersey, 2011

27. Perry, R. H., and D. Green, *Perry's Chemical Engineers' Handbook*, McGraw-Hill, 1997

28. Micheletto, S. R., et al., *Operational optimization of the utility system of an oil Refinery.* Computers&Chemical Engineering, 2008. **32**(1): p.174-177.

29. Papoulias, S. R. &Grossmann, I. E., *A structural optimization approach in process synthesis—i. utility systems.* Computers and Chemical Engineering, 1983. 7: p.695 – 706.

30. Hui, C.-W. & Natori, Y., An *industrial application using mixed-integer programming technique: A multi-period utility system model.* Computers & Chemical Engineering, 1996. S20: S1577 – S1582,

31. Bruno, J.C., Fernandez, F., Castells, F. & Grossmann, I.E., *A rigorous MINLP model for the optimal synthesis and operation of utility plants.* Chemical Engineering Research and Design, 1998. 76: p.246-258

32. Iyer, R. R., & Grossmann, I. E., *Optimal multiperiod operational planning for utility systems*. Computers and Chemical Engineering, 1997. 21: p.787–800

33. Papalexandri, K. P., Pistikopoulos, E. N., & Kalitventzeff, B., *Modelling and optimization aspects in energy management and plant operation with variable energy demands—application to industrial problems.* Computers and Chemical Engineering, 1998. 22: p.1319–1333

34. Velasco-Garcia, P., Varbanov P. S., Arellano-Garcia H., and Wozny G. *Utility systems operation*: *Optimisation-based decision making*. Applied Thermal Engineering, 2011. ISSN p.1359-4311

APPENDIX A

Table A. 1. Configuration of base case and Opt 1

		Unit	Base Case	OPT1	Delta
	BOILER1	TON/HR	0.00	0.00	0.00
	BOILER2	TON/HR	42.57	0.00	-42.57
	BOILER3	TON/HR	0.00	0.00	0.00
	BOILER4	TON/HR	0.00	0.00	0.00
	HRSG1	TON/HR	106.76	110.00	3.24
	BOILER5	TON/HR	0.00	0.00	0.00
	BOILER6	TON/HR	50.38	64.48	14.10
	BOILER7	TON/HR	0.00	0.00	0.00
	BOILER8	TON/HR	0.00	0.00	0.00
	VHP/HP PRS	TON/HR	49.92	8.30	-41.62
	MP/LP PRS	TON/HR	0.00	0.00	0.00
	HP/MP PRS	TON/HR	0.00	0.00	0.00
	HP/LP PRS	TON/HR	0.20	0.00	-0.20
	HRSG-2	TON/HR	103.32	111.90	8.58
	HRSG-3	TON/HR	100.68	111.90	11.21
	UHP-RUP/HP-RUP PRS	TON/HR	0.00	0.00	0.00
	UHP-RUP/LP-RUP PRS	TON/HR	0.00	0.00	0.00
	HP-RUP/MP-RUP PRS	TON/HR	29.49	29.49	0.00
	LMP-RUP/P-RUP PRS	TON/HR	0.00	0.00	0.00
	HP Steam Transfer to Facility 1	TON/HR	30.02	50.00	19.98
	LP Steam Transfer to Facility 2	TON/HR	91.71	92.00	0.29
	Back Pressure Turbines	TON/HR	291.44	281.64	-9.80
	Condensate Turbines	TON/HR	77.69	77.69	0.00
	Electric Motors	MW	28.40	28.40	0.00
	STG1	MW	7.00	7.65	0.66
	STG2	MW	0.00	0.00	0.00
	STG3	MW	0.00	0.00	0.00

	G1	MW	42.03	28.06	-13.97
	G2	MW	31.94	38.74	6.79
	G3	MW	34.02	38.74	4.72
	STG4	MW	18.99	20.79	1.80
	ELECTRICITY SALES	MW	10.98	10.98	0.00
	Total Energy of Fuel Consumed	Gcal/h	427.53	418.97	-8.55
	Total FG Burnt in the Utility Plants	TON/HR	9.57	8.29	-1.28
	Total NG Burnt in the Utility Plants	TON/HR	27.20	27.76	0.56
	Total FO Burnt in the Utility Plants	TON/HR	0	0	0
	Total Gain	%	2.521		

Table A. 2. Configuration of base case and Opt 2

		Unit	Base Case	OPT2	Delta
	BOILER1	TON/HR	0.00	0.00	0.00
	BOILER2	TON/HR	42.57	0.00	-42.57
	BOILER3	TON/HR	0.00	0.00	0.00
	BOILER4	TON/HR	0.00	0.00	0.00
	HRSG1	TON/HR	106.76	110.00	3.24
	BOILER5	TON/HR	0.00	0.00	0.00
	BOILER6	TON/HR	50.38	64.48	14.10
	BOILER7	TON/HR	0.00	0.00	0.00
	BOILER8	TON/HR	0.00	0.00	0.00
	VHP/HP PRS	TON/HR	49.92	8.30	-41.62
	MP/LP PRS	TON/HR	0.00	0.00	0.00
	HP/MP PRS	TON/HR	0.00	0.00	0.00
	HP/LP PRS	TON/HR	0.20	0.00	-0.20
	HRSG-2	TON/HR	103.32	111.90	8.58
	HRSG-3	TON/HR	100.68	111.90	11.21

	UHP-RUP/HP-RUP PRS	TON/HR	0.00	0.00	0.00
	UHP-RUP/LP-RUP PRS	TON/HR	0.00	0.00	0.00
	HP-RUP/MP-RUP PRS	TON/HR	29.49	29.49	0.00
	LMP-RUP/P-RUP PRS	TON/HR	0.00	0.00	0.00
	HP Steam Transfer to Facility 1	TON/HR	30.02	50.00	19.98
	LP Steam Transfer to Facility 2	TON/HR	91.71	92.00	0.29
	Back Pressure Turbines	TON/HR	291.44	281.64	-9.80
	Condensate Turbines	TON/HR	77.69	77.69	0.00
	Electric Motors	MW	28.40	28.40	0.00
	STG1	MW	7.00	7.65	0.66
	STG2	MW	0.00	0.00	0.00
	STG3	MW	0.00	0.00	0.00
	G1	MW	42.03	28.06	-13.97
	G2	MW	31.94	40.00	8.06
	G3	MW	34.02	40.00	5.98
	STG4	MW	18.99	20.79	1.80
	ELECTRICITY SALES	MW	10.98	13.50	2.53
	Total Energy of Fuel Consumed	Gcal/h	427.53	421.80	-5.73
	Total FG Burnt in the Utility Plants	TON/HR	9.57	8.16	-1.41
	Total NG Burnt in the Utility Plants	TON/HR	27.20	28.15	0.95
	Total FO Burnt in the Utility Plants	TON/HR	0	0	0
	Total Gain	%	2.75		

Table A. 3. Configuration of base case and Opt 3

		Unit	Base Case	OPT3	Delta
	BOILER1	TON/HR	0.00	0.00	0.00
	BOILER2	TON/HR	42.57	57.54	15.00
	BOILER3	TON/HR	0.00	0.00	0.00
	BOILER4	TON/HR	0.00	0.00	0.00
	HRSG1	TON/HR	106.76	110.00	3.24
	BOILER5	TON/HR	0.00	0.00	0.00

	BOILER6	TON/HR	50.38	0.00	-50.38
	BOILER7	TON/HR	0.00	0.00	0.00
	BOILER8	TON/HR	0.00	0.00	0.00
	VHP/HP PRS	TON/HR	0.00	0.00	0.00
	MP/LP PRS	TON/HR	0.00	0.00	0.00
	HP/MP PRS	TON/HR	0.00	1.00	1.00
	HP/LP PRS	TON/HR	0.20	20.61	20.41
	HRSG-2	TON/HR	103.32	111.90	8.58
	HRSG-3	TON/HR	100.68	111.90	11.21
	UHP-RUP/HP-RUP PRS	TON/HR	0.00	0.00	0.00
	UHP-RUP/LP-RUP PRS	TON/HR	0.00	0.00	0.00
	HP-RUP/MP-RUP PRS	TON/HR	29.49	29.49	0.00
	LMP-RUP/P-RUP PRS	TON/HR	0.00	0.00	0.00
	HP Steam Transfer to Facility 1	TON/HR	30.02	50.00	19.98
	LP Steam Transfer to Facility 2	TON/HR	91.71	92.00	0.29
	Back Pressure Turbines	TON/HR	291.44	248.19	-43.25
	Condensate Turbines	TON/HR	77.69	77.69	0.00
	Electric Motors	MW	28.40	29.00	0.49
	STG1	MW	7.00	9.00	2.00
	STG2	MW	0.00	0.00	0.00
	STG3	MW	0.00	0.00	0.00
	G1	MW	42.03	27.20	-14.83
	G2	MW	31.94	40.00	8.06
	G3	MW	34.02	40.00	5.98
	STG4	MW	18.99	20.79	1.80
	ELECTRICITY SALES	MW	10.98	13.50	2.52
	Total Energy of Fuel Consumed	Gcal/h	427.53	417.62	-9.91
	Total FG Burnt in the Utility Plants	TON/HR	9.57	7.9	-1.67
	Total NG Burnt in the Utility Plants	TON/HR	27.20	28.06	0.86
	Total FO Burnt in the Utility Plants	TON/HR	0	0	0
	Total Gain	%	3.451		

Table A. 4. Switched rolling equipment in Opt 3

EQP NAME	REFINERY MODE	OPT ACTION	DELTA PW CHANGE (MW)	EQP NAME	OPT ACTION	REFINERY MODE	DELTA STEAM CHANGE (TON/HR)
M-1	OFF	ON	0.14	T-1	OFF	ON	-5.64
M-2	OFF	ON	0.13	T-2	OFF	ON	-5.86
M-3	OFF	ON	0.07	T-3	OFF	ON	-3.11
M-4	OFF	ON	0.13	T-4	OFF	ON	-6.89
M-5	ON	ON	0.05	T-5	OFF	ON	-3.27
M-6	OFF	ON	0.10	T-6	OFF	ON	-4.76
M-7	OFF	ON	0.05	T-7	OFF	ON	-2.89
M-8	OFF	ON	0.06	T-8	OFF	ON	-3.75
M-9	OFF	ON	0.15	T-9	OFF	ON	-8.71
M-10	OFF	ON	-0.39				
TOTAL		0.49 MW		TOTAL		44.88 TON/HR	

VITA

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