ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Kasım ZOR

DEVELOPING A SOFTWARE PROGRAM TO DETERMINE THE OPTIMAL CAPACITY RATING OF COGENERATION AND TRIGENERATION PLANTS DRIVEN BY GAS ENGINES FOR UNLICENSED GENERATION OF ELECTRICITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

ADANA, 2015

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 14/01/2015.

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ABSTRACT

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Internal combustion engine based cogeneration and trigeneration plants are capable of producing several energy types from a single fuel input simultaneously, and an increase in the number of cogeneration and trigeneration plants especially in hotels, hospitals and industrial facilities day by day has strengthened the role of cogeneration and trigeneration plants in the study of energy efficiency and distributed generation. In addition to those, realization of license exemption for facilities want to produce electricity just for their energy demands by ensuring the condition of 80% total efficiency, low carbon emission of systems contain gas engines, rapid operation for synchronization and shortness of payback periods make cogeneration and trigeneration plants popular in recent years.

In this thesis, fundamentals containing calculations, synchronization methods, actual legislation, and current status in Turkey of gas engine driven cogeneration and trigeneration plants have been investigated in detail, an investment payback period analysis for a University Hospital cogeneration and trigeneration plant has been performed as a case study, and a software program has been developed with proposing a methodology in order to determine the selection of the optimal capacity rating fulfilling unlicensed generation of electricity criteria of EMRA by providing maximum efficiency.

With the designed software program, it is expected to prevent from unproductive plants due to inaccurate sizing and extra costs by contributing the national economy positively. Besides, the energy efficient conversion of natural gas into electricity, heating and cooling will be achieved by selecting optimal capacity of the cogeneration or trigeneration plant.

Key Words: Cogeneration, Trigeneration, Energy Efficiency, Distributed Generation, Software Development.

ÖZ

YÜKSEK LİSANS TEZİ

GAZ MOTORLARI TARAFINDAN TAHRİK EDİLEN KOJENERASYON VE TRİJENERASYON SANTRALLERİNİN LİSANSSIZ ELEKTRİK ÜRETİMİ İÇİN EN UYGUN KAPASİTE DEĞERİNİ BELİRLEYEN YAZILIM PROGRAMININ GELİŞTİRİLMESİ

Kasım ZOR

ÇUKUROVA ÜNİVERSİTESİ
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İçten yanmalı gaz motorları ile eş zamanlı olarak doğal gazdan birden fazla enerji tipinin birlikte üretildiği kojenerasyon ve trijenerasyon santrallerinin, özellikle oteller, hastaneler ve sanayi tesislerinde sayılarının gün geçtikçe artması, bu sistemlerin enerji verimliliği ve dağınık üretim çalışmalarındaki rolünü güçlendirmiştir. Ayrıca, EPDK'nın %80 verimlilik şartını yerine getiren ve sadece kendi ihtiyaçları için elektrik üretmek isteyen tesislere lisans muafiyeti getirmesi, gaz motorlu sistemlerin karbon salınımının az olması, devreye girme sürelerinin hızlı olması ve geri ödeme sürelerinin kısalığı, kojenerasyon ve trijenerasyon santrallerinin son dönemlerde ilgi odağı haline gelmesini sağlamıştır.

Bu tezde, ülkemizde yaygın bir şekilde kullanılan ve önümüzdeki yıllarda da kullanılacağı öngörülen gaz motoru tahrikli kojenerasyon ve trijenerasyon santrallerine ait hesaplamaları içeren temeller, senkronizasyon yöntemleri, güncel mevzuat ve Türkiye'deki mevcut durumu detaylı incelenmiş, bir Üniversite Hastanesi için yatırım geri dönüş süresi analizi yapılmış, EPDK mevzuatındaki lisanssız elektrik üretimi kriterlerini karşılayarak maksimum verimle kullanılabilmesine olanak sağlayacak en uygun kapasite değerinin belirlenmesi amacıyla bir metodoloji önerilerek yazılım geliştirilmiştir.

Hazırlanan yazılım ile, hatalı kapasite seçimi durumunda verimsiz çalışacak atıl tesislere ve meydana gelecek ekstra maliyetlere engel olunarak ülke ekonomisine katkıda bulunacağı öngörülmektedir. Ayrıca en uygun kojenerasyon veya trijenerasyon santral kapasitesi değerinin belirlenmesiyle büyük ölçüde ithal edilen doğal gazın en verimli şekilde elektrik, ısı ve soğutmaya dönüşümü sağlanmış olacaktır.

Anahtar Kelimeler: Kojenerasyon, Trijenerasyon, Enerji Verimliliği, Dağınık Üretim, Yazılım Geliştirme.

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LIST OF SYMBOLS

ACS	: Absorption Chiller Saving
AS	: Aftercooler Saving
Av	: Availability
$c_{cchp(opt)}$	: Optimal Capacity Rating for Trigeneration Plant
$c_{chp(opt)}$	: Optimal Capacity Rating for Cogeneration Plant
c_e	: Electrical Capacity Rating
c_h	: Heat Capacity Rating
CE	: Cogeneration Plant Expense
CS	: Cogeneration Plant Saving
EJWS	: Exhaust and Jacket Water Saving
ES	: Electrical Saving
F	: Input Fuel
F_c	: Fuel Consumption
FCE	: Fuel Consumption Expense
h	: Hour
HS	: Heat Saving
Hz	: Frequency
IECE	: Internal Electrical Consumption Expense
JWS	: Jacket Water Saving
kV	: Kilovolt
kVA	: Kilovolt-Ampere
kW	: Kilowatt
kWh	: Kilowatthour
L_{min}	: Minimum Load for Plant Operation
lb	: Libra
lb/MWh	: Libra per Megawatthour
LHV	: Lower Heating Value
m^3	: Cubic meter
min	: Minute

MW	: Megawatt
MWh	: Megawatthour
p_e	: Unit Price of Electricity Generation by Natural Gas in a Cogeneration or Trigeneration Plant
$p_{g,16}$	: Unit Price of Grid Electricity for Daytime and Primetime Periods
$p_{g,24}$	: Unit Price of Grid Electricity
p_{ng}	: Unit Price of Natural Gas
ppm	: Parts per Million
P	: Electrical Power
P_{aux}	: Electrical Power of Auxiliary Equipment
$P_{c(\min)}$	: Electric Demand Corresponding of Minimum Cooling Demand
P_{ecu}	: Absorption Chiller Unit Corresponding of Electric Chiller Unit
$PESR$	: Primary Energy Savings Ratio
$P_{h(\min)}$	: Electric Demand Corresponding of Minimum Heat Demand
P_{ins}	: Installed Power
P_{max}	: Maximum Electric Demand
P_{min}	: Minimum Electric Demand
P_{net}	: Net Electrical Output Power (Internal consumption excluded)
P_t	: Useful Thermal Power
$P_{t(a)}$	: Aftercooler Thermal Output Power
$P_{t(ejw)}$	: Exhaust and Jacket Water Thermal Output Power
$P_{t(exh)}$	: Exhaust Thermal Output Power
$P_{t(jw)}$	: Jacket Water Thermal Output Power
Ra	: Reliability
OE	: Operator Expense
S	: Scheduled Maintenance Time
sec	: Second
SS	: Steam Saving
SSE	: Service and Spare Part Expense
T	: Time for the Operation Hour of the Plant
TE	: Trigeneration Plant Expense

THS : Trigeneration Plant Heat Saving

TR : Total Revenue

TS : Trigeneration Plant Saving

U : Unscheduled Maintenance Time

UF : Utilization Factor

V : Volt

η_b : Boiler Effiency

η_e : Electrical Effiency

η_{exc} : Exchanger Effiency

$\eta_{exc(a)}$: Aftercooler Exchanger Effiency

$\eta_{exc(jw)}$: Jacket Water Exchanger Effiency

η_t : Thermal Effiency

η_o : Overall Effiency

η_{spe} : Efficiency for the Separate Production of Electricity

η_{sph} : Efficiency for the Separate Production of Heat

¢ : US cent

$: US Dollar

LIST OF ABBREVATIONS

^0C	: Centigrade Degrees
ASHVE	: American Society of Heating and Ventilating Engineers
ASHRAE	: American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BCHP	: Building Combined Heat and Power
BEA	: Building Energy Analyzer
BSc	: Bachelor of Science
BTU	: British Thermal Unit
CCHP	: Combined Cooling, Heat and Power (Trigeneration)
CHP	: Combined Heat and Power (Cogeneration)
CO	: Carbon Monoxide
CODE	: Cogeneration Observatory and Dissemination Europe
Cont.	: Continuous
COP	: Coefficient of Performance
CO_2	: Carbon Dioxide
CS	: Compressor Station
DOE	: US Department of Energy
EEE	: Electrical and Electronics Engineering
EMRA	: Republic of Turkey Energy Market Regulatory Authority
EPA	: US Environmental Protection Agency
ET AL	: And Others
E.G.	: For Example
GE	: General Electric
GHG	: Greenhouse Gas
HP	: High Pressure
HT	: High Temperature
HV	: High Voltage
HVAC	: Heating, Ventilating, and Air Conditioning
IC	: Internal Combustion

ICE	: Internal Combustion Engine
IEEE	: Institute of Electrical and Electronics Engineers
JCI	: Joint Commission International
LHV	: Lower Heating Value
LP	: Low Pressure
LT	: Low Temperature
LV	: Low Voltage
MCCB	: Molded Case Circuit Breaker
MSc	: Master of Science
NCV	: Net Calorific Value
NG	: Natural Gas
NH_3	: Ammonia
NOx	: Nitrogen Oxides
NREL	: US National Renewable Energy Library
O_2	: Oxygen
ORNL	: Oak Ridge National Laboratory
PESR	: Primary Energy Savings Ratio
PhD	: Doctor of Philosophy
PM	: Permanent Magnet
PMUM	: Market Financial Settlement Center
PV	: Photovoltaic
RES	: Renewable Energy Sources
SCR	: Selective Catalytic Reduction
SWLF	: Solid Waste Landfill Facility
SOx	: Sulfur Oxides
SO_2	: Sulfur Dioxide
TEIAS	: Turkish Electricity Transmission Company
WWTP	: Waste Water Treatment Plant
YEKDEM	: Mechanism of Supporting Renewable Energy Sources
Y-connected	: Star connected

1. INTRODUCTION

In this chapter, an introduction to the thesis with its general aims, background, research motivation, objectives and disposition, and contributions of the thesis are presented.

1.1. Background and Research Motivation

In recent years, industrial and social facilities are seeking alternative ways to reduce their energy bills by implementing more energy efficient and environmentally friendly systems (Zor and Teke, 2014). When depletion of fossil fuels, global warming and other environmental factors are considered together, reducing energy costs only is not adequate for future generations of humanity and for a sustainable Earth. Thus, studies in the field of energy efficiency and distributed generation systems are encouraged by the idea of cheaper electricity generation with lower carbon emission systems, and utilization of energy on-site with lesser losses (EPA, 2010a).

Cogeneration is the simultaneous production of electric power and usable heat from a single fuel input (Çakir et al., 2012). Similarly, trigeneration concept refers to production of electricity, heat and cooling at the same time. Trigeneration can be seen as an evolution of the cogeneration concept (Chicco and Mancarella, 2006). In Figure 1.1, a conventional system that has a coal fired thermal power plant with an electrical efficiency of 38% and a natural gas fired steam boiler with a thermal efficiency of 90% is compared with a natural gas engine driven cogeneration plant that has an electrical efficiency of 41.33% and a thermal efficiency of 48.59%. For both conventional and cogeneration plants, the produced outputs are the same. As shown in Figure 1.1, separate production consumes more energy than cogeneration (Zor and Teke, 2014).

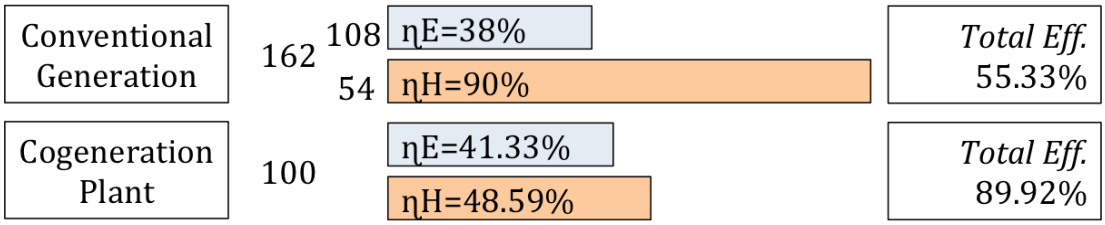


Figure 1.1. Efficiency comparison of conventional and cogeneration plants

Natural gas is a fuel type with low carbon emission and Turkey can be stated as a geographic bridge that connects eastern and western natural gas pipelines due to its strategic location between European Union and Asia. In the past, there were several barriers against encouraging the use of natural gas in Turkey, such as instability of natural gas prices and limitation of natural gas utilization to certain regions. After natural gas pipelines have become widespread all over Turkey, installations of cogeneration plants are becoming very advantageous especially for facilities that need several energy types simultaneously (Zor and Teke, 2013).

In cogeneration and trigeneration plants, mechanical power is produced by prime movers and the produced mechanical power is converted into electric power by synchronous generators. The most common prime mover technologies are internal combustion engine (ICE), gas turbine, fuel cell and microturbine. In Table 1.1, power range, electrical and overall efficiencies of prime mover technologies are indicated (Knowles, 2011).

Table 1.1. Power range and efficiencies of prime mover technologies

Production Technology	Power Range	Electrical Efficiency	Overall Efficiency
ICE	50 kW-5 MW	25-44%	95%
Gas Turbine	500 kW-500 MW	20-45%	80%
Fuel Cell	5 kW-2 MW	30-40%	75%
Microturbine	30 kW-250 kW	25-30%	75%

Table 1.2. Performance characteristics of prime mover technologies

Technology	ICE	Gas Turbine	Fuel Cell	Microturbine
Power/Heat Ratio	0.5-1	0.5-2	1-2	0.4-0.7
Part Load	Ok	Poor	Good	Ok
Availability	92-97%	90-98%	>95%	90-98%
Hours to Overhauls	>50,000	25,000-50,000	32,000-64,000	20,000-40,000
Start-up Time	10 sec	10 min-1 h	3 h-2 days	60 sec
Fuel Pressure (bar)	1.1-4.1	7.9-35.5 (Compressor)	1-4.1	4.5-6.5 (Compressor)
Fuels	Natural Gas, Biogas, Propane, Landfill Gas	Natural Gas, Biogas, Propane, Oil	Hydrogen, Natural Gas, Propane, Methanol	Natural Gas, Biogas, Propane, Oil
Noise	High	Moderate	Moderate	Low
Uses for Thermal Output	Hot Water, LP Steam	Heat, Hot Water, LP-HP Steam	Hot Water, LP-HP Steam	Heat, Hot Water, LP Steam
NO_X (lb/MWh)	2-30	0.3-4	0-0.02	0.4-2.2

In Table 1.2, power/heat ratio, part load, availability, hours to overhauls, start-up time, fuel pressure, fuels, noise, uses for thermal output and NO_x characteristics (Hyman and Stadnik, 2010) of prime mover technologies are shown (EPA, 2010b).

In Table 1.3, advantages and disadvantages of prime mover technologies are indicated (EPA, 2010b).

Table 1.3. Advantages and disadvantages of prime mover technologies

Technology	Advantages	Disadvantages
ICE	• High power efficiency with part-load operational flexibility. • Fast start-up. • Relatively low investment cost. • Can be used in island mode and have good load following capability. • Can be overhauled on-site with normal operators. • Operate on low-pressure gas.	• High maintenance costs. • Limited to lower temperature cogeneration applications. • Relatively high air emissions. • Must be cooled even if recovered heat is not used. • High levels of low frequency noise.
Gas Turbine	• High reliability. • Low emissions. • High-grade heat available. • No cooling required.	• Require high-pressure gas or in house gas compressor. • Poor efficiency at low loading. • Output falls as ambient temperature rises.
Fuel Cell	• Low emissions and low noise. • High efficiency over load range. • Modular design.	• High costs. • Low durability and power density. • Fuels requiring processing unless pure hydrogen is used.
Microturbine	• Small number of moving parts. • Compact size and light weight. • Low emissions. • No cooling required	• High costs. • Relatively low mechanical efficiency. • Limited to lower temperature cogeneration applications.

In this thesis, reciprocating ICE (spark ignited) is chosen as prime mover because of its several advantages listed above. Two types of ICEs have been used in industrial application; spark ignition engines, which are powered mainly by natural gas and compression ignition engines, using diesel fuel, as well as other oil based products, like heavy fuel oil or biodiesel. Reciprocating engines applied in various

ranges of size and are suitable in cogeneration and trigeneration plants. In addition to rapid powering up capability and fair operating reliability, users are provided with high efficiency at partial load operation, making it ideal candidates for distributed generation applications (Shams et al., 2013). An internal combustion gas engine driven cogeneration plant is shown in Figure 1.2 (MTU REPORT, 2014).



Figure 1.2. An internal combustion gas engine driven cogeneration plant

In 1914, German engineers were recovering heat from internal combustion engines to warm factories. Many professional engineering organizations devoted some of their resources to cogeneration systems including the ASHVE, the forerunner to the present day ASHRAE. The first World Power Congress was held in London in 1924, where waste heat utilization was a topic of discussion. A full session was devoted to cogeneration at the second congress in Berlin in 1932 (Meckler and Hyman, 2010).

In 1926, Oscar Faber, a trained structural engineer, won the first contract for his newly formed engineering consultancy. These were times of great unrest with

high unemployment and frequent riots in the streets of London. In the reconstruction of Bank of England in Threadneedle Street, Oscar Faber was asked to install power generation deep inside the building as the Bank feared that the new national grid could be a target in industrial disputes and wished to remove its dependence on external and centralized generation. A state of art diesel engine power plant was installed, but Oscar had to deal with the problem of removal of the waste heat of power generation. Oscar used the waste heat for building heating, created an on-site power cogeneration plant and this was one of the first use of cogeneration in a commercial building (Knowles, 2011).

The first internal combustion gas engine driven cogeneration plant in Turkey was installed in Pisa Textile Factory in Yenibosna, İstanbul in 1995 by Borusan Power Systems with a capacity of 1,020 kW (Okan, 2014).

Gas engine driven cogeneration and trigeneration plants were spread over all regions of Turkey by improvements and extensions in natural gas pipelines, and incentives for biogas applications.

Statistical data, which is stated after this paragraph, is obtained by 4 distributor company installing cogeneration and trigeneration plants in Turkey. Table A.1, Table A.2, Table A.3 (Bayazıt, 2014); Table A.4, Table A.5 (Okan, 2014); Table A.6, Table A.7, Table A.8, Table A.9 (Çakır, 2014); Table A.10, Table A.11, and Table A.12 (Iltekno, 2014) containing the data of installation year, name of the facility, installed power and location of cogeneration and trigeneration plants with respect to manufacturers are given in Appendix A.

Installed natural gas and biogas (In this thesis, biogas and biomass are considered together as biogas) engine based cogeneration and trigeneration plant capacities by January 2015 are 822.020 MW and 199.665 MW respectively. In Figure 1.3, percentile of natural gas and biogas engine based cogeneration and trigeneration plant capacities are indicated.

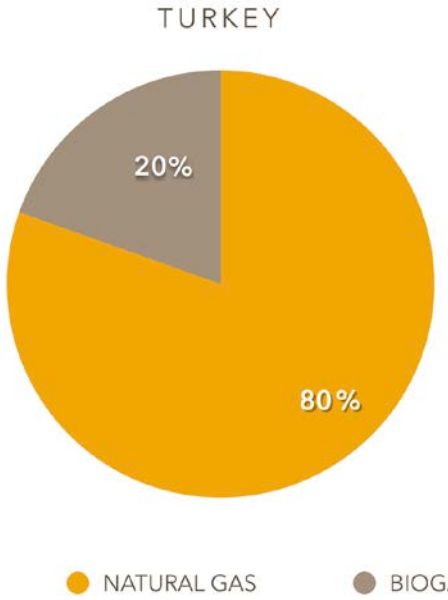


Figure 1.3. Percentile of natural gas and biogas engines in Turkey

Regional capacities of natural gas engine based cogeneration and trigeneration plants in Turkey can be sorted as:

1. Marmara Region 374.629 MW,
2. Mediterranean Region 163.160 MW,
3. Central Anatolia Region 90.965 MW,
4. Southeast Anatolia Region 79.819 MW,
5. Aegean Region 75.379 MW,
6. Black Sea Region 34.630 MW,
7. Eastern Anatolia Region 3.438 MW.

In Figure 1.4, regional capacity of natural gas engine based cogeneration and trigeneration plants in Turkey is shown.

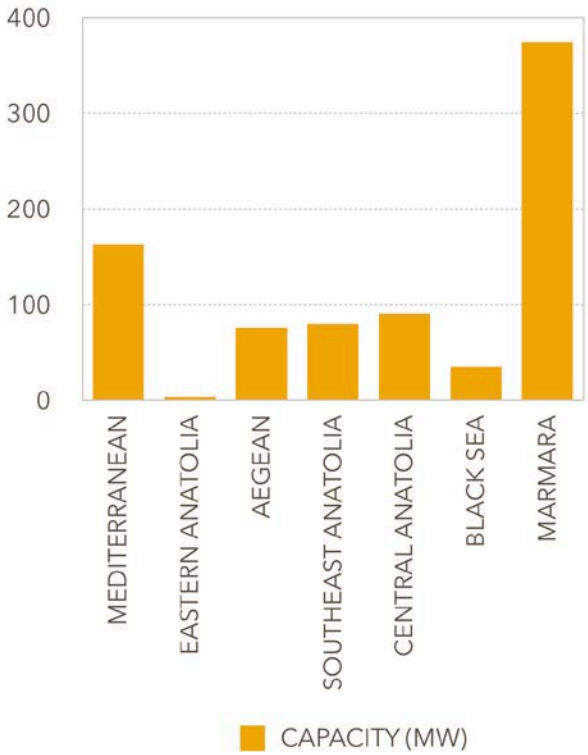


Figure 1.4. Regional capacities of NG engine based plants in Turkey

Regional capacities of biogas engine based cogeneration and trigeneration plants in Turkey can be sorted as:

1. Marmara Region 83.305 MW,
2. Central Anatolia Region 64.948 MW,
3. Mediterranean Region 23.593 MW,
4. Southeast Anatolia Region 8.966 MW,
5. Black Sea Region 7.731 MW,
6. Aegean Region 6.701 MW,
7. Eastern Anatolia Region 4.421 MW.

In Figure 1.5, regional capacity of biogas engine based cogeneration and trigeneration plants in Turkey is indicated.

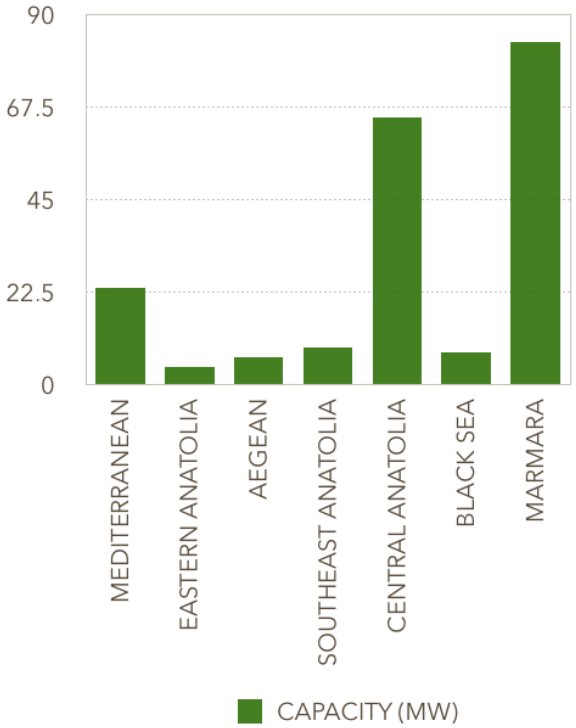


Figure 1.5. Regional capacities of biogas engine based plants in Turkey

Biogas based cogeneration and trigeneration plants can be divided into 3 categories according to biogas production technologies:

1. Landfill Gas 161.598 MW,
2. Raw Material 19.961 MW,
3. Waste Water Treatment 18.106 MW.

In Figure 1.6, percentile of different biogas technologies used in cogeneration and trigeneration plants in Turkey is shown.

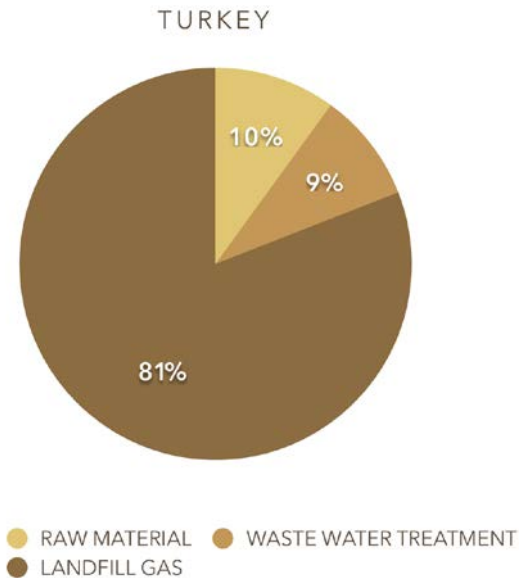


Figure 1.6. Percentile of biogas based plants in Turkey

In 2013, EMRA announced that cogeneration and trigeneration legislation has changed. Autoproducer licenses become void and converted to generation license. Plants with generation licenses can sell energy in the free electricity market over PMUM. A new era has begun with unlicensed electricity generation for facilities that satisfy the condition for overall efficiency of 80%. In the past, autoproducers, who have natural gas engine based cogeneration and trigeneration plants, could sell 20% of produced energy to the grid. But now, it is not possible for natural gas based cogeneration and trigeneration plants without generation license. Biogas engine based cogeneration and trigeneration plants are classified in renewable energy resources, they can sell without limit, and they have incentives for selling energy to the grid with a constant price (Zor and Teke, 2014). For natural gas engine based cogeneration and trigeneration plants without generation licenses, it is vital to determine the optimal capacity rating, because they can not sell surplus energy to the grid.

In this thesis, a software program is developed for satisfying unlicensed electricity generation criteria of EMRA to determine the optimal capacity rating of natural gas engine based cogeneration and trigeneration plants.

1.2. Objectives and Disposition of Thesis

The main objectives of this thesis is as follows:

- To propose a methodology and to develop a software program for satisfying unlicensed electricity generation criteria of EMRA in order to determine the optimal capacity rating of cogeneration and trigeneration plants driven by natural gas fired gas engines.
- To describe fundamentals, grid synchronization, environmental effects, and capacity sizing criteria of gas engine driven cogeneration and trigeneration plants from Electrical and Electronics Engineering's point of view.
- To identify the current status with installed plant information, and legislation of gas engine driven cogeneration and trigeneration plants in Turkey.
- To present a case study contains a feasibility analysis of a University Hospital.
- To present literature survey studies on developing software programs about cogeneration and trigeneration plants.

After an introductory section where the background and research motivation of the study and current status of gas engine driven cogeneration and trigeneration plants in Turkey are introduced, the structure of this thesis is as follows:

In Chapter 2, literature survey studies on developed software programs from 1989 to 2015 are presented.

In Chapter 3, fundamentals, grid synchronization, and environmental effects of gas engine driven cogeneration and trigeneration plants are presented.

In Chapter 4, capacity sizing criteria, flowchart of the proposed methodology and a software program to determine the optimal capacity rating of unlicensed natural gas engine based cogeneration and trigeneration plants are presented.

In Chapter 5, a feasibility analysis for both cogeneration and trigeneration plant scenarios of a University Hospital as a case study is presented.

In Chapter 6, the conclusions, contributions of the thesis and author's recommendations for future works are explained.

Finally, all of the references used in the thesis, biographical information of the author and the Appendix are presented.

1.3. Statement of Contribution to Knowledge

To the author's best knowledge, the followings are original contributions in the thesis:

1- Developed software program in this thesis is the first developed software which determines the optimal capacity rating of gas engine driven cogeneration and trigeneration plants for unlicensed generation of electricity in Turkey. By this program, it is expected to prevent from unproductive plants due to inaccurate sizing and extra costs by contributing the national economy positively.

2- This is the first time in Turkey, a detailed installed plant capacity of gas engine driven cogeneration and trigeneration plants have been identified. Future studies can use these data.

3- Fundamentals, current legislation, synchronization and environmental effects of gas engine driven cogeneration plants for unlicensed generation electricity have been investigated the first time from Electrical and Electronics Engineering's point of view.

4- This thesis contains the first cogeneration and trigeneration plant feasibility study for a University Hospital in Turkey.

2. REVIEW OF RELATED LITERATURE

The research papers and practical studies on developed software programs to determine the optimal capacity rating cogeneration and trigeneration plants are presented in this section. Under the following sections, the latest literatures including research articles, conferences, e-books, company reports, web pages, MSc and PhD theses related with the topic of this thesis are summarized.

2.1. Developed Software Programs in the Literature

COGENMASTER (Limaye and Balakrishnan, 1989) compares CHP alternatives to a base case system where electricity is purchased from the utility and the thermal energy is produced on-site. Different financing strategies can also be considered. The software can be operated under different types of input specifications:

- With a constant average load specified for each hour of the year,
- Hourly data for three typical days of the year,
- Hourly data for three typical days of each month.

BCHP Screening Tool (Fischer and Glazer, 2002) is also a comprehensive detailed hourly simulation program. It is an add-on to DOE 2.1 in that the detailed hourly building loads computed are used to simulate the performance of a CHP plant and compute associated economics. Several databases are in-built:

- Typical Meteorological Year data for 239 cities in the United States,
- Commercial gas and electric rates for 160 cities in the United States,
- Performance and cost for HVAC equipment,
- Performance and cost for power generating equipment,
- Building design parameters.

Various types of reports and outputs in the form of tables and graphs allow easy interpretation and comparison of results. Users can construct a base case and up to 25 alternative scenario for comparison.

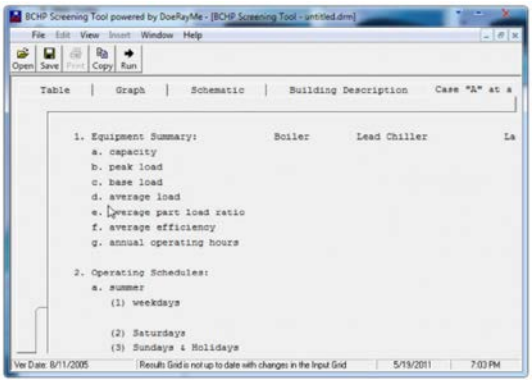


Figure 2.1. Screenshot of BHCP Screening Tool

HOMER Legacy Version 2.0 (HOMER, 2003) is a computer program developed by NREL, meant to evaluate alternative off-grid and grid-connected system options (such as wind, hydro, PV, traditional prime movers, batteries, and hydrogen) for a variety of applications. It uses hourly simulations to evaluate a large number of technology costs, and energy resource availability options. It allows results to be compared based on economic (net present worth) and technical merits. The program also has in-built routines for sensitivity analysis and optimization. HOMER Pro Version 3.0.9 was released in December 2014.

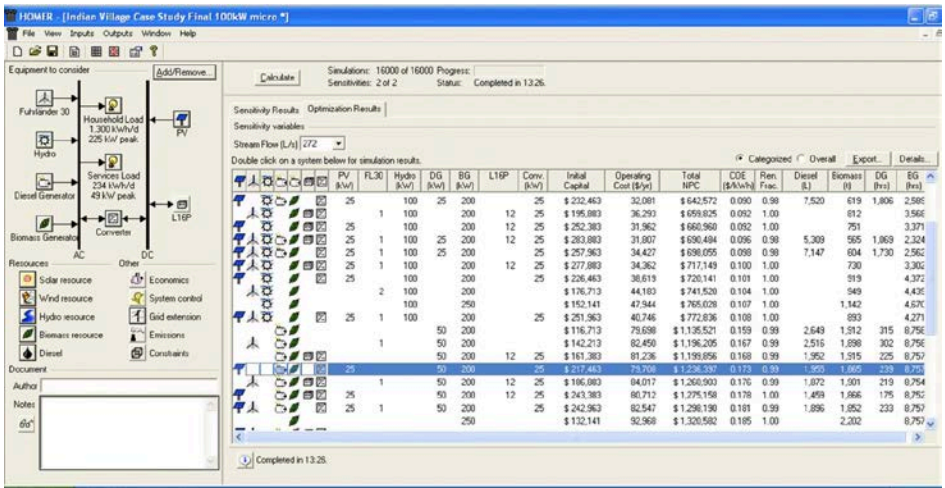


Figure 2.2. Screenshot of HOMER computer program

Cogeneration Design (Ozgirgin, 2004) is a computer program for conceptually designing cogeneration power plants. The user inputs numerical values, as the design point, and the program computes heat and mass balance, system performance, and gives outputs for an optimal design such as electric and heat (steam) production. Cogeneration Design is easy to use, and it takes a few minutes to finish the conceptual design of a cogeneration plant. The user adjustable inputs help to create a wide range of design projects. Code of the Cogeneration Design program is written using Visual Basic 6.0. Number of forms and modules are prepared for the program. Forms are the interactive windows created for user to read or input necessary values during design procedure. Modules are the subprograms that are called when a specific task has to be carried out more than once during the run.

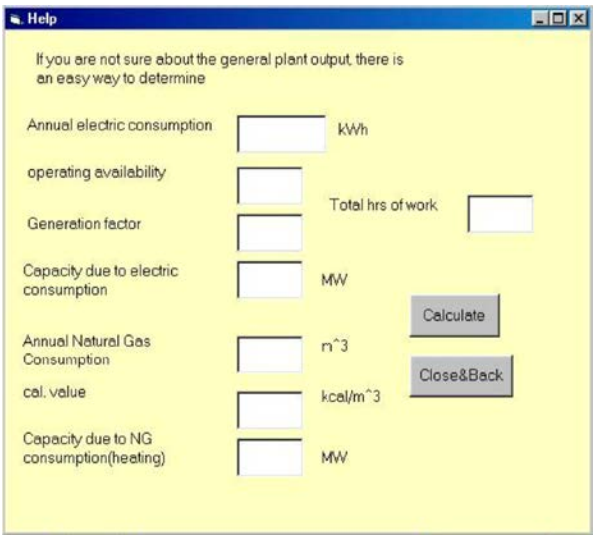


Figure 2.3. Screenshot of Cogeneration Design computer program

The Combined Heat and Power (CHP) Tool (ORNL, 2004) is designed to evaluate the feasibility of using heat from power generation equipment such as a gas turbine-generator in industrial heating applications. The results of the analysis give an approximate cost and payback period for the selected application based on the given data. This analysis is intended to provide a preliminary estimate for the payback period and help the user decide whether further detail engineering-economic analysis should be pursued.

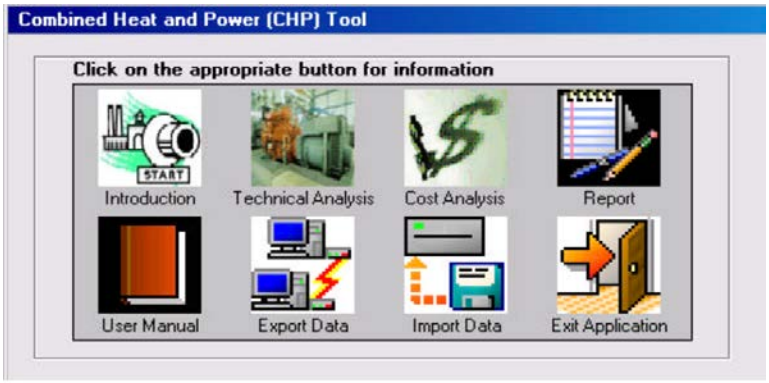


Figure 2.4. Screenshot of CHP Tool

The Building Energy Analyzer (BEA, 2004) was developed by the Gas Technology Institute in 2002 and upgraded to Building Energy Analyzer Pro in 2004. This screening software tool is meant to simplify energy audits in commercial buildings and evaluate the technical and economic potential of CHP systems in such buildings. Several modifiable templates of commercial buildings are built in. It can be used to evaluate several on-site power technologies and cooling options (such as absorption cooling and desiccant dehumidification). It performs hourly calculations over each hour of the year and includes data form numerous locations and utility rates.

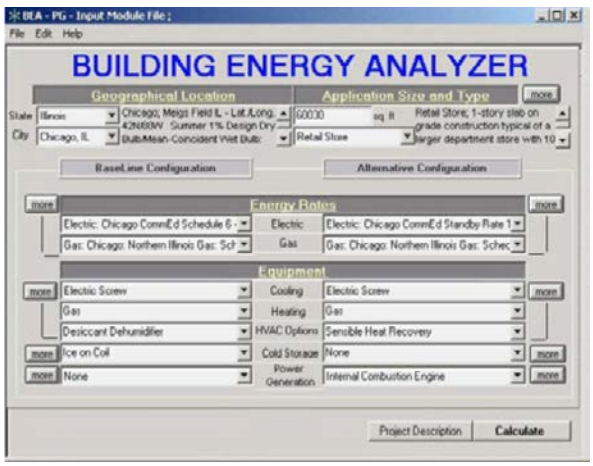


Figure 2.5. Screenshot of Building Energy Analyzer

In 2005, a program was designed for a PhD thesis named as “A Research on Autoproducer Cogeneration Power Plants with Natural Gas Fuel for Rural Areas”

(Yenice, 2005). Technical and economic analysis is done by program and the results are presented in tables. The program was designed in Visual Basic 6.0.

CHP Capacity Optimizer (Hudson, 2005) is an automated stand-alone spreadsheet program that computes the optimal capacities of prime movers and chillers that will maximize life cycle, net present value savings from the CHP system. It is based on a methodology involving nonlinear optimization and hourly operation simulation of the CHP prime movers and absorption chillers. The original intent of this tool was to help equipment manufacturers in identifying sizes of CHP equipment most suited to meet current requirements.

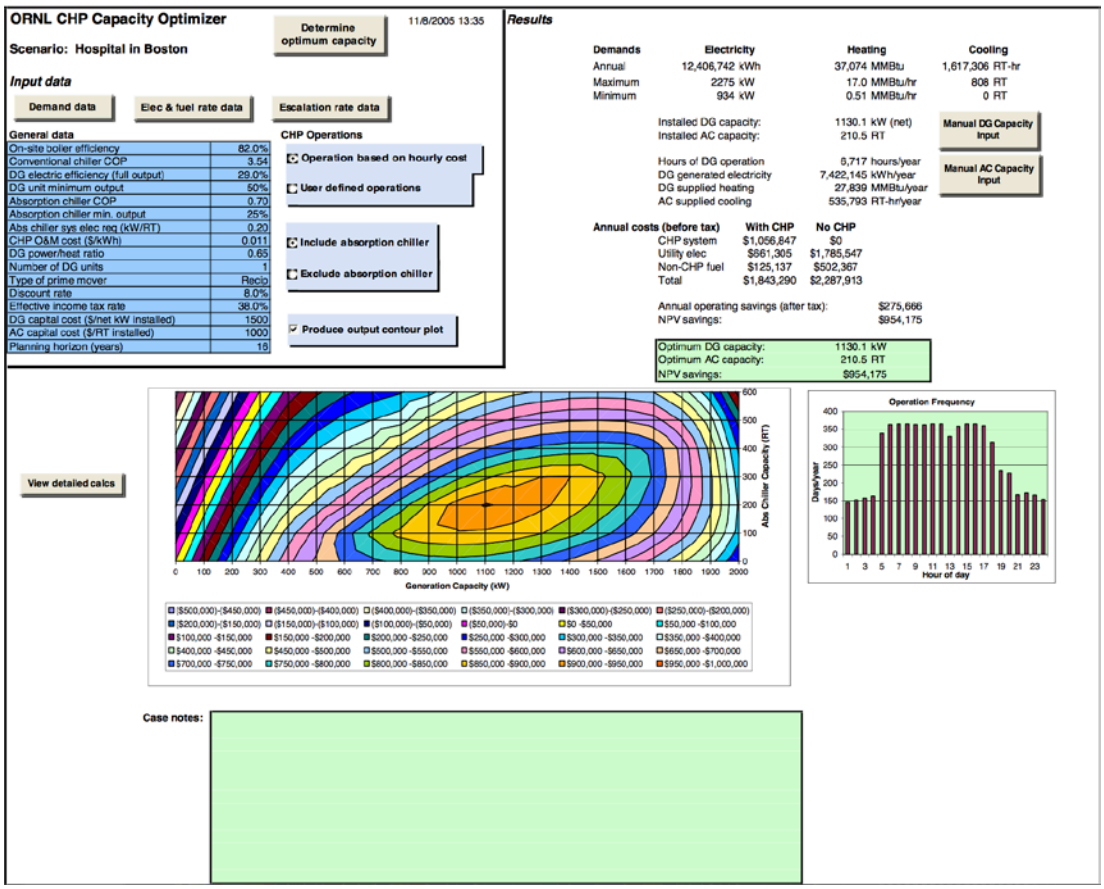


Figure 2.6. Screenshot of CHP Capacity Optimizer

RETScreen (RETScreen, 2005) is another convenient automated spreadsheet program that can analyze CHP and district systems. It requires monthly values of heating, cooling, and power loads and equipment description in order to perform the

simulations. It has capability of adding different CHP equipment (either from an existing database or new ones) and computes life-cycle costs and greenhouse gas emission reductions as well. It has been validated by independent consultants and compared with other models as well.

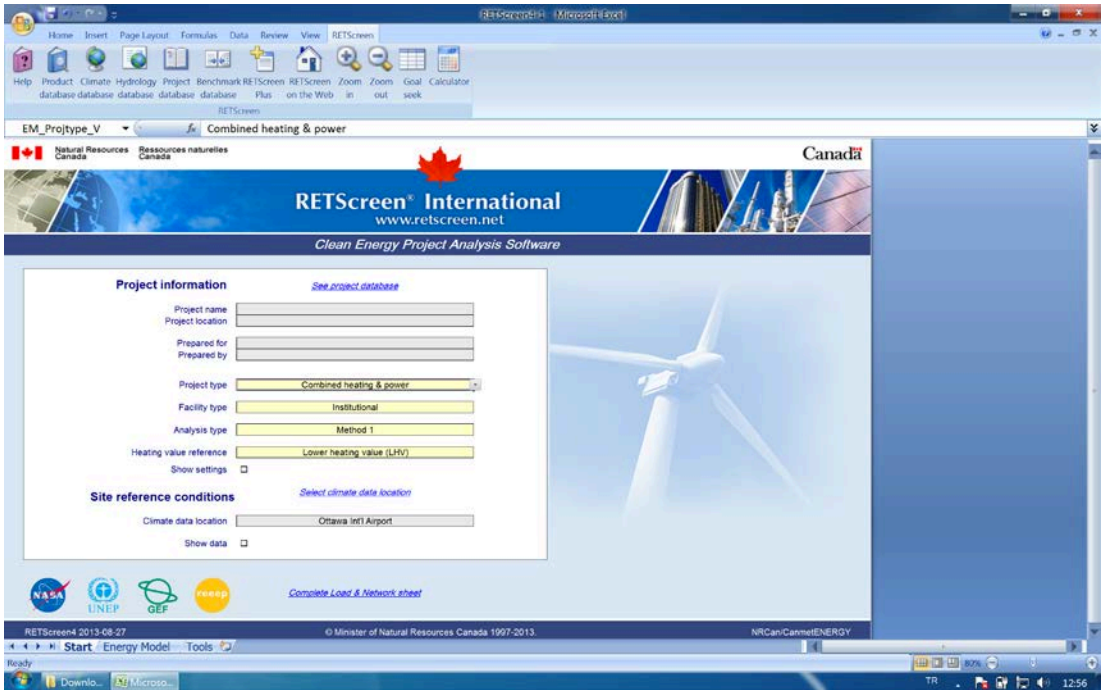


Figure 2.7. Screenshot of RETScreen Software

DCOGEN code (DCOGEN, 2006) is a simulation tool developed for forecasting energy, environmental and economical yearly balances of complex co/trigeneration power plants and cogenerative districts (link to cogeneration). DCOGEN code optimizes on an economic basis the operating conditions of the tri-generation plant determining the best operating modality for each of the 8760 hours of the year. Other optimizing strategies, as best energy saving, or minimum pollutant emissions, or other combinations of economic, energetic and environmental achievement could be easily specified. The code can perform the simulation of several prime mover (i.e. internal combustion engines, microturbines, stirling engines, gas turbines, fuel cells) based power plants, with absorption and/or compression chillers and an auxiliary burner. Thus, from small scale systems for

distributed generation (with an optional heat storage) to large scale industrial power plants can be analyzed.



Figure 2.8. Screenshot of DCOGEN code simulation tool

In 2007, a program was designed in MATLAB for a MSc thesis named as “Exergetic Analysis of Cogeneration System with Natural Gas” (Akdeniz, 2007).

SmartCHP (SmartCHP, 2014) tool enables fast prefeasibility check for small-scale CHP applications in industry, services and households. Economic evaluation on the CHP project level enables fast analysis of the key project variables on the profitability of the CHP application. The SmartCHP tool was developed as part of the CODE2 project (Cogeneration Observatory and Dissemination Europe).

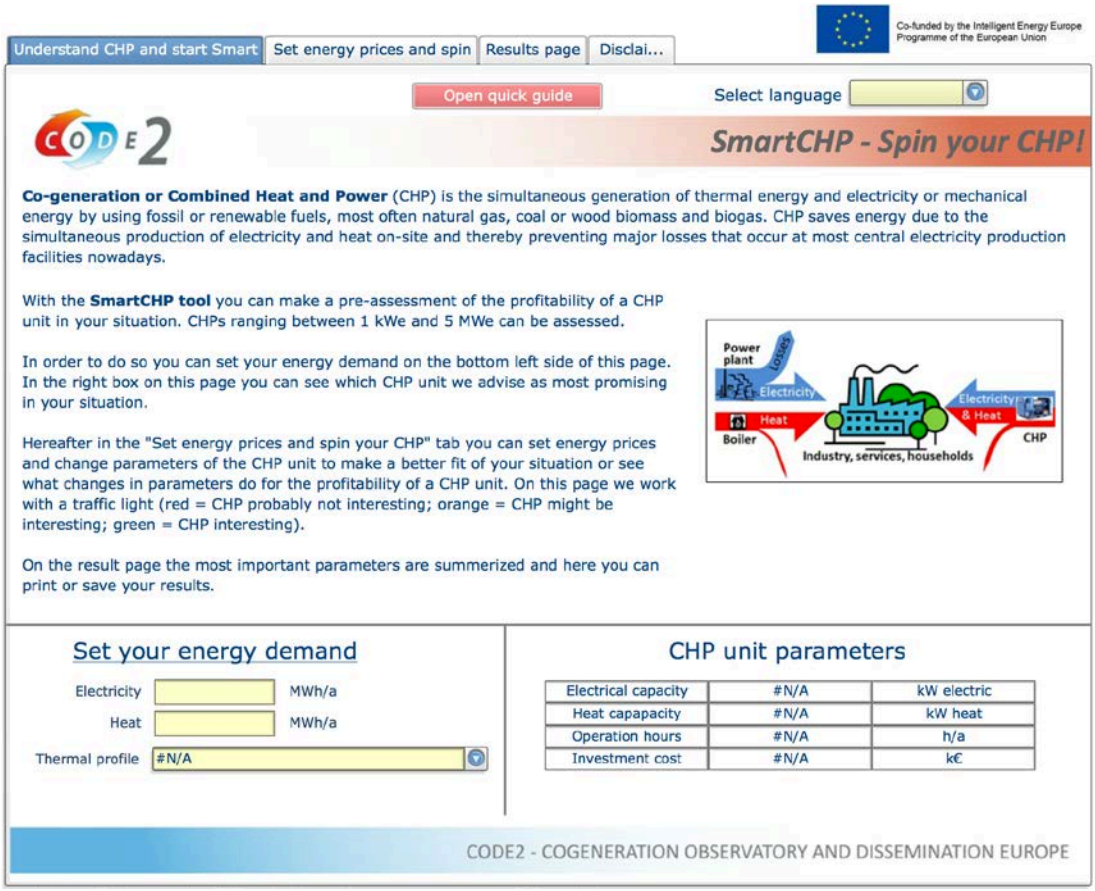


Figure 2.9. Screenshot of SmartCHP Tool

3. COGENERATION AND TRIGENERATION PLANTS

In this chapter, fundamentals, current legislation, grid synchronization, and environmental effects of gas engine driven cogeneration and trigeneration plants are presented.

3.1. Fundamentals of Gas Engine Driven Cogeneration and Trigeneration Plants

Natural gas based engine driven cogeneration plants produce electrical and heat energy simultaneously, while trigeneration plants provide electricity, heating and cooling at the same time. Outputs of a typical gas engine driven cogeneration plant is illustrated in Figure 3.1 (Zor and Teke, 2013).

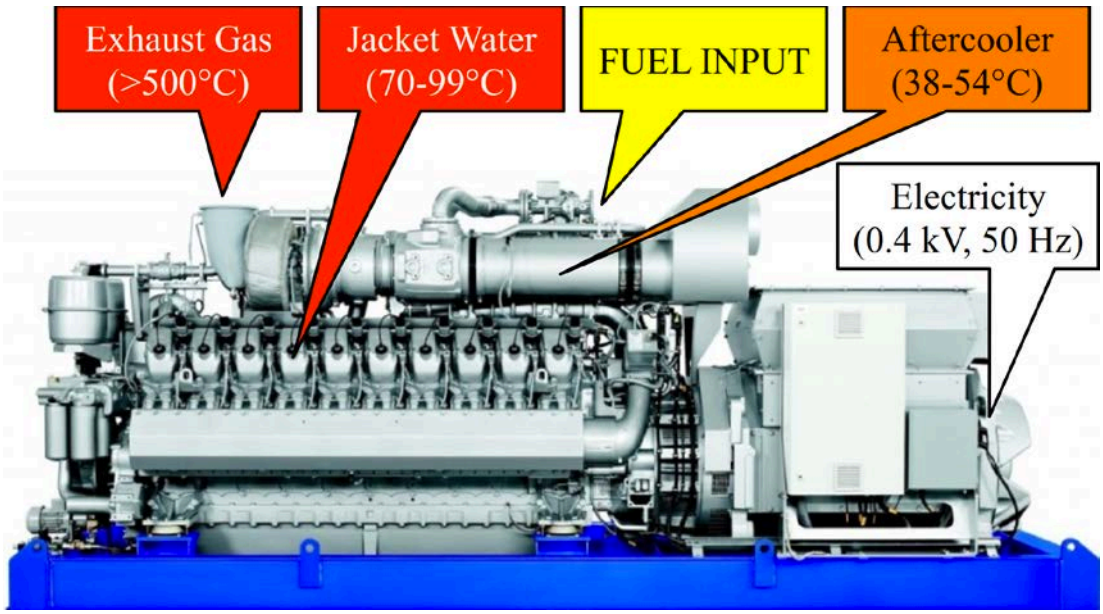


Figure 3.1. Outputs of a typical NG engine based cogeneration plant

Natural gas is combusted in the combustion chamber of reciprocating ICE, and mechanical power is produced. Mechanical power is converted to electricity by alternator which is generally a three-phase Y-connected permanent magnet (PM) synchronous generator with an efficiency over 95% and a voltage output of 0.4 kV.

Characteristics of a three-phase Y-connected PM synchronous generator is given in Table 3.1 (Stamford, 2009).

Table 3.1. Characteristics of a three-phase Y-connected PM synchronous generator

Class-Temp Rise	**Cont. F - 105/40ºC**				**Cont. H - 125/40ºC**			
50 Hz, Star (V)	**380**	**400**	**415**	**440**	**380**	**400**	**415**	**440**
kVA	2660	2800	2800	2630	2895	3050	3050	2865
kW	2128	2240	2240	2104	2316	2440	2440	2292
Efficiency (%)	96.2	96.3	96.3	96.4	96.1	96.2	96.2	96.4
kW Input	2212	2327	2325	2182	2411	2538	2535	2378

Generated electricity is interconnected to a LV switchgear or to a step-up transformer via a generator circuit breaker. Step-up transformer is used to increase voltage level to HV switchgear. Further electrical information is given under the following headline “Synchronization of Gas Engine Driven Cogeneration and Trigeneration Plants” in detail.

In efficiency calculations of cogeneration and trigeneration plant, LHV (also named as NCV) of the fuel should be used (Directive, 2004). In Equation 3.1, electrical efficiency calculation of a cogeneration or trigeneration plant is given as,

$$\eta_e = \frac{P}{F} \tag{3.1}$$

where η_e is electrical efficiency of the cogeneration or trigeneration plant; P is produced electrical power, kW; and F is input fuel, kW. (Onovwiona and Ugursal, 2006).

Exhaust gas can generate steam, hot oil or hot water by boilers in cogeneration plants, and provide cooling by indirect fired single-effect and double-effect absorption chillers in trigeneration plants (Oflaz, 2010).

Jacket water is the liquid of the closed circuit that may be stated as HT circuit. Regime temperatures may differ due to various engine manufacturers, but engine input of HT circuit is 70°C at least, and engine output of HT circuit is 99°C at

most. Heated jacket water must be cooled for an efficient and proper operation of the engine. There are two ways to chill the jacket water. First is the use of heat exchangers to transfer the heat from HT output to the cooler liquid of facility via a plate heat exchanger as illustrated in Figure 3.2 (PHE, 2014).

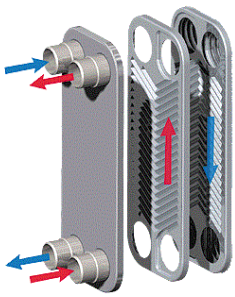


Figure 3.2. A plate heat exchanger used for heat transfer

If the cooler liquid may not transfer the necessary heat energy for the proper operation of engine, then the second way is the use of radiators to cool down the jacket water and also the engine. HT plate heat exchanger transfers its heat energy to the facility usually for preheating purposes in cogeneration plants, and extracts its energy to single-effect or double-effect absorption chiller for cooling in trigeneration plants.

Aftercooler circuit (also LT circuit) is very similar to HT circuit, but LT circuit is used for cooling the charge air prior to combustion. In LT circuit, air-cooled heat exchanger and water-cooled heat exchanger constitute a closed circuit. It is defined as low, because its regime temperature is smaller than HT circuit. Regime temperatures may differ due to various engine manufacturers, but engine input of LT circuit is 38°C at least, and engine output of LT circuit is 54°C at most (Zor and Teke, 2013). If LT circuit can not be cooled by the same methods used in HT circuit and intake air temperature of engine is greater than the regime temperatures of LT circuit, the engine will fail. Therefore, LT circuit has an important role in cooling of the engine and for the continuous operation of the plant. Heat energy provided by LT circuit plate heat exchanger is directly used for warming up water (e.g., in kitchen).

In Figure 3.3 and Figure 3.4, schematics of typical gas engine driven cogeneration and trigeneration plants are illustrated respectively.

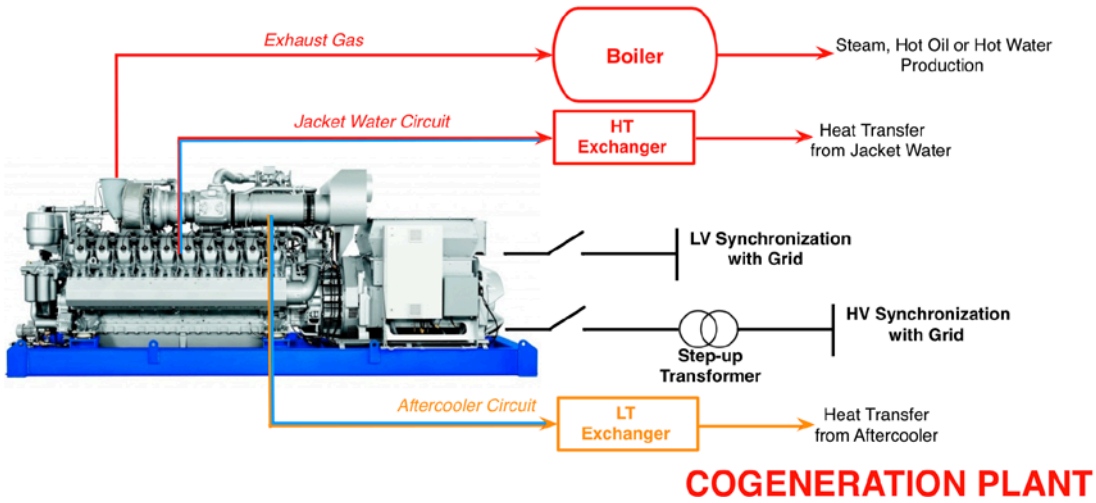


Figure 3.3. A schematic for a typical gas engine driven cogeneration plant

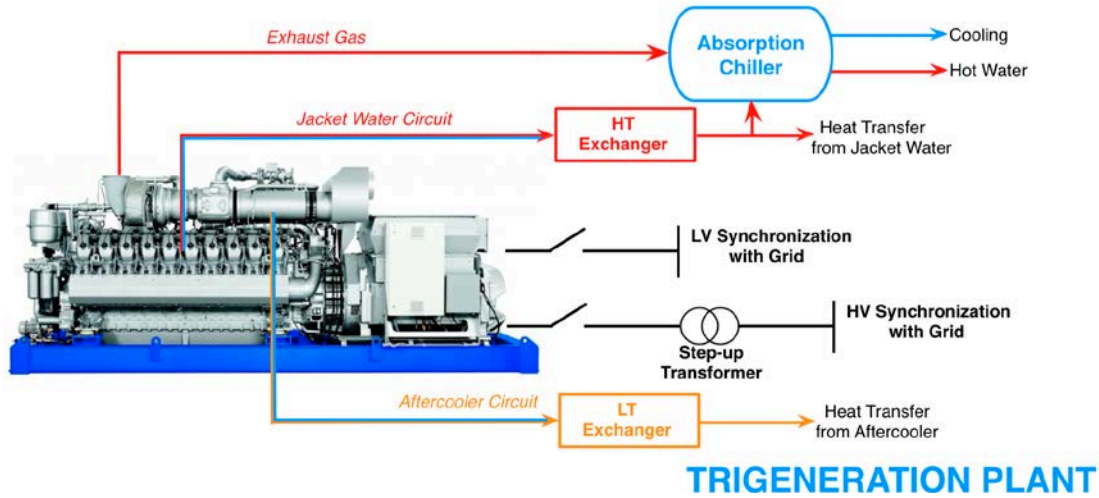


Figure 3.4. A schematic for a typical gas engine driven trigeneration plant

In Equation 3.2, thermal efficiency of a cogeneration or trigeneration plant can be found as,

$$\eta_t = \frac{P_t}{F} \tag{3.2}$$

where η_t is thermal efficiency of the cogeneration or trigeneration plant; P_t is produced and consumed useful heat, kW. Useful heat can be stated as summation of consumed outputs of exhaust gas, jacket water, and aftercooler.

In Equation 3.3, overall efficiency of a cogeneration or trigeneration plant is given as,

$$\eta_o = \frac{P_t + P}{F} \tag{3.3}$$

where η_o is overall efficiency of the cogeneration or trigeneration plant.

Reliability is determined by the amount of unscheduled outage as a result of equipment failure, while availability is the proportion of time the cogeneration or trigeneration plant is available for use when needed (Major, 1995).

In Equation 3.4 and 3.5, reliability and availability of a cogeneration or trigeneration plant is respectively calculated as,

$$Ra = \frac{T-(S+U)}{T-S} \times 100 \tag{3.4}$$

$$Av = \frac{T-(S+U)}{T} \times 100 \tag{3.5}$$

where *Ra* is reliability as percentage; *A* is availability as percentage; *S* is scheduled maintenance time, h/year; *U* is unscheduled maintenance time, h/year; and *T* is time for the operation hour of the plant during a year, h/year (Major, 1995).

In Equation 3.6, primary energy savings ratio (PESR) of a cogeneration plant is given as,

$$PESR = \left[1 - \frac{1}{\left(\eta_e / \eta_{spe} + \eta_t / \eta_{sph}\right)}\right] \tag{3.6}$$

where η_{spe} and η_{sph} are the efficiencies for the separate production of electricity and heat, respectively. (Frangopoulos, 2012).

3.2. Synchronization of Gas Engine Driven Cogeneration and Trigeneration Plants

The electrical power generated by a cogeneration or trigeneration plant is utilized in different modes of operation and each has different switchgear design considerations. The most basic is in a stand-alone (island mode) configuration, where the cogeneration or trigeneration plant is the only power source for a facility, or part of a facility. This switchgear design is the simplest, because there is no paralleling between multiple sources required. The generator of the cogeneration or trigeneration plant is connected to the switchgear in a manner similar to any utility source, via a load interrupter switch, a vacuum circuit breaker, or a molded case circuit breaker (MCCB). However, several other modes of operation require more specialized distribution and control (Mamer et al., 2010).

In standby mode, if any failure occurs related with the grid, the cogeneration or trigeneration plant can be operated as a backup generator. It is considered that cost of a cogeneration or trigeneration plant is much higher than a standby diesel generator, hence it is rare for a cogeneration or trigeneration plant to operate in standby mode.

Peak shaving mode can be expressed as, when a facility wishes only to purchase a specific amount of energy from the grid, either for contractual reasons or economic ones, it will use energy from its cogeneration or trigeneration plant to supplement that grid power when its energy needs exceed that which they receive from the grid.

In base load mode, a facility will use the energy generated by the cogeneration or trigeneration plant up to its maximum capability and will only use the grid when its needs exceed its plant capacity. It is fundamentally opposite of the peak shaving mode.

In export mode, excess energy generated by the cogeneration or trigeneration plant not needed to serve the facility loads and will be transported back onto the grid.

In any of these applications, the switchgear must be capable of being fed by both the grid and the cogeneration or trigeneration plant. Each of the incoming

energy sources are capable of feeding into the switchgear bus at the same time, and because of this there are a number of considerations and capabilities which should be taken into account for the switchgear serving a cogeneration or trigeneration plant.

One such consideration that warrants attention is the type of bussing in the switchgear. If the bus is physically separated into two or more discrete sections for various design reasons (e.g., load distribution), these sections would require connection to each other via a tie circuit breaker. In this example, the main circuit breakers directly upstream from the energy sources are both interlocked with a tie breaker so that the incoming feeds are physically separated at all times. Another possible method of configuring the switchgear to accommodate the multiple source input is paralleling switchgear, in which all incoming sources feed the same physical bus at the same time. To effectively utilize paralleling switchgear, the switchgear must have a synchronizing system that ensures that all generated electric power is operating together at the same rated voltage, frequency, and phase.

In both of these cases, the switchgear and its associated distribution system will feed all downstream loads if sufficient energy is available from a combination of grid and cogeneration or trigeneration plant. Prime mover load control in the switchgear will ensure that power from all sources is balanced and efficient. However, if one of the sources is lost, or for some other reason inadequate energy is generated to serve the facility (e.g., voltage irregularities or low frequency), load shedding will be required to control the ability of the switchgear to drop or shed certain lower priority electric loads.

Another capability to be considered in switchgear design includes voltage and reactive power control, which refers to controlling voltage regulation delivered by each energy source and automatic adjustments for varying reactive power levels. Another design consideration for remote overcurrent and protection controls, includes either automatic on/off and reset capabilities of overcurrent devices or manual capabilities from a remote location. Each of these key elements of switchgear design should be carefully considered by the designer of the cogeneration or trigeneration plant to ensure maximum optimization and safety of the system (Mamer et al., 2010).

In Figure 3.5, a LV switchgear synchronized gas engine driven cogeneration plant single line diagram is illustrated.

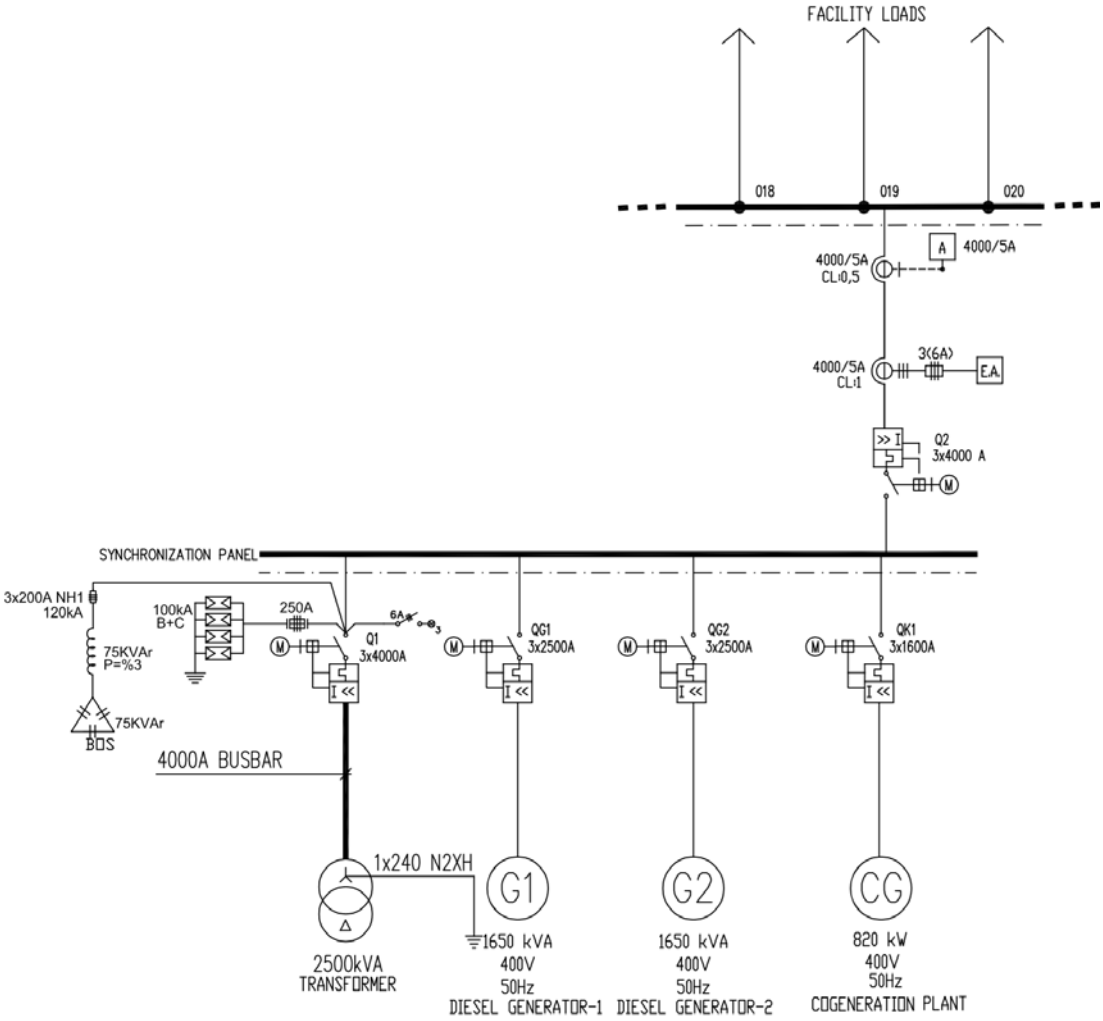


Figure 3.5. A single line diagram for a peak shaving mode scenario of a 820 kW cogeneration plant

In the scenario of cogeneration plant shown in Figure 3.5, a 820 kW generator is coupled via a 1600 A MCCB to synchronization panel of LV switchgear with two 1650 kVA standby diesel generators. In this formation, cogeneration plant operates with the grid in peak shaving mode. For contractual reasons, facility has to purchase 100 kWh energy per hour from the grid, and the rest is produced by the cogeneration plant. Diesel generators run only due to a failure of the grid.

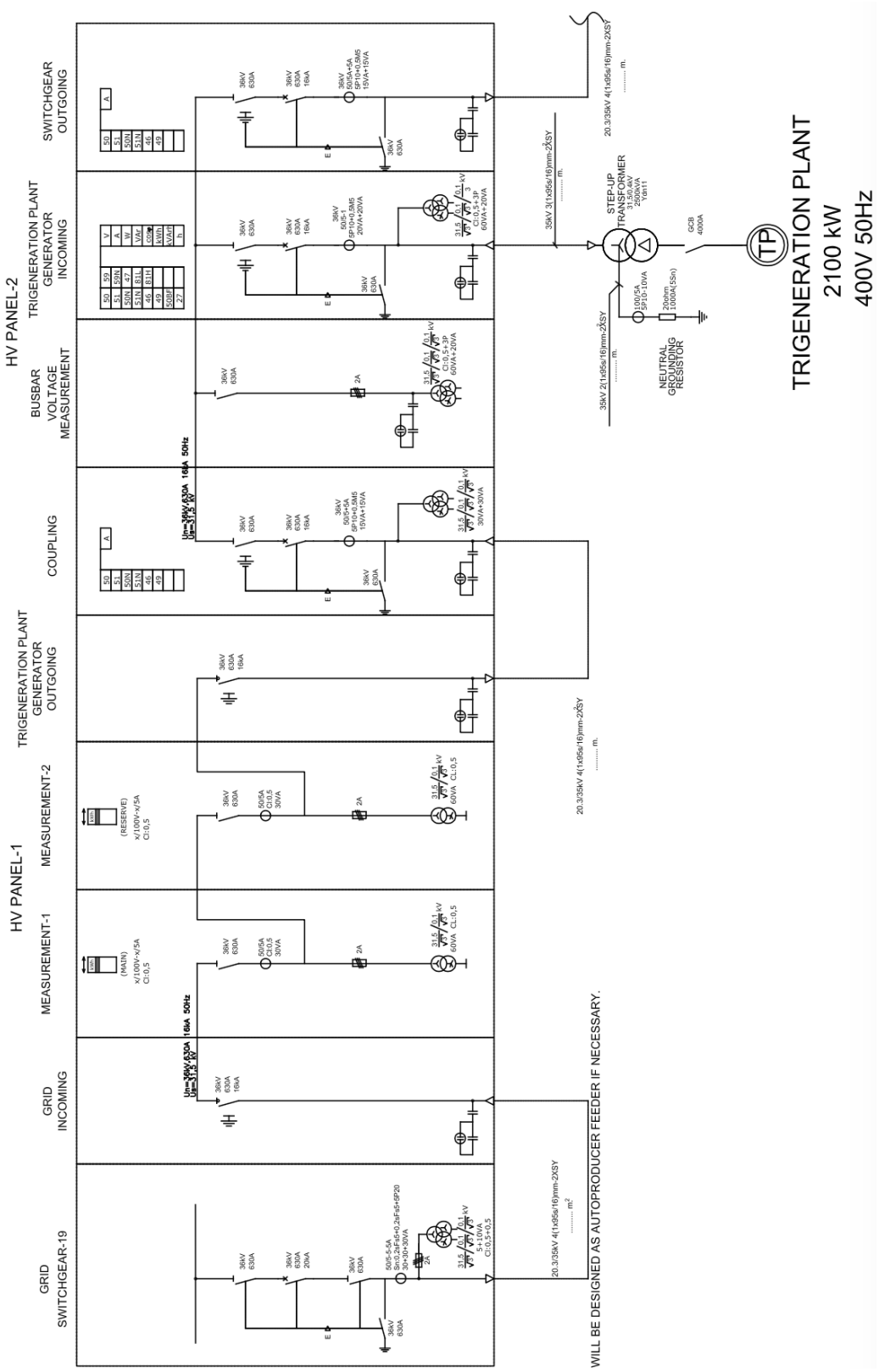


Figure 3.6. A single line diagram for an export mode scenario of a 2100 kW trigeneration plant

In Figure 3.6, a HV switchgear synchronized gas engine driven trigeneration plant single line diagram is demonstrated. In the scenario of trigeneration plant, a 2100 kW generator is respectively coupled via a 4000 A MCCB and a 0.4/31.5 step-up transformer to synchronization panel of HV switchgear. In this formation, trigeneration plant operates with the grid in export mode. Facility sells surplus energy to the grid.

Consequently, selection of either LV or HV switchgear for synchronization depends on electrical structure and needs for each facility. Basically, for facilities that have several distribution transformers and does not consider feeding a specific one by a cogeneration or trigeneration plant, HV switchgear synchronization is recommended. On the contrary, a facility that has only one distribution transformer or wants to feed a specific bus of a transformer by a cogeneration or trigeneration plant should consider LV switchgear synchronization.

3.3. Current Legislation for Cogeneration and Trigeneration Plants in Turkey

There were two alternatives for licenses of cogeneration and trigeneration plants in Turkey before the amendment of Electricity Market Law in 14 March, 2013 (EMRA, 2013). The first option was autoproducer license. 20% (increased to 50% at different times for energy needs) of the produced electricity in the cogeneration or trigeneration plant can be sold to grid and the rest was used by autoproducers in their facilities. The latter option was electricity generation license that allows facilities or plants to sell electricity to grid without limit. By the amendment, autoproducer license was voided, and exemption for facilities satisfying efficiency circumstance was provided by unlicensed generation of electricity.

According to EMRA, it is possible to install a cogeneration or trigeneration plant without having an electricity generation license and establishing a new company. For cogeneration and trigeneration plants without licenses, there is no installed capacity limit despite limitations of regulations related with interconnections between electric power transmission and distribution systems, and condition of having at least 80% overall efficiency shall be ensured.

Cogeneration plants without licenses can only be installed to satisfy the needs for owners of the plants. These plants shall not sell the surplus energy that is injected to the grid. If this redundant energy is injected to the grid, this energy is considered as a contribution to the Mechanism of Supporting Renewable Energy Sources (YEKDEM) and any compensation is not paid to the owners of these plants.

Biogas based cogeneration and trigeneration plants are encouraged to sell electricity to the grid with a constant price shown in Table 3.2 (EPGRES, 2005).

Table 3.2. Applicable prices for plants generating electricity based on RES

Type of Plants Generating Electricity Based on Renewable Energy Sources	Applicable Prices (¢/kWh)
a. Hydraulic Power Plant	7.3
b. Wind Power Plant	7.3
c. Geothermal Power Plant	10.5
d. Biomass Power Plant (Landfill gas included)	13.3
e. Solar Energy Based Power Plants	13.3

13.3 ¢/kWh, constant price can be increased by using fluidized bed steam boiler, gasification and gas purification group, internal combustion engine, generator and power electronics, and cogeneration system manufactured domestically as demonstrated in Table 3.3 (EPGRES, 2005).

Table 3.3. Extra addition for ICE driven cogeneration and trigeneration plants contain domestically manufactured equipment

Domestically Manufactured Equipment	Extra Addition (¢/kWh)
Fluidized Bed Steam Boiler	0.8
Gasification and Gas Purification Group	0.6
ICE	0.9
Generator and Power Electronics	0.5
Cogeneration System	0.4

Cogeneration plants may synchronize with the grid either from LV level or HV level. For LV synchronization, if distribution transformer belongs to local electric distribution authority, installed capacity of the cogeneration plant can not exceed 30% of the distribution transformer capacity; if else the distribution

transformer belongs to the owner of the cogeneration plant, installed capacity of the cogeneration can be equal to the total capacity of the distribution transformer (EMRA, 2015a). For HV synchronization, capacity limit is 2 MW for each transformer. Up to 2 MW capacity limit, local electric distribution authorities are decision-makers for installed capacities. If installed capacity limit is greater than 2 MW, local electric distribution authorities shall ask Turkish Electricity Transmission Company (TEIAS) for permission and TEIAS decides (TEIAS, 2012).

For licensed electricity generation, license fees are given in Table 3.4 (EMRA, 2015b). Annual license fee is 0.003 kr per generated kWh.

Table 3.4. License fees for 2015

Installed Power (P_{ins})	**License Fee (TL)**
$0 < P_{ins} \leq 10$ MW	5,500 TL
$10 < P_{ins} \leq 25$ MW	11,000 TL

For licensed facilities generating electricity with cogeneration or trigeneration plants, satisfying the efficiency condition is not required. They can sell the produced electricity to free electricity market via PMUM. It is recommended for small scale and medium scale gas engine driven cogeneration and trigeneration plants to generate electricity without license for not competing with large-scale power plants in the same field and not occupying distribution and transmission lines. Unlicensed electricity generation for on-site cogeneration and trigeneration plants ensuring the efficiency condition of at least 80%, has changed the mentality in Turkey from "Generate, use and sell surplus energy to the grid" to "Generate as much as you need and use the produced energy onsite" as in most countries of the European Union.

3.4. Environmental Effects of Gas Engine Driven Cogeneration and Trigeneration Plants

Most applications of cogeneration and trigeneration plants use natural gas or biogas. Since gaseous fuels are used most often in cogeneration and trigeneration

plants and the sulfur content of most gaseous fuels is low, SO_x emissions are generally not a concern for cogeneration and trigeneration plants (Punwani, 2010).

Untreated NO_x emission levels vary from very high, more than 30 lb/MWh for diesel engines, to almost nonexistent below 0.02 lb of NO_x per megawatthour for fuel cells. Natural gas IC engines have NO_x emission levels in a range of 2 to 30 lb/MWh, NO_x emission levels for gas turbines and microturbines vary between about 0.3 to 0.4 and 0.4 to 2.2 lb/MWh, respectively (Hyman and Stadnik, 2010).

ICEs are designed to operate either in rich burn or lean burn mode. Rich burn operations use fuel-air ratios that are higher than the stoichiometric ratio (defined as the fuel-air ratio theoretically required for complete combustion of the fuel.). Generally rich burn mode is more common for engine capacities smaller than 500 kW. Emissions of NO_x from rich burn engine are in the range of 30 to 50 lb/MWh (or 625 to 1060 ppm at 15% oxygen). Exhaust from rich burn engines is generally treated by a three-way catalyst. A three-way catalytic converter accomplishes the reduction of nitrogen oxides to nitrogen and oxygen, oxidation of carbon monoxide to carbon dioxide, and oxidation of unburnt hydrocarbons to carbon dioxide and water. The efficiency of a three-way catalyst system for reducing emissions of NO_x and CO is in the range of 85 to 95 percent, depending on the exhaust gas temperature, air-fuel ratio, and catalyst volume. A three-way catalyst can reduce NO_x emissions to as low as 0.5 lb/MWh.

Lean burn operations use fuel-air ratios that are lower than stoichiometric ratio. The energy efficiency of lean burn engines is slightly higher than those for the rich burn engines. Without any treatment of the exhaust gases, NO_x emissions from lean burn engines are in the range of 2 to 6 lb/MWh (42 to 127 ppm at 15% oxygen). Many installations using lean burn engines do not require exhaust treatment. If exhaust treatment is needed to reduce NO_x emissions, the most common treatment is the use of selective catalytic reduction (SCR). An SCR system selectively reduces NO_x emissions by injecting ammonia (NH_3) into the exhaust gas upstream of catalyst. NO_x, ammonia, and oxygen in the air react on the surface of catalyst to form nitrogen and water. An SCR treatment system has the potential to reduce NO_x

emissions from natural gas and dual fuel fired lean burn reciprocating IC engines by up to 90% (Punwani, 2010).

Combustion of all fossil fuels results in the emissions of CO_2, which is considered to be a major greenhouse gas (GHG). Significant worldwide efforts are underway to reduce the emissions of CO_2, including those from the use of fossil fuels for electric power production and for providing thermal energy needs.

The average carbon footprint (weight of CO_2 emitted) per unit (MWh) of electric energy produced by remote electric power utilities is different for various cities and regions because it depends on the mix of coal, gas, oil, biomass, and nuclear fuels used in that place for power generation. In addition, the carbon footprint of electric power production during peak (nonbaseload) period is generally higher than that during the baseload period. This is because less efficient electric power plants are required to be brought online to meet the peak demand (Punwani, 2010).

Several GHG emission calculators are available such as U.S. EPA GHG Equivalency Calculator that is developed by EPA.

As an example, assume a cogeneration plant with electrical efficiency of 41.33% and thermal efficiency of 48.59%. If this plant is compared with a system making conventional generation that contains a combined cycle power plant with an electrical efficiency of 50% and a natural gas fired steam boiler with a thermal efficiency of 90%, the PESR is found as 0.268 from the Equation 3.6. If a 1 MW gas engine based cogeneration plant with a fuel consumption of 240m^3 natural gas per hour is assumed, 64.4m^3 natural gas is saved per hour by choosing cogeneration over separate production. For 10 years life length (8400 h/year), the consequences of this saving are expressed as GHG emissions, CO_2 emissions and carbon sequestration in Figure 3.7, Figure 3.8, and Figure 3.9, respectively (EPA, 2015).



Figure 3.7. Equivalent GHG emissions saved by using 1 MW cogeneration plant for 10 years

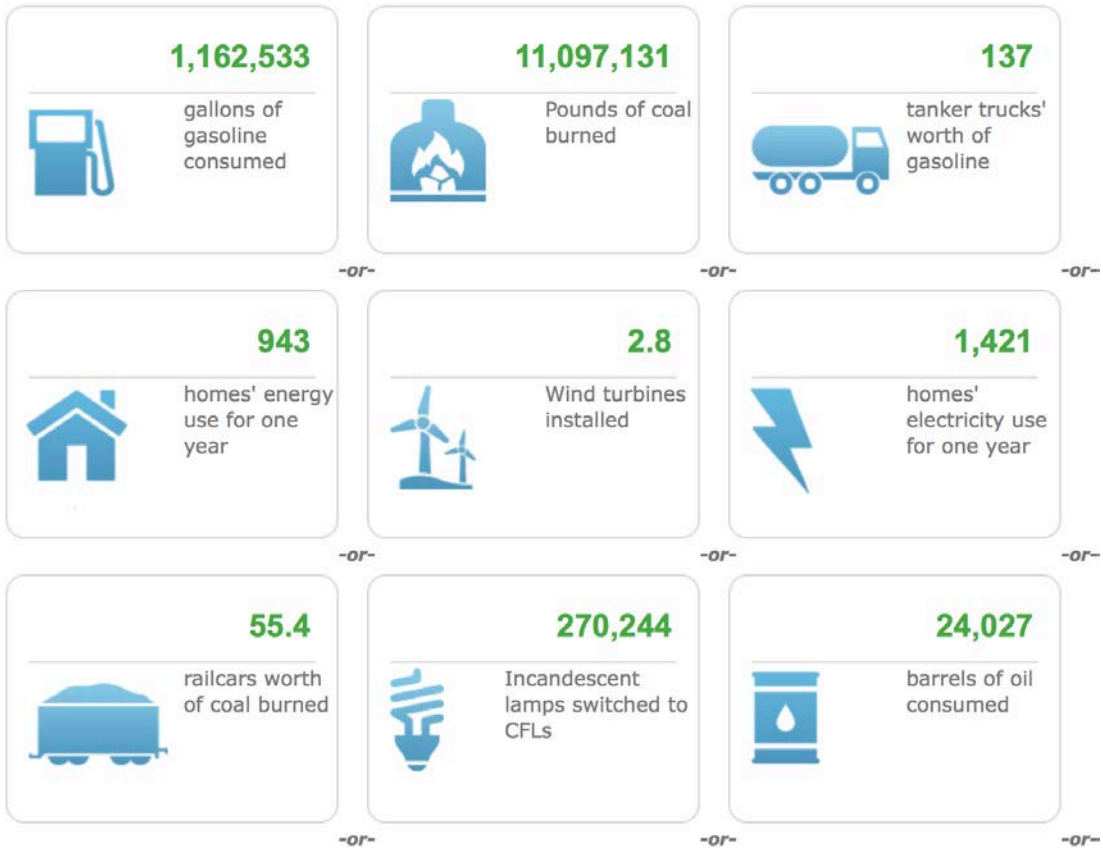


Figure 3.8. Equivalent CO_2 emissions saved by using 1 MW cogeneration plant for 10 years



Figure 3.9. Number of 10 years old tree seedlings saved by using 1 MW cogeneration plant for 10 years

4. DEVELOPMENT STAGES OF SOFTWARE PROGRAM

In this chapter, software development of program that determines the optimal capacity rating of gas engine driven cogeneration and trigeneration plants for unlicensed generation of electricity is expressed by stating capacity sizing criteria, proposed methodology and the interface of software program.

4.1. Capacity Sizing Criteria for Cogeneration and Trigeneration Plants

Capacity sizing is crucial for cogeneration and trigeneration plants in order to have a proper and energy efficient operation during lifetimes of plants.

Gamou et al. (2002) considered uncertain energy demands as continuous random variables for optimal unit sizing of cogeneration systems. Cardona and Piacentino (2003) proposed a general and innovative criterion for sizing a trigeneration plant in Mediterranean areas. Beihong and Weiding (2006) suggested and optimal sizing method for cogeneration plants. Biezma and San Cristobal (2006) applied different techniques to the selection between two CHP units for a tire factory in Spain. Sanaye et al. (2008) studied at off-design point in the selection of a CHP system. Oh et al. (2007) recommended optimal planning and economic evaluation of cogeneration system based on the annual cost method. Kavvadias et al. (2010) researched for the design of a CCHP system sizing, operation strategy selection and parametric analysis. Cho et al. (2012) presented a simple approach for CHP unit capacity for high-heat power ratio buildings without selling excess electricity to the grid. Gimelli and Muccillo (2013) expressed optimization criteria for cogeneration systems by multi-objective approach and application in an hospital facility. Yun et al. (2013) proposed a power generation and heat recovery model for reciprocating ICEs. Bracco et al. (2013) developed an economic and environmental optimization model for the design and the operation of a combined heat and power distributed generation system in an urban area. Facci et al. (2014) investigated the optimization of combined heat power and cooling systems operation strategy using dynamic programming. Costa and Fichera (2014) created a mixed-integer linear programming

model for the evaluation of CHP system in the context of hospital structures. Rossi et al. (2014) proposed artificial neural networks and physical modeling for determination of baseline consumption of CHP plants. A simple sizing method based on load duration curve for combined heat and power units was suggested by Cho and Lee (2014). Arcuri et al. (2014) presented a mixed integer non-linear programming model for optimal design of a small size trigeneration plant in civil users. Lastly, Salata et al. (2015) proposed a method for energy optimization with reliability analysis of a trigeneration and teleheating system on urban scale through a case study.

In all studies, fundamentals of capacity sizing criteria based on electrical load profile, thermal load profile, future variations in both of the demands, fuel availability, cost of electricity and fuel, cost of supplying and installing the equipment, space requirement, environmental impact, overall efficiency and heat-to-power ratio suitability, appropriateness of alternative supply, cost and benefit analysis with financial arrangements, and selection of correct prime mover (Patel, 2007).

4.2. Proposed Methodology for Software Program

In the proposed methodology demonstrated in Figure 4.1, evaluation of 1-year retrospective electrical, cooling and heating data should be obtained at first. Unit price of cogenerated or trigenerated electricity is found by using fuel consumption per hour, unit price of natural gas, and net electrical output power that excludes power per hour of auxiliary equipment and absorption chiller unit. Calculated unit price is compared with unit prices of grid for daytime, primetime and nighttime periods. Cogeneration or trigeneration plant should operate during periods having more expensive prices than the cogenerated or trigenerated electricity unit price. Then, montly electricity bills are investigated to calculate an average consumption per hour representing a month for periods in which cogeneration or

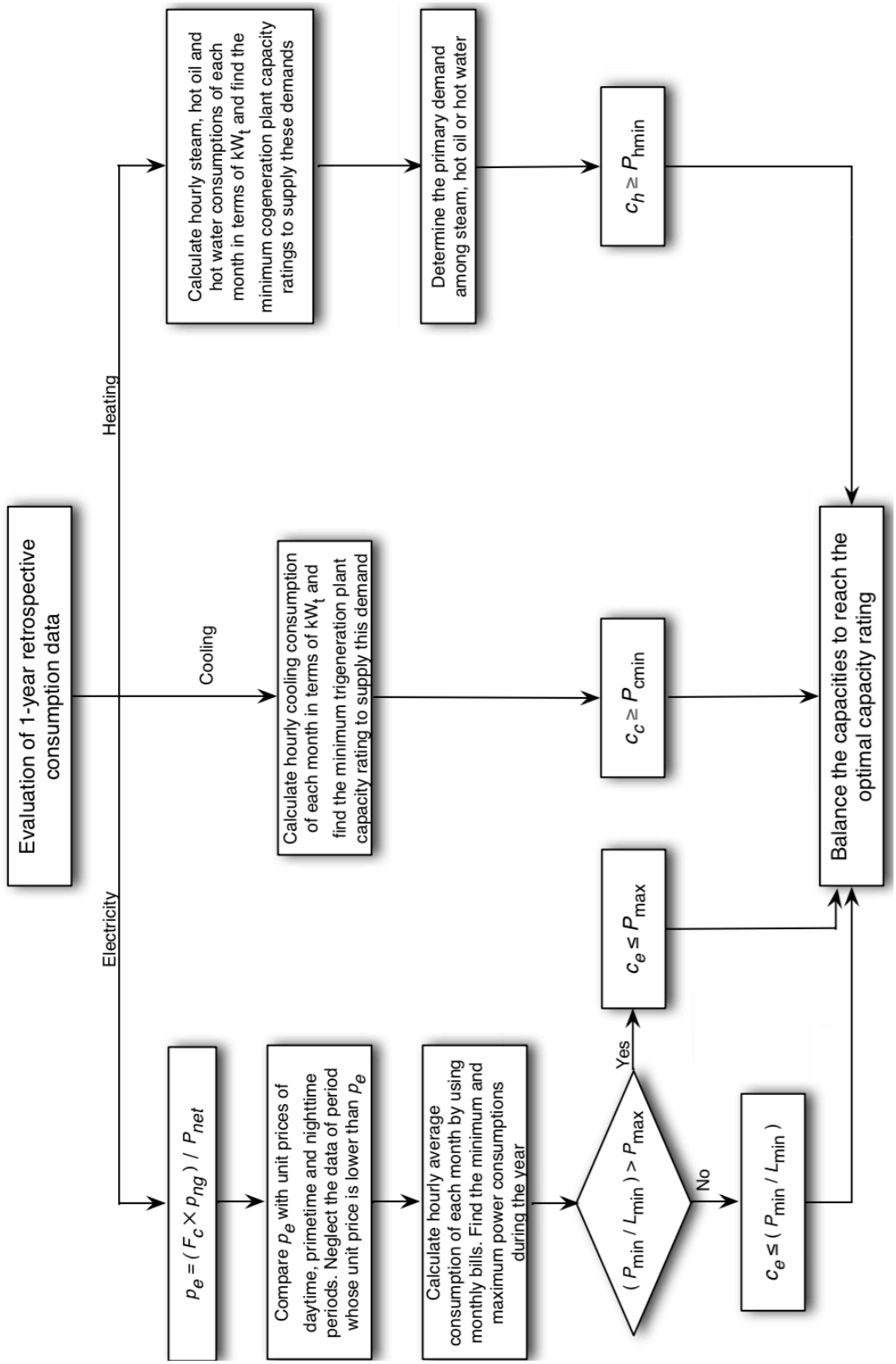


Figure 4.1. Flowchart of the proposed methodology

trigeneration plant will operate. Average electrical consumptions for each month (recommended to be at least 12 months) are sequenced. Minimum and maximum consumptions are calculated to specify borders for a programming loop that finds and results electrical capacity rating for the maximum electrical energy production for a year.

For cooling, data of at least last 12 months is obtained. The minimum demand of cooling in thermal kW is converted to electric kW by calculation of COP value by requesting absorption chiller type used in trigeneration plant from user and found capacity rating is defined as cooling capacity rating in order to compare with electrical and heat capacity ratings to balance.

In order to find the heat capacity rating, thermal consumption data belonging steam, hot oil or hot water boiler in thermal kW and equipment efficiencies are acquired. User determines the primary energy need for only one boiler type. Minimum electric kW value for cogeneration plant to produce corresponding to thermal kW is specified, and found capacity rating is stated as heat capacity rating.

Finally, three capacity ratings are compared to balance the plant capacity, to fulfill efficiency condition of EMRA and to reach the optimal capacity rating for cogeneration or trigeneration plant.

4.3. Developed Software Program

Software program is designed in Delphi environment to find the optimal capacity rating of gas engine driven cogeneration and trigeneration plants for unlicensed generation of electricity. The program is intended to be efficient and user-friendly.

In Figure 4.2, welcome screen of the program is illustrated. In the projects screen, data containing facility name, user name of program, phone and e-mail, and the optimal capacity rating of projects are saved and displayed. English and Turkish language options are available.

In Figure 4.3, user information screen is demonstrated. Facility name for cogeneration or trigeneration plant, and user info can be entered via this screen.

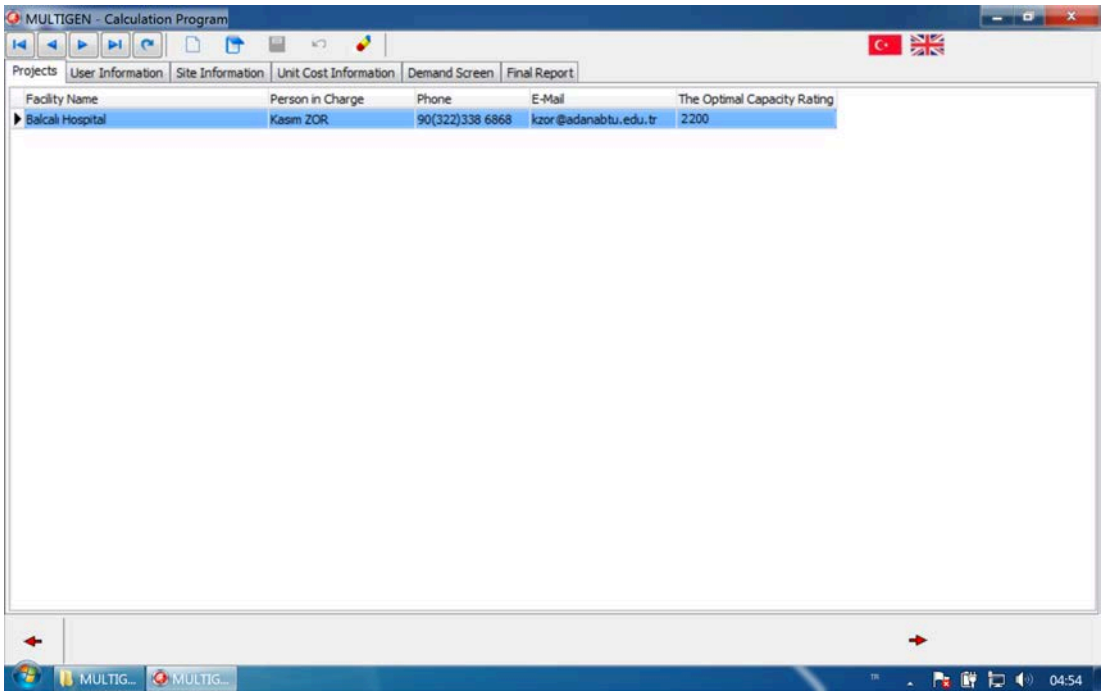


Figure 4.2. Welcome screen of the software program

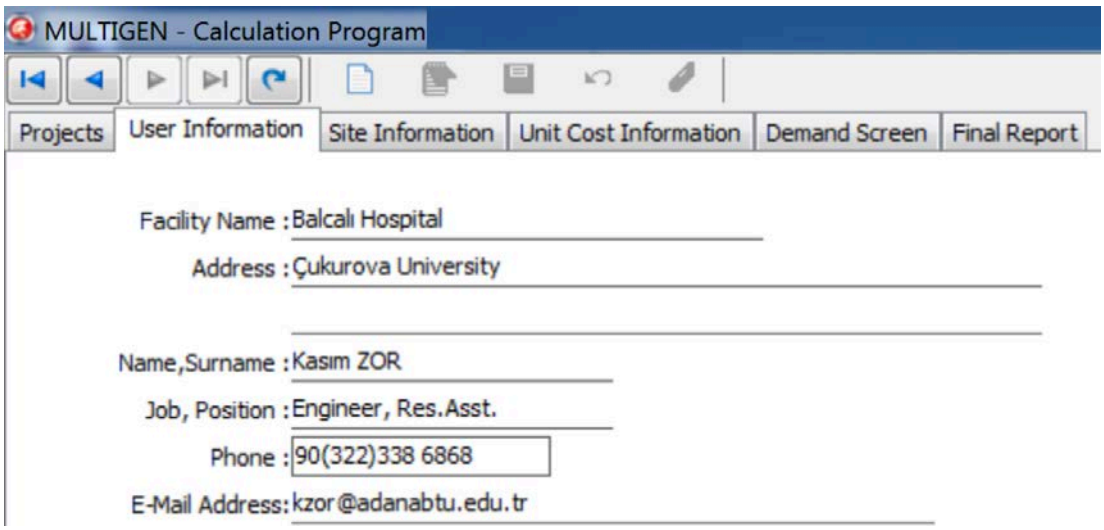


Figure 4.3. User information screen of the software program

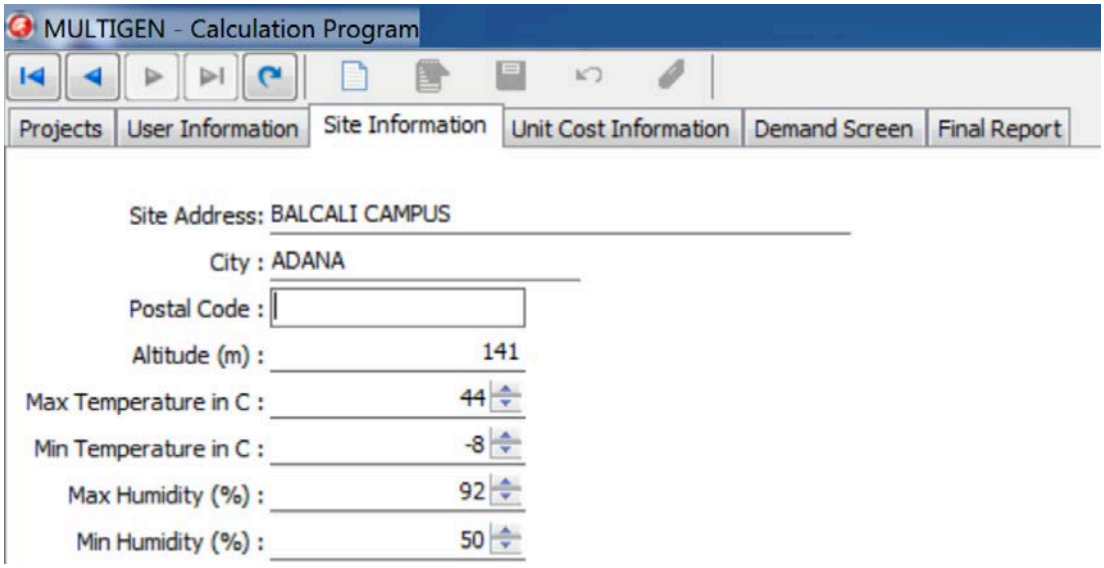


Figure 4.4. Site information screen of the software program

In Figure 4.4, site information where cogeneration or trigeneration plant will be installed is indicated. Site address, altitude, maximum and minimum temperature and relative humidity values are shown.

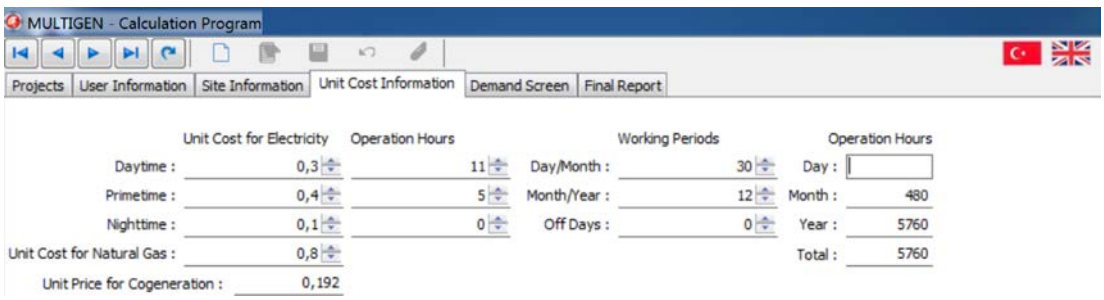


Figure 4.5. Unit cost information screen of the software program

In Figure 4.5, unit natural gas price and electricity prices of daytime, primetime and nighttime periods are entered by the user, then program calculates the unit price for cogenerated or trigenerated electricity. Operation hours during periods, days, months and off days information are calculated by this screen.

In Figure 4.6, demand screen for electrical, cooling and heat demands is indicated. Each consumption type is supported by a graphical interface for users. User chooses a month and a year initially, program completes the rest for the user. For report, an optimal capacity rating is determined and all of the data entered in the program is sent to user with recommendations by e-mail.

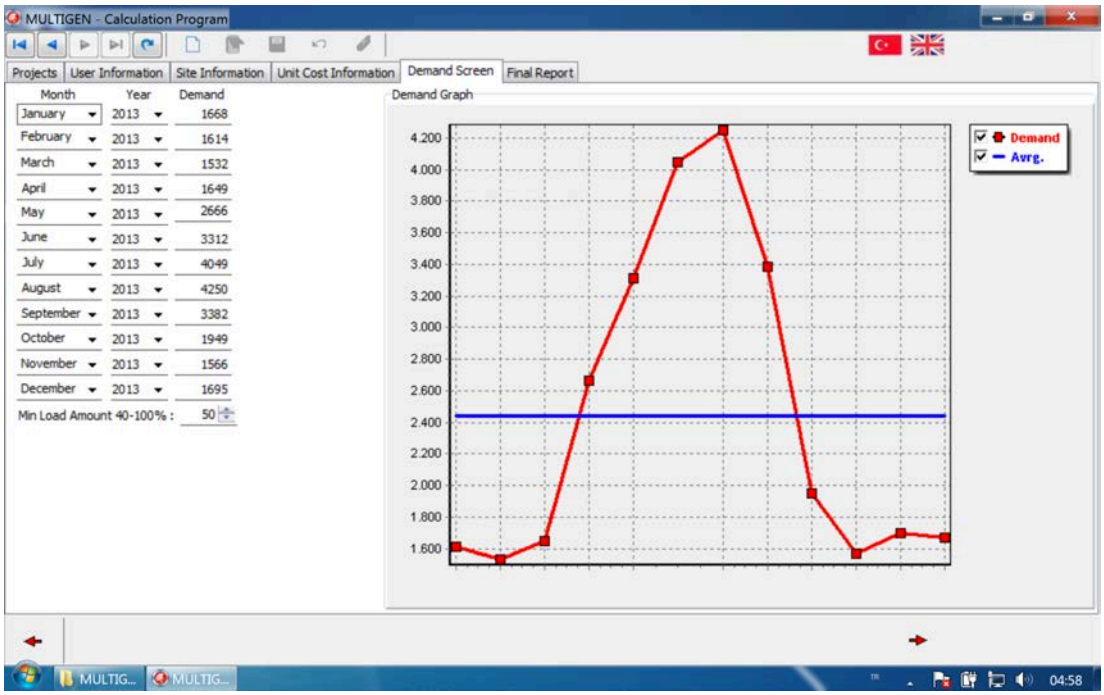


Figure 4.6. Demand screen of the software program

5. CASE STUDY OF A UNIVERSITY HOSPITAL

5.1. Hospital Information and Energy Demands

Çukurova University Balcalı Hospital, a pioneer health institution in Çukurova Region (covers the area containing Adana, İçel, Osmaniye, Hatay), serves unceasingly, thus it has continuous demands to supply electricity, cooling and heating for one emergency service, forty two polyclinics, twelve intensive care unit, twenty three operating room, forty three clinical services, five laboratories, one radiology unit, nuclear medicine, one blood center, one burn unit, one sterilization unit, and one pharmacy with also surgery rooms, laundries, kitchens and a morgue. Balcalı Hospital is accredited by Joint Commission International (JCI), serves more than 3000 patients per day with more than 3000 personnel and has an installed capacity around 10 MVA (Timur, 2013).

Hospitals are ideal candidates for cogeneration and trigeneration plants, they serve 365 days a year, 24/7 and they require round-the-clock energy. Cogeneration and trigeneration plants enable hospitals to reduce energy costs, hedge against rising electricity prices, improve environmental performance and increase energy reliability (Zor and Teke, 2014).

To determine the installed capacity of cogeneration or trigeneration plant, it is vital to identify geographical characteristics of location such as altitude, temperature, humidity and the demands such as electrical, cooling, steam, hot oil, hot water or warm water of a facility by evaluating at least 1-year retrospective consumption data of that facility (Zor and Teke, 2013). Balcalı Hospital is located in Adana with an altitude of approximately 141 meters as shown in Table 5.1.

Table 5.1. The location of Çukurova University Balcalı Hospital

Location	**Altitude (m)**	**Relative Humidity**	**Maximum Temperature (°C)**	**Minimum Temperature (°C)**
Çukurova University, Adana, Turkey	141	Above 50%	44	-8.1

For this altitude level, it is unexpected to trouble power deration in a reciprocating gas engine of an installed cogeneration or trigeneration plant. In Adana, the engine can properly operate in winters, but it is too hard to cool down the LT circuit of engine in summer months. In order to prevent from such a failure, it is recommended to build up a strong system for engine cooling.

Electricity consumption graphs of the hospital in 2013 with respect to tariff periods (Daytime period is between 06:00 and 17:00, primetime period is between 17:00 and 22:00, and nighttime period is between 22:00 and 06:00, respectively.) are illustrated in Figure 5.1, Figure 5.2, and Figure 5.3, respectively.

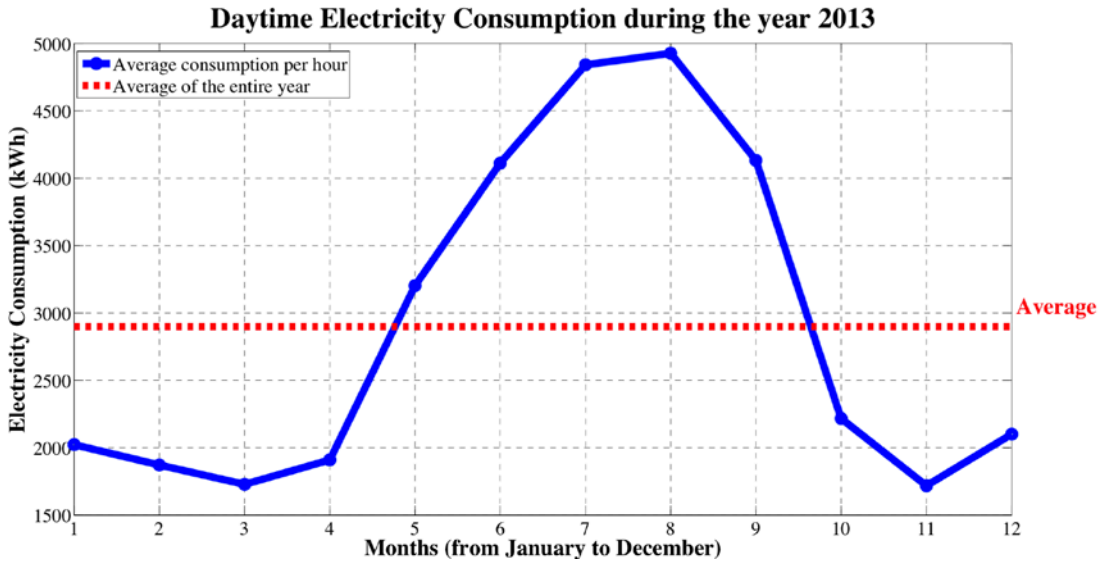


Figure 5.1. The daytime electricity consumption of hospital during 12 months

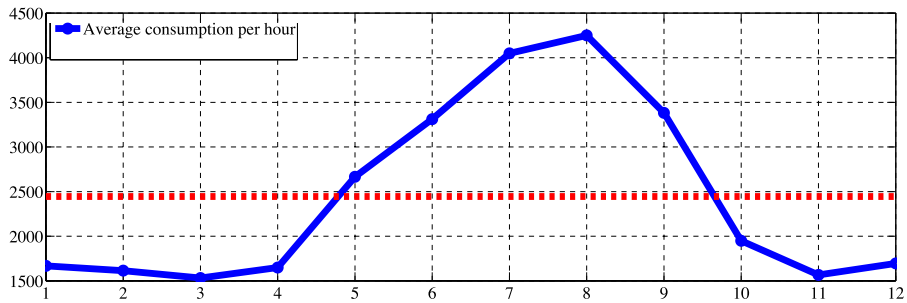


Figure 5.2. The primetime electricity consumption of hospital during 12 months

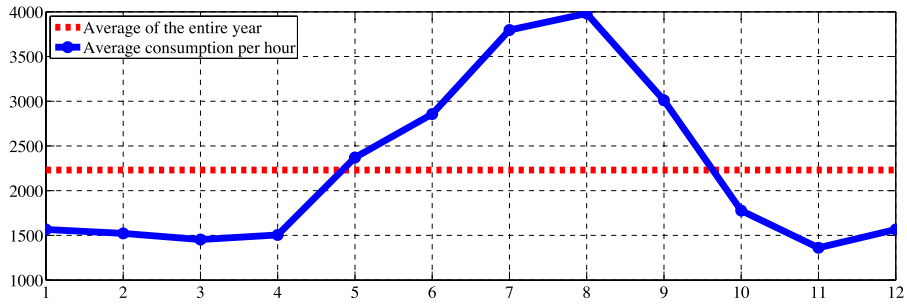


Figure 5.3. The nighttime electricity consumption of hospital during 12 months

According to the local electrical distribution authority, without taxes and additional fees, unit price of the daytime period is 0.102 $/kWh, the primetime period is 0.167 $/kWh and the nighttime period is 0.053 $/kWh. Average of given tariff prices for 24 hours operation and 16 hours operation (nighttime is not considered) including taxes and additional fees are approximately calculated as 0.121 $/kWh and 0.145 $/kWh respectively. It is important to show that electricity generation by a cogeneration or trigeneration plant using natural gas is more feasible than buying electricity from local electrical distribution companies in daytime and primetime periods. Therefore, unit price of electricity production in a cogeneration or trigeneration plant can be calculated as given in Equation 5.1:

$$p_e = (F_c \times p_{ng}) / P_{net} \tag{5.1}$$

where p_e is unit price of electricity generation by natural gas per kWh, F_c is engine fuel consumption per hour, p_{ng} is unit price of natural gas and P_{net} is the net electrical output power for one hour respectively. For instance, if a cogeneration or trigeneration plant with an energy production of 2,145 kW/h is considered, fuel consumption of gas engine is 513.9 m^3/h, unit price of natural gas in Adana region with taxes is 0.393 $/$m^3$ and net electrical power production for one hour is 2,090 kW (55 kW is reduced owing to energy consumption of auxiliary equipment in cogeneration or trigeneration plant), then the unit price of electricity generation by natural gas is 0.097 $/kWh. This unit price is lower than the tariff prices of the hospital provided by local electrical distribution companies. Consequently, electricity

generation in a cogeneration or trigeneration plant by natural gas is more feasible for the hospital than buying electricity from the grid. The obtained unit price for cogeneration or trigeneration plant also mentions that buying electricity from the grid is more advantageous than producing electricity by cogeneration or trigeneration plant at nights, hence nighttime tariff is approximately 0.053 $/kWh and indicates that it is not feasible to run cogeneration or trigeneration plant at nighttime periods.

When heat energy demands of the hospital are investigated, the hospital needs steam for sterile storage, laundry and kitchen with a pressure of 4.5 bar and at least 1.5 tonnes/h during the whole year as illustrated in Figure 5.4.

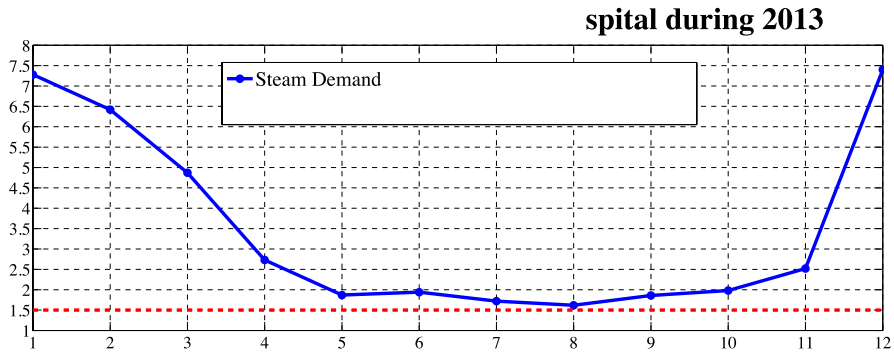


Figure 5.4. Steam consumption of university hospital during 12 months

For cooling, the hospital has significant demands between May and November as shown in Figure 5.5. Thus, a trigeneration plant with a double-effect absorption chiller may be considered for this hospital in order to obtain hot water between November and May, and cool water between May and November.

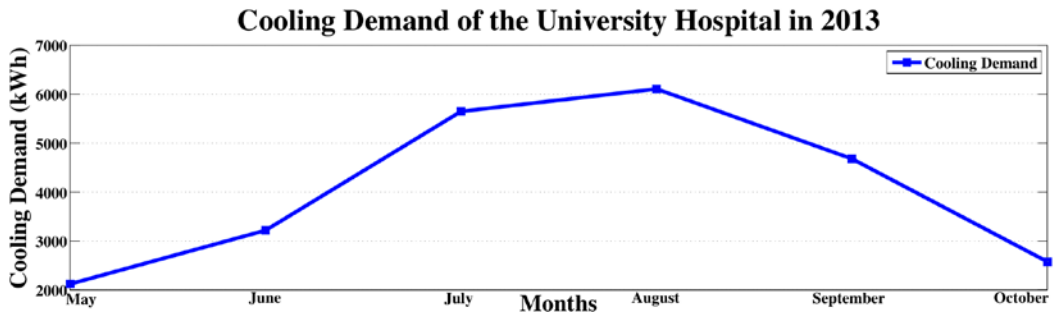


Figure 5.5. Cooling demand of university hospital between May and November

5.2. Validation of the Proposed Methodology

A stable operation for cogeneration or trigeneration plants should be provided by balancing the cooling, heat and electrical energy production at the same time by selecting a capacity that can satisfy the desired demands at the highest level. For the hospital, the proposed methodology demonstrated in Figure 4.1 will be applied.

In the hospital, the feasible period of the operation of cogeneration or trigeneration plant contains daytime and primetime periods for cheaper electricity production. When the electric demands of the university hospital are analyzed, the hospital has minimum demands of approximately 1.5 MW per hour in March and November. It is an undesirable condition for reciprocating gas engines to operate below 50% of full load. Hence, the electric power capacity of the suggested cogeneration or trigeneration plant should be less than or equal to 3 MW per hour as given in Equation 5.2,

$$c_e \leq P_{min} / L_{min} \tag{5.2}$$

In order to determine the optimal capacity rating with respect to steam demands of the hospital, the minimum steam demand should be considered and that is 1.5 tonnes/h for the hospital in August. A reciprocating gas engine with a capacity of 2 MW per hour electricity generation can provide 1.5 tonnes/h at a pressure of 4.5 bar. Therefore, the heat capacity of the suggested cogeneration plant should be equal to or greater than 2 MW per hour as given in Equation 5.3,

$$c_h \geq P_{h(min)} \tag{5.3}$$

For installing a trigeneration plant, it is important to determine the cooling capacity of absorption chillers by evaluating cooling demands of the hospital. When the cooling demand is analyzed, the minimum cooling demand during summer period is about 2 MW_t per hour in May which can be obtained in a double-effect absorption chiller driven by a reciprocating engine should have an electrical energy

production capacity that is equal to or greater than 2 MW per hour as given in Equation 5.4,

$$C_c \geq P_{c(\min)} \tag{5.4}$$

In determining the optimal capacity ratings for cogeneration and trigeneration plants, MTU Onsite Energy Natural Gas Engine (MTU, 2015) with an electricity generation capacity of 2.145 MW per hour was selected for both plants with respect to Equation 5.5 and Equation 5.6, respectively,

$$C_{chp(opt)} = C_e \cap C_h \tag{5.5}$$

$$C_{cchp(opt)} = C_e \cap C_c \tag{5.6}$$

Table 5.2. MTU Onsite Energy AoE20V4000L63 Gas Engine Characteristics (MTU, 2015)

MTU Onsite Energy AoE20V4000L63	**Gas Engine-Generator Set with Heat Recovery System Compatible for Cogeneration and Trigeneration Plants**
Electrical Output Power (kW_e/h)	2,145
Steam Production with a Pressure of 4.5 bar (tonnes/h)	At least 1.5 (1,204 kW_t/h)
Thermal Output of Jacket Water (kW_t/h)	1,155
Thermal Output of Aftercooler (kW_t/h)	140
Cooling Output of Double-effect Absorption Chiller Corresponding to Electric Chiller (kW_e/h)	880
Fuel Consumption (m^3/h)	513.9

Consequently, MTU Onsite Energy cogeneration or trigeneration plant with selected capacity rating operates at full load or near full load during an entire year and the hospital consumes produced cooling, heat and electricity totally.

5.3. Suggested Cogeneration Plant for the Hospital

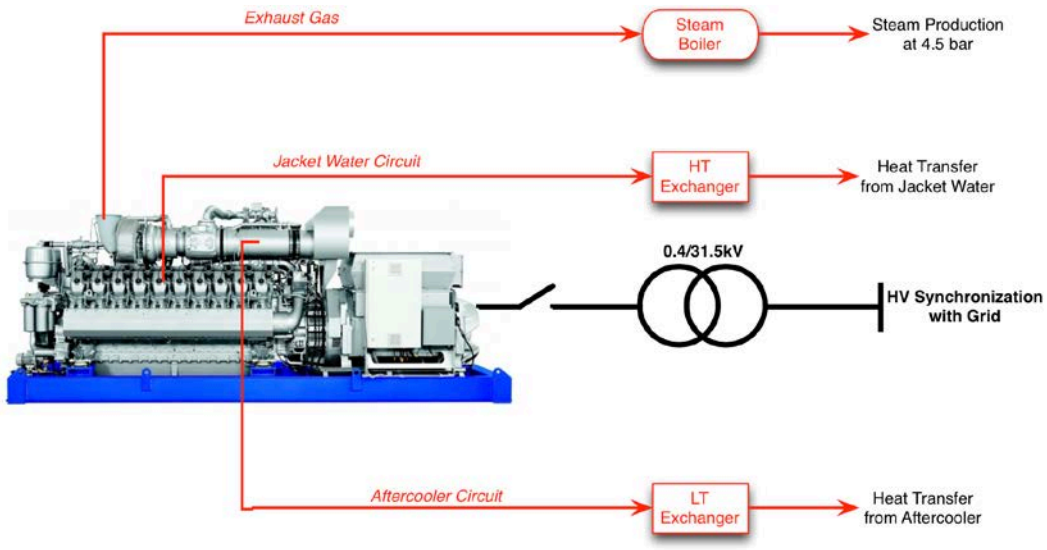


Figure 5.6. Cogeneration plant scenario of the hospital

Cogeneration plant scenario of the hospital is illustrated in Figure 5.6. It is also critical to locate the cogeneration plant to a place that is close to heat centers and HV switchgear of the hospital. Here in this hospital, there is an available site to establish cogeneration plant very close to both heat collectors of the hospital and HV switchgear as shown in Figure 5.7 (Timur, 2013). The red lines indicate cogeneration pipelines and the blue lines indicate trigeneration pipelines. The cogeneration plant is planned to settle inside of the existing heat center of the hospital. For this situation, pipeline installation cost will be decreased automatically. All the current pipelines can be used in the new cogeneration plant of the hospital. An efficient cogeneration plant contains engine-generator set, steam boiler, 0.4kV/34.5kV step-up transformer and a container can be settled at the hospital.

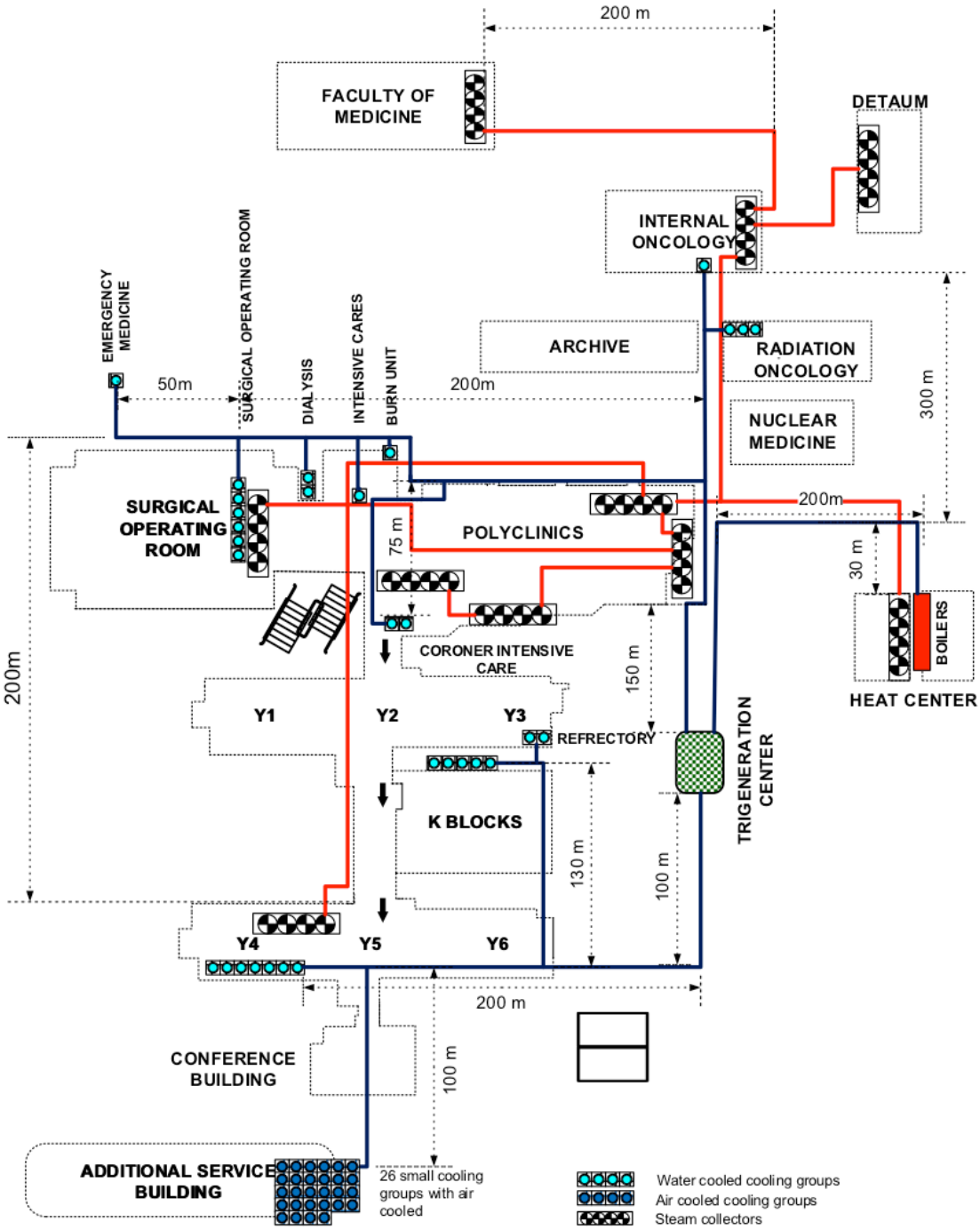


Figure 5.7. Schematic view of cogeneration and trigeneration plants

A feasibility study is performed to calculate cost saving and investment costs for planned cogeneration plant. Generating electricity by cogeneration plant reduces electrical energy consumption from the grid, thus not buying expensive electricity from the grid is a significant saving.

Electrical savings calculation is indicated below:

$$ES = T \times P \times p_{g,16} \times UF \tag{5.7}$$

where *ES* is electrical savings for one year, *T* is operating hour of cogeneration plant during a year, *P* is electrical output power produced for one hour, $p_{g,16}$ is the unit price of grid electricity for 16 hours use in daytime and primetime periods (cogeneration plant will not operate in nighttime) and *UF* is utilization factor which is the ratio of average electric power production for an hour during an average day and total electric power at full load (in order to calculate hourly changing part loads). If we consider that cogeneration plant will operate 16 hours per day (considering 5,400 hours per year excluding failures and maintenances), produce 2,145 kW electrical output power in an hour, utilization factor is 91.89% (average for a typical day is 1,971 kW) and the unit price of grid electricity for 16 hours/day is 0.145 $/kWh, then electrical saving of cogeneration plant is calculated as 1,543,325 $/year.

Heat savings are steam savings, jacket water savings and aftercooler savings. Producing steam, hot water and warm water by cogeneration plant reduces heat costs of the hospital. Steam saving calculation is illustrated below:

$$SS = (T \times P_{t(exh)} \times p_{ng} \times UF) / (LHV \times \eta_b) \tag{5.8}$$

where *SS* is steam saving for one year, $P_{t(exh)}$ is thermal output power generated by exhaust gas during one hour, η_b is steam boiler efficiency, p_{ng} is the unit price of natural gas, *UF* is utilization factor which is the ratio of average heat power production for an hour during an average day and total heat power at full load for steam boiler (in order to calculate hourly changing part loads), and *LHV* is lower heating value. If we consider that cogeneration plant will operate 5,400 hours per year, it can produce 1,204 kW_t thermal output power in an hour, have a steam boiler efficiency of 80%, a utilization factor of 92.54% and lower heating value of 10

kWh/m^3, and unit price of natural gas is 0.393 \$/m^3, then steam saving of cogeneration plant is calculated as 295,564 \$/year.

Jacket water saving calculation is stated below:

$$JWS = (T \times P_{t(jw)} \times p_{ng} \times UF) / (LHV \times \eta_{exc(jw)}) \quad (5.9)$$

where *JWS* is jacket water saving for one year, $P_{t(jw)}$ is thermal output power of jacket water during one hour, $\eta_{exc(jw)}$ is jacket water exchanger efficiency. If we consider that cogeneration plant will operate 5,400 hours per year, produce 1,155 kW_t thermal power in an hour, have a jacket water exchanger efficiency of 80%, a utilization factor of 91.17% and lower heating value of 10 kWh/m^3, and unit price of natural gas is 0.393 \$/m^3, then jacket water saving of cogeneration plant is calculated as 279,338 \$/year.

Aftercooler saving calculation is calculated as given in Equation 5.10,

$$AS = (T \times P_{t(a)} \times p_{ng} \times UF) / (LHV \times \eta_{exc(a)}) \quad (5.10)$$

where *AS* is aftercooler saving for one year, $P_{t(a)}$ is thermal output power of aftercooler during one hour, $\eta_{exc(a)}$ is aftercooler exchanger efficiency. If we consider that cogeneration plant will operate 5,400 hours per year, produce 140 kW thermal power in an hour, have an aftercooler exchanger efficiency of 80%, a utilization factor of 91.19% and lower heating value of 10 kWh/m^3, and unit price of natural gas is 0.393 \$/m^3, then aftercooler saving of cogeneration plant is calculated as 33,866 \$/year.

Total heat savings are resulted in the following equation:

$$HS = SS + JWS + AS \quad (5.11)$$

where *HS* is total heat savings and summation of all heat related savings. Hence, for this case, total heat saving is calculated as 608,768 \$/year.

Cogeneration plant saving is the sum of electrical saving and total heat saving as given below:

$$CS = ES + HS \tag{5.12}$$

where *CS* is cogeneration plant saving for one year and it is 2,152,093 $/year.

Total fuel consumption expense of the gas engine can be calculated as given below:

$$FCE = T \times F_c \times p_{ng} \times UF \tag{5.13}$$

where *FCE* is total fuel consumption expense. For 5,400 operation hours, engine fuel consumption at full load is 513.9 m^3/h, unit price for natural gas is 0.393 $/$m^3$ and *UF* is 92.26%, then total fuel consumption expense is calculated as 1,006,186 $/year.

Calculation of internal electrical consumption expense for auxiliary equipment of cogeneration plant is indicated below:

$$IECE = T \times P_{aux} \times p_{g,16} \times UF \tag{5.14}$$

where *IECE* is internal electrical consumption expense for one year, *T* is operating hour of cogeneration plant during a year, P_{aux} is electrical output power of auxiliary equipment for one hour, $p_{g,16}$ is the unit price of grid electricity for 16 hours use and utilization factor is 91.89%. If we consider that cogeneration plant will operate 5,400 hours per year, auxiliary equipment consume 55 kW electrical power in an hour, the unit price of grid electricity for 16 hours/day is 0.145 $/kWh, then internal electrical consumption expense of cogeneration plant is calculated as 39,572 $/year.

For cogeneration plants, service and spare part expenses are considered as a single fee per operating hour. If cogeneration plant will operate 5,400 hours in a

year, and if service and spare part expense is nearly 17 $/h for one engine-generator set, then service and spare part expense (*SSE*) is calculated as 91,800 $/year.

In this hospital, the cogeneration plant is planned to operate for 16 hours in two shifts by two different operators, and gross salary for each operator is 3,600 $/month. For one year, total operator expense (*OE*) is calculated as 86,400 $/year and cogeneration plant expense will be found as,

$$CE = FCE + IECE + SSE + OE \tag{5.15}$$

where *CE* is the cogeneration plant expense for one year and it is 1,223,958 $/year.

Total revenue can be calculated as shown in the following formula and therefore total revenue (*TR*) for one year is calculated as 928,135 $/year for this plant.

$$TR = CS - CE \tag{5.16}$$

Planned cogeneration plant should consist of engine-generator set in a sound-isolated container, heat recovery steam boiler and its mechanical piping, switchgear units for high voltage synchronization by using step-up transformer, neutral resistor and electrical cabling. For such needs, an investment cost (C_{inv}) of 1,400,000 $ is offered for cogeneration plant installation. Finally, payback time (T_p) can be found illustrated below:

$$T_p = C_{inv} / TR \tag{5.17}$$

Due to the total revenue founded above and offered price for the cogeneration plant the payback time is calculated as 1.51 year. A cogeneration plant with a steam boiler and electrically synchronized from high voltage switchgear would be a very sensible investment for Balcalı Hospital according to the above calculations.

5.4. Suggested Trigeneration Plant for the Hospital

When cooling demands of the hospital are analyzed, it is seen that electric chiller units of the hospital operate between May and November. Between November and May, hospital needs hot water. A trigeneration plant with a double-effect absorption chiller unit satisfies the need of this hospital during an entire year. From May to November, trigeneration plant will produce cold water; from November to May, it will produce hot water. Planned trigeneration scenario is demonstrated in Figure 5.8. An efficient trigeneration plant contains an engine-generator set, a double-effect absorption chiller unit with cooling tower, a 0.4kV/34.5kV step-up transformer and a sound-isolated container can be settled at the hospital.

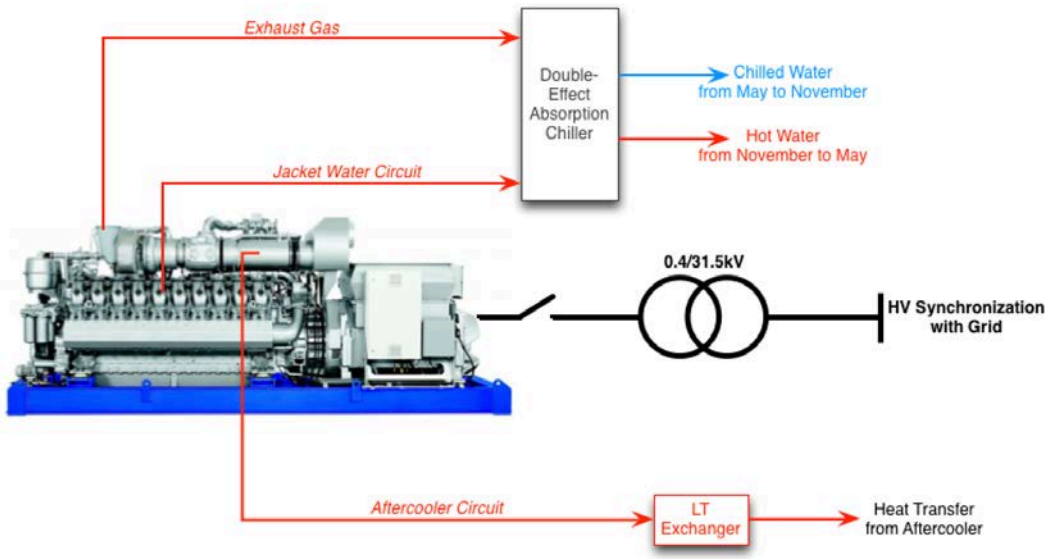


Figure 5.8. Trigeneration plant scenario of the hospital

A similar feasibility study as in the suggestion of cogeneration plant has savings and expenses to calculate the payback period of the planned trigeneration plant. Generating electricity by trigeneration plant is the same with cogeneration plant calculated in the previous section and will provide 1,543,325 $/year electrical savings.

Cool water production by absorption chiller unit reduces the utilization of electric chiller units and this causes a saving in the energy bill. This cooling saving can be formulated as:

$$ACS = T \times P_{ecu} \times p_{g,16} \times UF \tag{5.18}$$

where *ACS* is absorption chiller cooling saving, P_{ecu} is the correspondent electric chiller unit power of double-effect absorption chiller unit. If trigeneration plant produces cold water 16 hours/day from May to November (2,700 hours/year by excluding failures and maintenances), correspondent electric chiller unit power of double-effect absorption chiller unit is 880 kW, the unit price of grid electricity for 16 hours/day is 0.145 $/kWh, and the utilization factor is 90%, then the absorption chiller cooling saving is calculated as 310,068 $/year.

Heat savings in trigeneration plant are exhaust-jacket water savings and aftercooler savings. Producing hot water and warm water by trigeneration plant reduces heat costs of the hospital. Exhaust-jacket water saving calculation is stated below:

$$EJWS = (T \times P_{t(ejw)} \times p_{ng} \times UF) / (LHV \times \eta_{exc}) \tag{5.19}$$

where *EJWS* is exhaust and jacket water saving for one year, $P_{t(ejw)}$ is total thermal output power of exhaust and jacket water during one hour, η_{exc} is exchanger efficiency. If we consider that trigeneration plant will operate 2,700 hours per year (from November to May), produce 2,050 kW thermal power in an hour, have an exchanger efficiency of 80%, a utilization factor of 91.17% and lower heating value of 10 kWh/m^3, and unit price of natural gas is 0.393 $/$m^3$, then exhaust-jacket water saving of trigeneration plant will be 247,897 $/year.

Aftercooler saving calculation is the same with cogeneration plant calculated in the previous section and will provide 33,866 $/year. Total heat savings are resulted in the following equation:

$$THS = EJWS + AS \tag{5.20}$$

where *THS* is trigeneration heat savings and summation of all heat related savings. Hence, for this case, total heat saving is 281,763 $/year.

Trigeneration plant saving is the sum of,

$$TS = ES + ACS + THS \tag{5.21}$$

where *TS* is trigeneration plant saving for one year and it is 2,135,156 $/year.

Total fuel consumption expense of the gas engine is the same with cogeneration plant calculated in the previous section and the expense is 1,006,186 $/year.

Internal electrical consumption expense for auxiliary equipment and absorption chiller unit of trigeneration plant is calculated as in Equation 5.14, just P_{aux} is 70 kW for an hour and different than cogeneration because of absorption chiller unit, then internal electrical consumption expense of trigeneration plant is calculated as 50,365 $/year.

Service and spare part expense for trigeneration plant is the same with cogeneration plant calculated in the previous section and that is 91,800 $/year.

Operator expense for trigeneration plant is the same with cogeneration plant calculated in the previous section and that is 86,400 $/year.

Trigeneration plant expense,

$$TE = FCE + IECE + SSE + OE \tag{5.22}$$

where *TE* is trigeneration plant expense for one year and it is 1,234,751 $/year.

Total revenue can be calculated as shown in the following formula and therefore total revenue will be 900,405 $/year for this plant.

$$TR = TS - TE \tag{5.23}$$

Planned trigeneration plant should consist of an engine-generator set in a sound-isolated container, a double-effect absorption chiller unit, cooling tower and extra piping, switchgear units for high voltage synchronization by using step-up transformer, neutral resistor and electrical cabling. For such needs, an investment cost of 2,050,000 $ is offered for trigeneration plant installation. Finally, payback time can be found from the Equation 5.17. and will be 2.27 year.

5.5. Financial Viability for the Suggested Plants

The optimal capacity ratings for both cogeneration and trigeneration plants were calculated as 2.2 MW in the developed software program for Balcalı Hospital. A capacity rating of 2.145 MW was chosen for payback analyzes. For this rating, cogeneration plant with a steam boiler has an investment cost of 1,400,000 $, annual revenue of 928,135 $ and calculated payback time of the investment is 1.51 year. For trigeneration plant with double-effect absorption chiller, system cost is 2,050,000 $, annual revenue of the system is 900,405 $ and payback time of the system cost is 2.27 year.

Table 5.3. Financial viability for the suggested plants

	Cogeneration Plant	**Trigeneration Plant**
Investment Cost ($)	1,400,000	2,050,000
Annual Revenue ($)	928,135	900,405
Payback Time (year)	1.51	2.27

The suggested cogeneration plant is more feasible than the suggested trigeneration plant for Balcalı Hospital as shown in Table 5.3. It is recommended to select cogeneration plant over the trigeneration plant.

6. CONCLUSION AND FUTURE WORK

6.1. Conclusion

Cogeneration and trigeneration plants generate several energy types simultaneously using a single fuel input, utilize higher efficiency ratings compared with conventional plants having separate production, and consolidate its role in energy efficiency and distributed generation day by day.

Unlicensed electricity generation for on-site cogeneration and trigeneration plants ensuring the efficiency condition of at least 80%, has changed the cogeneration mentality in Turkey from "Generate, use and sell surplus energy to the grid" to "Generate as much as you need and use the produced energy onsite" as in most countries of the European Union.

Internal combustion gas engines are used in cogeneration and trigeneration plants for having lower carbon emission, rapid operation of synchronization, part load operational flexibility, good load following capability and short payback periods. By January 2015, installed capacity of gas engine driven cogeneration and trigeneration plants exceeds 1 GW in Turkey.

Eventually, Turkey's geographical location, natural gas pipelines passing through Turkey and share of natural gas fuelled power plants are considered together, cogeneration and trigeneration plants will sustain their advantages in order to generate cheaper electricity independently from changes in electrical and natural gas prices.

In this thesis, a methodology is proposed and a software program is developed for satisfying unlicensed electricity generation criteria of EMRA in order to determine the optimal capacity rating of cogeneration and trigeneration plants driven by natural gas fired gas engines. Fundamentals, grid synchronization, current legislation in Turkey, environmental effects, capacity sizing criteria of gas engine driven cogeneration and trigeneration plants are described from Electrical and Electronics Engineering’s point of view. Current status of gas engines in Turkey is identified and supported with appendix in detail. A feasibility analysis of Çukurova

University Balcalı Hospital as a case study is achieved for both cogeneration and trigeneration. Literature survey of developed software programs is presented.

According to proposed methodology, optimal capacity ratings for both cogeneration and trigeneration plants for University Hospital were calculated as 2.2 MW in the developed program, 2.145 MW capacity rating was selected for the gas engine. According to the payback calculations for determined capacity rating, payback times are 1.51 and 2.27 year for cogeneration and trigeneration plants respectively. These results prove that developed software program is working properly for determining the optimal capacity ratings of cogeneration and trigeneration plants.

6.2. Recommendations for Future Work

Further research can be carried out in the following areas:

1- Developed software program in this thesis can be supported by machine learning methods for the best optimization with manufacturers and engine characteristics database.
2- A feasibility mechanism can be implemented in the designed program.
3- A detailed feasibility study can be prepared with a life-cycle cost analysis method.
4- Environmental effects can be observed by obtained data from a real operational plant.
5- Hybrid cogeneration and trigeneration plants can be researched to meet plant’s internal electricity consumption.

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BIOGRAPHY

Kasım Zor was born on 4 January 1987 in Adana. He graduated from Seyhan Anatolian High School in 2004. He completed Erasmus Exchange Program in Linköping Institute of Technology in Linköping, Sweden in 2007 and received his BSc degree in Electrical and Electronics Engineering (EEE) from Çukurova University in 2010.

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APPENDIX

APPENDIX A: Natural Gas and Biogas Engine Based Cogeneration and Trigeneration Plants in Turkey

Table A.1. MTU Onsite Energy NG engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2010	AKMETAL MINING PLANT	2,145	ADANA
2011	ACIBADEM ADANA HOSPITAL	849	ADANA
2011	AKMETAL MINING PLANT	4,290	ADANA
2011	MELTEM CHEMISTRY PLANT	2,145	ADANA
2011	BURSA HILTON HOTEL	1,286	BURSA
2011	ACIBADEM ESKİŞEHİR HOSPITAL	849	ESKİŞEHİR
2011	EMSEY HOSPITAL	849	İSTANBUL
2011	SARAY CARPET FACTORY	4,290	KAYSERİ
2011	TURGUTLU STATE HOSPITAL	1,235	MANİSA
2011	GÜMÜŞTAŞ GOLD MINING PLANT	1,286	NİĞDE
2011	DIZAYN TEKNIK PLASTIC FACTORY	2,145	TEKİRDAĞ
2012	KIVANÇ TEXTILE PLANT	2,145	ADANA
2012	MAXX ROYAL HOTEL	5,139	ANTALYA
2012	VOYAGE BELEK HOTEL	849	ANTALYA
2012	CORNELIA HOTEL	2,294	ANTALYA
2012	CORNELIA DELUXE HOTEL	849	ANTALYA
2012	HOTEL RIU KAYA	1,286	ANTALYA
2012	BİFA BISCUITS	2,145	KARAMAN
2012	ACIBADEM KAYSERİ HOSPITAL	849	KAYSERİ
2012	BAMEN TEXTILE PLANT	2,145	KAYSERİ
2012	MAVI JEANS	1,712	TEKİRDAĞ
2013	BPLAS DOSAP	2,145	BURSA

2013	BPLAS 5. KM	849	BURSA
2013	SELVA FOOD INDUSTRY	1,712	KONYA
2013	MEDICANA HOSPITAL	849	KONYA
2013	BiNATOM - EMET PROJECT	4,290	KÜTAHYA
2013	ALPERTEKS TEXTILE PLANT	4,290	UŞAK
2014	TAI	10,725	ANKARA
2014	ROBINSON NOBILIS HOTEL	854	ANTALYA
2014	ELA QUALITY RESORT HOTEL	854	ANTALYA
2014	CARYA GOLF RESORT HOTEL	2,572	ANTALYA
2014	RADISSON HOTEL	849	KAYSERİ
2014	ENKA MILK FACTORY	854	KONYA
2015	SUENO HOTEL	2,140	ANTALYA
2015	OMMER HOTEL	1,286	KAYSERİ
2015	MEDOVA HOSPITAL	854	KONYA

Table A.2. MTU Onsite Energy raw material biogas engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2011	ÇUMRA SUGAR FACTORY	1,560	KONYA

Table A.3. MTU Onsite Energy WWT biogas engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2014	GENOVA WWTP	2,986	ANTALYA

Table A.4. Caterpillar NG engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
1995	PISA TEXTILE PLANT	1,020	İSTANBUL
1997	ULTAŞ TEXTILE PLANT	1,020	İSTANBUL
1998	TÜP MERCERIZED TEXTILE PLANT	1,020	KIRKLARELİ

1998	SÖNMEZ FILAMENT FACTORY	4,120	BURSA
1998	DOĞUŞ TEXTILE PLANT	1,020	TEKİRDAĞ
1998	SARKUYSAN COPPER PLANT	7,690	KOCAELİ
1998	NURYILDIZ TEXTILE PLANT	768	İSTANBUL
1998	ATLAS CARPET FACTORY	1,020	TEKİRDAĞ
1998	İSTANBUL IRON & STEEL PLANT	7,690	İSTANBUL
1998	TÜRK HENKEL	1,020	KOCAELİ
1998	BAYDEMİRLER TEXTILE PLANT	1,020	İSTANBUL
1999	BAHARİYE TEXTILE PLANT	1,020	İSTANBUL
1999	ECZACIBAŞI BAXTER	1,020	İSTANBUL
2000	AYDIN TEXTILE PLANT	1,020	İSTANBUL
2000	BAYDEMİRLER TEXTILE PLANT	2,040	İSTANBUL
2003	TANRIVERDİ TEXTILE PLANT	4,660	TEKİRDAĞ
2003	AKTİN TEXTILE PLANT	1,465	TEKİRDAĞ
2003	ÇELİK WIRE INDUSTRY	2,330	KOCAELİ
2003	SÜPERBOY TEXTILE PLANT	1,020	İSTANBUL
2003	AKMAN TEXTILE PLANT	1,465	TEKİRDAĞ
2004	MERCEDES-BENZ TÜRK	10,000	İSTANBUL
2004	BAYDEMİRLER TEXTILE PLANT	6,000	İSTANBUL
2004	BOTAŞ NEHİR TEXTILE PLANT	1,165	TEKİRDAĞ
2004	ZEYNEP TEXTILE PLANT	1,165	TEKİRDAĞ
2005	KÜÇÜKÇALIK TEXTILE PLANT	8,000	BURSA
2005	ELSE TEXTILE PLANT	3,168	TEKİRDAĞ
2005	EROĞLU TEXTILE PLANT	1,165	TEKİRDAĞ
2005	ŞIK MAKAS TEXTILE PLANT	1,584	TEKİRDAĞ
2005	MELİKE TEXTILE PLANT	1,584	GAZİANTEP
2006	CONRAD HOTEL	1,584	İSTANBUL
2006	KİL-SAN INDUSTRY	3,168	İSTANBUL
2006	MİSİS APRE TEXTILE PLANT	1,584	ADANA
2006	KURTOĞLU COPPER INDUSTRY	1,605	TEKİRDAĞ

2006	FOUR SEASONS HOTEL BOSPHORUS	1,165	İSTANBUL
2006	MARDAN PALACE HOTEL	2,330	ANTALYA
2007	MAURI BREWING	2,000	BALIKESİR
2007	BAHÇIVAN FOOD INDUSTRY	1,165	KIRKLARELİ
2007	GRAND ANKARA RIXOS HOTEL	2,000	ANKARA
2007	AYTAŞ CONSTRUCTION	1,605	ANKARA
2007	KONYA SUGAR FCATORY	1,600	KONYA
2007	POLAT RENAISSANCE HOTEL	1,605	İSTANBUL
2007	LAFARGE DALSAN	1,165	KOCAELİ
2008	MELİKE TEXTILE PLANT	1,605	GAZİANTEP
2008	NAKSAN PLASTIC	8,000	GAZİANTEP
2008	TESCOKİPA ÇİĞLİ MALL	2,330	İZMİR
2009	NESA MINING PLANT	1,584	ADANA
2009	KESKİNOĞLU POULTRY	3,495	MANİSA
2009	BİNATOM ELECTRIC	2,000	KÜTAHYA
2009	ISG AIRPORT	4,000	İSTANBUL
2010	DURUM FOOD INDUSTRY	2,000	İÇEL
2010	DURUM FOOD INDUSTRY	1,605	İÇEL
2010	KÜÇÜKBAY OIL FACTORY	1,605	İZMİR
2011	ODE INSULATION COMPANY	2,022	TEKİRDAĞ
2011	TARABYA HOTEL	1,200	İSTANBUL
2011	SWISS HOTEL	1,200	İZMİR
2011	AKDENİZ CHEMISTRY PLANT	4,044	İZMİR
2011	KESKİNOĞLU POULTRY	6,000	MANİSA
2011	ABALIOĞLU FEED INDUSTRY	6,066	İZMİR
2011	EGEPARK SHOPPING MALL	2,022	İZMİR
2011	CVK-PARK HOTEL	2,022	İSTANBUL
2011	ORA SHOPPING MALL	4,815	İSTANBUL
2012	DURUM FOOD INDUSTRY	2,022	İÇEL

2012	BİNATOM ELECTRIC	2,022	KÜTAHYA
2012	MERCEDES-BENZ TÜRK	2,022	İSTANBUL
2012	BEYBO INDUSTRY	2,022	TEKİRDAĞ
2012	AKMETAL MINING PLANT	2,022	ADANA
2012	AKOVA MILK & FOOD INDUSTRY	2,022	KONYA
2012	KOLİN CONSTRUCTION	1,000	İSTANBUL
2012	TEPE-TESAN DOLPHIN	1,589	ANKARA
2012	MEY ALCOHOL FACTORY	1,000	NEVŞEHİR
2012	BUMAS KARAMAN FOOD IND.	4,044	KARAMAN
2012	TAV İZMİR AIRPORT	10,110	İZMİR
2012	TURKISH AIRLINES - HABOM	6,066	İSTANBUL
2013	ÇİNKOM FACTORY	2,022	KAYSERİ
2013	FLAMENT TEXTILE PLANT	2,022	GAZİANTEP
2013	ÖZMAYA BREWING	2,022	ADANA
2013	MELTEM TEXTILE PLANT	2,022	GAZİANTEP
2013	RIXOS PREMIUM BELEK HOTEL	2,022	ANTALYA
2013	HASBOY	2,022	K.MARAŞ
2013	KUVEYT TÜRK HEADQUARTERS	2,022	KOCAELİ
2013	BOTAŞ ESKİŞEHİR CS	1,200	ESKİŞEHİR
2014	BİNATOM	4,300	KÜTAHYA
2014	EROĞLU TEXTILE	1,000	AKSARAY
2014	ELİF PLASTIC	4,000	İSTANBUL
2014	ANI BISCUITS	1,200	KARAMAN
2014	MEY ALCOHOLIC DRINK FACTORY	1,200	NEVŞEHİR
2014	HİTİT UNIVERSITY	400	ÇORUM
2014	ECZACIBAŞI ESAN	6,000	ESKİŞEHİR
2014	AZRA BISCUITS	1,200	KARAMAN
2014	GEMCİLER METAL	2,000	K.MARAŞ
2014	KARBOY/NEVRES TEXTILE	1,560	K.MARAŞ
2014	BOSSA TEXTILE	4,300	ADANA

2014	MATESA TEXTILE	17,200	K.MARAŞ
2014	MADOSA TEXTILE	800	K.MARAŞ
2014	MEM TEXTILE	4,300	K.MARAŞ
2014	NET TEXTILE	1,200	K.MARAŞ

Table A.5. Caterpillar WWT biogas engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2007	ANTALYA WWTP	1,165	ANTALYA

Table A.6. GE Jenbacher NG engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2000	BOTAŞ AMBARLI NG CS	803	İSTANBUL
2001	PAKMAYA BREWING	2,096	DÜZCE
2001	ASİL FOOD INDUSTRY	2,096	KOCAELİ
2002	ALTINMARKA FOOD INDUSTRY	2,096	İSTANBUL
2003	ATATEKS TEXTILE PLANT	9,105	TEKİRDAĞ
2003	TEKBOY TEXTILE PLANT	2,188	KIRKLARELİ
2004	ALTINMARKA FOOD INDUSTRY	1,413	İSTANBUL
2004	BOTAŞ DOĞUBEYAZIT NG CS	836	AĞRI
2004	STANDARD PROFILE	6,564	DÜZCE
2006	FLOKSER	2,130	İSTANBUL
2006	SÜETSER	2,130	TEKİRDAĞ
2008	SÜETSER	3,044	TEKİRDAĞ
2009	BOTAŞ NG CS	835	SİVAS
2010	GÜRTEKS YARN PLANT	6,698	GAZİANTEP
2010	NIL WEAVING PLANT	2,677	TEKİRDAĞ
2010	GÜVEN YARN PLANT	2,006	GAZİANTEP
2011	ÖZGÜMÜŞ TEXTILE	1,189	BURSA
2011	ALTINSU TEXTILE	1,189	BURSA

2011	DERHAN TEXTILE	1,189	BURSA
2011	ÖZMAYA BREWING	5,354	AMASYA
2011	BURKAY TEXTILE	1,189	BURSA
2011	DURKAR CARPET FACTORY	2,433	GAZİANTEP
2011	GÜRTEKS SYNTHETIC	3,349	GAZİANTEP
2011	BOSSAN CARPET FACTORY	3,349	GAZİANTEP
2011	BOSSA	6,698	ADANA
2011	BOTAŞ ERZİNCAN CS	1,002	ERZİNCAN
2012	DEMİRER CABLE	1,063	BİLECİK
2012	DEMİRER CABLE	1,413	BİLECİK
2012	UNIVERSAL TEXTILE	3,349	TEKİRDAĞ
2012	CEMRE TEXTILE	793	GAZİANTEP
2012	RADISSON HOTEL ŞİŞLİ	527	İSTANBUL
2012	RADISSON HOTEL TAKSİM	330	İSTANBUL
2013	TEKSMAK	2,677	BURSA
2013	GÜR YARN PLANT	3,358	GAZİANTEP
2013	BEYZA POULTRY IND.	2,004	ADANA
2013	TEKNIK PLASTIK	3,358	İSTANBUL
2013	KORUMA KLOR	13,396	KOCAELİ
2013	KORUMA KLOR	10,047	HATAY
2013	KÖKNAR PAPER	3,349	KIRKLARELİ
2013	UŞAK CERAMIC	6,698	UŞAK
2013	ADANA SHERATON HOTEL	627	ADANA
2013	KORUMA KLOR	6,698	DENİZLİ
2014	YÜKSEL CERAMIC	2,974	AYDIN
2014	VEZİRAĞAÇ PAPER	6,716	SAMSUN

Table A.7. GE Jenbacher raw material biogas engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2008	FRITOLAY	660	İÇEL
2009	FRITOLAY	635	KOCAELİ
2010	TÜBİTAK	330	KOCAELİ
2010	İLCI AGRICULTURE	249	KIRŞEHİR
2011	AK FOOD INDUSTRY - ARBIOGAZ	1,487	SAKARYA
2012	SÜTAŞ KARACABEY	2,134	BURSA
2012	SÜTAŞ AKSARAY	3,201	AKSARAY
2012	GÖNEN ENERGY	2,134	BALIKESİR
2012	AFYON ENERGY	4,017	AFYON
2013	POLRES	793	ANKARA
2014	ALTACA _II	1,487	BALIKESİR
2014	POLRES _II	637	ANKARA
2014	AKSÜT	637	MALATYA

Table A.8. GE Jenbacher WWT biogas engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2004	WEST ADANA WWTP	803	ADANA
2007	EAST ADANA WWTP	803	ADANA
2008	KONYA WWTP	2,505	KONYA
2009	TOKAT WWTP	330	TOKAT
2010	MUĞLA WWTP	249	MUĞLA
2012	DİYARBAKIR WWTP	1,911	DİYARBAKIR
2013	ERZURUM WWTP	1,054	ERZURUM

Table A.9. GE Jenbacher landfill gas engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2000	İSTAÇ SWLF	4,024	İSTANBUL
2004	ECOPROTECHSYNGAS SWLF	588	İSTANBUL
2004	ITC MAMAK SWLF	25,488	ANKARA
2008	ITC KONYA SWLF	5,652	KONYA
2008	ORTADOĞU ENERGY ODAYERİ SWLF	29,736	İSTANBUL
2008	ORTADOĞU ENERGY KÖMÜRCÜODA SWLF	12,744	İSTANBUL
2009	ITC ADANA SWLF	15,576	ADANA
2009	ITC SINCAN SWLF	14,160	ANKARA
2010	BEREKET ENERGY SWLF	635	DENİZLİ
2010	CEV GAZİANTEP SWLF	5,655	GAZİANTEP
2010	CEV BOLU SWLF	1,131	BOLU
2010	ITC BURSA SWLF	9,891	BURSA
2012	KIRIKKALE SWLF	1,003	KIRIKKALE
2012	KÖRFEZ ENERGY SWLF	4,252	KOCAELİ
2013	ORTADOĞU ENERGY SWLF	1,063	İSTANBUL

Table A.10. MWM NG engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2003	CAN ENERGY 1	4,000	TEKİRDAĞ
2003	ŞAHİNLER ENERGY	4,000	TEKİRDAĞ
2003	METEM ENERGY	20,000	TEKİRDAĞ
2004	POLYPLEX 1	4,000	TEKİRDAĞ
2004	KIVANÇ TEXTILE PLANT	4,000	ADANA
2005	SAY ENERGI	6,000	KAYSERİ
2005	ACIBADEM HOSPITAL	600	İSTANBUL

2005	SWISS HOTEL	1,600	İSTANBUL
2006	DOĞANER	1,600	ANKARA
2006	TAV ESENBOĞA AIRPORT	4,000	ANKARA
2007	POLYPLEX 2&3	8,000	TEKİRDAĞ
2008	MİNA	1,600	ANKARA
2008	GÜLLE TEXTILE 1	4,000	TEKİRDAĞ
2008	FALEZ 1	12,000	ANTALYA
2008	İNEGÖL INDUSTRY ZONE	4,000	BURSA
2009	İÇTAŞ ANTALYA AIRPORT	8,000	ANTALYA
2009	SELÇUK TEXTILE 1	4,300	GAZİANTEP
2009	RB KARESİ TEXTILE	8,600	BURSA
2009	CANAN TEXTILE	4,000	GAZİANTEP
2009	CAN ENERGY 2	8,000	TEKİRDAĞ
2010	BURTEKS	4,300	GAZİANTEP
2010	ZAFER	1,600	GAZİANTEP
2010	BEYPİLİÇ	8,600	BOLU
2010	SAMUR CARPET	4,300	ANKARA
2010	ISPARTA TEXTILE	4,300	ISPARTA
2010	MAKYOL	600	İSTANBUL
2010	MUTLU PASTA	2,000	GAZİANTEP
2010	SELÇUK TEXTILE 2	4,300	GAZİANTEP
2010	BOYTEKS	8,000	KAYSERİ
2010	HASIRCI 1	2,000	GAZİANTEP
2010	BOYAR CHEMISTRY	2,000	GAZİANTEP
2010	GÜLLE TEXTILE 2	4,300	TEKİRDAĞ
2010	KNAUF PLASTER	2,000	ANKARA
2010	JTI	4,000	İZMİR
2010	ASAŞ ALUMINUM	8,600	SAKARYA
2011	ABS PLASTER	1,600	İÇEL
2011	HASIRCI 2	4,300	GAZİANTEP

2011	ANADOLU YARN	8,600	TEKİRDAĞ
2011	POLYPLEX RESINS	8,600	TEKİRDAĞ
2011	ŞİMŞEK BISCUITS	1,600	KARAMAN
2011	PİRİ REİS UNIVERSITY	1,600	İSTANBUL
2011	PLASKO	2,000	KIRKLARELİ
2011	TAT TEXTILE	2,000	GAZİANTEP
2011	BİLKUR	2,000	K.MARAŞ
2011	EUROPEN	2,000	ESKİŞEHİR
2011	ENERFLEX - ÖZDİLEK	4,300	BURSA
2012	LÜTUF TEXTILE	2,000	K.MARAŞ
2012	AĞAOĞLU AYAZMA	12,900	İSTANBUL
2012	DOKUBOY	4,300	K.MARAŞ
2012	ARSAN	4,300	K.MARAŞ
2012	İSKUR	8,600	K.MARAŞ
2012	TAT TEXTILE 2	2,000	GAZİANTEP
2012	BUPİLİÇ	2,000	BALIKESİR
2012	SANKO HOSPITAL	1,200	GAZİANTEP
2012	AK AMYLUM	2,000	KIRKLARELİ
2012	ABATEKS	4,300	K.MARAŞ
2012	GEP KARAMAN INDUSTRY ZONE	4,800	KARAMAN
2012	GEP GUSAP	14,500	BURSA
2012	GEP H2O2	4,300	BALIKESİR
2012	GEP - İPEK BULGUR	8,600	MARDİN
2013	F. NIGHTINGALE HOSPITAL	800	İSTANBUL
2013	BEYPİ FEED	4,300	BOLU
2013	RB KARESİ 2	4,300	BURSA
2013	UĞUR RECYCLING	1,200	TEKİRDAĞ
2013	ARSAN 2	4,300	K.MARAŞ
2013	AYDIN TEXTILE	4,300	SAKARYA
2013	CARGILL	8,600	BURSA

2013	KERVANSARAY LARA HOTEL	800	ANTALYA
2013	KERVANSARAY THERMAL HOTEL	200	BURSA
2013	NURYILDIZ	1,200	TEKİRDAĞ
2013	MONO ORİON SHOPPING MALL	1,200	TEKİRDAĞ
2013	KURTEKS	2,000	K.MARAŞ
2013	ÇANAKCILAR CERAMIC	600	ZONGULDAK
2013	KÜÇÜKÇALIK TEXTILE	8,600	BURSA
2013	SEHER YILDIZI TEXTILE	4,300	SAKARYA
2013	TEKAS	800	K.MARAŞ
2014	FIRAT UNIVERSITY	1,600	ELAZIĞ
2014	AK AMYLUM 2	2,000	İSTANBUL
2014	ERSA HOTEL	1,600	İSTANBUL
2014	FORZA ZEYNEP HOTEL	800	ANTALYA
2014	ATATÜRK AIRPORT, TURKISH AIRLINES NEW CARGO TERMINAL	4,000	İSTANBUL

Table A.11. MWM WWT biogas engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2006	GASKİ WWTP	1,400	GAZİANTEP
2009	ESKİŞEHİR WWTP	2,100	ESKİŞEHİR
2012	DENİZLİ WWTP	600	DENİZLİ
2012	ORDU WWTP	600	ORDU
2013	ASKİ WWTP	1,600	ADANA

Table A.12. MWM landfill gas engine based plants in Turkey

YEAR	FACILITY NAME	POWER (kW)	LOCATION
2010	HEXAGON SWLF	1,400	SAKARYA
2011	SAMSUN AVDAN 2	1,200	SAMSUN
2011	KÖRFEZ ENERGY	1,200	KOCAELİ

2011	HER ENERGY 1	1,600	KAYSERİ
2012	SAMSUN AVDAN 3	1,200	SAMSUN
2012	HER ENERGY 3	1,600	KAYSERİ
2012	ORTADOĞU ENERGY	4,200	İSTANBUL
2012	HER ENERGY 2	1,200	KAYSERİ
2013	MODERN ENERGY SWLF	6,000	TEKİRDAĞ
2013	DOĞU STAR 2	1,200	MALATYA
2013	SAMSUN AVDAN 4&5	2,400	SAMSUN
2013	HER ENERGY UŞAK	1,200	UŞAK
2013	HER ENERGY 4	1,600	KAYSERİ
2013	DOĞU STAR	1,200	MALATYA
2014	HER ENERGY 5	1,600	KAYSERİ
2014	BOĞAZKÖY SWLF	1,200	AMASYA