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OPTIMUM POWER MODELING FOR A COMBINED HEAT AND POWER

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Abstract- The energy crisis, generation, transmission, distribution losses and increased energy consumption created the necessary and appropriate incentive to move to local production (retail) of the energy. Thus, it is recommended to use combined turbine-steam optimum power systems in order to make local production concept more efficient. This article first discusses the importance of local production with combine systems. Different types of combine systems are examined in terms of main loop and actuator type, selection constraints due to the amount of heat and power demand. The results showed that the combined turbine-steam optimum power systems are accompanied by benefits such as technological developments, the construction and maintenance of large power plants and nationwide transmission and distribution networks, reducing energy losses, environmental problems, passive defense and provides rapid return of system.

Keywords: Combined Heat and Power, Cogeneration, Steam Turbines, Natural Gas, Generator.

1. INTRODUCTION

In large industrial and residential buildings, electrical and thermal energy is produced from the same facility using combined systems instead of being produced separately. Combined systems ensure that local energy production is more efficient, is more economical and produces less environmental pollution. In combined systems, electricity generation, heat, steam, hot water, cooling and heating is done in the same facility. The most famous and widely used combined facilities are called CHP and CCHP systems. By comparing combined systems with conventional systems, it is observed that it has an efficiency of 50 to 95 percent and at the same time reduces fuel consumption by 35 to 50 percent. In

Figure 1 A general energy and efficiency analysis in given. According to this analysis, efficiency is 42.5 percent and fuel consumption is calculated as 8,470 kJ/kWh in conventional systems net. In combined systems, the efficiency has increased to 85 percent and fuel consumption has dropped to 4,235 kJ/kWh. Considering the reduction in consumption in combined systems from a national perspective, it provides both savings in consumption of fossil fuels and a more efficient use of fossil fuels. In addition to this advantage, it reduces the production of toxic gases such as NO_x, CO_2, CO and UHC to a high extent, thus causing them to use more in the national industry.

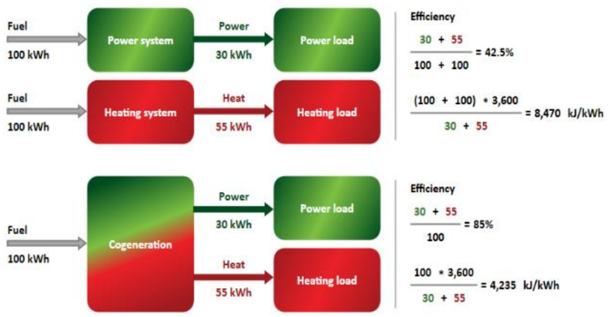

Figure 1. Efficiency analysis in RETScreen Expert application [1]

Combined systems are used when electricity and thermal energy need, long-term operation, electricity purchase price from the network is higher than fuel and there is no electricity grid. It has more advantages when compared to traditional systems of combined systems. For example; energy efficiency, low cost of providing primary energy to the consumer, providing high quality electricity, reliable and flexible heat supply, low environmental pollution, low maintenance cost, possibility to sell additional electricity to the grid, manufacturing industry, hospitals, large buildings, offices, land and etc.

Combined systems are valid in all power plants and are open to the use of all kinds of fuels, so they are used more widely and comprehensively. Although there is a decrease in fuel consumption rate in combined systems, a large proportion of greenhouse gases are produced since fossil fuels are used. Among all burning fuels, biomass and natural gas fuels have the lowest greenhouse gas production, especially if fossil fuels must be used, natural gas may be the best option. Natural gas fuel produces about 50 percent less carbon dioxide and sulfur dioxide [2]. Natural gas fuel is considered as one of the most common fuels used in most applications and innovation technologies and its biggest advantage when it provided both economically (cheap price) and accessibility issues [3]. When comparing biomass fuel with natural gas fuel, it has more disadvantages. Since biomass fuels are not carbon neutral, they produce more fertilizers, their greenhouse gas production rate is high, and they are expensive and costly compared to natural gas.

2. COMPONENTS OF COMBINED SYSTEMS

Combined systems are used in all kinds of systems and facilities as mentioned in the previous section. Their components also vary depending on the system used. However, every facility has some important components that must be used. For example; prime movers, electrical different equipment's and equipment for thermal supply (may vary depending on the system). In combined systems, prime movers are selected according to their production rate and size, advantages and disadvantages. It is defined as the main prime movers steam turbine, gas turbine, piston engine and fuel cells, which are present in combined systems and are frequently used. Sizes are used from 50 kW to 250 MW, 500 kW to 40 MW, 4 kW to 65 MW and 200 kW to 250 kW, respectively.

In combined systems, the heat supply is generated by the boiler and is carried to the heater and cooler systems by means of heat pumps. In other words, it provides the conversion of steam or heat energy produced in the boiler into another energy. Transformed energy is used in different places and situations. For example: steam generated in various systems such as electricity generation, mechanical movement, and food industry etc. [4]. Heat pumps are used as carriers to use the generated energy in another system, such as: heating, cooling systems, and cooking units, etc. Heat pumps consist of two parts, compression and absorption system. The areas where the heat pumps are used can be in air conditioning, heating and cooling systems in residential, commercial and various industries, a low power heat pump to provide hot water, in activities such as livestock and greenhouses, to provide steam in industrial sectors. The advantages of heat pumps are that they reduce the harmful effects of the environment and pollutants by replacing fossil fuels with new energy sources. At the same time, can reduced consumption costs for heating and cooling systems, also is can be pointed to a significant reduction in industrial, domestic and commercial consumption in the amount of carbon dioxide produced in the energy sector. Three to six units of applied thermal energy production per unit of energy consumption.

3. APPLICATION OF A COMBINED SYSTEM FOR A FACILITY

3.1. Facility Requirements

If there are local production plants in the industry, combined systems are preferred for the more efficient and economical establishment of local productions. Some data are measured and calculated for the establishment of a facility in factories. The most important of this data is the measurement of the electrical and thermal loads of the factory. There are some methods for calculating the electrical and thermal loads, but the most accurate and precise measurement and calculation is to measure the daily, monthly and annual consumption of energy. Thus, more detailed data can be obtained and targeted. The thermal load of the combined system to be established in this facility is projected as steam and hot water. At the same time, heating and cooling systems are fed with steam. For the sample system, electric charge demand is given in Table 1 and Table 2.

Table 1. Hourly average electricity demand for each month

Month	Hourly-kW
January	7,525.00
February	7,588.09
March	8,177.02
April	7,536.93
May	7,609.55
June	6,730.93
July	7,479.19
August	7,863.21
September	8,833.53
October	7,287.00
November	7,614.97
December	7,614.97

Table 2. The amount of electricity consumption of the facility throughout the year [kWh]

Month	Electric [kWh]
January	4,695,599.00
February	4,734,966.00
March	5,102,460.00
April	4,703,046.80
May	4,748,360.00
June	4,200,098.40
July	4,667,016.00
August	4,906,646.00
September	5,512,122.00
October	4,547,086.00
November	4,751,740.02
December	4,751,740.02

Table 3. Monthly thermal load demand

Month	Steam kW	Hot Water kW	Total Heat kW
January	1,736,804	2,384,554	4,121,358
February	1,736,804	2,384,554	4,121,358
March	1,736,804	2,384,554	4,121,358
April	1,736,804	2,384,554	4,121,358
May	1,736,804	2,384,554	4,121,358
June	1,736,804	2,384,554	4,121,358
July	1,736,804	2,384,554	4,121,358
August	1,736,804	2,384,554	4,121,358
September	1,736,804	2,384,554	4,121,358
October	1,736,804	2,384,554	4,121,358
November	1,736,804	2,384,554	4,121,358
December	1,736,804	2,384,554	4,121,358
Total	20,841,649.92	28,614,643.20	49,456,293

In Table 3, the thermal load (steam, hot water and total thermal energy) is given on a monthly basis. In Table 2 and Table 3, the electrical and total thermal energy consumption measured are shown. According to these measurements, the annual electricity demand is 57,320,880.20 kWh and the total thermal load is 49,456,293 kWh.

3.2. Efficiency of the Combined System to be Used in the Facility

One of the most important parameters in energy production is to calculate the efficiency of the facility. As in combined systems, its efficiency is calculated in its facility. When the combined system is installed the efficiency calculation depends on several variables [5]. These variables are called the total combined system efficiency (η_{total}), FERC efficiency standard (PURPA) and fuel use efficiency (η_{fuel}). The equation for calculating the efficiency of the combined system is as follows.

$$\lambda_{total} = \frac{P+Q}{F} \quad (1)$$

$$P_e = \frac{P+\frac{Q}{2}}{F} \quad (2)$$

$$\lambda_{fuel} = \frac{P}{F-\frac{Q}{\lambda_q}}, \; \lambda_q = \frac{Q}{E} \quad (3)$$

The efficiency of the combined system to be used in the facility is designed and calculated using the Thermo flow application.

Figure 2 shows the design of a combined system on the Thermo flow application and Table 4 show the efficiency of the combined system of the Thermo flow application.

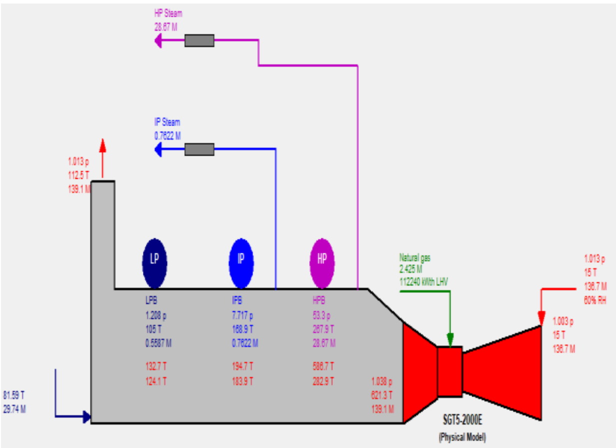

Figure 2. Simulation of the combined system on thermo flow

Table 4. Efficiency analysis on thermo flow application

PLANT EFFICIENCIES			
PURPA efficiency	λ_t: Total efficiency	Power gen. eff. on chargeable energy, %	Canadian Class 43 Heat Rate, kJ/kWh
%	%		
50.31	84.72	61.15	4653

A combined system is designed in Figure 2, and in this design, high (HP), medium (IP) and low (LP) pressure hot water and steam are predicted in 3 stages. Different pressures are used in different parts of the facility, for example, high pressure steam is designed to meet the need for hot water both in the conversion of the generator and during cooking, in facilities such as medium pressure water heating, cooling, and medium pressure water in the facility. From Table 4, the efficiency of the combined systems designed for the facility, has increased to 84.72 percent. Combined system showed an increase of 45-60 percent compared to traditional plants. Therefore, combined systems are preferred for use in many facilities because of their high efficiency.

3.3. Fuel Analysis

One of the most important issues in combined systems is prediction of the fuel usage, and therefore, fuel analysis of the designed facility is required. All energy units must be converted into national units before the analysis is calculation. In Table 5, the conversion amount of the energy unit to MBtu (British thermal unit) unit is given.

Table 5. Energy conversion units

One barrel (42 gallons) of crude oil	5,800,000 BTU
(4)One gallon of diesel	124,000 BTU
One gallon of heat oil	139,000 BTU
One gallon of diesel fuel	139,000 BTU
One domestic oil fuel barrel	6,287,000 BTU
One cubic meter of natural gas	1,026 BTU
A gallon of propane	91,000 BTU
A ton of coal	20,681,000 BTU
One kWh	3,412 BTU

After the energy conversion, the first calculated unit is the net thermal output rate. Therefore, the heat output rate is given in Equation (5).

$$Q = (\frac{55}{30} \times 8\text{MW}) \times 3.41 = 193.4 \text{ MBtu/hr} \quad (5)$$

After the net thermal energy ratio, one of the second parameters is the net power output. The net power output is calculated in Equation (6).

$$P = 8\text{MW} \times 3.41 = 27.28 \text{ MBtu/hr} \quad (6)$$

8 MW: Plant output power
3.41 MBtu: each kWh

For the chosen facility, 55 percent thermal energy, 30 percent electricity production and 100 percent energy input values are accepted. Thus, the efficiency of the combined system is calculated as 84.72 percent, as shown in Table 4. Before calculating fuel savings, the fuel input must be calculated for both combined systems and conventional systems.

$$F_c = \frac{P+Q}{\lambda_t} = \frac{27.28+193.4}{0.8472} = 260.48 \text{ MBtu/hr} \quad (7)$$

$$F_t = \frac{P+Q}{\lambda_t} = \frac{27.28+193.4}{0.425} = 519.3 \text{ MBtu/hr} \quad (8)$$

$$\lambda_t = \frac{30+55}{100+100} = 42.5\% \quad (9)$$

The fuel saving of the designed combined system is calculated as follows.

$$F_s = F_T - F_C = 519.3 - 260.48 = 258.82 \text{ MBtu/hr} \quad (10)$$

As shown in Equation (10), the fuel saving of the designed facility is calculated as 258.82 MBtu/hr, which means 49.99 percent fuel saving, which is approximately 50 percent. If the designed facility works for 7,500 hours per year, there will be 1,941,375 MBtu annual savings and assuming 2 Euro per MBtu of energy, this facility saves 3,882,300 Euro per year.

3.4. Technology Selection

In the combined systems: the amount of electricity consumption mainly depends on the motor selection. In Table 2 and Table 3, the hourly and monthly electricity consumption of the facility is given. In addition, the facility has been determined as a working condition of 26 days and 24 hours for a month. Measuring the hourly consumption amount is one of the most important factors for gas engines and at the same time, the internal consumption amount of the engine is also should be included in the calculation. Thus, the peak consumption amount in the motor selection of the facility affects very much. The gas engine selection of the facility is summarized in Table 6.

Table 6. Facility engine selection chart

	Motor Selection	Unit
1 Piece	3,356.00	kW
1 Piece	3,356.00	kW
1 Piece	2,000.00	kW
Total	8,712.00	kW
internal consumption predicted deducted	8,494.20	kW
At 90% Load	7,644.78	kW

In Table 6, 3 gas engines with a total capacity of 8.7 MW are selected for the plant. If the internal consumption of the engine is taken into account, the capacity of the engine has been reduced to approximately 8.5 MW. At the same time, since the hourly average consumption of the facility is calculated to be 7.6 MW, the selected engines operate with 90 percent load condition. Calculation of hourly natural gas consumption (HNGC) amount of gas engines selected for combined systems is given in Equation (11).

$$HNGC = \frac{P_m}{\frac{8250}{860} \times 0.425} \quad (11)$$

0.425: electrical efficiency in field conditions was taken as 42.5 percent.
8250: The heat obtained by burning 1 m^3 of fuel is called the calorific value of that fuel and is measured with Kcal. This rate is 8250 Kcal in natural gas.
1 kW - 860 Kcal

Table 7 shows the natural gas consumption amount of the facility. Gas engines selected according to the data are calculated as 2,139.85 m^3 per hour, 1,333,393 m^3 per month and 16,000,710.8 m^3 per year.

Table 7. Facility natural gas consumption

Piece	Motor power	Unit	Hourly Gas Consumption	Unit
1 Piece	3,356.00	kW	823.15	m^3
1 Piece	3,356.00	kW	823.15	m^3
1 Piece	2,000.00	kW	490.55	m^3
Total	8,712.00	kW	2,136.85	m^3

In addition to the natural gas consumption of the facility, the selected engines have saturated steam, hot water and thermal production. The amount of energy produced is given in Table 8 for each motor.

Table 8. Thermal energy production amount of selected motors

Motor power	Steam energy	Hot water energy	Heat energy
3.3 MW	1.8 ton	70-90 ºC	1583 kW
3.3 MW	1.8 ton	70-90 ºC	1583 kW
2 MW	1.1 ton	70-90 ºC	1080 kW
Total	4.7 ton	70-90 ºC	4.246 kW

In Table 8, the hourly thermal energy produced by the facility is shown as a total of 4.7 saturated steam, 4.246 kW of heat energy and 70 to 90 degrees of hot water. In this facility, cooling demand is met by chiller devices. These devices reduce hot water to 7 to 12 degrees and turn it into cold water, thus around 7 to 12 degrees of cold air is obtained. The most important advantage of chiller devices is that they have 70 percent efficiency.

3.5. Economic Analysis

The method used to optimize the energy consumption of combined systems, reduce network losses and fuel consumption. One of the most important analyses of the combined systems is their economic analysis. Economic analysis is calculated by various methods [8]. For example; Cost Analysis (CA), Cost Effectiveness Analysis (CEA), Cost Utility Analysis (CUA) and Cost Benefit Analysis (CBA). CBA analysis is a common economic calculation method in the industry. The CBA method enables the facility to use the resources in the best and appropriate way; then choosing the best way to get optimum results [9]. After all the data and the conceptual design for the designed facility are clarified, the total investment cost, revenues of the facility, the economy and feasibility study are done via the CBA method. The total investment cost of the facility has been calculated as 3,000,000.00 Euro and a detailed summary is given in Table 9. The total cost of the facility is calculated by adding up the maintenance cost and the total natural gas cost. In Table 10, the total maintenance cost is calculated and summarized.

Table 9. Total investment cost of the facility

Quantity	Explanation	Euro
1 Piece	3356 kW Gas Engine	775,000.00
1 Piece	3356 kW Gas Engine	775,000.00
1 Piece	2000 kW Gas Engine	500,000.00
-	Mechanical Integration	450,000.00
-	Electrical Integration	350,000.00
-	Build	50,000.00
-	Natural gas	50,000.00
-	Other expenses	50,000.00
-	Total	3,000,000.00

Table 10. Total maintenance cost of the facility

Explanation	Expenses (Euro)
Personnel Expense / Annual	55,384.62
Insurance etc. expenses	27,692.31
Maintenance Expense	83,077.68
Oil Change	21,840.00
Fat Consumption	12,600.00
Antifreeze	5,250.00
Total Maintenance Cost	205,844.60

The total natural gas cost of the facility is calculated at 0.26 Euros per cubic meter, so it can be calculated the annual natural gas consumption by multiplying the consumption amount by 0.26 Euros each month. In Table 11, the total natural consumption is summarized for each month.

Table 11. Total monthly investment cost of the facility

Month	Monthly m^3 Consumption	Monthly Consumption Euro
January	1,333,393	346,682.07
February	1,333,393	346,682.07
March	1,333,393	346,682.07
April	1,333,393	346,682.07
May	1,333,393	346,682.07
June	1,333,393	346,682.07
July	1,333,393	346,682.07
August	1,333,393	346,682.07
September	1,333,393	346,682.07
October	1,333,393	346,682.07
November	1,333,393	346,682.07
December	1,333,393	346,682.07
Total	16,000,710.8	4,160,184.8

Therefor total cost of the facility was calculated as 4.366.029, 41 Euro and is calculated as follows.

$$T_c = T_m + T_n = 205,844.60 + 4,160,184.8 = \\ = 4,366,029.41 \text{ Euro} \quad (12)$$

The annual cost of the facility depends on the annual thermal and electrical energy income. The efficiency of the boiler installed in the facility has been calculated as 90 percent. The total annual thermal income is calculated as follows.

$$ATEI = \frac{T_t \times C_1}{6.5} = \frac{42,546,293 \times 0.18746}{6.5} = \\ = 1,427,661.38 \text{ Euro} \quad (13)$$

$$C_1 = \frac{1.62}{\frac{8250}{860} \times 0.9} = 0.18764 \text{ TL/m}^3$$

At the same time, the electricity energy income of the facility is calculated by multiplying the total electricity energy production and the electricity cost of 1 kW. The electrical energy cost is measured at 0.075 Euro per 1 kW. The total electrical energy production of the facility is calculated on a monthly basis in Table 12 and the calculation method is calculated by Equation (13).

$$A_i = T_e \times T_{ec} = \frac{57,220,880.24 \times 0.483591}{6.5} = \\ = 4,257,154.26 \text{ Euro} \quad (14)$$

$$A_c = ATEI + A_i = 1,427,661.38 + 4,257,154.26 = \\ = 5,684,815.65 \text{ Euro} \quad (15)$$

Table 12. Total annual electricity energy production of the facility

Day	Month	Electric [kWh]
31	January	4,695,599.00
28	February	4,734,966.00
31	March	5,102,460.00
30	April	4,703,046.80
31	May	4,748,360.00
30	June	4,200,098.40
31	July	4,667,016.00
31	August	4,906,646.00
30	September	5,412,122.00
31	October	4,547,086.00
30	November	4,751,740.02
31	December	4,751,740.02
	Total	57,220,880.24

The annual net worth method is an important method in terms of financial matter. This method compares whether the investment cost returns to profit and the investment amount with the return on investment. The net value of the year represents the present value of the time, cash flow of the investment and it also contributes greatly to the investors in drawing the investment plan. Thus, the net present value of the facility is calculated as follows [10].

$$A_n = A_c - T_c = 5,684,815.65 - 4,366,029.41 = \\ = 1,318,786.24 \text{ Euro} \quad (16)$$

One of the most important parameters affecting the installation plan of a facility is the rate of return on investment. Return on investment is calculated as follows [11].

$$R_i = \frac{C}{T_r} = \frac{3,000,000.00}{1,318,786.24} = 2.27 \text{ years} \quad (17)$$

4. CONCLUSION

Combined systems have greater advantages coupling to the other facilities in terms of both efficiency and economy. In addition to electricity and heat energy, hot water and steam are also produced in the chosen facility; so, the efficiency of the system is increased to 84.72 percent. At the same time, thanks to hot water and steam production, the facility has a continuous heating, and cooling system in different areas. As a result of the designed combined system, it reduces both fossil fuel consumption and greenhouse gas production.

As a result; before the facility is established, it is calculated as 3,698,646.34 Euro for only natural gas and 4,257,156.26 Euro for electricity purchased from the grid. So, the total energy cost is equal to 7,955,803.6 Euros. The establishment of the combined system takes only 3,000,000 Euros, which means the investment converts the expense into income in 2.27 years. Since combined systems have high efficiency and better economic value, it gets more interest and advantage from the industrial standpoint, which leads to the development of local production systems and hence more usage. In this way, it reduces the energy loss of generation, transmission and distribution networks, increases the network capacity, decreases fuel consumption, industrial harmonics and the reduction of injected reactive power etc.

Therefore, it helps to reduce additional investments in the country's energy grid. In other words, it helps the country to carry out its development plan with less cost. In the designed facility, the rate of heat emanating from the exhaust ranges from 10 to 15 percent, and the noise pollution ranges from 65 to 75 decibels per meter in the industrial area. In special cases, it is possible to decrease the noise to 30 decibels every 60 meters. Therefore, as is seen from present paper as well for practical applications combined systems are strongly recommended especially for the large power consumed facilities.

NOMENCLATURES

1. Symbols / Parameters

A_c: Annual cost of revenue
A_i: Annual electricity income
A_n: Annual net worth
ATEI: Annual Thermal Energy Income
C: cost
C_1: 1 kW thermal cost
E: Total energy input to the combined system
F: Total fuel input to the combined system
F_c: Fuel input for combined
F_t: Fuel input for traditional
F_s: Fuel saving
P: Net output from the combined system
P_e: PURPA efficiency
P_m: Motor power
Q: Net useful thermal energy obtained from combined system
R_i: Return on investment
T_e: Total energy production
T_{ec}: Total energy cost
T_r: Total revenue
T_t: Total thermal kW
T_c: Total cost of expenses
T_m: Total maintenance
T_n: Total natural gas cost
λ_q: Efficiency of thermal generation
λ_t: Efficiency of traditional system

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BIOGRAPHIES

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