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Industrial Design Energy Efficiency and GHG Emission Reduction via Steam and Power Systems Optimization

Mana Al-Owaidh, Abdulrahman Hazazi, Solomon Oji and Abdulaziz Dulaijan

Abstract

The energy supply side for a large oil, gas, refinery, or petrochemical facility is designed to provide the site with sufficient heating, cooling, and power utilities requirements. Reducing capital and operating costs from energy supply side is essential to maximize the value added from the industrial facility. Thus, optimization solutions are often developed to optimize industrial utility design and operation, reduce costs while improving the overall system's efficiency and inevitably reducing CO₂ emission. Our topic in the chapter is related to a new methodology that aims to identify the optimum design and operation of the energy supply side of a new industrial facility. One major cause for utility design inefficiency is the fact that in a typical project setup, there are different project teams handling the design of the utility supply side and process design independently. This often results in high capital cost, and lower operating efficiency. The potential improvement expected from the optimum design compared with a typical design case for a new industrial facility is over 15% from base-case life cycle cost. This chapter also covers several examples to explain the concept and expected benefits from applying a new Combined Heat and Power (CHP) optimization solution during new project design.

Keywords: CHP, steam system optimization, system's efficiency, GHG emission reduction, steam and power optimum design, industrial utility system, grassroots facility

1. Introduction

Today, optimizing energy consumption, improving energy efficiency, and reducing GHG emissions are essential for a sustainable operation and lower operating cost of an industrial facility such as Oil, Gas, Refining, and Petrochemical facilities. Every industrial facility depends on more than one form of utilities for its operation. Examples of these utilities include power generation, steam system, instrument and plant air, nitrogen system, hot oil system, etc.

Process streams such as gas and liquid are usually heated or cooled by indirect heat exchange with another fluid: either another process stream or a utility stream such as steam, hot oil, cooling water, or refrigerant. Heating utilities are necessary for proper usage of condensers, distillers, and several other integral types of equipment in the hydrocarbon processing facilities. In hydrocarbon processing plants, steam is the most commonly heat utility used.

Steam is used both as utility and a process fluid (heating agent, diluent to absorb heat of reaction, feedstock, and stripping agent in adsorbers and absorbers). It can be used to drive mechanical drivers such as compressors and pumps, heat exchangers, and ejectors (for producing a vacuum). There are few advantages of using steam as opposed to other methods of process heating. For example, see [1].

In general, the supply-side utility systems for industrial facilities are used to produce the required energy for the facility, and the most common system used is steam system. Other alternatives include hot oil and hot water systems.

Steam system is a better choice for a facility with high power demand and high heating demand required by process and at different level of temperatures. Thus, most of the gas plants, refineries, and petrochemicals that are using steam system often include both boilers and Cogen, as the base-case option. The reason behind using steam system for industrial facilities required both heating and power demand can be summarized as follows:

- Generating steam at high pressure and using steam turbines to recover the energy available in the steam for power generation will improve the overall system efficiency of the supply side to reach a level over 70%.
- Using the lower pressure steam extracted from steam turbines for process heating making use of the available latent heat in the steam for a better heat recovery.
- In addition, steam is a clean service that provides energy and heat for the industrial facility.

2. Background of a combined heat and power (CHP) system

For a majority of process plants, the bulk of the energy required is supplied through the utility system. On most facilities, the required heating is provided by combined heat and power (CHP) systems. A CHP system is a combination of two or more systems that are used in the generation and distribution of steam and power through gas turbine generators (GTGs), heat recovery steam generators (HRSGs), boilers, and steam turbines. The use of CHP plants means that the efficiency of the processing facility in terms of its energy consumption is reliant on efficiency of both the process side and the operation of the utility system. Steam is used for various purposes such as heating, drying, and providing a heat source for air conditioning or motive energy for a power generation via steam turbines.

As illustrated in **Figure 1** (Gas-Turbine-Based CHP Plant), a typical CHP starts with the Bryton Thermodynamic cycle where the combustion of a fuel and air mixture in a gas turbine combustion chamber occurs, the combustion product is then channeled through a series of blades attached to a rotating shaft and a generator, which then generates power and hot flue gas through the gas turbine exhaust system. The exhaust gas, which has a high energy content, becomes the heating

Figure 1.
Gas-turbine-based CHP plant.

Figure 2.
Boiler-based CHP plant.

medium in the next heat recovery Rankine Cycle of the CHP, the flue gas is channeled through an HRSG to heat up boiler feed water and produce steam. The generated steam is then used to drive a steam turbine generator (known as a combined cycle) or sent to a process plant to be used as a heating medium in a heat exchanger or to mechanically drive rotating equipment such as pumps and compressors (known as cogeneration).

Figure 2 (Boiler-Based CHP Plant) illustrates an alternative type of CHP system. In a boiler-based CHP system, one or more boilers are used to generate steam, and steam turbine generators (STGs) are then used to generate power. In certain configurations, steam is extracted from the steam turbine generator (STG) to be used for process heating via heat exchangers. Most of Saudi Aramco’s facilities or plants have a combination of both gas turbine and boiler-based CHP systems. For example, see [2].

3. Toward optimum design of industrial steam and power systems

The concept of simultaneous process and utility design optimization was developed by Saudi Aramco protected by 2-granted patents. **Figure 3** provides an overview of the steps used for the optimization. In Refs [3, 4], the techniques used in optimizing new CHP systems are being derived from unit commitment and economic dispatch power generation concepts. Our optimization problem includes integer (binary), linear, and nonlinear relations between the objective function, variables, and constraints.

Figure 3.
Key elements of a steam system optimization tool.

The problem formulation for a typical steam system can be summarized as follows:
Objective function is the Net Present Value (NPV) for the new design, and it is a function of capital cost of equipment as well as the expected operating cost of the system configuration.

$$\text{Objective function} = \sum_{i=1}^n NPV \left(Capex_i + Opex_i * \frac{Hrs}{yr} * LC \right) \quad (1)$$

Where,

NPV: Net Present Value for the project.

LC: Life Cycle of the new facility, normally used 25 years.

The total capital cost includes major equipment used in the optimization analysis as decision variables

$$= \sum_{i=1}^n (Capex_{Blr_i} + Capex_{Cogen_i} + Capex_{STG_i} + Capex_{STi} + Capex_{Motor_i} + Capex_{RO} + Capex_{MED}) \quad (2)$$

Capital cost would be function of number and sizes of major equipment (i.e., decision variables for the optimization algorithm):

- Boilers
- Cogeneration units
- Steam turbine generator
- New steam turbine drivers
- Motors-driven equipment as alternative drives with steam turbines and
- Water desalination facilities and makeup system

The total operating cost is function of the equipment performance and the impact on the energy consumption of the facility. The operating cost includes the following key elements:

- Fuel consumption
- Power export and import tariffs
- Makeup water treatment and chemicals
- CO₂ emissions

In the optimization analysis, there are key constraints that have to be met by the optimizer to confirm the validity of the results. Some of these constraints are related to equipment limitations and others related to systems limitations. Below are some examples of the key constraints used in the optimization analysis:

- Equipment constraint: such as steam generation from boiler should be less than maximum limit and greater than minimum generation limit.
- System constraint: steam production from steam supply equipment shall be greater than or equal to steam demand required.
- System constraint: available steam reserve from boilers should be more than or equal to required steam reserve.
- Steam constraint: input to a steam header should be equal to steam out from steam header
- Mathematical model constraint. Non-negative flows in the steam distribution network

Below is a generic mathematical representation for the steam system:
 Steam balance representation includes:

$$\text{Steam balance for a steam header (a)} = \sum_{i=1}^n Stm_{in} - Stm_{out} \quad (3)$$

Where i and n are representing the equipment connected to this steam header.
 Boiler Feed Water (BFW) Balance is calculated as per the formula below

$$= \sum_{i=1}^n Blr_{BFW} + \sum_{i=1}^n Cogen_{BFW} - \sum_{i=1}^n DSH_{BFW} \quad (4)$$

Makeup water compensates for all losses from steam system, thus makeup water is equal to all losses in the steam system.

BFW makeup balance is calculated as follows:

$$= \sum_{i=1}^n Proc_{stm} * (1 - RC\%) + \sum_{i=1}^n Blr_{BD} + \sum_{i=1}^n Cogen_{BD} + \sum_{i=1}^n Vent_{stm} \quad (5)$$

Whereas,
BFW: Boiler feed water.
B_BFW: Boiler feed water to boilers.
COG_BFW: Boiler feed water to Cogen units.
DSH_BFW: De-super heater water into steam network.
BD: Blow down flow.
Bstm: steam generation from boilers.
COG_stm: steam generation from Cogen units.
Steam users.

Case study: grassroot facility.

This section covers the (CHP) optimization assessment to identify the optimum configurations and equipment sizing for the supply side of a new petrochemical complex. References [5–7] include other examples, which can help explaining the concept further.

The assessment for the optimum configuration started with reflecting the utility’s initial design data into a newly developed (CHP) for design. The CHP model key input is shown in **Table 1** summary.

For new facilities, 70% (HHV basis) is considered as the minimum efficiency of a site’s overall CHP systems thermal efficiency. CHP systems’ thermal efficiency for the site can be defined as the ratio between all useful energies generated by the system and total energy input as fuel:

$$CHP\ system\ Thermal\ Eff.\% = \frac{Useful\ Energy\ Out}{Energy\ Input} \tag{6}$$

Where:

Useful Energy Out = Total net power generated by Cogen and STGs + total mechanical power recovered in the steam system by STs + total mechanical power driven by GTs + total heat consumed by process at different headers in (MMBtu/hr);

Energy Input = Total fuel consumed by the facility including boilers, Cogeneration units, simple cycle gas turbines, process heaters generating steam, other process heaters, and SEC equivalent fuel for imported power in (MMBtu/hr).

The CHP optimization study evaluated four design scenarios. The CHP analysis and its related economics considered the optimum configuration meeting operational and design requirement. The design requirement accounts for one steam supply unit under T&I and a trip of another unit. The CHP analysis covered the following cases:

Steam Demand		
VHP	101	T/h
HP	978	T/h
MP	936	T/h
LP	413	T/h
Returned Condensate %	65%	

Note: Five different cogeneration frames from different GT manufacturers have been used for the CHP optimization analysis. This is just to give a better understanding and more accurate outcomes from energy efficiency point of view. It is worth highlighting that the analysis for each case is based on the average result of the different frames and not for any specific one.

Table 1.
Process steam headers.

- 1. Base Case: (5 Cogen Units – 1 standby boiler).
- 2. Case-1: (4 Cogen Units – 2 boiler Units).
- 3. Case-2: (3 Cogen Units – 3 boiler Units).
- 4. Case-3: (2 Cogen Units – 4 boiler Units).

Base Case: The base case composed of five gas turbines each with its heat recovery steam generator and two STGs and with one spare boiler, as shown in **Table 2**.

Table 3 shows that the average CHP model’s output from overall supply-side thermal efficiency is in the range of 69%, which is slightly lower than the minimum efficiency requirement of (70%).

Case-1: In this case, the CHP configuration includes four Cogen units, two boiler, and two STGs. The result showed that the average steam system efficiency for the different frames is around 70–73% (**Tables 4** and **5**).

Case-2: In this case, the configuration is composed of three Cogen units, three boilers, and two STGs, where the average steam system efficiency is around (74%) (**Tables 6** and **7**).

Equipment	Number of units	Avg. size per unit
Cogen	5	260 (MW)
Boiler	1 (standby)	341 (T/h)
STG	2	100 (MW)

Table 2.
Base-case scenario.

Option	System eff.%	Tot. fuel (MMBTU/H)	Tot. STGs (MW)	Net pwr gen (MW)	CO2 emissions reduction (MM ton Co2/year)
Cogen A	71%	10,310	170	1225.2	2.9
Cogen B	70%	10,289	147	1174.9	2.6
Cogen C	69%	10,937	182	1284.9	3.0
Cogen D	68%	14,012	278	1813.7	4.8
Cogen E	69%	11,994	230	1459.0	3.6

Table 3.
Base-case CHP model output.

Equipment	Number of units	Avg. size per unit
Cogen	4	260 (MW)
Boiler	2 (1 standby)	341 (T/h)
STG	2	80 (MW)

Table 4.
Case-1 design basis.

Option	System eff.%	Tot. fuel (MMBTU/H)	Tot. STG (MW)	Net pwr gen (MW)	CO2 emissions reduction (MM ton Co2/year)
Cogen A	73%	8475	113	957.5	2.1
Cogen B	72%	8976	123	1005.2	2.1
Cogen C	70%	11,436	200	1428.2	3.6
Cogen D	71%	9821	161	1144.5	2.6
Cogen E	72%	10,462	178	1297.3	3.2

Table 5.
Case-1 CHP model output.

Equipment	Number of units	Avg. size per unit
Cogen	3	260 (MW)
Boiler	3 (1 standby)	341 (T/h)
STG	2	50 (MW)

Table 6.
Case-2 design basis.

Option	System eff.%	Tot. fuel (MMBTU/H)	Tot. STG (MW)	Net pwr gen (MW)	CO2 emissions reduction (MM ton Co2/year)
Cogen A	75%	7098	95	728.0	1.3
Cogen B	75%	7204	79	740.7	1.3
Cogen C	74%	8860	122	1042.8	2.4
Cogen D	75%	7649	93	830.0	1.7
Cogen E	75%	8129	105	944.6	2.1

Table 7.
Case-2 CHP model output.

Case-3: in this case, the CHP configuration composed of two Cogen units, four boilers, and two STGs resulted in steam system supply-side efficiency around 69%. The reason for having a larger STG in this case is to reduce the power import as much as possible (**Tables 8 and 9**).

To identify the optimum steam and power systems configurations for petro-chemical complex, all options have been simulated via CHP optimization model as shown in the previous section.

Equipment	Number of units	Avg. size per unit
Cogen	2	260 (MW)
Boiler	4 (1 standby)	341 (T/h)
STG	2	100 (MW)

Table 8.
Case 3 design basis.

Option	System eff.%	Tot. fuel (MMBTU/H)	Tot. STG (MW)	Net pwr gen (MW)	CO2 emissions reduction (MM ton Co2/year)
Cogen A	67%	7520	218	640.5	0.6
Cogen B	67%	7771	223	664.4	0.6
Cogen C	75%	7154	114	728.0	1.3
Cogen D	69%	8120	236	728.0	0.8
Cogen E	73%	7482	168	728.0	1.1

Table 9.
Case-3 CHP model output.

Figure 4.
System efficiency summary of the different design configurations.

Figure 5.
Base case: Petrochemical complex steam system CHP.

Figure 6.
Case 3: Petrochemical complex steam system CHP.

The study evaluated (4) different cases and compares the outcomes with the base case to identify the best configuration. In summary, in all cases there exist at least two GT frames that can meet the 70% minimum steam system efficiency requirement (**Figures 4–6**).

4. Conclusions

The CHP model includes all the elements involved in the generation and distribution of energy to drive the process and supporting infrastructure. Optimizing such complex system requires a sophisticated model.

Within Saudi Aramco, the CHP model of each operating facility was found to be extremely useful in understanding the interactions between the various utilities' components. The interactions between these components could have been very complex without constructing a reasonably accurate mathematical model. Such tools are used during the design phase of capital projects to optimize cogeneration system sizes and configurations, explore alternatives, and conduct thermal efficiency synthesis to estimate what the final design would look like.

For operating facilities, the CHP model is used to evaluate potential efficiency enhancements, monitor the performance of existing equipment, identify energy saving opportunities, change operation and control based on optimum operational advice, and evaluate the impact of process variations on the CHP utilities system. The features of the model can be summarized in the following points:

- Excel-based model along with Visual Basic (user-friendly)
- Utilize a powerful solver optimization tool
- Include all steam properties
- For real-time asset management, consider connecting the CHP model to a data historian for real-time data
- Account for all system constraints

In summary, having a systematic approach for analyzing operational improvements is viable using CHP optimization solutions. These solutions have been found to be useful with the right features to support plant operation. Following list gives a summary of typical optimization handles from the model for operational modification actions:

1. Minimize steam flow to fin-fan condensers
2. Optimize steam turbine operating load (switch ability of running steam turbines and motors)
3. Boiler load management
4. Maximize cogeneration operation
5. Maintain operation within optimum set points

In addition, optimum design of a new facility will help saving major capital and operating cost. As shown in the example from the case study, the potential benefit from a case and optimum case can exceed 15% in the NPV of the project life cycle.

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