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# Combined heat and power – multi-objective optimization with an associated petroleum and wet gas utilization constraint

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ABSTRACT

Associated petroleum gas and wet gas are byproducts of oil field operations. The use of both gases as low-cost, low-quality fuel in oil field operations has several downfalls, such as a low Modified Wobbe Index and high hydrogen sulfide content. Modified Wobbe Index represents fuel interchangeability which affects gas turbine reliability. High hydrogen sulfide content may result in failures on the gas pipeline. The purpose of this research is to develop a multi-objective combined heat and power optimization by considering associated petroleum and wet gas utilization. The optimization model utilizes thermodynamic equations to represent gas turbine and heat recovery steam generator performance when subjected to low-quality fuel. Optimization also considers power system parameter as constraints. Three conflicting objective functions will be considered: cost vs. Modified Wobbe Index vs. hydrogen sulfide content. Optimization will use two algorithms for comparison purposes: Goal Attainment and NSGA-II. The result shows that the optimization model can analyze the tradeoffs between the three conflicting parameters.

## 1. Introduction

Oil field operations produce associated petroleum gas (APG) and wet gas as byproducts. APG comes from gas caps inside the saturated oil reservoir (Attanasi and Freeman, 2013). Once the reservoir is drilled, the oil together with APG is extracted to the earth's surface. In addition to oil reserves, oil field explorations usually find nearby marginal/stranded gas reserves. These reserves have low quantity gas, which is uneconomic to process and transport as commercial gas. Both APG and wet gas are utilized as low-cost low-quality gas in oil field operations, mainly in the field of power generation/Gas to Wire (Khalilpour and Karimi, 2012).

The use of APG and wet gas as fuel faces several challenges. Compared to natural gas, APG is much lower quality. Typical APG has low methane content (50–70%), highly inert components (nitrogen and carbon dioxide, 2–20%) and has higher hydrocarbons. Higher hydrocarbons can cause thermal regime failure in a gas turbine (Zyryanova et al., 2013). APG and wet gas also have high hydrogen sulfide content which is very corrosive to gas pipelines (Verlaan and Van der Zwet, 2013).

Modern gas turbines currently are designed to accept different types of gas fuel (Jones et al., 2011). In addition to natural gas, gas turbines can also run on low and medium calorific value gases which can contain a large fraction of inert components, such as nitrogen and carbon dioxide. One parameter to assess fuel interchangeability is the Modified Wobbe Index (MWI), which correlates the gas heating value and gas specific gravity (Segers et al., 2011). Both APG and wet gas may have a low heating value which affects gas turbine performance. Due to its low heating value, to produce the same power output, gas turbines require a higher mass flow of APG and wet gas compared to natural gas (Anosike, 2013). Thus, the use of APG and wet gas as fuel must also meet MWI specifications as published by the gas turbine manufacturer.

For convenience, we refer to APG and wet gas as field gas in the next section of this paper.

Several studies have been conducted regarding field gas utilization. Anosike (2013) performed a techno-economic study to assess APG usage as a gas turbine fuel. Rajovic et al. (2016) performed a life cycle assessment of APG as fuel for combined cycle gas turbines and heat boilers in an oilfield operation. Watanabe et al. (2016) proposed the use of associated and stranded gas as fuel for a gas turbine combined cycle system with high voltage direct current transmission. Vanadzina et al. (2015) proposed APG utilization as fuel for power generation in the reformed electricity market. Arutyunov (2011) proposed to convert APG to syngas for better gas turbine performance. Gorbachev and Mikhailutsa (2011) demonstrated the utilization of 2.5 and 6 MW gas turbine generators fueled by APG. To the best of our knowledge, there

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has not been any study related to steam and power economic dispatch optimization with APG as fuel.

Combined heat and power (CHP) systems produce steam by utilizing a gas turbine's hot exhaust gas to heat water inside a heat recovery steam generator (HRSG). The benefit of this system is higher thermodynamic efficiency, up to 80% (Vasebi et al., 2007) compared to 30–40% efficiency when the gas turbine is only used to produce power (Mohammadi-Ivatloo et al., 2013). Some HRSGs also have additional duct burners (DB) to enable higher steam production. In addition to the CHP system, steam is also produced by gas-fired boilers. Produced steam is injected into the ground to ease the oil flow to the surface.

In previous studies, combined heat and power economic dispatch (CHP-ED) optimization is usually based on empirical equations of objective function and constraints. Rooijers and van Amerongen (1994) model a cost objective function as polynomial equations. In a CHP system, the steam output is dependent on power output. Steam vs. power output must be modeled through a feasible operating region. The most common model uses linear equations proposed by Guo and van Ooijen (1996).

Heuristic and deterministic methods have been utilized to solve multi-objective combined heat and power optimization, such as normal boundary intersection (Ahmadi and Moghmi, 2015), Bender's decomposition (Sadeghian and Ardehali, 2016), particle swarm optimization (Wang and Singh, 2008), line up competition algorithm (Shi et al., 2013), modified dichotomic search algorithm (Rong et al., 2014), bacterial foraging (Motevasel and Niknam, 2013), and merging algorithm (Rong et al., 2015). Although a large number of algorithms have been developed, most research still uses an empirical model and only involves one fuel type with a constant fuel price.

Kim and Edgar (2014) proposed a new approach in CHP modeling using thermodynamic equations. Operating parameters such as temperature, pressure and fuel heating content can be easily implemented into the model. However, this study only uses a constant and predefined fuel price with a single fuel source so the effect of low quality fuel and fuel mixing was not discussed.

Oil companies are expected to significantly reduce their oil lifting costs. Therefore, oil field operation relies on optimization tools to ensure efficient, safe and reliable operation. Since oil operation involves power and steam generation, CHP-ED is the most suitable tool to perform daily optimization. This paper proposes a different approach for CHP-ED. The proposed CHP-ED model can optimize fuel cost using multiple fuel streams, e.g.: natural gas and field gas. Field gas becomes an interesting alternative fuel, considering its availability and low cost. There is a significant price difference between field and natural gas. Such a condition brings a unique problem, where the natural – field gas mixture becomes a variable that must be optimized as well. However, field gas utilization has several negative impacts, such as low Modified Wobbe Index and high $H_2S$ content. MWI represents fuel interchangeability which affects gas turbine reliability. $H_2S$ is very corrosive and high $H_2S$ content may result in failures on the gas pipeline. Thus, the proposed model can also analyze the tradeoffs between field gas utilization, reliability (represented by MWI) and pipeline integrity (represented by $H_2S$ content). Due to the involvement of multiple fuel streams, the empirical model of gas turbines and HRSG would not suffice. In the proposed model, we use thermodynamic equations to represent gas turbine and HRSG performance when subjected to different mixtures of field gas and natural gas.

The model is based on two different algorithms, a deterministic method called Goal Attainment (Gembicki and Haimes, 1975) and a very popular heuristic method, NSGA-II (Deb et al., 2002). The simulation uses a simplified CHP system in one of South East Asia's oil fields.

## 2. System overview

The case studies use a simplified CHP system in South East Asia, which consists of twelve gas turbines, five HRSGs, three HRSGs with duct burners and ten gas boilers. The gas turbines produce power to a power system with a 450 MW average load, twenty-two substations and three voltage levels: 230, 115, 13.8 kV and 18 segments of transmission lines. Fig. 1 shows the simplified single line diagram.

Table 1 shows the maximum capability of the gas turbine generator with the base load heat rate. The gas turbines consist of four different types, divided into four groups. For example, group MG 2–4 consists of three units of type 4 gas turbines.

Gas turbines AG 1–5 are equipped with HRSG while gas turbines DG 1–3 are equipped with HRSG-DB. Ten gas-fired boilers (GBs) are also utilized to produce additional steam. Table 2 shows the HRSG's and the GB's steam production capability. Natural gas is the only fuel source for gas turbines DG 1–3 and gas boilers. Gas turbines AG1-5, MG1 and MG2-4 are supplied with a mixture of natural gas and field gas.

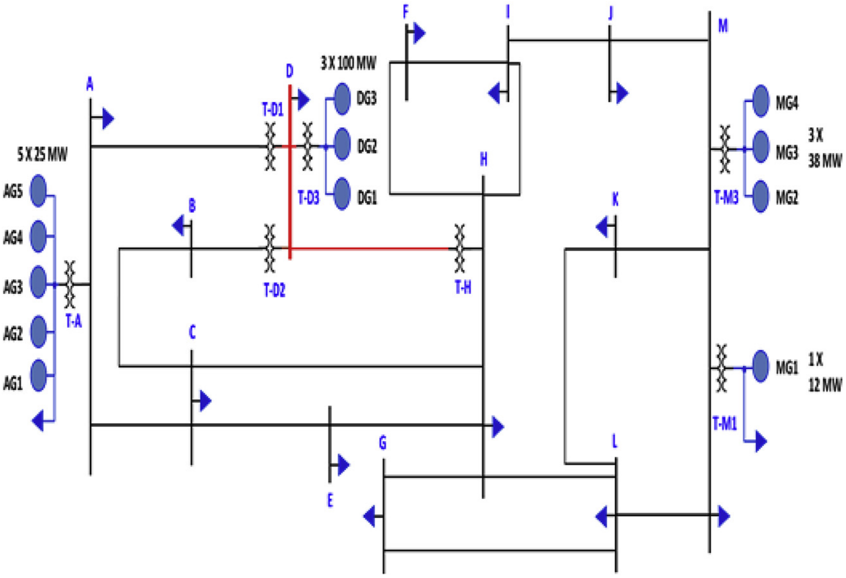

**Fig. 1.** Simplified single line diagram.