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Cogeneration versus natural gas steam boiler: A techno-economic model

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HIGHLIGHTS

- Both cogeneration and conventional systems may significantly reduce the costs.
- One heat exchanger is used for the two states of the cogeneration system.
- Using dynamic programming, we obtain analytical formulas for the expected costs.
- The cogeneration system's ROI is usually no longer than 7 years.
- High variances of steam demands lead to profitability of the conventional system.

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ABSTRACT

Energy usage can constitute a substantial operational expense for corporations. To reduce expenses, corporations may seek out decentralized solutions for generating electricity, based on sustainable energy or on conventional energy resources. The main goal of this research is to resolve an organization's dilemma regarding whether to adopt a cogeneration system or to replace a conventional diesel steam boiler with a boiler fueled by natural gas. We analytically calculate the total expected initial setup and operational costs under the two models, and determine which model is preferable. We numerically show that implementation of a cogeneration system may yield rapid return-on-investment and may lead to cost savings of more than 25%, as compared with the conventional system. However, low electricity tariffs or high operation costs lead to slower return-on-investment and the conventional model becomes significantly better for short-term processes. Furthermore, low uncertainty of steam demands leads to profitability of the cogeneration model. On the other hand, if the total expected demand of one type of product (electricity or steam) is significantly greater than that of the other, then the conventional model becomes preferable.

1. Introduction

Energy usage in corporations—e.g., in manufacturing, heating, cooling, lighting, and technology—can constitute a substantial operational expense [1]. Consequently, firms seek out reliable energy-saving solutions that can reduce their expenditures. The use of natural gas (NG) can enable organizations to enhance their efficiency while reducing emissions, thereby contributing to a cleaner environment [2].

By 2040, required net electricity generation worldwide is expected to increase to 39.0 trillion kilowatt-hours, from 20.2 trillion kilowatt-hours in 2010 [3]. So far, most countries are addressing this issue by increasing energy production capacity through the construction of centralized power plants on the one hand, and reducing demand by investing in facilities' efficiency on the other hand. Construction of new central power plants has many disadvantages, including high capital cost, low efficiency, environmental impact, and utilization of open spaces.

There are numerous alternative, decentralized/distributed solutions for generating electricity from sustainable energy sources (photovoltaic energy, wind power, hydroelectric power) or conventional energy resources [4]. Sustainable energy solutions are not always practical, as they can require large areas of land, and they may not be able to supply continuous energy in unfavorable weather conditions. However, decentralized fossil fuel solutions (such as NG) can provide high efficiency, reduce environmental impact (as compared with reliance on other fossil fuels), provide a continuous energy supply, and lower dependency on foreign oil.

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The use of NG to power conventional equipment such as steam boilers decreases financial expenditure and reduces emissions, in comparison with the use of coal- or oil-based energy. Efficiency can be enhanced even further if NG is utilized through cogeneration technology. Cogeneration is the simultaneous production of power and usable heat, based on using one type of energy source such as NG [5]. In most cogeneration applications, the energy types produced simultaneously are electric and heat energies, such as electricity and steam. Generally, cogeneration systems create heat by utilizing the waste heat energy produced during electricity generation. As a result, a single cogeneration system can produce a given amount of electrical and thermal energy using less fuel than would be needed to generate the same quantities of both types of energy with separate conventional technologies.

The main goal of this research is to enable an organization to identify which of the following approaches will provide it with the greatest reduction in energy expenditures: adopting an NG-powered cogeneration system (that produces both electrical power and steam) or replacing a conventional diesel steam boiler with an NG boiler while deriving all electrical power from the grid. We develop a model for each scenario (the "cogeneration model" and the "conventional model", respectively), calculating the scenario's profitability according to initial setup cost in addition to the operational costs corresponding to electricity and steam demand in each time period. Electrical bills have a structure of different tariffs, which can vary significantly according to season, day of the week and time of day. Implementation of a cogeneration system provides the organization with two electricity sources (grid or cogeneration), giving the organization the flexibility to decide when to turn the cogeneration system on or off, in accordance with tariff rates. Thus, with the appropriate capacity planning and operational strategy, the use of a cogeneration system has the potential to reduce the organization's energy expenditures. The disadvantage of the cogeneration model is the high setup cost.

Our model resolves the organization's dilemma while taking into account all available information that might influence the outcome of the investment. We find that with optimal initial configuration of the system, as well as an optimal operational policy regarding implementation of the system, a cogeneration system can be more profitable than a conventional NG system in the long term.

The rest of this paper is organized as follows. Section 2 presents a literature review. In Section 3 we present some general definitions and formulate the cogeneration and conventional models. Using backward dynamic programming we find the optimal solution that minimizes the total expected sum of planning and operation cogeneration costs. Then, we identify which model is preferable for the organization. Section 4 presents numerical examples for our analytical results. In particular, we show how model parameter values affect the choice of which model is preferable. Section 5 concludes.

2. Literature review

Researchers have investigated onsite cogeneration from technical, economic and environmental perspectives. Academic studies have introduced optimization methodologies for capacity planning, operational planning and combinations thereof. Most capacity-planning papers discuss optimization techniques that take into account site demands and that use various automatic methods. Studies on operation planning deal with operational system timing in accordance with economic constraints.

Ref. [5] proposes a techno-economic model of cogeneration for offices or buildings in Korea. Their model includes variable costs such as NG and electricity procurement from the grid with demand constraints. The model further takes into account equipment capacity cost. To derive the optimal solution, the researchers use a mixed-integer linear programming technique and a branch and bound algorithm. They find that adoption of a cogeneration system is not economically viable for office buildings but is feasible for hotels. However, their paper does not make a comparison between adoption of a cogeneration system and use of conventional steam boiler. In addition, the model does not take into account the option of exporting spare electricity to the grid, whereas our model does.

Ref. [6] presents an energy dispatch algorithm that minimizes the total cost of running a combined heat and power system over a time horizon, in order to satisfy the total energy demand. Their model takes into account the cost of electricity obtained from the grid and additional operational costs such as fuel costs. It further incorporates the possibility of exporting surplus electricity to the grid (as in our case). However, their model does not include planning aspects and grid usage costs. The authors use a linear programming technique to analyze the model and obtain an optimal solution.

Ref. [7] proposes an optimal unit sizing method for cogeneration systems, using a numerical study to explore how the optimal solution is influenced by the uncertainty of energy demand. Their model's aim is to minimize the expected annual total cost, taking into account the equipment capacity, energy flow rate and sampling vector. The authors find that the optimal capacity of the fuel cell unit decreases if the cogeneration system is designed such that it takes the uncertainties into account. However, their numerical study examines only three representative days in a one-year period, and they ignore the influence of operational methodology.

Ref. [8] introduces a global and regional emission impact evaluation of distributed cogeneration systems with partial-load models. Taking into consideration the facility's efficiency and emission factor, the authors introduce the expected NOX and CO emission level, locally and globally, in accordance with cogeneration system load values. They found that the NO_X rate increased while turbine load was low. However, the CO emission rate was high in every load.

Ref. [9] introduces the potential from implementing cogeneration in the plywood industry in India. The researchers use an "Annualized Life Cycle Cost" technique for investigating the most economic method of generating electricity and useful thermal energy. It was found that CHP with a steam turbine increases annual savings in operational energy.

Ref. [1] carries out a survey to obtain information regarding Jordan's energy consumption in the tourist accommodation sector and provide recommendations based on the results. The results show high willingness of hotels to reduce energy consumption by using efficient appliances. The authors suggest installing waste heat recovery systems in order to reduce diesel consumption.

Ref. [10] claims that combining investments in energy-efficient technologies with the promotion of good energy management practices can improve energy efficiency in the economy. Focusing on the European context, the authors argue that inclusion of energy management components in future energy policy will play an important role in Europe's ability to meet its energy efficiency targets for 2020, and later for 2050. Further research is suggested, quantifying the extent of the extended energy efficiency gap.

Ref. [11] reviews recent developments in technologies for waste heat recovery of exhaust gas from internal combustion engines. They discuss the potential energy savings and performances of organic Rankine cycle technologies. The authors find that using waste-to-heat technology can reduce emissions of greenhouse gas, sulfur oxides and nitrogen oxides.

Ref. [12] seeks to provide a better understanding of the processes applied in energy efficiency investment decisions. The author indicates that financial decision makers typically use