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Turbine investment optimisation for energy recovery plants by utilising historic steam flow profiles

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ABSTRACT

Burnable off-gases generated in engineering process plants are regularly utilised as energy sources. A common use is for steam production, where excess steam is allocated to power generation turbines. Fluctuating off-gas productions may, however, result in power generation losses from turbine trips, due to insufficient steam. Numerous power co-generation investment models exist, which are typically based on cost minimisations or meeting energy demands. These models do not, however, incorporate plant-specific historic steam profiles and typically use average-based patterns for decision making. This paper presents a novel stochastic mixed integer linear programming model that utilises historic steam profiles to determine optimal turbine investments in terms of the net present value. A further advantage is the ability to investigate the investment and procurement of a, typically very expensive, supplementary energy resource to assist during low off-gas flow periods. The proposed model is solved to optimise over 10 years for an engineering factory seeking to invest into an energy recovery plant. Optimal results demonstrate how natural gas in a fluctuating off-gas environment can increase power generation profits and should be invested in, together with a 30 MW turbine. Furthermore, an average-based approach yields sub-optimal investments and overestimates the net present value beyond 22%.

1. Introduction

For the engineering manufacturing industry there exists several different types of production plant layouts, where a plant refers to a process or a subset of processes delivering any number of products [1]. Plants can operate as independent entities or form part of an integrated process with other plants. These processes typically have integrated production chains, from which a number of by-products may be generated [2]. If such a by-product is present in a gaseous form and can combust when ignited in an oxygen enriched environment, it is also known as a *burnable off-gas*. A burnable off-gas possesses the potential to release heat during ignition and may therefore be utilised as an energy resource [1–3]. For the remainder of this paper any reference to off-gas will imply a burnable off-gas.

Fig. 1 shows a simplistic layout of a typical engineering plant under consideration. A number of raw materials are fed to the process plants where end-products are eventually produced [4,5]. For some of these process plants off-gases form that are consumed in other processes [2,6]. The off-gases not utilised in any plant processes, *i.e.* residual off-gases, are either used to generate steam in boiler houses or flared to the environment [2–4]. Steam is vital for various plant processes, mainly heating, and any excess steam that is available thereafter may be utilised for power generation [2,4,6]. Excess steam is directed to turbines, which are coupled to generators, to generate electricity.

The engineering process plants under investigation for this paper are as laid out in Fig. 1. It should be noted, however, for these plants power generation is not a main production focus, but merely a by-product due to excess steam availability. The additional electricity generated has typically no influence on the production outputs and is small in comparison to plant electricity usages. If power generation under the conditions of Fig. 1 does not occur, more off-gases will be flared and less steam produced. The process of power generation, due to the possibility of additional steam production, will be referred to in this paper as *energy recovery*.

It is important to note, for the purpose of this paper, energy recovery only refers to power generation from excess steam. This is the steam potentially available for power generation. These excess

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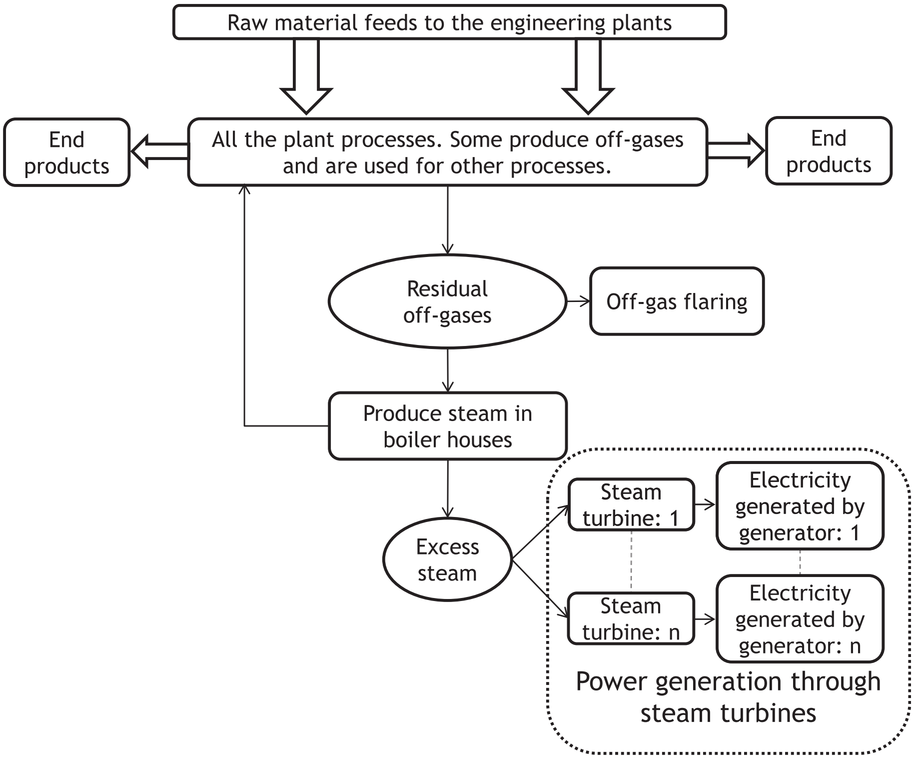

Fig. 1. A simplistic engineering plant layout demonstrating the concept of fluctuating energy recovery from excess steam.

steam quantities are, therefore, after all other usages have been satisfied. Usages include all process plant utilisations, internal boiler house consumptions and preheating of boiler feedwater.

Further note, for energy recovery under the above mentioned circumstances, boiler houses are typically sized to satisfy maximum steam availability for plat processes. To ensure adequate production levels, additional steam generation capacity is designed for when a boiler house unit needs to go off-line. Energy recovery is, therefore, typically not an initial design condition for such an engineering factory. As a result, possible investments into boiler houses will not form part of this paper's scope.

Variation in the quantities of raw material that feed to a process plant, or deviation of the chemical qualities thereof, may result in fluctuating off-gas productions over time [2]. In principle, fluctuating energy recovery is not necessarily problematic, unless power generation potential goes to waste, due to inefficient resource utilisation [6]. It should be noted that due to the continuous operating nature of an engineering plant, unutilised steam cannot be stored for later use and its power generation potential will consequently go to waste [1–4].

This paper presents a novel stochastic *mixed integer linear programming* (MILP) model that uniquely explores optimal investment options for energy recovery from plant-specific historic steam flow patterns. The proposed model also incorporates investment options related to the acquisition of a supplementary resource. A scenario-based approach is followed for representing uncertainty in the steam flow profiles as a finite set of scenarios. The objective of this model is to maximise the profitability of energy recovery by taking capital investment of turbines and procurement of a supplementary resource into account, as well as the operational costs involved in the supply thereof. In order to assess the financial benefit of the capital investments, the *net present value* (NPV) of all future cash flows is used as the evaluation criterion. The cash flows considered include only revenue from energy recovery and not any revenue from production sales.

2. Literature review

Various optimisation investment models exist for co-generation plants. These models are typically concerned with multiple power generation mediums and the minimisation of energy's fixed and operational costs in an attempt to determine optimal investment choices. Numerous optimisation models focus on linking energy demand with supply. Furthermore, as accustomed to typical engineering investment practises, average-based estimates over time are used for optimal investment purposes.

The author of [7] proposed an optimisation model, called MODEST, used for investment planning of municipal and national energy systems, by incorporating average-based estimates over time. Capital and operation costs of energy supply and demand-side management are minimised, using linear programming.

Mixed integer nonlinear programming was used by [8] to propose a method of optimal sizing for co-generation systems. The objective was to minimise the total annual operational costs of gas turbine plants, with energy demand and equipment performance characteristics as constraints. A MILP was proposed by [9] that can be used to determine the preliminary design of a co-generation system to minimise annual costs.

In order to match energy supply and demand, while using MILP models [10], investigated solving techniques for multi-objective optimisations. Further work by [11] focused on multi-objective and multi-period optimisation while integrating biomass as a resource. The aim was to minimise operational costs and carbon dioxide emissions.

The authors of [12] addressed plant design and production scheduling as an integrated optimisation model, rather than two separate problems. Optimal unit sizing methods for co-generation systems that deal with uncertainties in energy demand was