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Understanding steam costs for energy conservation projects

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HIGHLIGHTS

- Complex steam costing for utility systems.
- True steam costs can only be evaluated by utility system optimization.
- Develop marginal steam cost profiles and cumulative cost profiles for different steam savings.
- Explore the interaction of steam costs at different steam mains.
- Simplified steam costing would lead to incorrect economics evaluation for complex utility systems.

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ABSTRACT

The evaluation of energy conservation projects involving steam savings requires that the cost of steam be known. While it is straightforward in principle to calculate the heat load and steam flowrate corresponding to an energy conservation project, it is much less straightforward to calculate the cost of steam saved for the economic evaluation of projects. Various simplified methods for steam costing used in practice can be grossly misleading and lead to incorrect evaluation of the economics of energy conservation projects. This paper demonstrates the complexity of costing steam for complex utility systems. It shows that true steam costs can only be evaluated by an optimization model of the whole utility system. Two plots of marginal steam cost profiles and cumulative cost profiles for different steam savings are developed to help understand the cost reduction of steam savings.

1. Introduction

Utility systems provide heat and power to the processes. System analysis is necessary to systematically evaluate site-wide steam generation, steam distribution, and power generation [1]. In the past decades, research efforts focused on process integration to improve energy efficiency [2] at multiple scales [3].

Energy conservation projects in process plants most often save energy through saving steam. Process steam demands might change due to changes in site processes: process production scale adjustment; process retrofit; process operational optimization; more heat recovery within the individual process; heat recovery for steam generation from higher temperature process streams; and process heating by lower pressure steam replacing higher pressure steam, etc. For these energy conservation projects, techniques such as Pinch analysis [4] based on graphical methods [5] has been developed to obtain heat recovery and power targets [6] and to improve cogeneration. *R*-curve analysis [7] was also used for optimal design of cogeneration system [8]. Mathematical programming has been proposed to achieve deterministic synthesis [9] and operational optimization [10]. A near-optimal solution was also analysed [11] to achieve economic and environmental optimization [12]. The optimization under uncertainty has been studied, including multi-period synthesis [13] and optimization [14], flexibility analysis to seasonal demand variations [15] and market fluctuation [16], etc. While it is possible to calculate the saving as a heat load and a flowrate of steam, it is not so straightforward to relate this to the actual economic savings. Processes are most often connected to a complex steam system involving steam boilers, gas turbines with heat recovery steam generators (HRSGs), multiple steam headers, steam turbines, letdown stations linking the steam headers, and possibly condensing turbines. Not only are there complex degrees of freedom within such a steam system, the different processes on the site interact with each other through the steam system.

It is common practice to attribute a cost to different levels of steam on a site. Various methods have been used to calculate steam costs, such as the average steam cost [17], enthalpy based steam pricing [17], work-based pricing [18], and fuel equivalent

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Nomenclature

a	steam turbine model coefficient
b	steam turbine model coefficient
c	steam turbine model coefficient
CC	cumulative cost of steam, $/h
Cop	operating cost, $/y
Cop_{fuel}	the cost of fuel consumption, $/y
Cop_{BFW}	the cost of water, $/y
Cop_{elec}	imported power cost from the grid, $/y
Cop_{run}	the cost for running the steam and power generation, $/y
F	Equality constraints
G	Inequality constraints
MC	Marginal steam cost, $/t
m_{ST}	turbine steam flow, kg/s
W_{is}	turbine isentropic shaft power, kW
W_{ST}	turbine shaft power, kW
x	Decision variable
η_{boi}	the boiler efficiency
η_{is}	turbine adiabatic efficiency
η_{ST}	overall steam turbine efficiency
ΔH_{is}	the isentropic enthalpy drop across the turbine, kJ/kg
$\Delta Cost$	change in cost, $/t
Δm	change in steam demand, t/h

Subscripts

BFW	Boiler feed water
$elec$	Electricity import or export from the grid
$fuel$	fuel combustion in boilers or gas turbines
i	steam mains, HP, MP, or LP
max	the maximum
min	the minimum
pow	exported/imported power
run	running steam and power generation
ST	steam turbine
$turb$	Steam turbine
w	water

based steam pricing [19]. These approaches oversimplify the calculation of the steam costs, leading to errors in the value placed on steam. Correspondingly, the assessment of energy conservation projects based on incorrect steam costs would be misleading.

The concept of marginal steam cost (MC) [20] has been proposed to evaluate energy conservation and efficiency improvement projects based on a value-allocation procedure [21] and top-level analysis [22]. These methods of steam pricing calculated the cost for high pressure steam generation in the utility boilers or HRSGs associated with gas turbines. This is usually dominated by the cost of fuel, but other costs such as auxiliary steam and power required for steam generation, water and treatment chemicals, labor, and so on can be included. The approaches to steam costing must account for the power potential by high-pressure steam expansion in steam turbines as it is let down between different steam headers, and by steam condensation in condensing turbines. Knowing the amount of power that can be extracted allows the value of the power to be estimated, and this can be subtracted from the price of the high-pressure utility steam to obtain the price of the lower-pressure steam. Unfortunately, there are shortcomings in these methods. For example, steam turbine models [23] ignored the influence of changes in steam main pressures and superheating on turbine performance, such as power generation, turbine efficiencies and turbine exhaust temperatures, which have great influence on system conditions, especially temperatures of steam mains. On the other side, the verified steam mains would change equipment performance, steam distribution in the steam systems, and power generation as well. These methods did not take account of some practical constraints, such as individual equipment operating load between the minimum and maximum steam flowrates. The interaction between individual equipment operating variation and the system performance, and its impact on steam costs need to be explored more fully.

There are limits for steam costing only based on marginal steam cost in these methods: firstly, the MC cannot address the overall cost reduction due to the steam savings; secondly, the interaction between steam costs and steam savings at different steam mains is not accounted into the system analysis. It is not true the steam costs are unchanged at different system operating conditions due to steam savings. Real steam costs would be explored to obtain more economic steam saving scenarios in energy conservation projects.

This paper shows that steam savings must be evaluated properly based on complex utility system optimization accounting for the interaction between (1) process changes and the corresponding utility system operating adjustment, (2) individual equipment operation and the system performance, and (3) the steam system condition and steam costing. Marginal cost is changing at different steam saving conditions based on the realistic assessment taking account of individual equipment performance, system condition adjustment, and the constraints around the system. The interaction of steam costs at different steam mains is analyzed to determine steam saving scenarios in the process retrofit project. Steam cumulative cost profiles are firstly proposed to address the overall cost reduction due to steam savings. Both the marginal steam cost profiles and the steam cumulative cost profiles help understanding the cost benefits due to steam savings, and provide better insights of total site system operational assessment.

2. Optimization based steam costing

For a complex utility system with multiple boilers, multiple fuels, multiple steam mains, and optional steam and power generation paths, steam costs depend on system configuration, individual equipment type, size, and its operating load, and cost data. It is a complex optimization with practical considerations.

2.1. Steam system optimization

Fig. 1 shows an example of an existing site utility system [23]. Steam is generated at high pressure (HP), which is distributed around the site, along with steam at medium pressure (MP) and low pressure (LP). Steam is expanded through a network of steam turbines from the HP main to the lower-pressure mains. Letdown stations are used to control the mains pressures. Turbines *T*1–*T*4 generate electricity. Turbines *DRV*1 and *DRV*2 are driver turbines connected directly to process machines.