ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Decision rules for economic summer-shutdown of production units in large district heating systems

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HIGHLIGHTS

- In the study-case, the economic potential for summer-shutdown is 6.3 million €/yr.
- Optimal shutdown and start-up dates are characterized for 38 historical years.
- A fixed date rule achieves 90.7% of the potential and allows long-term planning.
- A load based rule achieves 95.8% but does not allow planning ahead.
- Using 15-day ahead forecast data increases the economic gain to 96.5% on average.

ARTICLE INFO

Keywords:
District heating
Decision rules
Long-term production planning
Heat load forecasting

ABSTRACT

Seasonal load variations in district heating systems are so large that some production units become superfluous during summer operations. There is great economic potential in shutting down these units during summer. The economic benefit of summer shutdown is highly dependent on the timing of the shutdown decision. The optimal shutdown and start-up dates depend on complex weather patterns and vary significantly from year to year. This study introduces three classes of decision rules to help production planners perform economically optimal summer shutdown: a fixed date rule, a heat load based rule and a load based rule augmented with weather forecasts. These decision rules are tested using 38 years of hourly weather data to simulate the heat load in Aarhus, Denmark. The large amount of weather data allows for the creation of highly robust decision rules that account for rare, but costly weather conditions. A fixed date rule allows for planning very far ahead and can reap 90.7% of the potential economic benefit of summer shutdown. A heat load based decision rule can salvage 95.8% of the potential shutdown savings at the cost of shorter planning horizons. Augmenting the load based decision rule with 15 day weather forecasts can boost the performance to 96.5%.

1. Introduction

The daily heat load in a district heating system varies by as much as a factor of 8 between summer and winter in a northern European climate. In continental climates, seasonal load variations are presumably even greater. In district heating systems with several production units, the seasonal load variations make some production units superfluous during summer.

Economically optimal production of heat often follows a simple merit order in which cheaper production units are given priority over more expensive ones. However, many cogeneration plants have a substantial minimum load. This means that if such a plant is kept in operation, typically to ensure low-cost security of supply, it may displace production from a cheaper alternative. Therefore, it can be economically beneficial to completely shut down a plant during the summer period when the demand can be safely met by lower cost units. However, the challenge in performing summer shutdown of such seasonally superfluous production units lies in the timing. As an example, an early warm spring may be interrupted by a sudden cold spell, where the cost of emergency backup reserves, e.g. oil boilers, outweighs the economic benefit of an early shutdown of one of the main units. Similarly, a late start-up in fall may also require the use of costly emergency reserves if the beginning of winter is not correctly anticipated. This means that the economically optimal shutdown and start-up dates depend on complex weather patterns that vary substantially from year to year. Therefore, good decision rules are necessary to help

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http://dx.doi.org/10.1016/j.apenergy.2017.09.040
Received 20 June 2017; Received in revised form 21 August 2017; Accepted 10 September 2017
0306-2619/

Please cite this article as: Dahl, M., Applied Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.09.040

Nomenclature

σ	standard deviation in heat load model [°C]
τ_1, τ_2, τ_3	load thresholds for load based decision rules [MWh/h]
θ_t^i	indicator function for the availability of unit i
a	slope in heat load model [MWh/h/°C]
c^i	operational production cost per unit heat for production unit i [€/MWh]
$C_{\text{fall}}(t_{\text{start-up}})$	total operational production cost in the fall given $t_{\text{start-up}}$ [$C_{\text{fall}}^{\text{no shutdown}}$]
$C_{\text{fall}}^{\text{no shutdown}}$	total operational production cost in the fall if shutdown is not performed [€]
$C_{\text{spring}}(t_{\text{shutdown}})$	total operational production cost in the spring given t_{shutdown} [$C_{\text{spring}}^{\text{no shutdown}}$]
$C_{\text{spring}}^{\text{no shutdown}}$	total operational production cost in the spring if shutdown is not performed [€]
c_t^{tot}	total operational heat production cost in hour t [€/h]
h	forecast horizon for load based decision rules with forecast [h]
$p(T_0')$	probability density function for the threshold temperature in heat load model
P^{tot}	total heat load of the city [MWh/h]
P_t^i	heat production from unit i in time step t [MWh/h]
P_0	base heat load in heat load model [MWh/h]
P_{max}^i	maximum heat output from unit i [MWh/h]
P_{min}^i	minimum heat output from unit i [MWh/h]
T_0	threshold temperature in heat load model [°C]
T_1,T_2,T_3	smoothing time scales for load based decision rules [h]
T_{anchor}	anchoring time scale for load based decision rules [h]
t_{fixed}	plant shutdown/start-up time decided by the fixed date rule
T_{out}	outdoor temperature [°C]
t_{shutdown}	plant shutdown time
$t_{\text{shutdown}}^{\text{opt}}$	optimal plant shutdown time
$t_{\text{start-up}}$	plant start-up time
$t_{\text{start-up}}^{\text{opt}}$	optimal plant start-up time

production planners perform optimal summer shutdown.

The economic potential in performing summer shutdowns of superfluous plants in large district heating systems is significant. In this paper, we use the large district heating system of Aarhus, Denmark, as a case to present decision rules that can reap almost all the benefit of shutting down a large CHP plant. This amounts to annual savings of 6.1 million €, which corresponds to about 5% of the total operational heat production cost. Environmental benefits are also significant in cases where a fossil fuel plant is shut down and the next plant in the merit order has lower carbon emissions. The economic potential is clear from the district heating perspective, but summer shutdown is economical from a system perspective as well. Combined heat and power plants (CHP) are under increasing economic pressure in many countries due to larger penetrations of renewable energy reducing electricity prices. This is especially true in summer when the heat demand is low. The overall profitability of a plant can be improved by shutting it down during the summer.

Cost-optimal operation and production planning of cogeneration systems have been studied extensively in the past. Many studies apply linear programming models (LP) [1] or mixed integer linear programming models (MILP) [2,3] to optimize the unit commitment and load dispatch in cogeneration systems. While these studies present theoretically optimal production plans, they do so under the assumption of known electricity prices and perfect load forecasts. In an actual planning situation, there will be uncertainties associated with the future heat load and electricity prices. Smart metering data are used in [4] to optimize the operation of a small district heating system with genetic optimization algorithms. Sensitivity analysis [4] and Monte Carlo simulations [5] are used to evaluate the effect of uncertain parameter estimates. Other studies account for uncertain forecasts by creating artificial price forecasts and validating the results against the assumption of perfect forecasts [6]. In [7], the authors explicitly model the uncertainties and design operational strategies based on information gap decision theory. A natural way to handle optimization under uncertainty is stochastic programming. It is used in e.g. [8] to optimize the operation of a district heating system with a strong coupling to the electricity sector through cogeneration, heat pumps and electric boilers.

None of these studies account for long production planning horizons of a month or longer. Production planning with horizons up to a month was considered in [9], and the author concluded that it is very difficult to use traditional optimization models to make relevant production plans on horizons as long as a month. In [10], a framework is introduced for modeling the planning under uncertainty on multiple time scales, the longest being more than a year. The formulation of the framework is concluded in a second paper [11], in which decision theory is used to evaluate long-term cogeneration planning decisions.

Optimal design of cogeneration systems has been studied extensively using MILP and mixed integer nonlinear programming models. Small systems, such as a single CHP unit at a building complex, are sized in [12,13] using MILP modeling. Larger systems have been sized in [14] with a special emphasis on legal constraints. Finally, some studies include optimization of the district heating grid in the system design [15,1]. In an entirely different approach, the study in [16] evaluates optimal energy sources from the viewpoint of different stakeholders in the construction of a distributed energy system.

In this work, we use 38 years of weather data to quantify the uncertainty in a specific shutdown decision, which is the optimal summer shutdown of the large CHP plant at Studstrup, from which the city of Aarhus, Denmark, gets most of its heat. For this case, we benchmark the performance of three classes of shutdown decision rules. The first class of rules uses fixed dates, shutting down and starting up the plant on the same date every year. This class of rules has the advantage of allowing for very long planning horizons. However, it does not reap the full benefit of summer shutdown, because it is too inflexible. The second class of rules uses information about the heat load up to the point of shutdown. This class of rules performs better, but it comes at the cost of shortening the planning horizon. The third class of rules augments the load based rule with heat load forecasts up to 15 days ahead in an attempt to improve the accuracy of the shutdown even further.

The decision rules are designed to be directly applicable by system operators, as opposed to outputs of large scale MILP optimizations. MILP optimizations of the production may result in summer shutdown of certain units if start-up costs are properly accounted for. However, these optimization studies do not provide a guide to decision makers that can help with timing the decision accurately. By focusing on a single decision and creating concrete decision rules, the results of this work can be directly implemented by production planners. Although weather based modeling is not new to load modeling in district heating, see e.g. [17–21], the magnitude of our data foundation is unprecedented. With 38 years of weather data, we are able to capture effects of rare, but costly weather phenomena. Weather based modeling on this scale has previously been applied to highly renewable electricity systems to characterize transmission needs [22,23], storage [24,25] and export schemes [26].

The novelty of this work can be summarized as follows. To the best of our knowledge, we are the first to use weather based heat load modeling with such a large quantity of data. The many years of weather data allow us to capture complex patterns in the heat load to make robust decision rules. This procedure accounts for rare weather phenomena that can potentially be very costly if they are ignored. Because