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► To cite this version:

Patricia Velasco-Garcia, Petar Sabev Varbanov, Harvey Arellano-Garcia, Günter Wozny. Utility Systems Operation: Optimisation -Based Decision Making. Applied Thermal Engineering, 2011, 31 (16), pp.3196. 10.1016/j.applthermaleng.2011.05.046 . hal-00789888

HAL Id: hal-00789888

<https://hal.science/hal-00789888>

Submitted on 19 Feb 2013

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Accepted Manuscript

Title: Utility Systems Operation: Optimisation –Based Decision Making

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PII: S1359-4311(11)00306-1

DOI: [10.1016/j.applthermaleng.2011.05.046](https://doi.org/10.1016/j.applthermaleng.2011.05.046)

Reference: ATE 3593

To appear in: *Applied Thermal Engineering*

Received Date: 12 April 2011

Revised Date: 19 May 2011

Accepted Date: 31 May 2011

Please cite this article as: P. Velasco-Garcia, P.S. Varbanov, H. Arellano-Garcia, Günter Wozny. Utility Systems Operation: Optimisation –Based Decision Making, *Applied Thermal Engineering* (2011), doi: 10.1016/j.applthermaleng.2011.05.046

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Utility Systems Operation: Optimisation –Based Decision Making

Patricia Velasco-Garcia¹, Petar Sabevarbanov^{2*}, Harvey Arellano-Garcia¹, Günter Wozny¹

¹Berlin University of Technology, Department of Process Dynamics and Operation, Straße des 17. Juni 135,
10623 Berlin, Germany

²Centre for Process Integration and Intensification – CPI², Research Institute for Chemical and Process
Engineering, Faculty of Information Technology, University of Pannonia, Egyetem utca 10, 8200 Veszprém,
Hungary, email: varbanov@cpi.uni-pannon.hu; phone: +3688421664

Abstract

Utility systems provide heat and power to industrial sites. The importance of operating these systems in an optimal way has increased significantly due to the unstable and in the long term rising prices of fossil fuels as well as the need for reducing the greenhouse gas emissions. This paper presents an analysis of the problem for supporting operator decision-making under conditions of variable steam demands from the production processes on an industrial site. An optimisation model has been developed, where besides for running the utility system, also the costs associated with starting up the operating units have been modelled. The illustrative case study shows that accounting for the shutdowns and start-ups of utility operating units can bring significant cost savings.

1 Introduction

Chemical plants operate in existing industrial sites, where a number of production processes are grouped together and are supplied with power and heat by a site utility system. Combined Heat and Power (CHP) production, also called cogeneration, is typical for modern utility systems. Optimisation of energy systems has been researched using Process Integration and Mathematical Programming, mainly from the viewpoint of process synthesis and scheduling [1, 2].

However, significantly less attention has been paid to optimising the operation of energy systems and especially accounting for such important dynamic effects as start-ups, shutdowns and load variations. They are common in utility systems due to the changes in process demands [3]. Another recent development has been the integration of renewable energy sources into the energy supply and utility systems in particular, also taking the advantage of joining additional energy users to the industry – e.g. residential and commercial building

complexes, resulting in the so-called Locally Integrated Energy Sectors [4, 5]. The most significant challenge before integrating renewables is their varying availability [5]. When variations in the availability of renewable energy and in the magnitude of the user demands takes place, the question arises whether it is worth activating or stopping certain devices. Currently, utility system operators still lack optimisation-based tools for making such decisions.

Many works have been published on synthesis and optimisation of utility systems where the models feature combinations of continuous (operation parameters) and discrete variables (units selection, switch on/off), leading to mixed-integer programming (MIP) formulations. One of the first system-level works in the field is that of Papoulias and Grossmann [6]. They presented a MILP approach to utility system synthesis for fixed site power and heat requirements.

Solving MINLP problems usually involves high computational effort. Thus, such models are unsuitable for real-time utility management problems. However, Prokopakis and Maroulis [7] have developed an approach to real-time optimisation applying an adapted MINLP model, which could be solved spending reasonable time and computational effort. Several specification options are available – using actual performance data from the equipment supplier, detailed / approximate models or the concept of operation at equal incremental cost. The latter is derived from Lagrangian analysis of the optimisation problem and analytical expressions involving loads and cost coefficients.

The multiperiod operation paradigm was introduced into the utility system model in [8]. The model was formulated as a MILP, including the operating and start-up/shutdown costs. In [9], a new improved approach is presented to model steam and gas turbines using the Willan's lines – including turbine part-load performance. Then optimisation of existing utility systems is carried out using Successive Mixed Integer Linear Programming (SMILP).

In [10], a new top-down procedure for retrofit of existing total sites was introduced. First, a top-level analysis of the utility system is performed to identify the scope for energy savings. They cannot be always translated to cost savings via reduction of fuel consumption because the latter is also related to the power import from the grid via the amount of steam generated

and expanded through the steam turbines. Different path alternatives for the steam surplus utilisation are evaluated in terms of power generation efficiency. As a final result, steam marginal prices for different steam headers are calculated at different rates of potential steam saving. Varbanov *et al.* [11] developed further the Top-Level Analysis methodology using successive operational optimisation to evaluate the marginal steam prices.

On industrial sites energy demands vary with time. Several researchers have studied the optimisation of utility systems taking this into account. For instance, in [12] Simulated Annealing was used for the synthesis of utility systems with variable demands. In [13], a model and an optimisation approach were suggested to deal with utility demand variability due to seasonal demands and uncertainties. The uncertainties in energy demand are handled by defining deviation ranges for each operating period. The switch conditions are explicitly modelled using binary variables. However, the main reasons for the switching costs have not been clarified. By modelling turbine efficiency uncertainties, different cases are considered and compared and the mean efficiencies modelled as polynomial functions of the steam flows through the turbines.

In [3] the optimisation of steam-supply systems under variable energy demands was also studied. The variable trend of the heat-power demand in the time is discretised in a piecewise-constant manner by approximating it with a set of rectangles whose heights correspond to the power/steam demands for the corresponding periods.

A more recent work [14] discusses the scheduling of utility system operation integrated with the schedule of the remainder of the process operations. This has illustrated the importance of accounting for the variation in the user energy demands. However, what is still missing there is the appropriate simultaneous representation of the costs and time constraints associated with the start-up and shut-down of key equipment types as boilers, steam turbines, gas turbines, etc.

The current paper is an attempt to provide model extensions for such operating units accounting for their start-up costs capable of both sufficient modelling accuracy and also simplicity, so that they will be suitable for integration into large-scale optimisation models. In the following sections, the utility system model and the used optimisation procedure are

described. An industrial case study is also provided to illustrate the applicability of the approach.

2 System optimisation

2.1 Utility system model

The main components of a utility system are boilers and the steam turbines. Steam boilers are modelled with a constant efficiency model, which has been accepted by the site engineers as providing sufficient accuracy for the considered example. A more elaborate boiler model can be employed [9], should this be necessary. Steam turbines are modelled using Willan's lines with fixed coefficients. This ensures a good balance between modelling simplicity and precision. The complete system model has been built following the methodology presented in [9] and is presented in Appendix A.

2.2 General formulation issues

The rigorous utility system model is non-linear mainly due to the bilinear equations it contains – *e.g.* enthalpy balances (Appendix A). In operating the system, both discrete and continuous decisions are involved. The former include the operation status of the devices (on/off), while the latter concern the values of variables corresponding to physical quantities such as flowrates, temperatures, enthalpies, *etc.*

Thus, in general, a MINLP (Mixed Integer Non-Linear Programming) formulation would be necessary for the optimisation of the system. Nevertheless, MILP (Mixed Integer Linear Programming) is commonly used for the optimisation of existing utility systems. The advantage of MILP is that it avoids the computational problems inherent to MINLP solution algorithms. It is possible to apply, however, only if a linear model can be obtained. Previous works on utility systems modelling obtain a linear model by either merely fixing the performance of the devices [6], or use the non-linear models directly [15].

In the current work, following [9], a simplified model has been used for optimisation, combined with successive rigorous simulations, thus taking advantage of the linear optimisation algorithms. This procedure is called Successive Mixed Integer Linear

Programming (SMILP), which allows using a sequence of MILP runs for solving the non-linear system without losing precision. The non-linearities are taken into account during the rigorous simulations.

For handling the variation of process energy demands, the costs associated with starting-up certain operating units are included into those for running the utility system. Thus, decision support to system operators is provided for optimal operation.

2.3 Changes of the operating state

A common situation, when running utility systems, is that the rates of steam supply to and demand from the site processes change with time. This occurs on a regular basis due to process shut-downs and start-ups. The variations are more frequent on sites including batch processes.

As a result of changing the overall steam supply-demands pattern, it usually becomes necessary to respond with changes in the operating specifications of the utility system. For example, a rise in the process steam demand leads to increased steam generation. The additional steam can be produced by different devices and it is necessary to decide which is the most advantageous way to operate – whether to increase the mass flow rate in a running boiler and/or to switch on other devices, and if required - which of them. Furthermore, increased steam generation may also be an opportunity to produce additional power by expanding the steam through steam turbines.

On the other hand, a decrease of the steam requirements means an excess of steam in the utility system. It may be most cost-effective either to save fuel by switching off some steam generator units, or to generate additional power by increasing the steam mass flow rate through active steam turbines. Another option might be to switch on a different steam turbine.

The operating efficiency of a utility system under varying steam demands is determined by a number of factors, among which the following are most significant:

- The direction of the change, *i.e.* increase or decrease and the magnitudes of the current and the new demands. Reduced demands usually result in steam surplus, which can be either utilised or saved.

- The utility level – *e.g.* at the HP, MP or LP steam headers. Changing demands for lower-pressure steam allows more power cogeneration than changing those for higher-pressure.
- The expected duration of the new demands. The effect of this factor is especially interesting for demand increases, since sustained higher demands usually justify activating more devices (*e.g.* boilers and steam turbines) than in the case of shorter or transient demand increases.

The changes in the operating states for utility system components can be of two types. They can be either started up (activated) or shut down (deactivated). Normally, starting up a unit involves the more significant costs, stemming from expenses for extra fuel consumption. In comparison, shutting down an operating unit involves much less costs, mainly bound to personnel, which are much less significant and can be neglected for simpler cases.

To evaluate the effect of changing the operating state and take into account the costs of possible operating unit start-ups, a binary variable y_{CHANGE} is defined for each operating unit. Its value is related to two other binary entities, defined for each operating unit. The parameter $y_{CURRENT}$ refers to the operation state for the current steam demand, while the variable y_{NEW} designates the operation state for the new demand. The binary variable y_{CHANGE} is used for estimating the start-up cost incurred when the device changes its operation state from idle to working. The other transition is not of interest, since the major costs are when starting a unit and not when shutting it down. Therefore, y_{CHANGE} assumes the value of 1 only if the unit features a state transition from idle to active. The logic of setting the value of y_{CHANGE} is illustrated in Table 1.

Using the defined binary entities, it can be judged if it is worth switching a device on or whether there might be a better operation alternative. Equations (1) to (3) allow implementing this logic in the model.

$$y_{CURRENT} \cdot y_{CHANGE} = 0 \quad (1)$$

$$y_{CHANGE} - y_{NEW} \leq 0 \quad (2)$$

$$y_{CHANGE} + y_{CURRENT} - y_{NEW} \geq 0 \quad (3)$$

2.4 Estimation of the device start-up costs

Variations in process demands involve start-ups, shut-downs and intermediate load variations. In this section, the developed framework for estimating the costs associated with starting-up equipment items is described. For clarity, simple methods for estimating the start-up costs of the operating units are used. More elaborate methods can be employed under the same framework, should the specific case require it. Starting-up a unit requires some time to heat up the device and to make it operational. In most cases, some fuel or steam is consumed and this involves a certain extra cost in addition to that for regular continuous operation. This observation is the basis for the proposed start-up cost estimation procedure.

In order to calculate the start-up cost for a steam boiler, the fuel necessary to reach steam generation conditions for the water contained in the boiler drum could be used to obtain an estimate. It can be eventually supplemented by the heat capacity of the various other parts of the boiler – including the casing. Thus, for a given start-up duration, the boiler start-up cost is determined by the following equation:

$$STupC_{BOILER} = m_{STup, FUEL} \cdot Price_{FUEL} \cdot t_{STup} \quad (4)$$

The introduced start-up duration parameter t_{STup} is different from the new process steam demands duration. It reflects the duration of the time period necessary to bring the boiler to the respective temperature at the specified fuel consumption.

In the case of steam turbines, the start-up cost is estimated using the mass flow-rate of steam passing through the turbine to heat it up from cold state until it reaches the required temperature. The price of the steam consumed for this purpose is obtained from a financial balance through the complete utility system in the way described by Smith and Varbanov [16]. The turbine start-up cost is calculated as:

$$STupC_{ST} = m_{STup, STEAM} \cdot Price_{ST, IN} \cdot t_{STup} \quad (5)$$

Start-up costs for an operating unit are charged only if it changes its operating status from idle (**off**) to active (**on**). Thus, the introduced binary variable y_{CHANGE} is multiplied by the device

start up cost (a parameter) reflecting the logic introduced above (see Table 1 and Eq. 1 to 3). The total start-up cost is expressed as a sum overall operating units as follows:

$$STupC = \sum_{UNITS} (STupC_{UNIT} \cdot y_{CHANGE,UNIT}) \quad (6)$$

2.5 General optimisation procedure

The main simplifications for obtaining a MILP formulation from the rigorous model include fixing the steam enthalpies in the system components (steam headers, steam turbine outlets) and optimising the flowrates. However, for better precision, each MILP run is followed by a simulation step using the rigorous model. This procedure is iteratively repeated until no enthalpy variations occur. The successive MILP optimisation procedure is described in detail in [17].

3 Case study

In this section, an industrially-based case study is presented to illustrate how the methodology can be applied. The notation of the system elements follows the conventions of the industrial source site. Different scenarios are analysed for the demand changes, starting from a given initial operating state. Following is the general description of the system. A more detailed set of data for the operating units is provided in Appendix B.

3.1 System description

Figure 1 shows the utility system flowsheet. Boiler 1 burns natural gas to generate High Pressure (HP) steam, while Boiler 2 (also gas-fired) produces Medium Pressure (MP) steam. There is also a 40 MW gas turbine consuming natural gas, operated at full load. Its flue gas goes through a two-pressure-level Heat Recovery Steam Generator (HRSG) with supplementary firing to generate HP steam, Low Pressure (LP) steam and heat up Boiler Feed Water (BFW) to be delivered to the Waste Incineration Plant (WIP). Specialised Heat Exchangers 1 and 2 (SHE1, SHE2) produce HP steam and heat up BFW for the WIP too. Steam, coming from the WIP, can be directed to the HRSG, the Specialised Heat Exchangers or be expanded through the letdown valve LD2. The flowrate of the water returned to the WIP

should slightly exceed the one of the received steam in order to cover the inherent losses (*e.g.* leaks). HP steam can be expanded through steam turbines ST1, ST2, letdown valve LD1 or the Turbocompressor driver TC. ST1 and ST2 have extraction outlets to the MP main and exhaust to the LP main. LD1 and TC exhaust to the MP main. Turbopumps (direct drive steam turbines) TP1, TP2, and TP3, and letdown valve LD3 expand MP steam to the LP header. There are HP, MP and LP steam demands for process heating.

The feed water pumps can be run by the direct drivers (Turbopumps 1, 2 and 3) or by electric motors. Similarly, the power necessary for the air compression can be provided by the turbine of turbocompressor TC or by an electric motor.

3.2 Case study setup

3.2.1 Assumptions

In presenting the case studies, the demands from process steam users before the change occurs are denoted as “current” and “new demand” denotes the process steam demand after the change has occurred.

Two different scenarios have been studied – one for the case when WIP produces steam (Scenario 1) and another when it is not working (Scenario 2). The rate of condensate return is assumed zero in both scenarios. The main data of the scenarios are shown in Table 2. Since the optimisation outcome depends on the duration of the new demand, two different durations are used to investigate this influence within each scenario. In the flowsheet figures, only the non-zero flowrates are shown.

The costs for the initial state are given in €/h, which reflects that its duration is not considered in the cost calculation. On the other hand the objective function in the optimisation problem considers the duration of the new demands, since in this case the operation cost depends on how long the new demands last. Therefore the costs in the optimal configuration are given in €.

3.2.2 Scenario 1

In this case, the WIP is online and supplies additional steam to the utility system. The current and new process steam demands for this case are given in Table 2.

The flowsheet with the initial steam flowrates for the current scenario is shown in Figure 2. The HRSG heats up part of the 20 t/h steam coming from the WIP to HP header condition. In addition, it also heats the 20.2 t/h feed water returned to the WIP and another 64.8 t/h of HP steam. The two standalone boilers and special heat exchangers are idle. From all steam turbines only ST2 is in operation, expanding 39.3 t/h steam to the MP main and 28.08 t/h steam to the LP main, thus generating 6.06 MW of electrical power. The utility system operating cost is 1183 €/h.

3.2.3 Scenario 2

The initial state for Scenario 2 is illustrated in Table 2 and Figure 3. Boiler 2 is active, supplying steam to the MP main. Turbine ST2 expands 30.62 t/h steam to the MP main and 26.47 t/h steam to the LP main. Steam turbine TP2 is also on, generating 5.22 MW of electrical power. The operation cost is 1342.5 €/h.

3.3 Results

3.3.1 Scenario 1

The optimisation results for Scenario 1 are shown in Figure 4 and Figure 5. In the initial state only steam turbine ST2 is ON and the operation costs are 1,183 €/h. As a consequence of the increase of the steam demand in the MP (middle pressure) main from 45 t/h to 60 t/h and in the LP (low pressure) main from 30 t/h to 60 t/h for 5 hours, Boiler 2 and turbines ST1, TP1 and TP3 have been turned on and turbine ST2 has been switched off. The reason for this result is that ST1 is slightly more efficient than ST2. Figure 4 shows these changes of the operation status in the different devices obtained by the optimisation. The cost of the operation during these hours adds up to 11,228 €. This operation state can be compared with other operation states. For example, if the steam is expanded through the letdowns instead of through the steam turbines, despite the start up cost savings, power for internal consumption should be bought from the power grid increasing the total cost to 12,828 €, which means a cost difference of 12 % compared to the optimisation.

Another duration of the new demands of 30 min has also been analysed. In this case the optimal configuration (Figure 5) shows that turbine ST1 was switched on and ST2 - off. The shorter duration of the demand increase and the smaller number of devices, involved in the status change, result in the cost having a lower value of 1,415 €. If an expansion through the letdowns is considered, the total cost would be 1,704 €, a 16% cost reduction is achieved by the optimisation.

To compare the optimal cases, the specific cost in €/h is estimated. When the new steam demands last 5 hours, the specific cost is 2,245.6 €/h, while the specific cost for a new demand duration of 30 min is 2,830 €/h. The specific cost is lower for a longer demand change because the start up cost is shared over a longer time interval. Hence the longer the duration is, the worthier is to start up a device because the start-up costs are easier to overcome. The optimisation results regarding the changes of the device statuses, the total and start-up costs, are summarised in Table 3.

3.3.2 Scenario 2

Scenario 2 analyses the operation of the utility system, when there is no steam coming from the Waste Incineration Plant. The optimisation results are shown in Figure 6 (5 h new demands duration) and Figure 7 (0.5 h new demands duration). The optimised operation for a load change during 5 h shows that Boiler 2 remains on and turbines ST1 and TP1 have been switched on, while turbine ST2 has been turned off. The costs for this scenario are 11,640 €. If an expansion through the letdowns is considered the total cost is then 12,625 €, which means a cost reduction of 8 % compared to the optimisation.

In the case of the shorter duration, the difference with the previous optimised state is that turbine TP2 remains on, instead of switching on the turbine TP1. The costs add up to 1,330.7 €. The comparison with a letdown expansion configuration gives a cost reduction of 21%, where the total cost in this case is 1,676 €.

The specific cost for a duration of 5 h is 2,328 €/h and for a duration of 30 minutes is 2,661.4 €/h. As for the other scenario, a higher specific cost is observed for a shorter duration here too.

The optimisation results concerning the changes of statuses, total and start up cost for Scenario 2 are summarised in Table 4.

4 Conclusions and future work

In this paper, an optimisation methodology has been presented for supporting operators in running utility systems in the most efficient way accounting for varying steam demands. The method presented includes the formulation of a utility system model, simulation and optimisation through mathematical programming. The tool provides the optimal utility system operating specifications when a demand change occurs for a certain expected duration. The optimal solution is found by minimising the operating costs, which also include the start-up costs of various system components.

The rigorous non-linear optimisation model is solved by a successive mixed integer linear programming (SMILP) procedure, where the non-linearities are taken into account with a rigorous simulation after each MILP optimisation step. The particular computational implementation for the presented work has been in the MATLAB environment. However, other tools could be used too – for example Thermoflow. The methodology has been applied to a real-life case study, thus demonstrating its validity and providing examples of its use. The results indicate that by accounting for start-up costs, sizable cost savings can be achieved – up to 20 %.

The optimisation model and procedure described in the current paper present the first step in developing a fully-featured framework for operational optimisation of utility systems under demand variations. The main results from this step are:

- The pattern for estimating device start-up costs has been developed
- Simple estimate models for start-up costs of steam boilers and steam turbines have been formulated

The further steps in the presented framework should investigate further model development, and improvement of the optimisation procedure, as detailed next.

4.1 Model development

In this work, simple models have been used to describe the utility system components. For instance, boilers are described using a constant-efficiency model and steam turbines using Willan's lines with fixed linear coefficients. Future implementations of the current methodology could use variable-efficiency boiler model and steam turbine performance coefficients depending on the turbine size and part-load, for example as introduced by Varbanov et al. [9]. For simplicity, the gas turbine has been assumed to work at full load with a constant exhaust temperature and mass flow. The proposed methodology can readily be extended to modelling the gas turbine part-load operation.

Furthermore, the models should include also more realistic and precise evaluation of the various cost items – besides the fuel costs, the various effluent treatments and CO₂ capture should also be accounted for [18, 19]. Considering the utility system dynamics via dynamic simulation may provide further insights into the system behaviour.

4.2 Improvements to the optimisation procedure

In the start up cost calculation, fuel mass flow (for boilers and special heat exchangers) and steam mass flow (for steam turbines and drivers) and the duration of the start-up process are used as an estimate of the start-up costs for the various equipment types. More accurate formulation of these start-up costs should be a further step towards creating a more practical methodology implementation.

Also the horizon for the optimisation has to be increased and the model should be able to optimise complete schedules for utility systems looking several periods ahead, compared with single-step optimisation, in the manner defined in [14]. Also, the variations in the process power demands as well as renewables availability should also be accounted for, thus providing a fully-fledged tool to the process operators.

One of the major challenges to achieve this lies in the appropriate introduction of the time constraints associated with the device start-ups, as they are generally quite diverse – while a gas or a steam turbine can be started in a matter of minutes up to several hours, a steam boiler start-up may need up to 24 h and longer. If certain variations in the demand and supply are

shorter, in many cases it may be more economic not to stop the devices. A further challenge is to introduce and model the “hot standby” mode for boilers.

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Appendix A. Model features

Steam turbine

The net power generated is modelled according to the Willan's line

$$W_{NET} = A \cdot m_{ST,IN} + B \quad (7)$$

The total power extracted from the steam expansion is derived taking into account the mechanical efficiency

$$W_{TOT} = \frac{W_{NET}}{\eta_M} \quad (8)$$

From the energy balance the enthalpy of the exhaust can be calculated as,

$$h_{ST,OUT} = h_{ST,IN} - \frac{W_{TOT}}{m_{ST,IN}} \quad (9)$$

Boiler

The boiler material balance is:

$$m_{BL,OUT} = m_{BL,BFW,IN} - m_{BL,BD} \quad (10)$$

To calculate the necessary fuel heat in the boiler and then the necessary fuel mass flowrate : the preheat, evaporation heat and superheat are estimated:

$$Q_{BL,PRE} = m_{BL,BFW,IN} \cdot \Delta h_{PRE} \quad (11)$$

$$Q_{BL,EVAP} = m_{BL,OUT} \cdot \Delta h_{EVAP} \quad (12)$$

$$Q_{BL,SH} = m_{BL,OUT} \cdot \Delta h_{SH} \quad (13)$$

$$Q_{BL,STEAM} = Q_{BL,PRE} + Q_{BL,EVAP} + Q_{BL,SH} \quad (14)$$

$$Q_{BL,FUEL} = \frac{Q_{BL,STEAM}}{\eta_{BL}} \quad (15)$$

$$m_{BL,FUEL} = \frac{Q_{BL,FUEL}}{NHV_{FUEL}} \quad (16)$$

Specialised Heat Exchanger

Steam Superheating

Steam coming from the incineration plant is expanded and then superheated to match the HP main conditions.

$$Q_{SH,SH} = m_{SH,ST,WIP} \cdot \Delta h_{SH} \quad (17)$$

The fuel needed for superheating is calculated,

$$Q_{FUEL,SH} = \frac{Q_{SH,SH}}{\eta_{SH}} \quad (18)$$

Water Preheating

Some boiler feed water is heated up to prespecified conditions and delivered to the incineration plant:

$$Q_{SH,PRE} = m_{SH,BFW,IN} \cdot \Delta h_{PRE} \quad (19)$$

The fuel needed for the preheating section is:

$$Q_{FUEL,PRE} = \frac{Q_{SH,PRE}}{\eta_{SH}} \quad (20)$$

Letdown

For isenthalpic valves, both material and energy balances are linear:

$$m_{LD,IN} = m_{LD,OUT} \quad (21)$$

$$h_{LD,IN} = h_{LD,OUT} \quad (22)$$

Desuperheater

Using mass balance and energy balance, the desuperheating water mass flow and then the outlet mass flow are calculated.

$$m_{DSH,IN} + m_{DSH,W} = m_{DSH,OUT} \quad (23)$$

$$m_{DSH,IN} \cdot h_{DSH,IN} + m_{DSH,W} \cdot h_{DSH,W} = m_{DSH,OUT} \cdot h_{DSH,OUT} \quad (24)$$

$$m_{DSH,W} = m_{DSH,IN} \cdot \frac{(h_{DSH,IN} - h_{DSH,OUT})}{(h_{DSH,OUT} - h_{DSH,W})} \quad (25)$$

Appendix B. Detailed case study data

General Parameters

The specifications used for the case studies are given in Table B1 and following. Some abbreviations: NG stands for natural gas, RG for residual gas, DA for deaerator and WIP for Waste Incineration Plant, have been used.

Boiler parameters

Boiler specifications are presented in Table B2. Boiler 1 (BL1) and Boiler 2 (BL2) have different capacity specifications.

Special heat exchanger parameters

In Table B3, the Specialised Heat Exchanger parameters are given. Both Specialised Heat Exchangers have the same parameters.

GT and HRSG parameters

In Table B4, HRSG parameters are specified.

Steam turbine parameters

The specifications for the steam turbines, ST1 (Steam turbine 1) and ST2 (Steam turbine 2) are provided in Table B5.

Driver parameters

The parameters for the drivers are given in Table B6. TC stands for Turbocompressor, TP1 for Turbopump 1, TP2 for Turbopump 2 and TP3 for Turbopump 3.

Pump parameters

The specifications for the pumps are provided in the Table B7.

Nomenclature

General

CRR	[-]	Condensate return rate
T_{BFW}	[°C]	Boiler feed water temperature
T_{HP}	[°C]	High pressure main temperature
P_{HP}	[bar]	High pressure main pressure
P_{MP}	[bar]	Medium pressure main pressure
P_{LP}	[bar]	Low pressure main pressure
$Price_{EXHAUST}$	[€/MWh]	Gas turbine exhaust price before supplementary firing
$Price_{FUEL}$	[€/t]	Fuel price
$Price_{NG}$	[€/t]	Natural gas price
$Price_{RG}$	[€/t]	Rest gas price
$Price_{MKW}$	[€/t]	Make up water price
$Price_{POWER}$	[€/MWh]	Power export price
$Price_{W,WIP}$	[€/t]	Price of the water turned back to the waste incineration plant
$Price_{ST,WIP}$	[€/t]	Price of the steam coming from the waste incineration plant
$STupC$	[€]	Total start up cost
$t_{NEW,DEMAND}$	[h]	New demand duration
t_{STup}	[h]	Start up duration
$y_{CURRENT}$	[-]	Unit current operating status
y_{CHANGE}	[-]	Change on the status
y_{NEW}	[-]	Unit new operating status

Boilers

η_{BL}	[-]	Boiler efficiency
-------------	-----	-------------------

$m_{BL,BFW,IN,MIN}$	[t/h]	Minimum boiler feed water inlet mass flow
$m_{BL,BFW,IN,MAX}$	[t/h]	Maximum boiler feed water inlet mass flow
$m_{BL,BFW,IN}$	[t/h]	Boiler feed water inlet mass flow
$m_{BL,FUEL}$	[t/h]	Fuel mass flow
$m_{BL,OUT}$	[t/h]	Steam outlet mass flow
$m_{STup,FUEL}$	[t/h]	Fuel mass flow used during start up of boiler or Specialised Heat Exchanger
NHV_{FUEL}	[MWh/t]	Net heating value
$STupC_{BOILER}$	[€]	Boiler start-up cost

HRSG

ΔT_{min}	[°C]	Minimum temperature difference required
Cp_{FG}	[MWh/t/°C]	Flue gas specific heat capacity
m_{FG}	[t/h]	Flue gas mass flow
$m_{HRSG,BFW,HP,MIN}$	[t/h]	Minimum Boiler Feed Water (HP-HRSG) mass flow
$m_{HRSG,BFW,HP,MAX}$	[t/h]	Maximum Boiler Feed Water (HP-HRSG) mass flow
$m_{HRSG,BFW,LP,MIN}$	[t/h]	Minimum Boiler Feed Water (LP-HRSG) mass flow
$m_{HRSG,BFW,LP,MAX}$	[t/h]	Maximum Boiler Feed Water (LP-HRSG) mass flow
$m_{HRSG,ST,HP,MIN}$	[t/h]	Minimum HP steam mass flow
$m_{HRSG,ST,HP,MAX}$	[t/h]	Maximum HP steam mass flow
$T_{FG,IN}$	[°C]	Temperature of the flue gas at the HRSG inlet

Specialised Heat Exchangers

η_{SH}	[-]	Specialised Heat Exchanger efficiency
-------------	-----	---------------------------------------

$m_{SH,ST,IN,MIN}$	[t/h]	Minimum steam inlet mass flow
$m_{SH,ST,IN,MAX}$	[t/h]	Maximum steam inlet mass flow
$m_{SH,W,IN,MIN}$	[t/h]	Minimum water inlet mass flow
$m_{SH,W,IN,MAX}$	[t/h]	Maximum water inlet mass flow

Steam turbines

A_{LP}	[MWh/t]	Slope Willan's line (second wheel)
A_{MP}	[MWh/t]	Slope Willan's line (first wheel)
B_{MP}	[MW]	Intercept Willan's line (first wheel)
B_{LP}	[MW]	Intercept Willan's line (second wheel)
η_{M1}	[-]	Efficiency of the first wheel
η_{M2}	[-]	Efficiency of the second wheel
$m_{ST,IN,MIN}$	[t/h]	Minimum inlet mass flow of steam for a steam turbine
$m_{ST,IN,MAX}$	[t/h]	Maximum inlet mass flow of steam for a steam turbine
$m_{ST,OUT1,MIN}$	[t/h]	Minimum extraction mass flow of steam for a steam turbine
$m_{ST,OUT1,MAX}$	[t/h]	Maximum extraction mass flow of steam for a steam turbine
$m_{ST,OUT2,MIN}$	[t/h]	Minimum outlet mass flow of steam for a steam turbine
$m_{ST,OUT2,MAX}$	[t/h]	Maximum outlet mass flow of steam for a steam turbine wheel of the steam turbine
$m_{STup,STEAM}$	[t/h]	Steam mass flow used during start up of steam turbines
$STupC_{ST}$	[€]	Steam turbine start up cost

Drivers

A	[MWh/t]	Slope Willan's line
B	[MW]	Intercept Willan's line
η_{DR}	[-]	Driver efficiency
$m_{DR,IN,MIN}$	[t/h]	Minimum inlet mass flow of steam for a driver
$m_{DR,IN,MAX}$	[t/h]	Maximum inlet mass flow of steam for a driver

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- Optimisation methodology for decision making on running utility systems
- Accounting for varying steam demands
- Optimal operating specifications when a demand change occurs
- Operating costs include start-up costs of boilers and other units
- Validated on a real-life case study. Up to 20 % cost savings are possible

Table 1. Possible combinations for the binary variables

$y_{CURRENT}$	y_{NEW}	y_{CHANGE}
1	0	0
0	0	0
1	1	0
0	1	1

Table 2. Steam demands for both Scenarios, (t/h)

	Current demand	New demand
HP steam demands	0	0
MP steam demands	45	60
LP steam demands	30	60
Scenario 1: Steam inlet from the Incineration Plant: 20 t/h		
Scenario 2: Steam inlet from the Incineration Plant: 0 t/h		

Table 3. Optimisation results for Scenario 1

Device	Initial state	Optimisation (new demand: 5 h)	Start-up cost (€)	Optimisation (new demand: 0.5 h)	Start-up cost (€)
Boiler 2	OFF	ON	527.54	OFF	0
Boiler 1	OFF	OFF	0	OFF	0
Steam turbine 1	OFF	ON	167.81	ON	167.81
Steam turbine 2	ON	<i>OFF</i>	0	<i>OFF</i>	0
Turbocompressor	OFF	OFF	0	OFF	0
Turbopump 1	OFF	ON	1.7880	OFF	0
Turbopump 2	OFF	OFF	0	OFF	0
Turbopump 3	OFF	ON	1.1920	OFF	0
Cost	1,183 €/h	11,228 € (2,245.6 €/h)	698.33 €	1,415 € (2830 €/h)	167.81€

Table 4. Optimisation results for Scenario 2

Device	Initial state	Optimisation (new demand: 5 h)	Start up cost (€)	Optimisation (new demand: 0.5 h)	Start up cost (€)
Boiler 2	ON	ON	0	ON	0
Boiler 1	OFF	OFF	0	OFF	0
Steam turbine 1	OFF	ON	185.73	ON	185.73
Steam turbine 2	ON	<i>OFF</i>	0	<i>OFF</i>	0
Turbocompressor	OFF	OFF	0	OFF	0
Turbopump 1	OFF	ON	5.6432	OFF	0
Turbopump 2	ON	<i>OFF</i>	0	ON	1.88
Turbopump 3	OFF	OFF	0	OFF	0
Cost	1,342.5 €/h	11,640 € (2328 €/h)	191.33 €	1,330.7 € (2661.4 €/h)	187.61 €

Table B1. General parameters

Parameter	Unit	Value
T_{BFW}	°C	105.00
T_{HP}	°C	500.00
P_{HP}	bar	70.00
P_{MP}	bar	20.00
P_{LP}	bar	4.00
P_{DA}	bar	1.30
CRR	-	0.00
NHV_{NG}	MWh/t	13.74
NHV_{RG}	MWh/t	10.42
$Price_{MKW}$	€/t	0.40
$Price_{NG}$	€/t	341.90
$Price_{RG}$	€/t	100.00
$Price_{EXHAUST}$	€/MWh	20.04
$Price_{ST,WIP}$	€/t	10.00
$Price_{W,WIP}$	€/t	0.00
$Price_{POWER}$	€/MWh	40.00

TableB2. Boiler parameters

Parameter	Unit	Value
η_{BL}	-	0.94
$m_{BL,BFW,IN,MIN}$ (BL1)	t/h	40.00
$m_{BL,BFW,IN,MAX}$ (BL1)	t/h	110.00
$m_{BL,BFW,IN,MIN}$ (BL2)	t/h	10.00
$m_{BL,BFW,IN,MAX}$ (BL2)	t/h	80.00

Table B3. Specialised Heat Exchanger parameters

Parameter	Unit	Value
η_{SH}	-	0.90
$m_{SH,ST,IN,MIN}$	t/h	20.00
$m_{SH,ST,IN,MAX}$	t/h	40.00
$m_{SH,W,IN,MIN}$	t/h	25.00
$m_{SH,W,IN,MAX}$	t/h	50.00

Table B4. GT and HRSG parameters

Parameter	Unit	Value
W_{GT}	MW	40
ΔT_{min}	$^{\circ}\text{C}$	40.00
m_{FG}	t/h	465.24
$T_{FG,IN}$	$^{\circ}\text{C}$	550.00
$m_{HRSG,ST,WIP,MIN}$	t/h	0.00
$m_{HRSG,ST,WIP,MAX}$	t/h	40.00
$m_{HRSG,ST,HP,MIN}$	t/h	55.00
$m_{HRSG,ST,HP,MAX}$	t/h	105.00
$m_{HRSG,BFW,HP,MIN}$	t/h	0.00
$m_{HRSG,BFW,HP,MAX}$	t/h	65.00

Table B5. Steam turbine parameters

Parameter	Unit	Value
η_{M1}	-	0.95
η_{M2}	-	0.95
$m_{ST,IN,MIN}$ (ST1)	t/h	20.00
$m_{ST,IN,MAX}$ (ST1)	t/h	92.00
$m_{ST,OUT1,MIN}$ (ST1)	t/h	0.00
$m_{ST,OUT1,MAX}$ (ST1)	t/h	40.00
$m_{ST,OUT2,MIN}$ (ST1)	t/h	0.00
$m_{ST,OUT2,MAX}$ (ST1)	t/h	60.00
A_{MP} (ST1)	MWh/t	0.07
B_{MP} (ST1)	MW	-1.96
A_{LP} (ST1)	MWh/t	0.10
B_{LP} (ST1)	MW	-0.12
$m_{ST,IN,MIN}$ (ST2)	t/h	25.00
$m_{ST,IN,MAX}$ (ST2)	t/h	79.00
$m_{ST,OUT1,MIN}$ (ST2)	t/h	0.00
$m_{ST,OUT1,MAX}$ (ST2)	t/h	55.00
$m_{ST,OUT2,MIN}$ (ST2)	t/h	20.00
$m_{ST,OUT2,MAX}$ (ST2)	t/h	52.00
A_{MP} (ST2)	MWh/t	0.07
B_{MP} (ST2)	MW	-0.90
A_{LP} (ST2)	MWh/t	0.10
B_{LP} (ST2)	MW	-0.38

Table B6. Driver parameters

Parameter	Unit	Value
$m_{DR_IN,MIN}$ (TC)	t/h	34.00
$m_{DR_IN,MAX}$ (TC)	t/h	36.00
A (TC)	MWh/t	0.07
B (TC)	MW	0.00
$m_{DR_IN,MIN}$ (TP1)	t/h	3.00
$m_{DR_IN,MAX}$ (TP1)	t/h	13.50
A (TP1)	MWh/t	0.09
B (TP1)	MW	-0.56
$m_{DR_IN,MIN}$ (TP2)	t/h	1.00
$m_{DR_IN,MAX}$ (TP2)	t/h	4.00
A (TP2)	MWh/t	0.06
B (TP2)	MW	-0.10
$m_{DR_IN,MIN}$ (TP3)	t/h	2.00
$m_{DR_IN,MAX}$ (TP3)	t/h	10.00
A (TP3)	MWh/t	0.09
B (TP3)	MW	-0.56

Table B7. Pump parameters

Parameter	Unit	Value
ΔP_{PIPES}	bar	2.00
ρ_{WATER}	kg / m^3	1000.00

Table 1. Possible combinations for the binary variables

$y_{CURRENT}$	y_{NEW}	y_{CHANGE}
1	0	0
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Table 2. Steam demands for both Scenarios, (t/h)

	Current demand	New demand
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Device	Initial state	Optimisation (new demand: 5 h)	Start- up cost (€)	Optimisation (new demand: 0.5 h)	Start-up cost (€)
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Steam turbine 2	ON	<i>OFF</i>	0	<i>OFF</i>	0
Turbocompressor	OFF	OFF	0	OFF	0
Turbopump 1	OFF	ON	1.7880	OFF	0
Turbopump 2	OFF	OFF	0	OFF	0
Turbopump 3	OFF	ON	1.1920	OFF	0
Cost	1,183 €/h	11,228 € (2,245.6 €/h)	698.33 €	1,415 € (2830 €/h)	167.81€

Table 4. Optimisation results for Scenario 2

Device	Initial state	Optimisation (new demand: 5 h)	Start up cost (€)	Optimisation (new demand: 0.5 h)	Start up cost (€)
Boiler 2	ON	ON	0	ON	0
Boiler 1	OFF	OFF	0	OFF	0
Steam turbine 1	OFF	ON	185.73	ON	185.73
Steam turbine 2	ON	<i>OFF</i>	0	<i>OFF</i>	0
Turbocompress	OFF	OFF	0	OFF	0
or					
Turbopump 1	OFF	ON	5.6432	OFF	0
Turbopump 2	ON	<i>OFF</i>	0	ON	1.88
Turbopump 3	OFF	OFF	0	OFF	0
Cost	1,342.5 €/h	11,640 € (2328 €/h)	191.33 €	1,330.7 € (2661.4 €/h)	187.61 €

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P_{LP}	bar	4.00
P_{DA}	bar	1.30
CRR	-	0.00
NHV_{NG}	MWh/t	13.74
NHV_{RG}	MWh/t	10.42
$Price_{MKW}$	€/t	0.40
$Price_{NG}$	€/t	341.90
$Price_{RG}$	€/t	100.00
$Price_{EXHAUST}$	€/MWh	20.04
$Price_{ST,WIP}$	€/t	10.00
$Price_{W,WIP}$	€/t	0.00
$Price_{POWER}$	€/MWh	40.00

TableB2. Boiler parameters

Parameter	Unit	Value
η_{BL}	-	0.94
$m_{BL,BFW,IN,MIN}$ (BL1)	t/h	40.00
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$m_{BL,BFW,IN,MIN}$ (BL2)	t/h	10.00
$m_{BL,BFW,IN,MAX}$ (BL2)	t/h	80.00

Table B3. Specialised Heat Exchanger parameters

Parameter	Unit	Value
η_{SH}	-	0.90
$m_{SH,ST,IN,MIN}$	t/h	20.00
$m_{SH,ST,IN,MAX}$	t/h	40.00
$m_{SH,W,IN,MIN}$	t/h	25.00
$m_{SH,W,IN,MAX}$	t/h	50.00

Table B4. GT and HRSG parameters

Parameter	Unit	Value
W_{GT}	MW	40
ΔT_{min}	$^{\circ}\text{C}$	40.00
m_{FG}	t/h	465.24
$T_{FG,IN}$	$^{\circ}\text{C}$	550.00
$m_{HRSG,ST,WIP,MIN}$	t/h	0.00
$m_{HRSG,ST,WIP,MAX}$	t/h	40.00
$m_{HRSG,ST,HP,MIN}$	t/h	55.00
$m_{HRSG,ST,HP,MAX}$	t/h	105.00
$m_{HRSG,BFW,HP,MIN}$	t/h	0.00
$m_{HRSG,BFW,HP,MAX}$	t/h	65.00

Table B5. Steam turbine parameters

Parameter	Unit	Value
η_{M1}	-	0.95
η_{M2}	-	0.95
$m_{ST,IN,MIN}$ (ST1)	t/h	20.00
$m_{ST,IN,MAX}$ (ST1)	t/h	92.00
$m_{ST,OUT1,MIN}$ (ST1)	t/h	0.00
$m_{ST,OUT1,MAX}$ (ST1)	t/h	40.00
$m_{ST,OUT2,MIN}$ (ST1)	t/h	0.00
$m_{ST,OUT2,MAX}$ (ST1)	t/h	60.00
A_{MP} (ST1)	MWh/t	0.07
B_{MP} (ST1)	MW	-1.96
A_{LP} (ST1)	MWh/t	0.10
B_{LP} (ST1)	MW	-0.12
$m_{ST,IN,MIN}$ (ST2)	t/h	25.00
$m_{ST,IN,MAX}$ (ST2)	t/h	79.00
$m_{ST,OUT1,MIN}$ (ST2)	t/h	0.00
$m_{ST,OUT1,MAX}$ (ST2)	t/h	55.00
$m_{ST,OUT2,MIN}$ (ST2)	t/h	20.00
$m_{ST,OUT2,MAX}$ (ST2)	t/h	52.00
A_{MP} (ST2)	MWh/t	0.07
B_{MP} (ST2)	MW	-0.90
A_{LP} (ST2)	MWh/t	0.10
B_{LP} (ST2)	MW	-0.38

Table B6. Driver parameters

Parameter	Unit	Value
$m_{DR_IN,MIN}$ (TC)	t/h	34.00
$m_{DR_IN,MAX}$ (TC)	t/h	36.00
A (TC)	MWh/t	0.07
B (TC)	MW	0.00
$m_{DR_IN,MIN}$ (TP1)	t/h	3.00
$m_{DR_IN,MAX}$ (TP1)	t/h	13.50
A (TP1)	MWh/t	0.09
B (TP1)	MW	-0.56
$m_{DR_IN,MIN}$ (TP2)	t/h	1.00
$m_{DR_IN,MAX}$ (TP2)	t/h	4.00
A (TP2)	MWh/t	0.06
B (TP2)	MW	-0.10
$m_{DR_IN,MIN}$ (TP3)	t/h	2.00
$m_{DR_IN,MAX}$ (TP3)	t/h	10.00
A (TP3)	MWh/t	0.09
B (TP3)	MW	-0.56

Table B7. Pump parameters

Parameter	Unit	Value
ΔP_{PIPES}	bar	2.00
ρ_{WATER}	kg / m^3	1000.00

Figure 1. Utility system flowsheet

Figure 2. Initial State Scenario 1

Figure 4. Optimal operation Scenario 1 (5 h)

Figure 5. Optimal operation for Scenario 1 (30 min)

Figure 6. Optimal configuration Scenario 2 (5 h)

Figure 7. Optimal configuration Scenario 2 (30 min)