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## Abstract

This task concerns with the development of a novel conceptual design method from energy-intensive process units. It is the sequential studies of Deliverable 1.1.

A utility system would be systematically evaluated for site-wide efficiency of energy generation, distribution, and utilization. Graphical manipulation and interpretation of energy system are carried out to synthesize the entire energy system, subject to energy recovery of processes, system targets, and combined heat and power generation.

The graphical method developed in Deliverable 1.1 - the steam cascade curves- enabled the integration of process heating loads, process indirect heat recovery, and utility system targets, and revealed the cogeneration improvement both through steam mains selection and process modification. However, the targets obtained from this method would not be achieved in practical application due to the assumption that steam mains were at saturation temperatures. Other graphical methodologies have this problem either.

This work has developed a new graphical methodology with practical considerations of boiler feedwater heating and steam superheating involving in steam generation, steam desuperheating for process heating, and condensate heat recovery. It overcomes the shortcoming of previous methods just allowing for steam at saturation temperature.

Steam composite profiles are constructed firstly in this work, containing issues of boiler feedwater preheating, steam generation at saturation temperature, steam superheating and desuperheating.

A utility energy targeting method is developed in this report, allowing for boiler feedwater heating/condensate cooling and steam superheating/desuperheating in steam generation and utilization, to address targets of VHP steam demand from fuel combustion, heat indirect recovery from processes through steam mains, and process steam generation and usage loads. Processes integration with utility systems can be analyzed quantitatively base on this proposed method to give the insights of their interaction.

A new energy targeting model has also been developed in this report with more practical constraints. Considerations of steam main superheat temperature and exhaust dryness from steam turbines lead to more realistic power estimation of the utility system.

The proposed graphical method and new power targeting model can be implemented using the software ‘EFENIS-Site’ developed by Centre for Process Integration (CPI) in the University of Manchester.

The systematic energy and power targeting methods will be evaluated on selected sites from industrial partners and used in the demonstration work packages.

# Contents

# 1 Introduction

Utility systems provide heat and power to various site processes. Utility system analysis includes fuel combustion and emissions, boiler feed water treatment, steam mains number and pressures, steam generation and distribution, power generation, steam balance, and energy audits.

A site utility system is complex with many potential interactions, and its analysis must include site processes as well as utility system itself. The performance of the system is mainly determined by system configuration and equipment performances, steam cascade at different steam mains, and steam/power generation. Thus, a synthetical methodology is required for total energy and power system design and optimization.

The graphical method developed in Deliverable 1.1 - the steam cascade curves, and other graphical methods did not account for some practical constraints, such as boiler feedwater (BFW) preheating and steam superheating for steam generation, steam desuperheating for process heating. The targets based on these methods would be difficult to be achieved in practice.

This work overcomes problems in the previous graphical methods, which did not account for heat loads for BFW preheating and steam superheating, etc. The graphical methodology is developed containing boiler feedwater heating/condensate cooling, steam superheating, and steam desuperheating, to provide more practical utility targets.

In this report, steam composite profiles are proposed firstly, which are constructed with steam superheating/desuperheating included. The heat for boiler feedwater (BFW) preheating is also included in the steam profiles.

Site profiles and site composite curves are constructed with practical constraints of these practical considerations to provide realistic utility energy targets.

A new power targeting model is also developed in this work for power estimation. Practical limits of steam main superheat temperatures and the dryness of exhaust from steam turbines lead to more realistic power target in the system. Power estimation by the new model is integrated with the proposed graphical energy targeting method.

Comparisons of utility energy and power targets based on different methodologies illustrate the effectiveness of the proposed energy and power targeting methods.

A software has been developed to implement the proposed energy and power targeting methods by the Centre for Process Integration (CPI) in the University of Manchester.

## 2 Previous energy and power targeting models

Utility systems are designed to satisfy process demands. Power and energy targets are important issues of the utility system performance.

Graphical methods based on the pinch analysis approach have been developed as a visualization tool for utility system conceptual design and optimization. Utility energy targets of site VHP steam demand and site steam saving due to process indirect heat recovery, and power target by steam expansion in steam turbines, can be addressed using graphical methods.

Figure 1 shows the basic synthesis procedure for total site energy and power targeting.

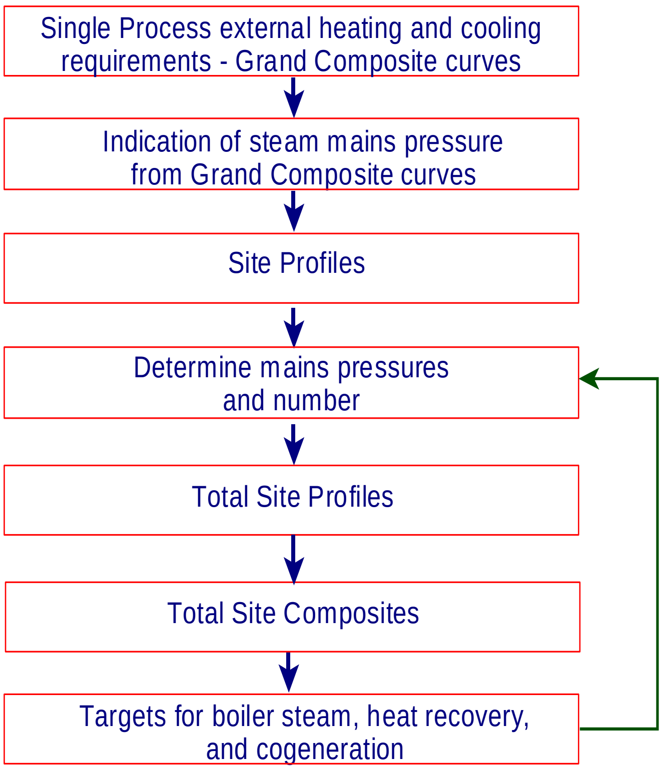


**Figure 1 Synthesis Procedure**

## 2.1 Energy targets

Site source-sink profiles (Dhole and Linnhoff, 1993) of the overall site utility system provide process quantified heating and cooling demands graphically, and implemented process and utility system integration. Site Composite Curves (Linnhoff et al. 1993, 1994; Klemes et al., 1997) address heat recovery among different processes through steam mains. The energy targets of the minimum site VHP steam demand and cooling demand for the utility system are obtained in the Site Composite Curves. Site utility grand composite curves (Raissi, 1994) allow visualization of steam cascade in the utility system, and shaft power potential by steam expansion in steam turbines can be calculated based on the T-H model.

A new graphical approach - the steam cascade curves - was developed in Deliverable 1.1 for utility energy and power targeting simultaneously. The effect of steam mains selection and process variation on cogeneration improvements can be addressed in the curves for processes and utility systems integration.

Other graphical methods have extended the pinch analysis for site-wide heat and power integration. Bandyopadhyay et al. (2011) proposed site level grand composite curve to estimate the cogeneration potential. Varbanov and Klemes (2010) set time slices into site profiles and site composite curves to integrate renewables into the corresponding total site CHP energy systems. Wan Alwi and Manan (2010) introduced a stream temperature and enthalpy plot technique to represent continuous individual hot and cold streams. Varbanov et al. (2012) specified process specific minimum temperature difference to obtain more realistic utility and heat recovery targets. Abbood et al.(2011) utilized a grid diagram table and chemical pinch analysis for the synthesis of chemical reactors or separation trains for a whole plant. Makwana et al. (1998), Wan Alwi et al. (2012) extended the application of total site targeting methodology in hybrid renewable energy system. Hackl et al.(2011) investigated the opportunities to deliver waste heat from one process to another using total site analysis.

However, the utility targets are achieved by all these graphical methods only if steam mains are at saturation temperatures. This is not realistic. In practice, steam is generated from boiler feedwater (BFW) to superheat temperature. These graphical methods can give a target difficult to achieve because it may need many sources of heat for BFW to achieve target.

## 2.2 Power targets

Power target implies the power potential by steam expansion in the system. Raissi (1994) investigated the temperature enthalpy (T-H) model to provide a graphical representation for power estimation. As shown in Figure 2, the power is approximately proportional to the area in the T-H chart with the assumption of the superheat removal of inlet steam and outlet steam to steam turbines. The same conversion coefficient for every steam expansion zone would cause errors for power estimation.

$$W=c*Q*(T_{in}- T_{out}) \quad (1)$$

Where

W = the shaft power generation by the steam expansion, kW

c = the power conversion coefficient based on concept of T-H model, $°C^{-1}$

Q = the heat duty of the inlet steam of the steam turbine, kW

$T_{in}$ = saturation temperature of inlet steam of the steam turbine, °C

$T_{out}$ = saturation temperature of outlet steam of the steam turbine, °C

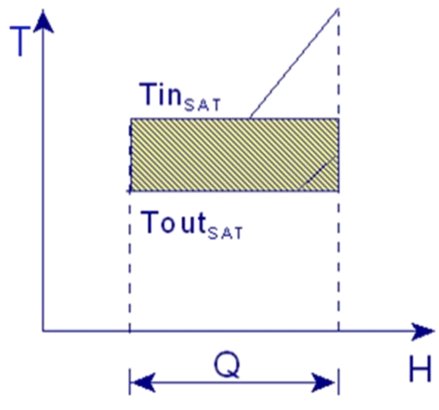


**Figure 2 T- H Model**

Other models were developed principally based on the exergy models (Dhole & Linnhoff, 1992; Raissi, 1994; Marechal & Kalitventzeff, 2007) for power estimation. Varbanov et al. (2004) and Aguilar et al. (2007) developed an improved turbine hardware model (THM). These models had limited accuracy due to the inbuilt assumption that coefficients in the models were determined only by inlet and exhaust steam saturation temperature across a turbine.

In addition, power generation was obtained by these methods not allowing for steam heads variations. In practice, power generation interacts with steam mains and steam cascade in the system. The correlation with power generation and steam cascade would be involved in a power targeting model development.

## 2.3 Practical considerations in energy and power targeting

The previous methods for energy targeting did not allow for some practical considerations such as BFW preheating and steam superheating during steam generation, that means power and energy targets obtained by previous methods are difficult to achieve because sources of heat are needed for BFW to saturation temperature and steam superheating.

The heat for BFW preheating, water vaporization at saturation temperature, and steam superheating can be identified from T-H chart and T-s chart.

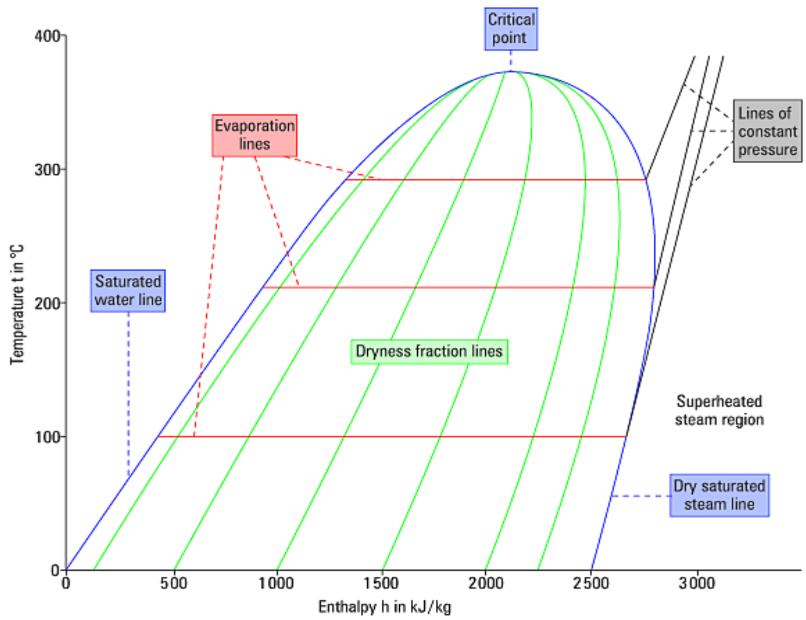


**Figure 3 Steam T-H Chart**

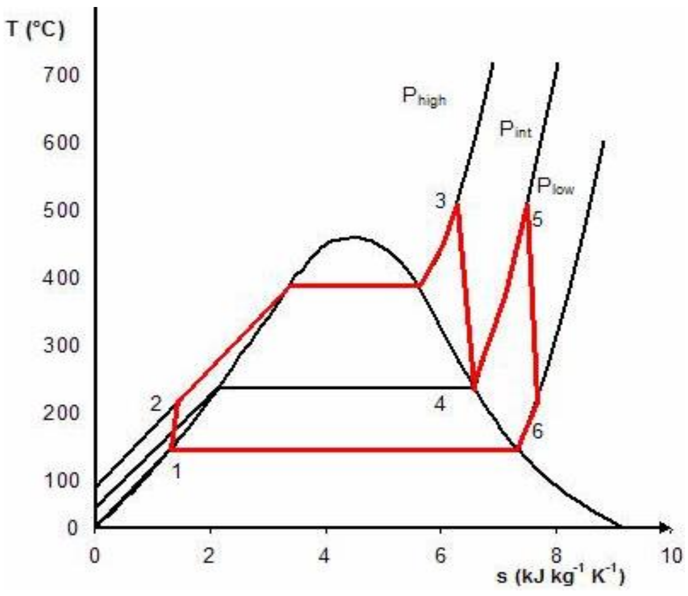


**Figure 4 Steam T-s Chart**

From Figure 3 and 4, the heat load for VHP steam superheating from 311 °C (VHP saturation temperature at 110bar) to 550 °C (superheat temperature) is almost same with the heat for steam vaporization at the saturation temperature (311 °C, 110bar). Obviously, BFW preheating and steam superheating should be included in graphical methods to address realistic steam generation target.

Steam normally is desuperheated to saturate temperature instead of superheated steam for process heating. There are benefits for desuperheated steam for process heating. Once the superheated steam is cooled to saturation temperature, the heat transfer coefficient increases dramatically, and the temperature at which the steam condenses back into water is constant. These greatly assist accurate sizing and control of heat transfer equipment. Saturated steam leads to high heat transfer coefficients, smaller and cheaper heat exchangers, and less damage for sensitive process fluid at saturation temperature.

Therefore, steam desuperheating is an important issue for steam usage targeting.

Heat recovery of the condensate from steam usage is an option for more steam generation for process heating and power generation. This is also a practical consideration, and should be included in the graphical method.

A power targeting model should be developed with practical constraints consideration. Steam expansion in steam turbines not only generates power, but also changes steam mains temperature and steam cascade. In practice, there are limits for steam main superheat, i.e., the maximum VHP steam temperature is 600°C, and the minimum LP superheat is 20 °C. They are included in the mode development.

# 3 A graphical methodology development for site energy targeting

A graphical methodology has been developed for more realistic graphical presentation of the steam system allowing for boiler feed water preheating and steam superheating in steam generation, steam desuperheating for process heating, and condensate heating recovery. There are conceptual insights retained in the graphical method.

## 3.1 New steam composite profiles

Figure 5 is the new steam composite curves including boiler feedwater preheating (BFW), steam generation at saturation temperature (SAT), and steam superheating (SH) in steam generation. It is the basis of graphical method development for energy targeting.

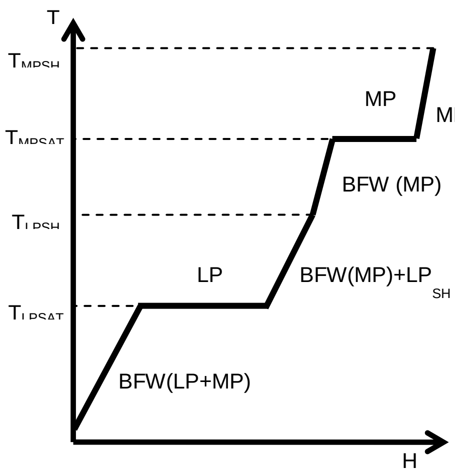


**Figure 5 New Steam Composite Curves**

### 3.2 Influences of practical considerations on site profiles

Figure 6 and 7 are site source-sink profiles bases on new steam composite curves. The site source profile provides the target of steam generation from BFW to the temperature of superheating. Steam usage from the superheat temperature to saturated condensate is addressed in the site sink profile.

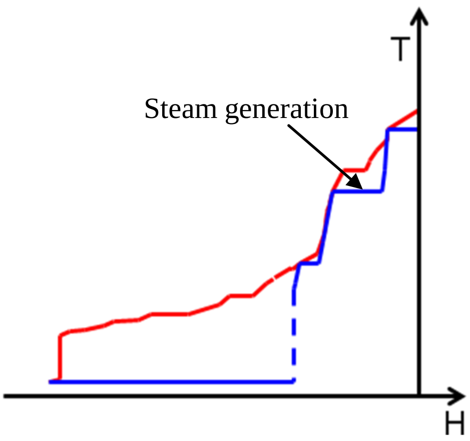


**Figure 6 Site Source Profile**

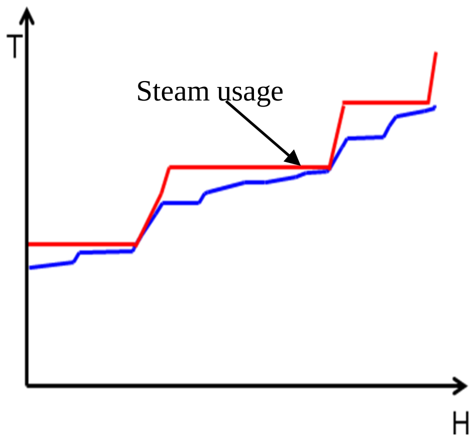


**Figure 7 Site Sink Profile**

#### 3.2.1 BFW preheating

BFW preheating is the important issue in the source profile for steam generation targeting.

The high temperature heat from processes for BFW preheating normally is not economic. Instead of preheating BFW, additional superheated steam could be generated. BFW can be preheated by process hot streams or lower pressure steam. It should be added to site sink profile as process heating stream.

Figure 8 addresses the target of steam generation from BFW at saturated temperature to the superheating temperature in the site source profile.

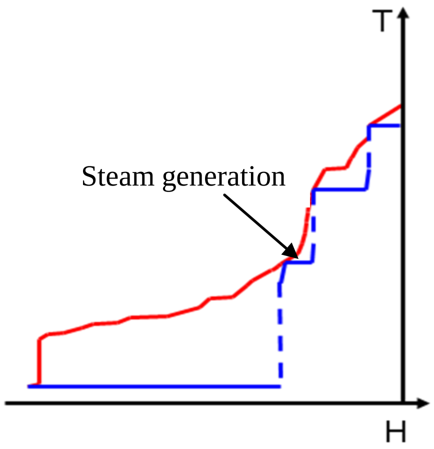


**Figure 8  Site Source Profile and Target of Steam Generation**

### 3.2.2 Steam desuperheating

Normally, actual steam mains are superheated, but steam supplied to the process is desuperheated.

Figure 9 shows the steam desuperheating flowsheet.

Figure 10 shows the site sink profile and the target of desuperheated steam usage for process heating.

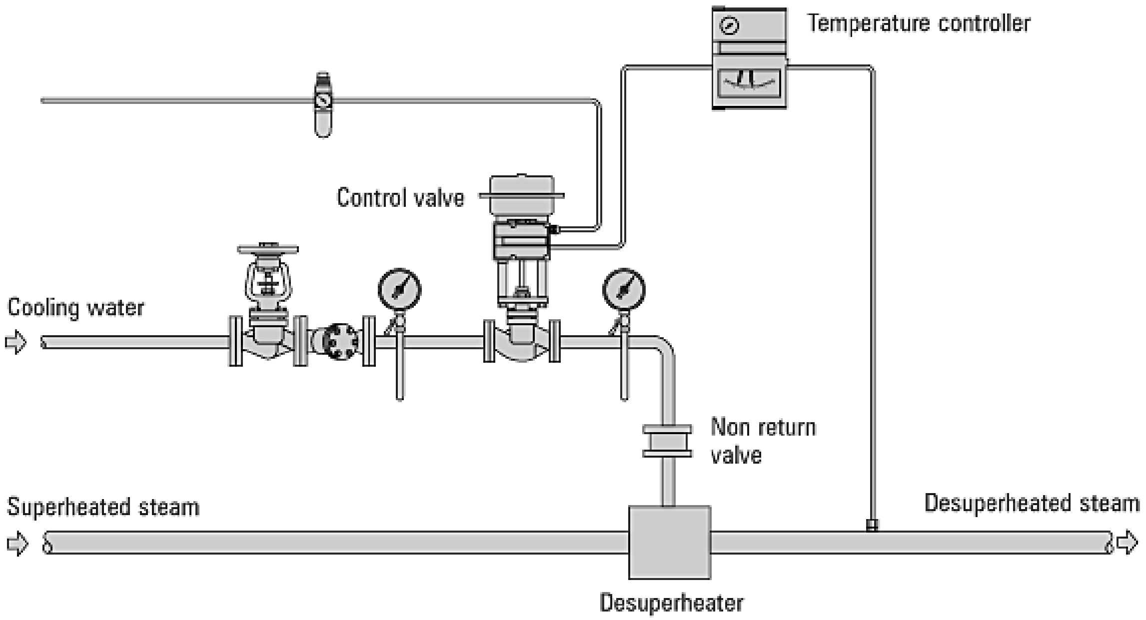


**Figure 9 Steam Desuperheating Flowsheet**

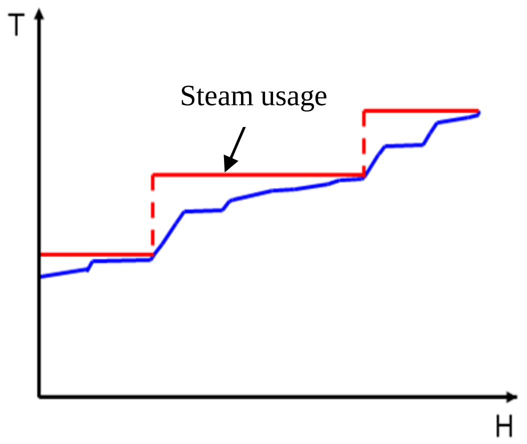


**Figure 10 Sink Profile and Target of Steam usage with Steam Desuperheating**

The site sink profile with desuperheating is similar with the previous profiles without desuperheating, but the steam flowrate is different from previous target due to the boiler feedwater added to the superheated steam.

### 3.2.3 Condensate heat recovery

Condensate heat recovery to generate more steam for process heating can reduce boiler load. Flash steam recovery is an alternative for condensate heat recovery, which can also reduce the boiler load. Figure 11 shows the site sink profile with condensate heat recovery.

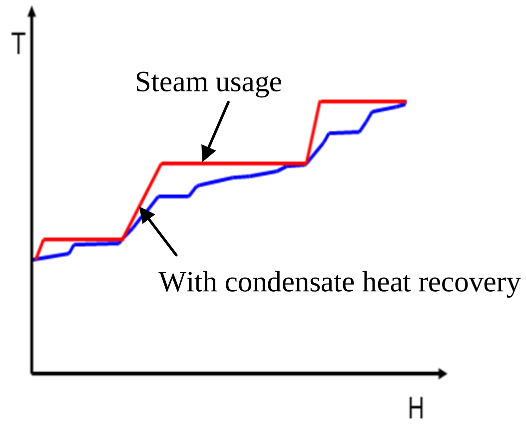


**Figure 11 Site Sink Profile and Steam Usage with Condensate Heat Recovery.**

### 3.3 Realistic energy targets

As shown in Figure 8 and Figure 10, the targets of steam generation and steam usage are addressed in the site source-sink profiles. These targets are more realistic to be achieved in practice.

The heat recovery from processes through steam mains implies site VHP steam saving. Site composite curves, shown in Figure 12, can provide the target of site VHP steam from fuel combustion and VHP saving from process indirect heat recovery.

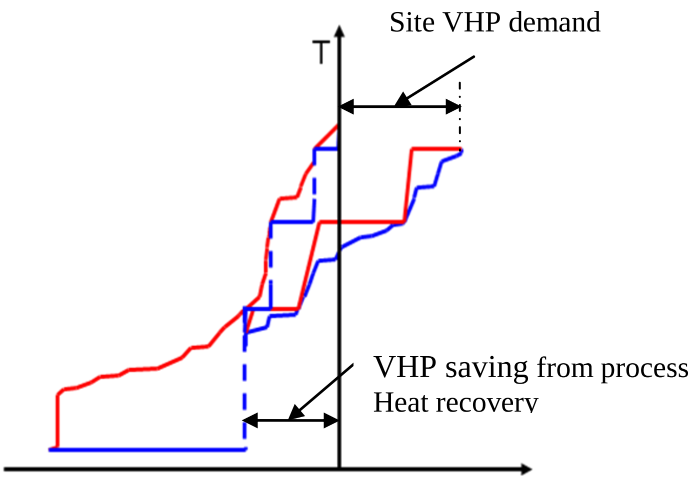


**Figure 12 Site Composite Curves and Target of Site VHP Demand**

## 4 A new power targeting method development

Power generation through steam expansion in steam turbines interacts with steam systems in terms of steam main temperature variations and steam cascade changes.

### 4.1 A new power model

A new power model is developed based on simulating a steam turbine at calculated steam mains conditions with practical constraints.

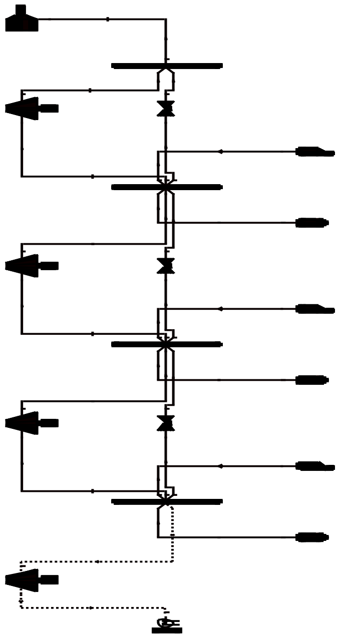

**Figure 13 Site utility System Diagram**

Figure 13 is the utility system diagram. Power generation by steam turbines is estimated by the isentropic efficiency model, shown in Equation (2). For different expansion zones, the turbine efficiency is different.

$$\eta = (H_1 - H_2) / (H_1 - H_{isentropic}) \quad (2)$$

Where

$\eta$ = steam turbine efficiency

$H_1$ = the enthalpy of turbine inlet steam, MW

$H_2$ = the enthalpy of turbine practical exhaust, MW

$H_{isenrropic}$ = the enthalpy of turbine exhaust by isentropic expansion, MW

The power target is calculated with constraints for the minimum main superheating temperature and the minimum dryness fraction exiting steam turbines. Normally, the dryness of the exhaust from the condensing turbine is required larger than 0.9, and the minimum LP superheat is 20 °C.

Based on the power targeting model, boiler flow is calculated to satisfy process steam requirements. Boiler steam temperature and boiler flow determine intermediate steam main temperatures at specified steam main pressures, which are key parameters for power generation in turbines.

Figures 14 illustrates the relationship between the boiler steam temperature and boiler steam flowrate. Figure15 implies the relationship between the boiler steam temperature and power generation potential. These figures indicate the expected trend of rising stream flowrate and reduced power production as boiler steam temperature decreases for a special case. There is a critical limit (420 °C) in this case. Below this value, some steam turbines are bypassed, and there is a large drop in power production.

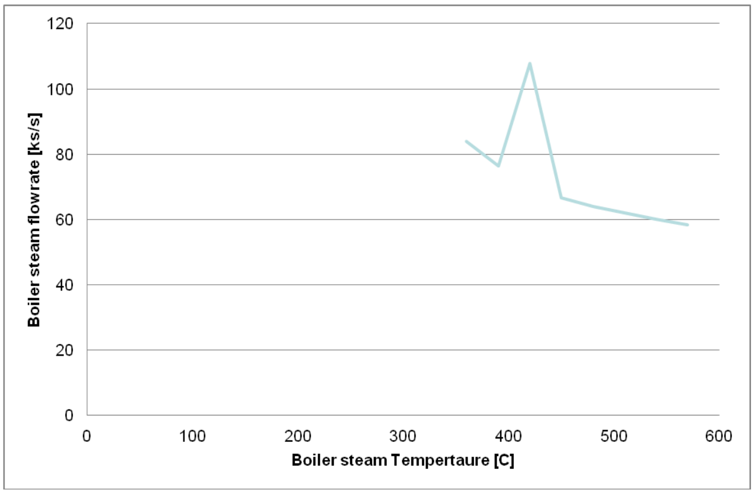


**Figure 14 Relationship between Boiler Steam Temperature and Boiler Rate**

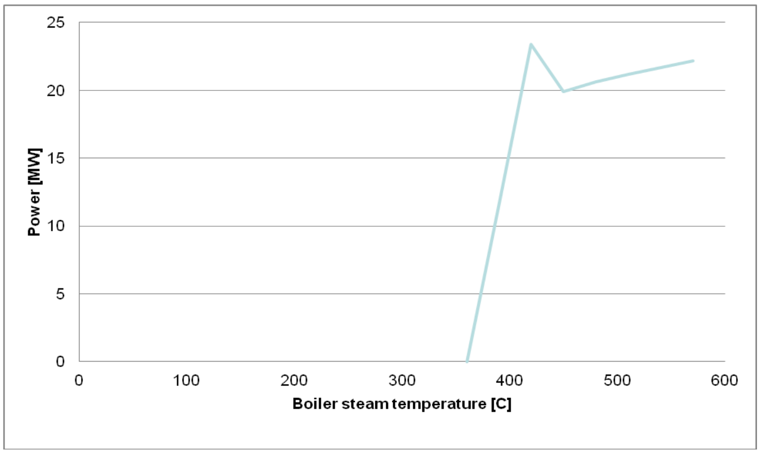


**Figure15 Relationship between Boiler Steam Temperature and Power Estimation**

There is integration between the power targeting model with graphical energy targeting method. In the power model, process heating loads and steam generation potential by process indirect heat recovery vary with steam main temperatures. They are obtained by site sink-source profiles.

### 4.2 Power and energy target comparisons based on different methods

Both energy and power targets are compared based on different methodologies to illustrate the effectiveness of the new energy and power targeting methods.

The boiler VHP target is compared for the same process utility demands in Table 1. The reason that boiler VHP target obtained by the new model is larger than that by the previous methodology is that BFW preheating and steam superheating consume extra heat from boiler VHP originally.

Table 2 lists the power targets for the same steam loads by different methods. The power target based on the new model is more realistic.

**Table 1 The Energy Power Target Comparison**

| Target | Previous methodology* | New model including BFW/SH ** |
|---|---|---|
| Boiler VHP (MW) | 85 | 108 |
| Power (MW) | 16.6 | 22.2 |

* Previous methodology: Original model not including BFW/ SH

** New model including BFW/SH: New model proposed in the work

**Table 2 The Energy Power Target Comparison**

| Target | Previous methodology* | New power targeting model** |
|---|---|---|
| Boiler VHP (MW) | 85 | 85 |
| Power (MW) | 16.6 | 13.9 |

* Previous methodology: Original model not including BFW/ SH

** New power targeting: New model proposed in the work

### 4.3 Processes integration with utility systems

Process and utility system integration and optimization is a trade-off between system power generation and site fuel consumption.

Measures for cogeneration improvements can be taken through steam mains selection and processes modification. Steam mains (number, pressure, temperature) are optimized to decrease fuel consumption or increase power generation. If a new steam main is introduced at the site pinch, the site pinch is relocated, and more site steam would be saved, implying less utility VHP steam target. If a new steam main is introduced away from the site pinch, there is no change of the site pinch, site steam saving, and site steam target. However, power generation is increased.

Variations of process operation affect the utility performance at site levels following '+/- principle'.

## 5 Software development

The software 'EFENIS-Site' has been developed to implement the new graphical energy targeting method.

Power generation potential from steam expansion can also be estimated by the software with practical constraints.

Processes integration with utility systems can be analyzed using the software.

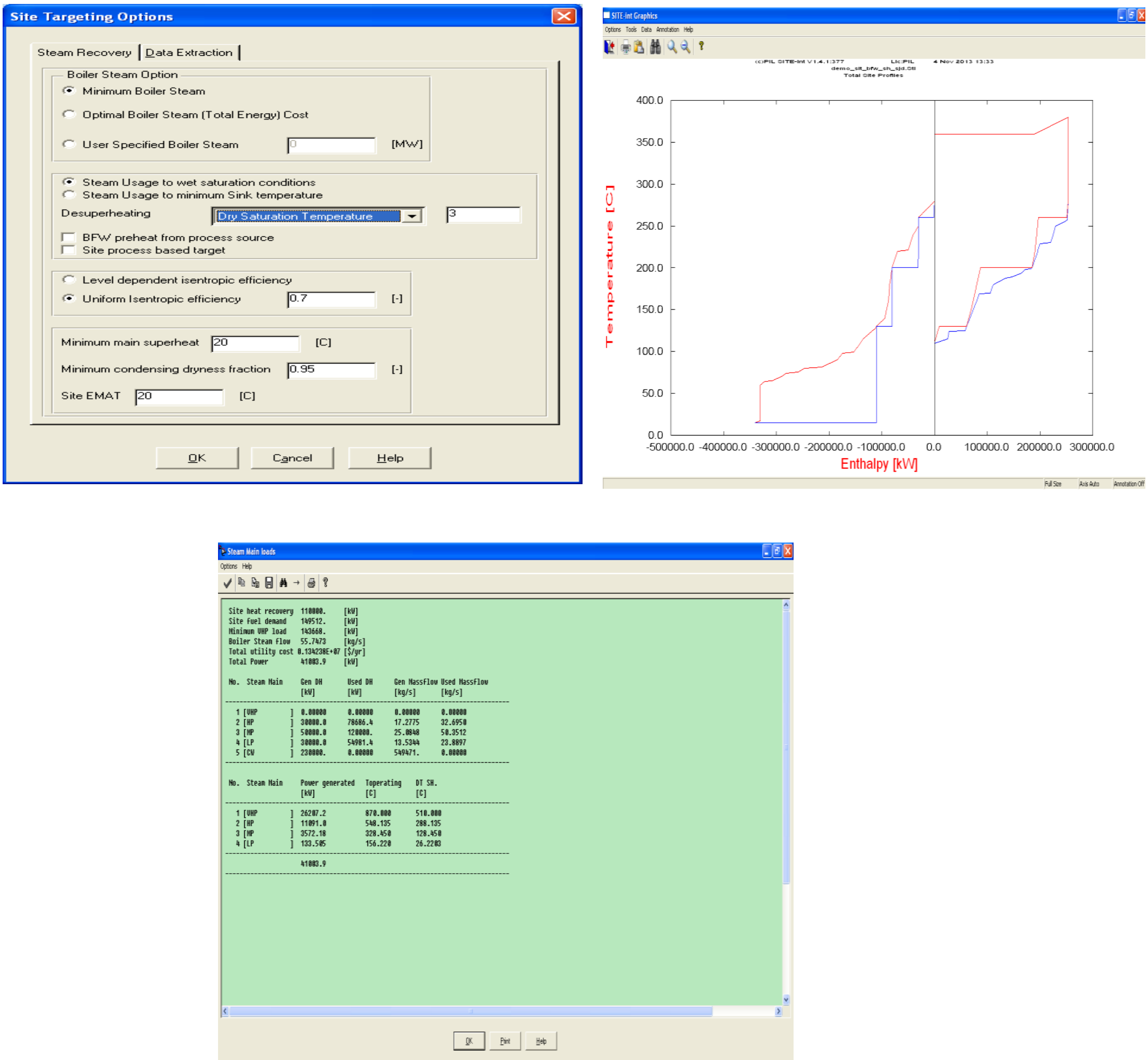


**Figure 16 Site Energy Targets Calculation using Software ‘EFENIS-Site’**

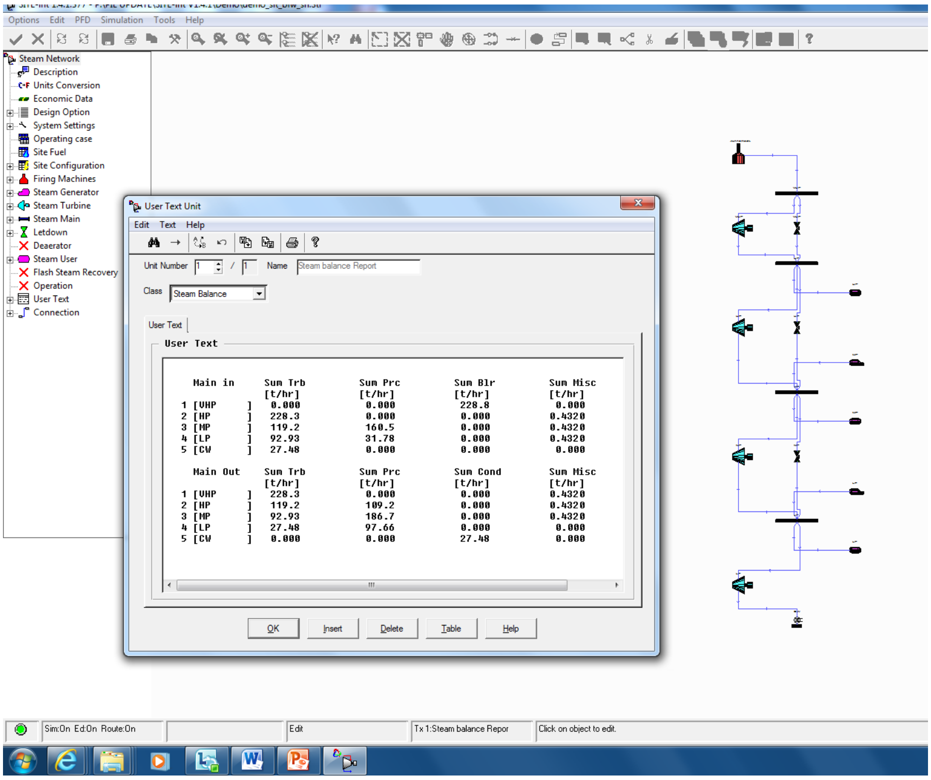


**Figure 17 Site Power Target Estimation using Software 'EFENIS-Site'**

# 6 Future work

New steam composite profiles are proposed firstly allowing for BFW preheating, steam superheating, and steam desuperheating. A graphical method considering practical constraints of BFW preheating, steam superheating/ desuperheating, and condensate recovery has been developed in this work to achieve more realistic utility energy targets.

A new power generation method has been developed based on the steam turbine isentropic efficiency model, and allows practical limits on steam main superheat temperature and exhaust dryness of steam turbines to be included. The new power model can capture the effect of the intermediate steam main operating conditions on power estimation.

The software has been developed to implement the proposed energy and power targeting methods by the Centre for Process Integration (CPI) in the University of Manchester.

The developed power and energy targeting methods can be used for utility system conceptual design and optimization, and will be evaluated on selected sites from industrial partners and used in the demonstration work packages.

In the future, more practical factors would be involved in the system design and optimization. For example, uncertainty factors such as utility price fluctuation and product demand variations lead to the optimization under uncertainty.

# References

Abbood N, Manan ZA, Wan Alwi SR. A combined numerical and visualization tool for utility targeting and heat exchanger network retrofitting. Journal of Cleaner Production 2011; 23:1-7.

Botros BB, Brisson JG. Targeting the optimum steam system for power generation with increased flexibility in the steam power island design. Energy 2011; 36(8):4625- 4632.

D.A. Harell, Resource Conservation and Allocation via Process Integration, Ph.D. thesis, Texas A&M University, 2004.

Dhole VR, Linnhoff B., 1993, Total site targets for fuel, co-generation, emissions and cooling. Computers & Chemical Engineering, 17(Suppl.):101-109.

F. Marechal, B. Kalitventzeff, Identification of the optimal pressure levels in steam networks using integrated combined heat and power method, Chemical Engineering Science 52 (1997) 2977-2989.

Hackl R, Andersson E, Harvey S, 2010,Targeting for Energy Efficiency and Improved Energy Collaboration Between Different Companies Using Total Site Analysis (TSA). Chemical Engineering Transactions, 21:301-306.

Hackl R, Andersson E, Harvey S., 2011, Targeting for energy efficiency and improved energy collaboration between different companies using total site analysis (TSA), Energy, 36(8):4609-4615.

Klemeš J, Dhole VR, Raissi K, Perry SJ, Puigjaner L. Targeting and design methodology for reduction of fuel, power and $CO_2$ on total sites. Applied Thermal Engineering 1997; 7: 993-1003.

K. Raissi, Total Site Integration, Ph.D. Thesis, UMIST, Manchester, UK, 1994.

Linnhoff B, Townsend DW, Boland D, Hewitt GF, Thomas BEA, Guy AR, 1982, A user guide on process integration for the efficient use of energy. Rugby, UK:Inst Chem Eng [last updated edition 1994].

Makwana Y, Smith R, Zhu XX. A novel approach for retrofit and operation management of existing total sites. Computer Chemical Engineering 1998; 22 (Suppl.): 793-796.

O. Aguilar, S.J. Perry, J.-K. Kim, R. Smith, Design and optimization of flexible utility systems subject to variable conditions, Part 1: Modelling Framework, Chem. Eng. Res. Des. 85 (2007) 1136-1148.

Perry S, Klemeš J, Bulatov I., 2008, Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors. Energy, 33: 1489-1497.

Raissi K. Total site integration. PhD Thesis, UMIST, UK; 1994.

Smith, R., 2005, Chemical Process Design and Integration. John Wiley & Sons Ltd, Chichester, England.

Varbanov P, Klemeš J. Total sites integrating renewables with extended heat transfer and recovery. Heat Transfer Engineering 2010; 31(9):733-741.

Varbanov P, Fodor Z, Klemeš J. Total Site targeting with process specific minimum temperature difference (ΔTmin). Energy 2012; 44 (1): 20-28.

Wan Alwi SR, Mohammad Rozali NE, Abdul-Manan Z, Klemeš J. A process integration targeting method for hybrid power systems. Energy 2012; 44(1): 6-10.