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ORIGINAL PAPER

Graphical cogeneration analysis for site utility systems

Li Sun · Steve Doyle · Robin Smith

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Abstract It is necessary to systematically evaluate site-wide power and heat generation, distribution, and utilization. A new graphical approach based on a Site Grand Composite Curve (SGCC) to targeting cogeneration in site utility systems is proposed to extend Pinch Analysis. The SGCC presents quantitative and visual process targets of heating and cooling requirements, site utility system targets for system steam generation and potential shaft power by steam expansion and condensation. Process indirect heat recovery by intermediate steam levels that can reduce fuel consumption is analyzed readily in the approach. The steam cascade in the SGCC clarifies the Total Site Pinch and site targets of utility very high pressure steam demand and site steam saving. This graphical analysis presents greater clarity for the quantitative interaction between processes and utility system targets than previous approaches. The influence of process variation and steam mains selection on cogeneration improvements is explored much clearer in this straightforward method.

Keywords Site Grand Composite Curve · Site targeting · Steam cascade · Cogeneration

Abbreviations

c	The power conversion coefficient based on the *T–H* model (°C^{-1})
C_m	Process cooling requirement (MW)
g	Steam generation from process heat recovery (MW)
Q_{in}	The heat duty of inlet steam of the steam turbine (MW)
Q_{VHP}	Utility VHP steam target (MW)
$Q_{VHPsave}$	Site VHP steam saving due to process indirect heat recovery through steam mains (MW)
T_{in}	Steam turbine inlet steam temperature (°C)
T_{out}	Steam turbine exhaust temperature (°C)
T_{cd}	The condensation temperature (°C)
u	Process heating requirement (MW)
W	The potential shaft power generation by steam expansion (MW)

Subscripts

cd	Condensation
cm	Cooling medium
i	VHP, HP, MP, and LP steam mains, respectively
IN	New steam main introduction
IN−1	Higher pressure steam main adjacent to the added new steam main
IN+1	Lower pressure steam main adjacent to the added new steam main

L. Sun · S. Doyle · R. Smith (✉)
Centre for Process Integration, School of Chemical Engineering and Analytical Science, University of Manchester, Manchester M13 9PL, UK
e-mail: robin.smith@manchester.ac.uk

Introduction

Various processes operate on the site and are connected to a common utility system. System analysis is necessary to evaluate site-wide power and heat generation, distribution, utilization and discharge of energy.

In the utility system, the source of utility very high pressure (VHP) steam is fuel combustion in boilers and gas turbines with heat recovery steam generators. VHP steam distributes to lower pressure steam mains for process heating. The steam cascade in the utility system is determined by utility VHP steam from boilers, process heating and cooling demands, and process indirect heat recovery through the utility medium. Utility power is generated by fuel combustion in gas turbines and steam expansion in steam turbines. In the system, one of the methods to implement high efficiency fuel combustion is cogeneration improvement. Cogeneration interacts with the utility VHP steam target and the steam cascade. Steam mains selection plays a significant role in the integration between processes and utility systems.

Both graphical approaches and mathematical programming methodologies have been developed to obtain power and energy targets (Smith 2005). Pinch technology (Linnhoff et al. 1982) is well utilized as the visual and computational aid to reflect the site-wide heat and power integration. Linnhoff et al. (1982) introduced Grand Composite Curves as a tool for individual process heat integration. Dhole and Linnhoff (1993) proposed Site Source-Sink Profiles to implement process and utility system integration and identified process quantified heating and cooling demands in the graph. Site Composite Curves (Raissi 1994) are constructed following the zero approach between the utility loads, and provide the target of process indirect process heat recovery and the minimum utility VHP steam demand. Site Utility Grand Composite Curves (Raissi 1994) are constructed based on the steam cascade extracted from the Site Composite Curves, and allow visualization of the steam cascade in the utility system. The shaft power generation during the steam expansion can be estimated by an enclosed area in the curves based on a temperature–enthalpy (*T*–*H*) model (Raissi 1994). However, there was no straightforward method to understand the interaction between steam mains selection and the cogeneration.

Other graphical methods have extended Pinch Analysis for site-wide heat and power integration. Perry et al. (2008) extended the Site Composite Curves to renewable energy sources and interactions with the existing grid. Bandyopadhyay et al. (2010) estimated the cogeneration potential at the total site level. Botros and Brisson (2011) improved the targeting by including sensible heating of steam in the Composite Curves. Crilly and Zhelev (2010) developed CO_2 emission Pinch Analysis. Wan Alwi and Manan (2010) introduced STEP (Stream Temperature vs. Enthalpy Plot) as a new graphical tool for simultaneous targeting and design of heat exchanger networks. Varbanov et al. (2012) specified process minimum temperature difference to obtain more realistic utility and heat recovery targets. Sun et al. (2013) analyzed cogeneration improvements based on steam cascade analysis. Krishna and Bandyopadhyay (2013) studied emission constrained electricity system planning.

The application of site targeting graphical methods has been explored by a number of studies (Klemeš and Varbanov 2013). Klemeš et al. (1997) proposed targeting for power and CO_2 reduction on the total site. Varbanov and Klemeš (2010) set time slices into the Site Profiles and Site Composite Curves to integrate the renewable energy into total site CHP energy systems. Fodor et al. (2010, 2012) selected the minimum temperature difference for total site utility systems and explored how it affected the heat recovery networks of the individual process. Saw et al. (2011) extended graphical targeting technique for direct reuse/recycle in concentration and property-based resource conservation networks. Hackl et al. (2011) used Total Site analysis to improve energy collaboration between different companies. Wan Alwi et al. (2012, 2013) adopted Pinch graphical tools to achieve the minimum electricity target in hybrid renewable energy systems. Krishna Priya and Bandyopadhyay (2013) studied the emission constrained power system planning based on the Pinch Analysis. Alwi et al. (2013) explored process changes via load shifting for hybrid power systems based on Power Pinch Analysis. Cucek et al. (2013) extened the Total Site Integration scope to the regional level. Mohammad Rozali et al. (2013) applied Power Pinch Analysis to the storage technology development in Hybrid Power System.

Mathematical programming models for utility system optimization can be divided into linear models (Mavromatis and Kokossis 1998) and non-linear models (Sorin and Hammache 2005; Prashant and Perry 2012). Rigorous mixed integer non-linear programming model would reach accurate results (Bruno et al. 1998). Other thermodynamic models (Medina and Picon-Nunez 2010), iterative Bottom-to-Top methods for shaft power targeting (Ghannadzadeh et al. 2012), a new cogeneration targeting model based on entropy, enthalpy and the isentropic efficiencies of the turbines (Mohammad et al. 2012), and targeting the integration of multi-period utility systems (Marechal and Kalitventzeff 2003) have been developed.

This paper explores a new Site Pinch-based graphical targeting method based on Site Grand Composite Curve (SGCC) to address system targets and the interaction among process heating and cooling requirements, steam mains selection, the Total Site Pinch, and cogeneration improvements.

The paper introduces the construction of the SGCC in the second section. The third section analyzes the new steam mains introduction and cogeneration improvements. Process heating demands, process indirect heat recovery, utility VHP steam target, shaft power potential by the steam expansion, as well as the Total Site Pinch, are all obtained while steam mains changes based on the SGCC. The straightforward method for process integration with utility systems based on the SGCC is addressed in the fourth section.

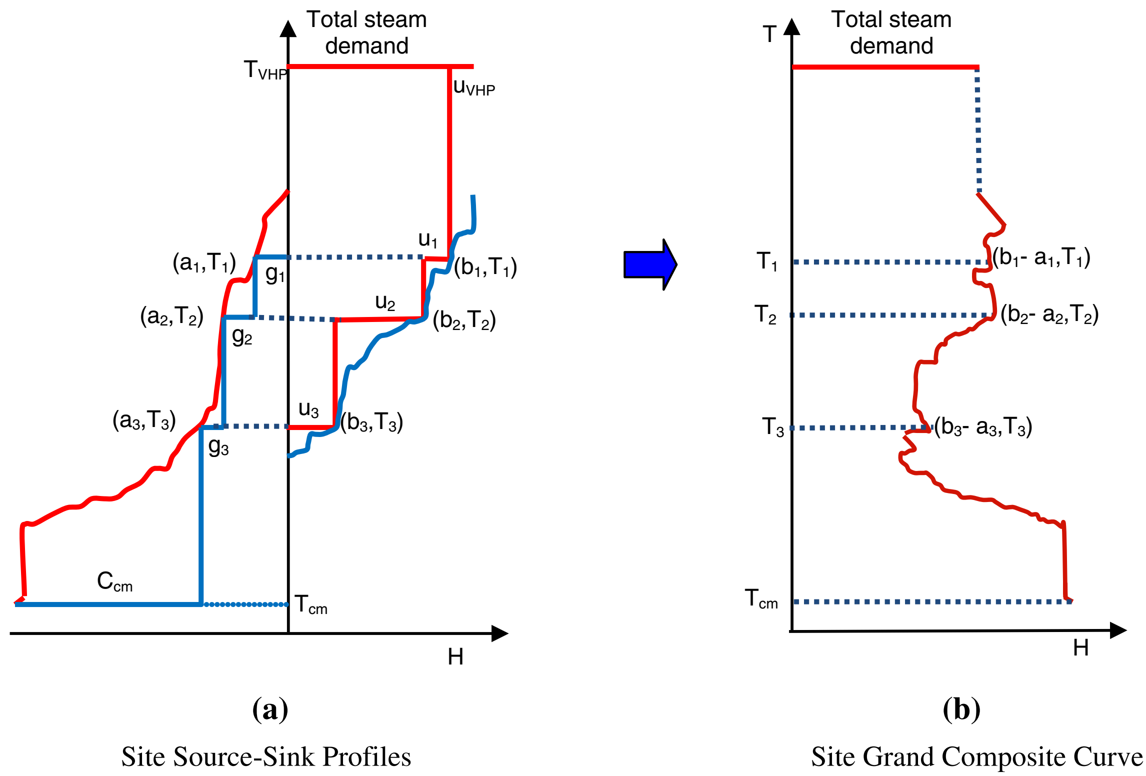

Fig. 1 Site Grand Composite Curve

The SGCC and system targeting

In this work, a new graphical representation of site targeting is explored. The SGCC is proposed to targeting the system and visualizes the integration of processes and utility systems.

The SGCC construction

The SGCC is built by the separation of Site Sink Profile and Site Source Profile.

As shown in Fig. 1, the coordinate of the SGCC (b_i-a_i, T_i) is the point at the Site Sink Profile b_i minus the point at the Site Source Profile a_i at the temperature T_i. It is related to process heating load u_i (MW) and steam generation g_i (MW) from process heat recovery at each steam main i. The steam main i includes VHP, high pressure (HP), medium pressure (MP), and lower pressure (LP).

$$i = 1,\ \text{HP steam main: } b_1 - a_1 = (b - a)_{\text{HP}} = \left(\sum u_i - u_{\text{VHP}}\right) + g_1 \quad (1)$$

$$i = 2,\ \text{MP steam main: } (b - a)_{\text{MP}} = \left(\sum u_i - u_{\text{VHP}}\right) + (g_1 - u_1) + g_2 = (b - a)_{HP} + g_2 - u_1 \quad (2)$$

$$i = 3,\ \text{LP steam main: } (b - a)_{\text{LP}} = \left(\sum u_i - u_{\text{VHP}}\right) + (g_1 - u_1) + (g_2 - u_2) + g_3 = (b - a)_{MP} + g_3 - u_2 \quad (3)$$

Even though the SGCC is constructed in a similar way to the process Grand Composite Curves, they are intrinsically different. The process Grand Composite Curves are used to set individual process cold and heat utility demands. They are useful in providing conceptual understanding of the individual process, but are not a suitable tool for the selection of utilities. The SGCC is more appropriate for understanding the interface between processes and utility systems. All the site energy and power targets and steam cascade are addressed in the SGCC.

Direct heat recovery within the individual process can be implied in the process Grand Composite Curve. However, for multiple processes on the site, direct heat recovery among different processes normally is not feasible due to practical limits.

The steam generation g_i from process heat recovery can supply for process heating to save both utility steam and fuel combustion, or improve power generation potential. Normally, the site steam saving is smaller than the sum of steam generation Σg_i by process heat recovery. The site steam saving is a key parameter. Its identification in the

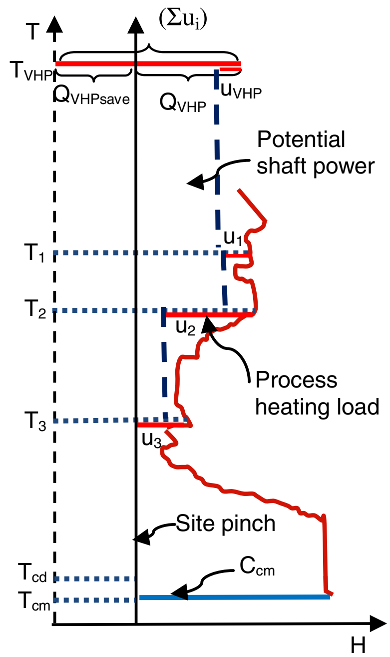

Fig. 2 Site targeting in the Site Grand Composite Curve

SGCC contributes to both utility VHP steam target and system cogeneration.

Steam cascade and utility targets in the SGCC

As shown in Fig. 2, the steam cascade is constructed by the SGCC minus the process heating load u_i at each steam main. It is not possible that the steam cascade falls from lower pressure to higher pressure. The minimum steam cascade would be empty. The removed steam cascade is the maximum site VHP steam saving due to process indirect heat recovery through steam mains. It implies fuel combustion saving in the system.

The process total steam demand is the summarization of the process steam load in Eq. (4). Based on the new steam cascade built by the site VHP saving removal in Fig. 2, the utility VHP target is addressed in the SGCC by the process total steam demand minus the site VHP saving.

$$\text{Total steam demand} = \sum u_i \tag{4}$$

$$Q_{\text{VHP}} = \sum u_i - Q_{\text{VHPsave}} \tag{5}$$

Shaft power potential by steam expansion

The potential shaft power generation by steam expansion in steam turbines or steam condensation in condensing turbines is a function of the steam load and saturation temperature drop between the inlet and outlet steam of the steam turbine based on the *T–H* model (Raissi 1994). It is proportional to the steam cascade rectangular area in the SGCC. This estimation ignores the superheat both of the inlet and outlet steam of the steam turbine.

$$W = c * Q_{\text{in}} * (T_{\text{in}} - T_{\text{out}}) \tag{6}$$

c is the power conversion coefficient based on *T–H* model. It is a proportionality constant relating the power output to the area. It is depending on turbine characteristics.

Table 1 lists the steam cascade and shaft power potential based on the SGCC. The total shaft power potential is estimated as the following equation:

$$W = c * \left[\sum g_i(T_i - T_{\text{cd}}) + \sum u_i(T_{\text{VHP}} - T_i) - Q_{\text{VHPsave}} * (T_{\text{VHP}} - T_{\text{cd}})\right] \tag{7}$$

Total Site Pinch

The Total Site Pinch (Klemeš 2013) is the steam zone without steam cascade in the SGCC. In Fig. 2, the Total Site Pinch lies in the condensing zone (T_3–T_{cd}).

The Total Site Pinch is distinctly different from the Process Pinch. The Total Site Pinch represents a bottleneck in site indirect heat recovery, but the Process Pinch provides the bottleneck in the process direct heat integration. The Total Site Pinch is determined by both process profiles and steam mains, but the Process Pinch is only affected by process hot and cold Composite Curves. The Total Site Pinch contains two adjacent steam mains, but the Process Pinch is the point of the closest approach between process hot and cold Composite Curves.

The Process Pinch separates the process into heat source and heat sink. The Total Site Pinch divides the SGCC into three sections, and clarifies the site VHP and cooling targets and site steam saving.

At the Total Site Pinch

The site steam just satisfies the process heating requirement. There is no steam cascade and no shaft power potential by steam expansion. Measures taken to increase the steam cascade at the Total Site Pinch might decrease utility VHP steam target.

Above the Total Site Pinch

The heat deficit of the system requires VHP steam from fuel burning in boilers. More process indirect heat recovery above the Total Site Pinch is beneficial for site steam saving, site VHP target reduction, and lower operating cost and CO_2 emissions.

Table 1 Steam cascade and shaft power potential

Steam mains zone	Steam cascade (MW)	Shaft power potential (MW)
VHP-HP	$u_{HP} + u_{MP} + u_{LP} - Q_{VHPsave}$	$c^*(u_{HP} + u_{MP} + u_{LP} - Q_{VHPsave})^*(T_{VHP} - T_{HP})$
HP-MP	$g_{HP} + u_{MP} + u_{LP} - Q_{VHPsave}$	$c^*(g_{HP} + u_{MP} + u_{LP} - Q_{VHPsave})^*(T_{HP} - T_{MP})$
MP-LP	$g_{HP} + g_{MP} + u_{LP} - Q_{VHPsave}$	$c^*(g_{HP} + g_{MP} + u_{LP} - Q_{VHPsave})^*(T_{MP} - T_{LP})$
LP-condensation	$g_{HP} + g_{MP} + g_{LP} - Q_{VHPsave}$	$c^*(g_{HP+}g_{MP} + g_{LP} - Q_{VHPsave})^*(T_{LP} - T_{cd})$

Table 2 Total Site Pinch and utility system targets

Case	Condition	Site VHP saving (MW)	Utility VHP target (MW)	Site Pinch
1	$g_{HP} > u_{HP}$	$u_{HP} + u_{MP} + u_{LP}$	u_{VHP}	VHP-HP
	$g_{HP} + g_{MP} > u_{HP} + u_{MP}$			
	$g_{HP} + g_{MP} + g_{LP} > u_{HP} + u_{MP} + u_{LP}$			
2	$g_{HP} < u_{HP}$	$g_{HP} + u_{MP} + u_{LP}$	$u_{VHP} + u_{HP} - g_{HP}$	HP-MP
	$g_{MP} > u_{MP}$			
	$g_{MP} + g_3 > u_{MP} + u_{LP}$			
3	$g_{MP} < u_{MP}$	$g_{HP} + g_{MP} + u_{LP}$	$u_{VHP} + u_{HP} + u_{MP} - g_{HP} - g_{MP}$	MP-LP
	$g_3 > u_{LP}$			
	$g_{HP} + g_{MP} < u_{HP} + u_{MP}$			
4	$g_{LP} < u_{LP}$	$g_{HP} + g_{MP} + g_{LP}$	$u_{VHP} + u_{HP} + u_{MP} + u_{LP} - g_{HP} - g_{MP} - g_{LP}$	LP-condensation
	$g_{MP} + g_{LP} < u_{MP} + u_{LP}$			
	$g_{HP} + g_{MP} + g_{LP} < u_{HP} + u_{MP} + u_{LP}$			

Below the Total Site Pinch

The process heat recovery can satisfy the process heating demand, and might have surplus steam condensing for power generation. Process hot streams are cooled by cold medium below the Total Site Pinch.

Table 2 illustrates the utility VHP steam target and site steam saving at different Total Site Pinch locations.

New steam mains introduction and cogeneration improvements

New steam mains introduction is beneficial for more steam generation from process heat recovery and lower pressure steam for process heating instead of higher pressure steam. Its effect on the boiler steam saving, utility VHP steam target and the shaft power potential depends on new steam mains introduction within or without the Total Site Pinch.

A new main introduction at the Total Site Pinch

Adding a new steam main at the Total Site Pinch would relocate the Total Site Pinch, and reach more site steam saving and utility VHP target reduction. Figure 3 demonstrates adding new steam main (IN) at T_{IN} between T_2 and T_3. The new Total Site Pinch relocates from $(T_2 - T_3)$ to $(T_{IN} - T_3)$. The steam cascade increases u_{IN} at the zone $(T_2 - T_{IN})$ and g_{IN} at the zone $(T_{IN} - T_3)$. The extra possible site steam saving is the minimum of g_{IN} and u_{IN}, and it implies the reduction of the VHP steam target and fuel combustion saving for steam and power generation.

At the fixed fuel consumption in the utility system, adding a new steam main (IN) at the Total Site Pinch can generate more shaft power for cogeneration improvements.

$$\begin{aligned}\Delta W &= c * [(T_{IN-1} - T_{IN}) * u_{IN} + (T_{IN} - T_{IN+1}) * g_{IN}] \\ &= c * ((T_2 - T_{IN}) * u_{IN} + (T_{IN} - T_3) * g_{IN})\end{aligned} \quad (8)$$

A new main introduction away from the Total Site Pinch

A new steam main added away from the total site pinch does not change the total site pinch. The boiler steam saving, utility VHP target and fuel combustion are not affected either.

As shown in Fig. 4, a new steam main introduction (IN) at T_{IN} causes extra higher pressure steam generation g_{IN} from process heat recovery, and lower pressure steam load u_{IN} for process heating. The steam expansion of u_{IN} from VHP to the new steam main IN and the steam expansion of g_{IN} from the new steam main IN might generate more power.

The new steam main introduction would improve the cogeneration.

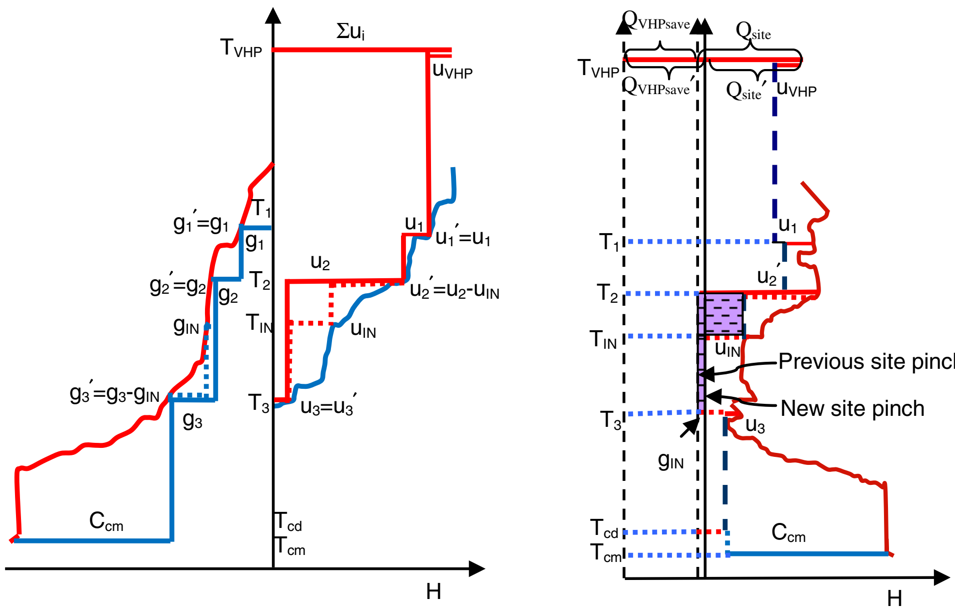

Fig. 3 New steam mains introduction at the Total Site Pinch

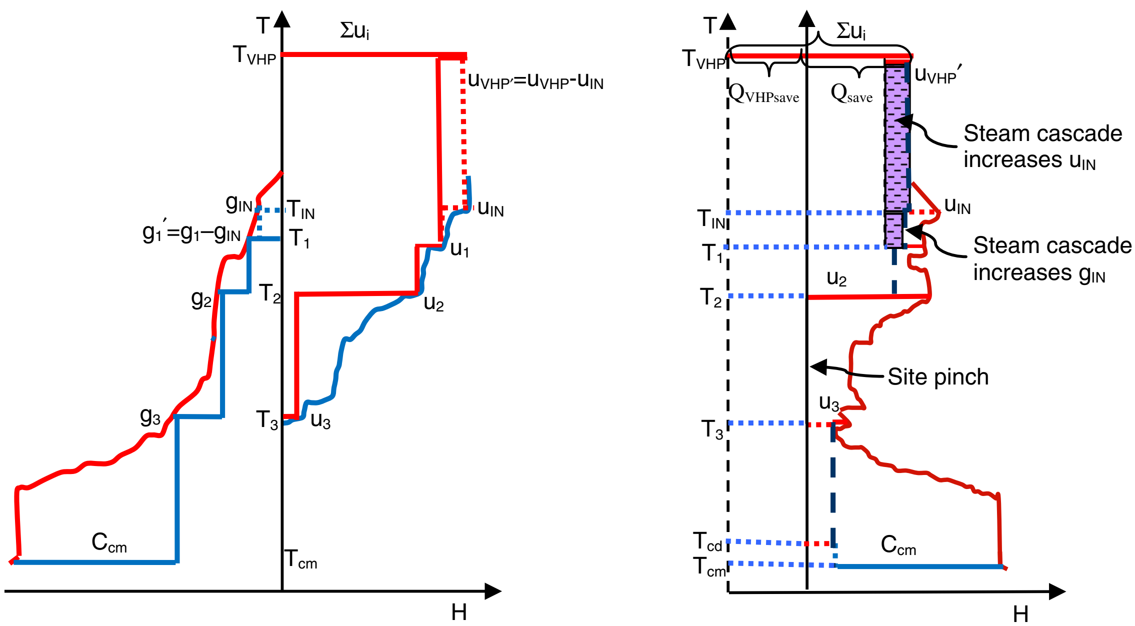

Fig. 4 New steam mains introduction away from the Total Site Pinch

$$\Delta W = c * [(T_{IN-1} - T_{IN}) * u_{IN} + (T_{IN} - T_{IN+1}) * g_{IN}] \\ = c * [(T_{VHP} - T_{IN}) * u_{IN} + (T_{IN} - T_1) * g_{IN}] \quad (9)$$

Even though the shaft power improvement has the same equation by adding the new steam main at or away from the Total Site Pinch, the first case in practice will save fuel combustion, and has far realistic significance for CO_2 emission reduction.

Process integration with utility systems based on the SGCC

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

Measures should be taken both from processes and utility systems to improve heat and power generation.

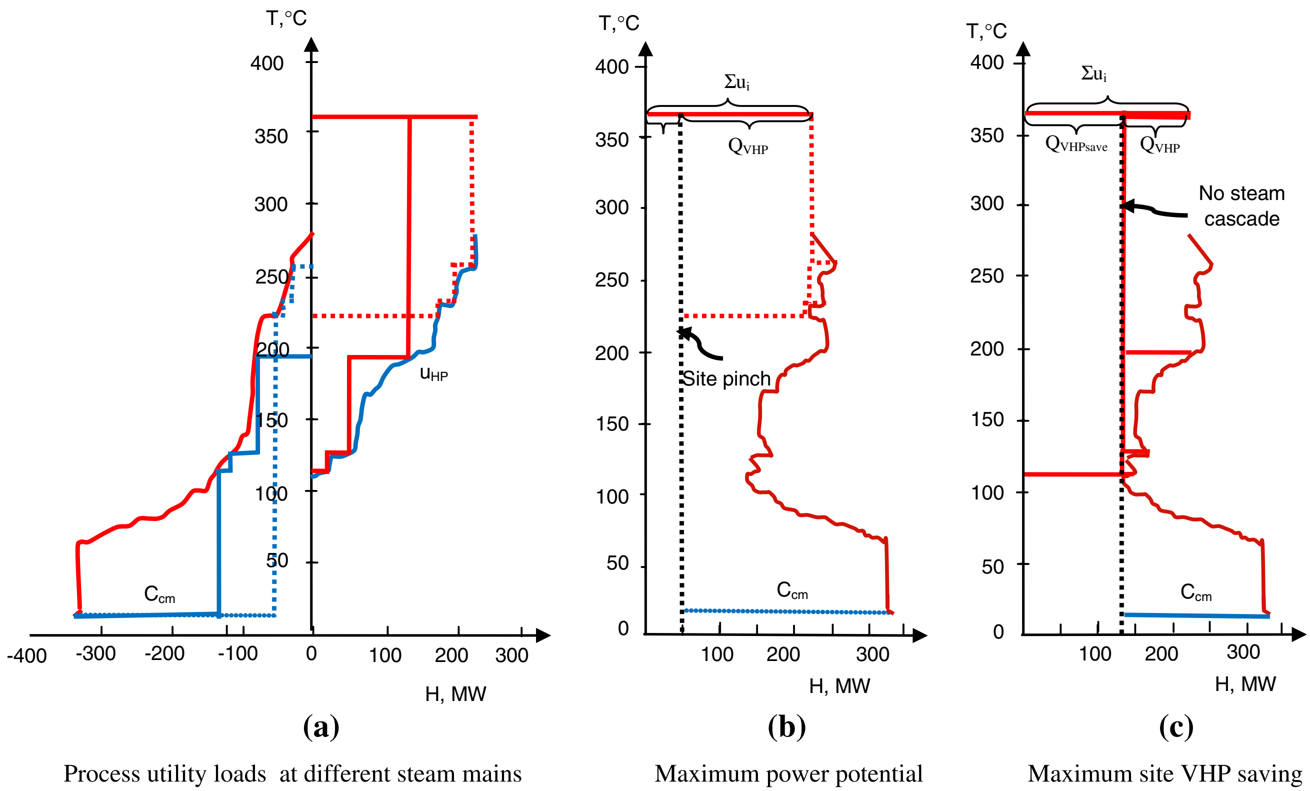

Fig. 5 Steam mains selection in the SGCC

1) Steam mains selection is an important decision affecting steam cascade and the Total Site Pinch in the system operation and design.
2) Processes modification will cause the variation of process utility demands. It must be done with caution to maintain realistic operation.

Steam mains selection

Steam mains selection influences process heating and cooling loads, process indirect heat recovery, and utility VHP steam target. The verified steam cascade induces the fluctuation of shaft power potential by steam expansion. The Total Site Pinch might be relocated either.

A case study illustrates the effect of steam mains selection on process steam demands and steam generation shown in Fig. 5a and the utility targets in the SGCC in Fig. 5b, c.

Steam mains might be selected for the maximum power generation in Fig. 5b and the maximum site VHP saving in Fig. 5c, depending on electricity price, fuel cost, or other site requirements. For instance, at the case of higher coal price, steam mains selection would be the optimization to minimize the utility VHP demand. The shaft power potential would decrease with the lowest fuel consumption.

Table 3 Steam mains selection and site system targets

Scenario	Steam mains (°C)	Q_{save} (MW)	Q_{site} (MW)	Fuel (MW)	Shaft power (MW)	Cooling water (MW)
Max shaft power	360/259.9/ 230.3/ 221.0	50.0	180.0	304.6	33.2	290.0
Max site steam saving	360.0/ 189.8/ 124.8/ 113.8	136.4	93.6	133.7	0	203.6

In this case study, the optimal steam mains selection to achieve the maximum energy recovery and maximum shaft power potential is shown in Fig. 5. Table 3 lists the effect of steam mains on site system targets.

Process variation and utility system performance

Process modifications change the SGCC. In a case shown in Fig. 6, extra steam Δw at T_1 is generated from process heat recovery, and others are unchanged. The SGCC moves parallel to the left by Δw. The steam cascade increases the load of Δw from the steam main at T_1 to the condensation, and would save site VHP steam Δw due to more heat recovery.

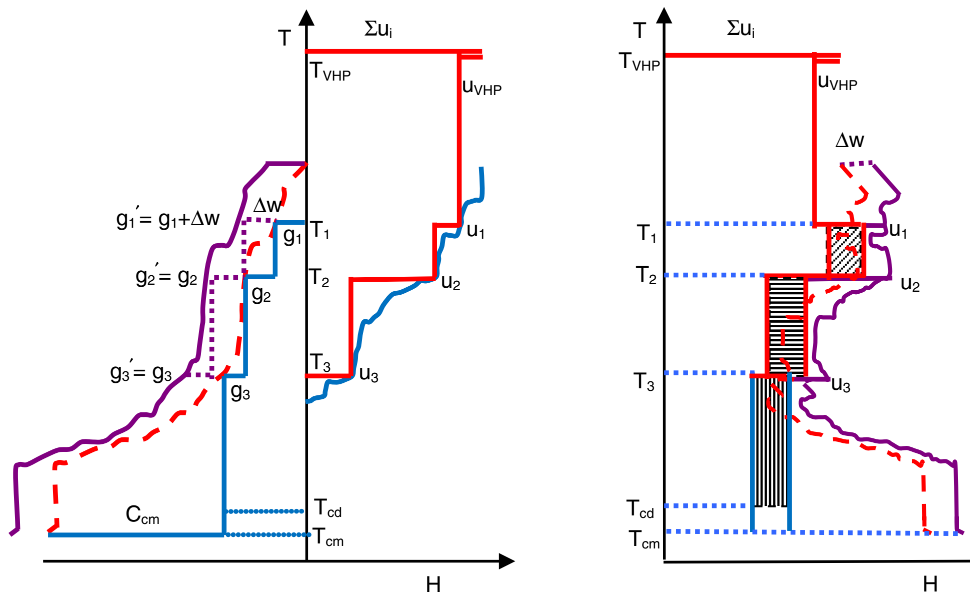

Fig. 6 More process heat recovery and utility system performance

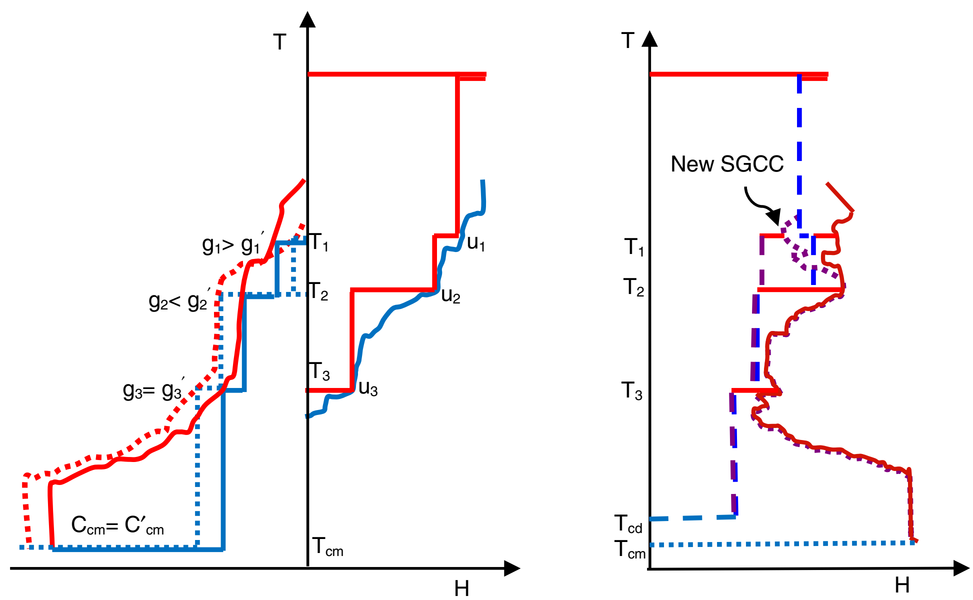

Fig. 7 Process variations and the SGCC

Figure 7 is another case study to illustrate the process modification and utility system performance on the SGCC. At this case, the changed SGCC and the fixed process heating loads induce different steam cascade and cogeneration.

Conclusion and discussion

This work developed a new graphical approach of Site Grand Composite Curve to extend Pinch Analysis for utility targeting. The SGCC embodies quantitative and visual targets of process heating and cooling demands, site steam saving by process indirect heat recovery through steam mains, the minimum utility VHP steam target, the potential shaft power generation, as well as the Total Site Pinch. This graphical analysis presents greater clarity for quantitative interaction between processes and utility systems than previous approaches.

The SGCC is primarily intended to be employed as a visualization tool for the utility system conceptual design and optimization without initial system configuration and any particular items selection. This graphical method would be helpful to scope the potential cogeneration improvements by changing steam mains or process operation quantitatively, and consequently to better understand the integration of processes and utility systems for high efficiency power and energy production, and cleaner site utility systems.

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