PROCESS INTEGRATION CONCEPTS AND THEIR APPLICATION TO ENERGY CONSERVATION

Uday V. Shenoy
Department of Chemical Engineering,
Indian Institute of Technology, Powai, Bombay 400 076.

Abstract

Process integration involves the networking of different unit operations in order to obtain optimal performance within the context of the overall plant site. The design of integrated processes may be systematically done by pinch analysis and mathematical programming. Targeting allows prediction of the best performance that can possibly be achieved in a process prior to any synthesis or detailed design, and is a key step at the conceptual design stage because of the large number of designs possible. Energy is a key resource, but other resources like capital investment must be considered to arrive at an energy-efficient, cost-effective design based on the classical energy-capital tradeoff.

Advances in energy integration techniques are discussed in this paper with special emphasis on the design of heat exchanger networks, distillation processes, utility systems and total sites. It is demonstrated how a comprehensive picture of the heat supply and heat demand over the entire temperature range may be used to set targets through novel representations of the processes on temperature-enthalpy diagrams.

Introduction

As optimization of individual units does not guarantee efficiency and economy at the global level, a systems engineering approach aimed at understanding and designing at the flowsheet level is needed. Pinch Analysis (Linnhoff, 1993) is one such approach to process integration. It has a strong thermodynamic basis and has been applied in a variety of industries (e.g., petroleum refining, pulp and paper, food, steel, cement, pharmaceuticals, and chemicals).

This paper briefly summarizes how process engineers may establish minimum energy targets for processes at a plant site, plan utility systems and cogeneration schemes, determine the cost-optimal loads for multiple utilities, and design distillation processes. Further details of various calculation procedures are provided by Shenoy (1995).

Heat Exchanger Network Design through Composite Curves

The first step in designing heat exchanger networks (HENs) is to target the minimum utility requirements for the process through composite curves. The cooling needs for the all the hot streams are combined on a temperature-enthalpy (*T*-*Q*) diagram to construct a hot composite curve (HCC). The heating requirements of all the cold streams are similarly combined into a cold composite curve (CCC). The HCC and CCC provide a comprehensive picture of the heat supply and heat demand for the overall process over the entire temperature range. When the two composite curves are drawn on the same *T*-*Q* axis (Figure 1), their relative horizontal position is not defined since the enthalpy axis for the hot and cold profiles can be independently chosen so long as temperatures and enthalpy changes are preserved. The enthalpy overlap of the two composite curves signifies the opportunity for process-to-process heat recovery. This overlap may be maximized subject to the specification of the minimum temperature difference for heat exchange (ΔT_{min}).

The composite curves then come to a point of closest approach, which is ΔT_{min} apart. This point is termed the pinch since it represents the most constrained region for heat recovery. The pinch corresponds to a particular temperature level and divides the process into two thermodynamically separate regions. Above the pinch, only hot utility is required and its magnitude corresponds to the enthalpy overshoot of the CCC. Below the pinch, only cold utility is necessary and its magnitude is given by the overshoot of the HCC. These utility requirements are thermodynamically the minimum possible and provide the energy targets for the process based on only the stream data.

Utility System Design through Grand Composite Curve and Total Site Profiles

The grand composite curve (GCC) is a useful representation for multiple utility targeting, evaluation of steam-raising potential, placement of heat pumps, and profile matching in combined heat and power systems. It is a plot of shifted temperatures vs. heat flows and may be analytically computed by the Problem Table Algorithm (Shenoy, 1995). Graphically, the GCC may be obtained by plotting the enthalpy differences (horizontal distances) between the composite curves after shifting the HCC down by $\Delta T_{min}/2$ and the CCC up by $\Delta T_{min}/2$. Thus, the GCC is a suitable summation of the two composite curves and represents a heat cascade (i.e., the heat flow from high to low temperature). At the pinch point, the GCC touches the temperature axis indicating zero enthalpy flow. There is a process heat sink profile above the pinch that needs to be matched by hot utilities, and there is a process heat source profile below the pinch that needs to be matched by cold utilities as shown in Figure 2. These observations on the GCC provide three fundamental rules of pinch analysis: only hot utility must be used above the pinch, only cold utility must be used below the pinch, and heat must not flow across the pinch from a process stream above the pinch temperature to one below it. Violation of any of these three design rules leads to a double energy penalty (i.e., an increase in both the hot and cold utility requirements).

The location of the pinch is of fundamental importance when integrating a cogeneration scheme into a process. Recall that the process is an overall heat sink above the pinch and an overall heat source below it. Therefore, the exhaust from a heat engine (e.g., steam turbine, gas turbine, gas engine) should be integrated totally above the pinch because the heat engine is then rejecting heat into the process heat sink. Alternatively, a heat engine which absorbs and rejects heat below the pinch is properly located because it converts surplus process heat, that would otherwise have been wasted to cold utility, into work. The concept, based simply on overall energy balances, can be generalized and stated as the appropriate placement principle: the proper placement of a heat engine is either totally above or totally below the pinch. If a heat engine is placed across the pinch, then no benefit is gained by the integration and it is better to leave it stand-alone.

Furthermore, a quantitative tool is necessary to quickly identify cogeneration alternatives and other options for satisfying plant energy requirements without extensive, detailed design calculations. The GCC provides such a tool because it graphically shows both the load and level requirements for utilities. All that needs to be done is to treat the heat engine exhaust like any other hot utility. For example, Figure 2 could correspond to two levels of back-pressure steam from a steam turbine matched to a process GCC above the pinch. In such a case, the integrated system permits the conversion of heat to work at 100% marginal efficiency. Alternatively, process heat below the pinch may be used to raise steam for a steam turbine.

The GCC depicts the utility requirements of a single process, but a total site comprises several processes and a utility system that consumes fuel, generates power and distributes steam. The processes are treated as operationally independent regions of integrity, and this imposes constraints on the potential heat recovery. If inter-process heat recovery is potentially attractive, then it may be achieved by direct or indirect heat transfer. Direct heat transfer utilizes straight matches between a hot stream in one process and a cold stream in another process. Though operational independence is sacrificed, this may be offset by the capital cost gains. Clearly, such matches recommended from the viewpoint of an energy-efficient network need to be reviewed considering practical constraints like safety, plant layout and operability. Indirect heat transfer maintains the operational independence as it involves the utility system as a buffer. However, the heat recovery in two stages involves a loss in temperature driving forces; consequently, there is an area penalty with additional capital cost implications.

Inter-process heat recovery by indirect heat transfer may be analyzed using the individual process GCCs. However, this may be cumbersome when there are many processes on a site. The difficulty may be circumvented by using total site profiles (Dhole and Linnhoff, 1993a), which combine the information from several GCCs (corresponding to different processes) into simply two curves. The site sink profile and the site source profile are obtained by summing the portions of the individual GCCs above and below the individual process pinches, respectively. Targets may now be set based on these total site profiles (Figure 3). From the site source profile, steam-raising potential at particular levels is ascertained (which in turn sets the cooling water load). The steam raised is then used to meet some of the steam requirements on the site. Additional steam demands in accordance with the site sink profile must be supplied by the turbines. This allows calculation of the VHP steam load in the boiler and the power output from the turbines. The fuel requirement is determined in terms of the enthalpy projection of the flue gas line (which extends from the theoretical flame temperature to the ambient temperature).

Multiple Utilities Targeting through Optimum Load Distribution Plots

Energy targeting implies maximization of the process-to-process heat recovery in terms of the overlap of the composites and determination of the minimum utility requirements in terms of the overshoots. The utility requirements and consequently the operating costs decrease when the vertical gap (ΔT_{min}) between the composites is reduced. However, the heat exchange area requirements and consequently the capital costs increase with decreasing ΔT_{min}. Based on this classical energy-capital tradeoff, there is an optimum value of ΔT_{min} for which the total annual cost (TAC) is a minimum.

The procedure of pre-design optimization for ΔT_{min} based on TAC is called supertargeting (Linnhoff and Ahmad, 1989).

The concept of supertargeting on a TAC plot has been extended to multiple utilities by Shenoy et al. (1998). Note that the method of targeting loads and levels for multiple utilities by profile matching on the process GCC involves maximizing the use of the cheapest utility available at each stage, and consequently minimizes only the utility costs without considering the capital costs. For example in Figure 2, the LP steam load is maximized before considering the use of MP steam and the VLP steam-raising load is maximized before considering the use of cooling water (CW). The two utility pinches created by LP steam and VLP steam-raising as well as the process pinch are based on a global value of ΔT_{min}.

The targeting methodology proposed by Shenoy et al. (1998) to determine the optimum loads for multiple utilities is based on the Cheapest Utility Principle (CUP), which simply states that the temperature driving forces at the utility pinches once optimized do not change even when the minimum approach temperature (ΔT_{min}) at the process pinch is varied. In other words, it is optimal to increase the load of the cheapest utility and maintain the loads of the relatively expensive utilities constant while increasing the total utility consumption. By optimizing the utility pinches sequentially and recognizing that these optimized utility pinches essentially do not change with the process ΔT_{min}, the results are elegantly represented through optimum load distribution (OLD) plots (Figure 4). The TAC target curves (Figure 5) are then established from the OLD plots for pre-design screening of various options that lead to near-minimum cost heat exchanger networks, but involve different combinations of utilities and load distributions. Rather than determine that single value for the global optimum corresponding to the minimum TAC, it is beneficial in practice to define an optimum ΔT_{min} range because the TAC curves are often reasonably flat in the neighborhood of the minimum and consequently provide useful flexibility in terms of capital investment. Shethna et al. (1999) have shown that the network based on the CUP-based approach (when compared to the GCC-based approach) saved up to 25% on TAC for a fluidized catalytic cracking downstream gas processing unit.

Distillation Process Design through Invariant Rectifying-Stripping Curves

The analogs of hot utility load, cold utility load, and ΔT_{min} in HENs are reboiler duty, condenser duty, and reflux ratio in distillation. The problem of deciding loads amongst multiple utilities in HENs is equivalent to the case of distributing duties between side-reboilers and side-condensers in distillation.

The concept of the GCC has been extended to distillation (Dhole and Linnhoff, 1993b; Bandyopadhyay et al., 1998) and is referred to as the column grand composite curve (CGCC). The CGCC is generated using stagewise information on compositions and enthalpies from the output of a converged simulation of a distillation column. The CGCC depends not only on the operating reflux, but also on the feed location in the column. Dhole and Linnhoff (1993b) assumed the feed stage location for the column had been appropriately chosen beforehand. Although they indicated that appropriate feed stage location should be identified before targeting for any column modification, no methodology for locating the feed was suggested by them. Improper feed location leads to energy penalties in the reboiler and condenser.

In order to target minimum energy and feed location in distillation, Bandyopadhyay et al. (1999) proposed invariant rectifying-stripping (IRS) curves that are independent of the feed location, the feed condition and the operating reflux of the distillation column. IRS curves represent the enthalpy surpluses and deficits in the rectifying and stripping sections, respectively, as a function of temperature for all possible values of reflux and reboil. Importantly, they are calculated based on the minimum thermodynamic condition neglecting the effect of the feed. In fact, the IRS curves capture all the CGCCs for a separation problem (corresponding to different feed stage locations and total number of stages in the distillation column). When the IRS curves are horizontally translated (Figure 6) accounting for the constant enthalpy difference based on the first law of thermodynamics (Δ), the intersection point of the two curves defines the target temperature for locating the feed (T_F). On circumscribing the portion of the invariant rectifying curve below T_F and the portion of the invariant stripping curve above T_F with a right-angled trapezium, the widths of the parallel sides of the trapezium provide targets for the thermodynamic minimum energy requirements in the reboiler and condenser. The IRS curves are useful in properly locating the feed (Bandyopadhyay et al., 2004), deciding on feed preheating/cooling (Bandyopadhyay et al., 2003), determining the minimum utility requirements, targeting loads for side reboilers/condensers, and reducing the tedium of repeated simulations.

Conclusion

Targeting is a key step in energy integration. It involves predicting the best performance that can possibly be achieved in a process, before actually attempting to achieve it. Targeting allows objective performance prediction and assessment for an integrated process prior to any synthesis and detailed design (Muralikrishna and Shenoy, 2000). Thus, it effectively performs preliminary screening of the numerous design alternatives early at the conceptual design stage, ahead of detailed evaluation and simulation. Methodologies for targeting minimum utility requirements, optimum loads/levels for multiple utilities, and cogeneration have been briefly covered here in the context of heat exchanger networks, distillation processes and total sites.

Energy integration is part of the broader area of process integration. Indeed, energy is a vital world resource, but process integration includes other resources such as water (Prakash and Shenoy, 2005a; 2005b), hydrogen (Agrawal and Shenoy, 2006), mass separating agents (Shenoy and Fraser, 2003; Fraser and Shenoy, 2004; Fraser et al., 2005), time and capital (Singhvi and Shenoy, 2002; Singhvi et al., 2004). The development and use of sound process integration tools is becoming increasingly important in today's competitive industrial scenario. The ultimate aim of process integration is to arrive at design solutions that are technologically efficient, cost effective, environmentally agreeable, and industrially acceptable for both grassroots and retrofit situations.

References

Agrawal, V. and Shenoy, U.V. (2006) "Unified conceptual approach to targeting and design of water and hydrogen networks", *AIChE J.*, **52**(3), 1071-1082.

Bandyopadhyay, S., Malik, R.K. and Shenoy, U.V. (1998) "Temperature-enthalpy curve for energy targeting of distillation columns", *Computers & Chem. Eng.*, **22**(12), 1733-1744.

Bandyopadhyay, S., Malik, R.K. and Shenoy, U.V. (1999) "Invariant rectifying-stripping curves for targeting minimum energy and feed location in distillation", *Computers & Chem. Eng.*, **23**, 1109-1124.

Bandyopadhyay, S., Malik, R.K. and Shenoy, U.V. (2003) "Feed preconditioning targets for distillation through invariant rectifying-stripping curves", *Ind. Eng. Chem. Res.*, **42**(26), 6851-6861.

Bandyopadhyay, S., Mishra, M. and Shenoy, U.V. (2004) "Energy-based targets for multiple-feed distillation columns", *AIChE J.*, **50**(8), 1837-1853.

Dhole, V.R. and Linnhoff, B. (1993a) "Total site targets for fuel, cogeneration, emissions, and cooling", *Computers & Chem. Eng.*, **17** Supplement, S101-109.

Dhole, V.R. and Linnhoff, B. (1993b) "Distillation column targets", *Computers & Chem. Eng.*, **17**(5/6), 549-560.

Fraser, D.M. and Shenoy, U.V. (2004) "A new method for sizing mass exchange units without the singularity of the Kremser equation", *Computers & Chem. Eng.*, **28**(11), 2331-2335.

Fraser, D.M., Howe, M., Hugo, A. and Shenoy, U.V. (2005) "Determination of mass separating agent flows using the mass exchange grand composite curve", *Trans. IChemE. Chem. Eng. Res. Des.*, **83**, Part A, December, 1381-1390.

Linnhoff, B. (1993) "Pinch analysis - A state-of-the-art overview", *Trans. IChemE. Chem. Eng. Res. Des.*, **71**, Part A5, 503-522.

Linnhoff, B. and Ahmad, S. (1989) "Supertargeting: Optimum synthesis of energy management systems", *ASME J. Energy Resources Tech.*, September, **111**(3), 121-130.

Muralikrishna, K. and Shenoy, U.V. (2000) "Heat exchanger design targets for minimum area and cost ", *Trans. IChemE. Chem. Eng. Res. Des.*, **78**, Part A, March, 161-167.

Prakash, R. and Shenoy, U.V. (2005a) "Targeting and design of water networks for fixed flowrate and fixed contaminant load operations", *Chem. Eng. Sci.*, **60**(1), 255-268.

Prakash, R. and Shenoy, U.V. (2005b) "Design and evolution of water networks by source shifts", *Chem. Eng. Sci.*, **60**(7), 2089-2093.

Shenoy, U.V. (1995), *Heat exchanger network synthesis: Process optimization by energy and resource analysis*, Gulf Publishing Company, Houston, Texas, USA.

Shenoy, U.V., Sinha, A. and Bandyopadhyay, S. (1998) "Multiple utilities targeting for heat exchanger networks", *Trans. IChemE. Chem. Eng. Res. Des.*, **76**, Part A, March, 259-272.

Shenoy, U.V. and Fraser, D.M. (2003) "A new formulation of the Kremser equation for sizing mass exchangers", *Chem. Eng. Sci.*, **58**, 5121-5124.

Shethna, H.K., Singh, H., Makwana, Y., Shenoy, U.V. and Castillo, F.J.L. (1999) "Multiple utilities optimization to improve process economics", *Petroleum Technology Quarterly*, Autumn, 133-139.

Singhvi, A. and Shenoy, U.V. (2002) "Aggregate planning in supply chains by pinch analysis", *Trans. IChemE. Chem. Eng. Res. Des.*, **80**, Part A, September, 597-605.

Singhvi, A., Madhavan, K.P. and Shenoy, U.V. (2004) "Pinch analysis for aggregate production planning in supply chains", *Computers & Chem. Eng.*, **28**, 993-999.

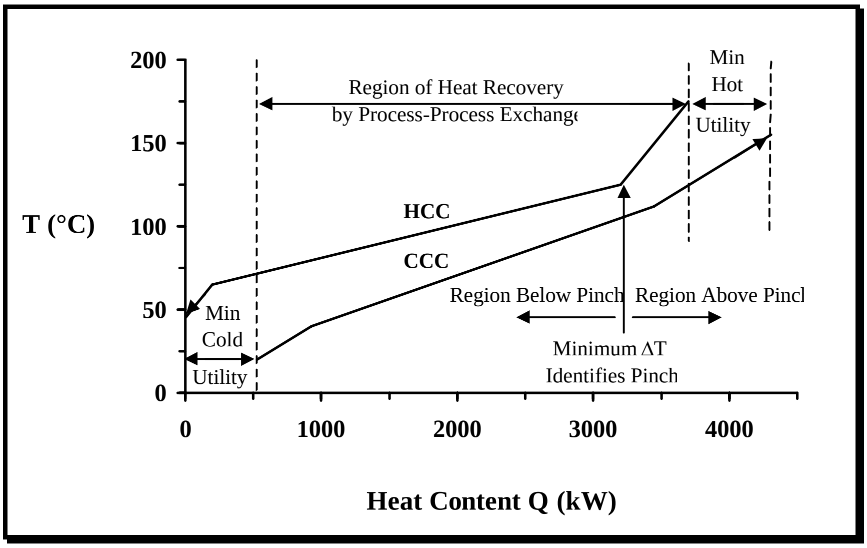

Figure 1. Composite curves target the thermodynamic minimum utilities prior to design.

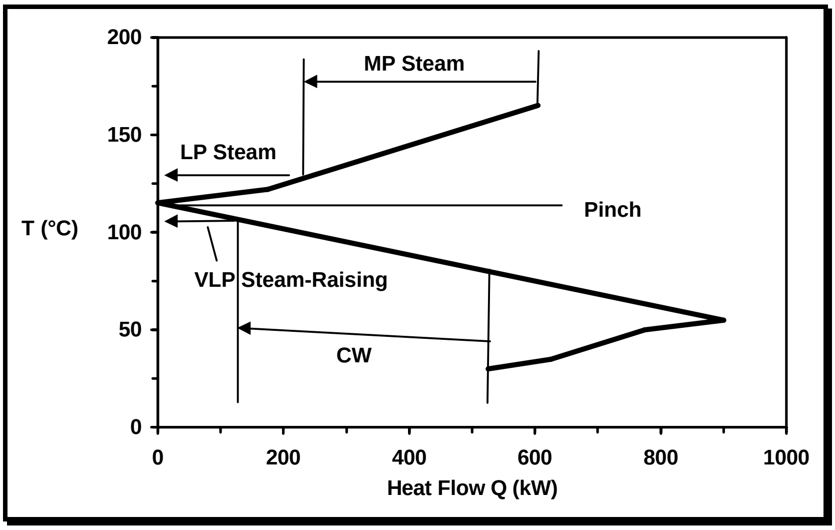

Figure 2. Grand composite curve targets minimum energy cost by profile matching.

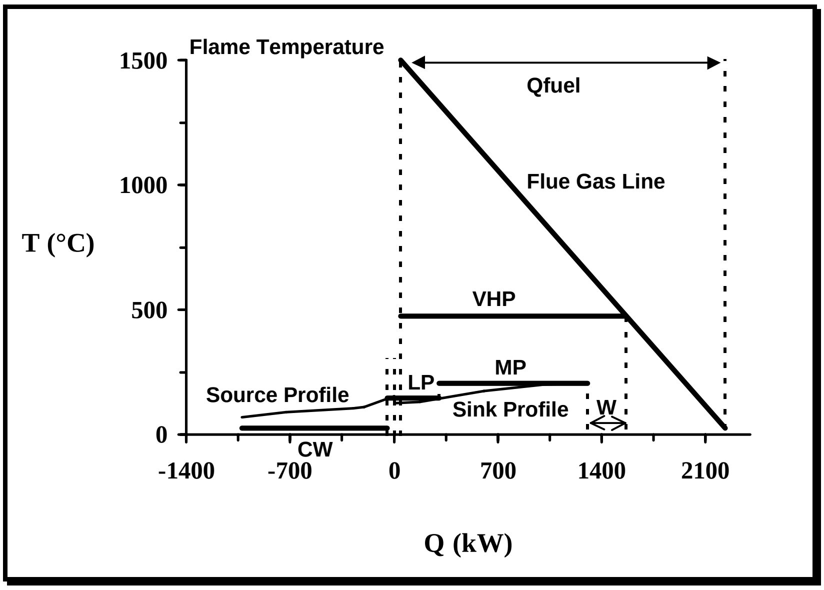

Figure 3. Total site profiles target process heating/cooling, cogeneration and fuel.

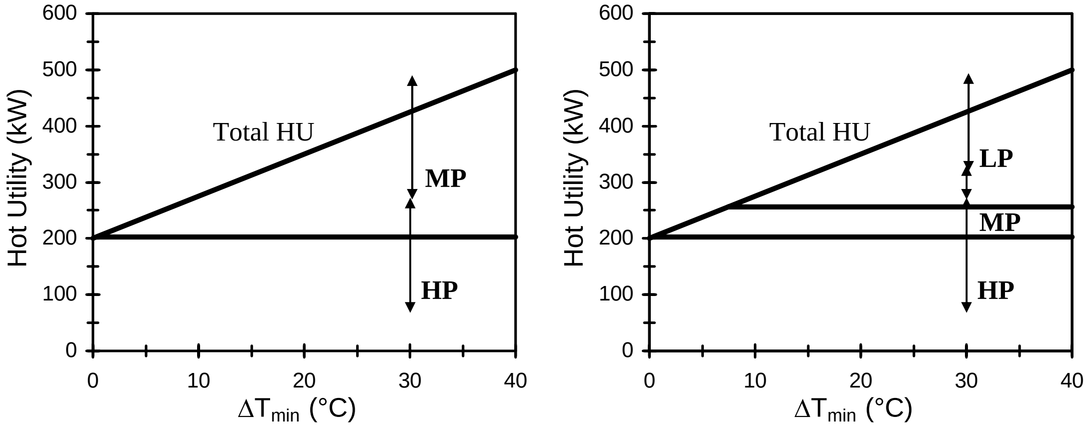

Figure 4. Optimum load distribution plots target multiple utilities as a function of ΔT_{min}.

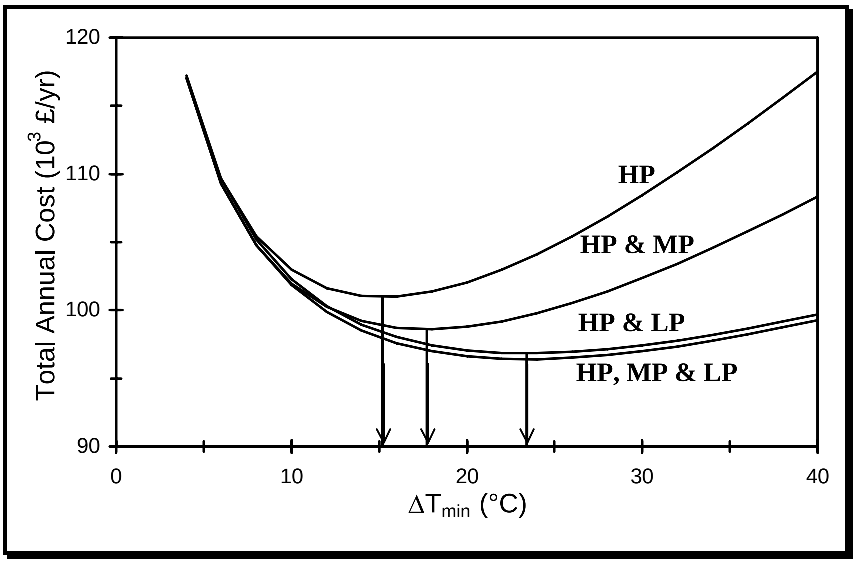

Figure 5. Total annual cost (TAC) targets for different combinations of utilities.

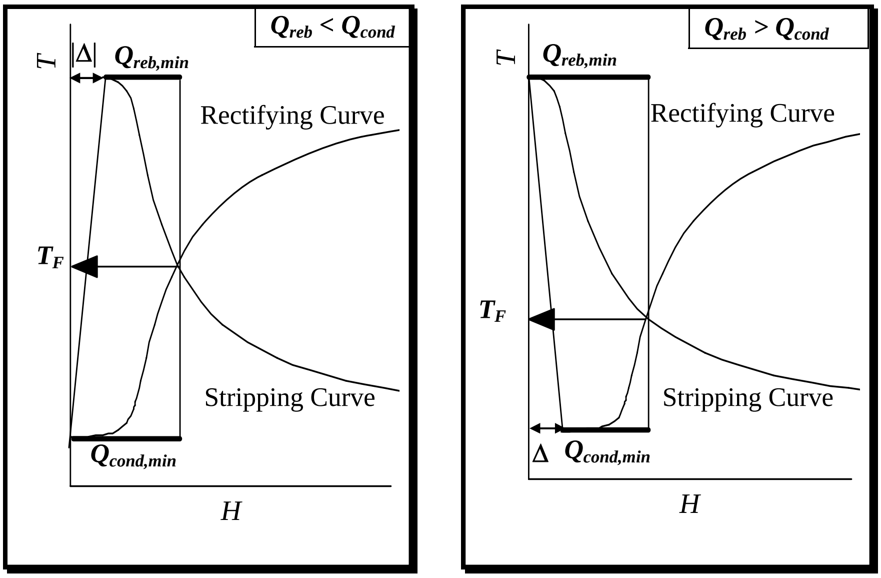

Figure 6. Invariant rectifying-stripping curves target feed location and minimum energy.