Towards sustainable energy systems – role and achievements of heat integration

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SUMMARY

This paper presents an established sustainable and integrated design methodology for the efficient heating and cooling of individual buildings and complexes. The methodology includes the design basis for combined heat and power systems, refrigeration, air conditioning and heating with pump systems. It is equally applicable for single family houses as well as large building complexes and meets a major challenge in the design of heating and cooling systems, namely, the complexity of energy and power integration. The efficient use of available heating and cooling resources for serving buildings of various sizes and designations can significantly reduce energy consumption and emissions. Although heat integration (or Pinch Technology) has been around for several decades and has been very successfully applied in large industrial applications, it has only recently been applied for improving the energy efficiency of buildings and building complexes. There is significant scope for application, as energy prices rise and energy related emissions are required to be reduced. This methodology can also be used to integrate renewable energy sources such as biomass, solar PV and solar heating into the combined heating and cooling cycles. Case studies are used to illustrate the methodology. The paper makes suggestions how the methodology can be applied for energy and emissions reduction in single buildings and complexes.

INTRODUCTION

Since 1995 the energy consumption of the EC member countries rose by 11 %, to the value of 1637Mt of oil equivalent [1]. The population of the EC member states however is growing at a much slower rate, approximately at 0.4 %/y [1]. In the UK domestic energy consumption has risen from 35.6 Mt of oil equivalent to 48.5Mt in the period 1971 to 2001, an increase of 36%, despite energy efficiency increases [2]. The increase in energy consumption per household was less, at 5 %, over the same period, better reflecting the increase in energy efficiency in individual dwellings. However in the UK it is proposed that the number of houses built over the next 10 years should increase by 200,000/y, to account for the smaller number of people per household, and the demand for housing [3]. This will have serious implications for energy consumption and greenhouse gas emissions. To date the increase in energy consumption from individuals [2], dwellings, and buildings generally has been met by the burning of carbon based fuels, or in some cases, by the increase in nuclear power. Although renewable energy has seen a large increase, the contribution towards total domestic energy use is still small (in the UK 1.0 Mt of oil equivalent compared to a total use of 47.0 Mt of oil equivalent).

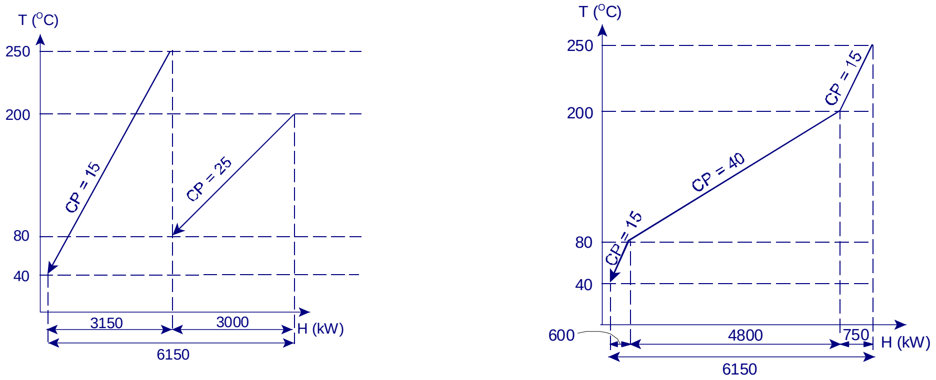
SUSTAINABLE ENERGY AND HEAT INTEGRATION

Heat Integration (or Pinch Technology/Process Integration) is an energy saving methodology that has been extensively used in the processing and power generating industry over the last 30 years. This method examines the potential of exchanging heat between heat sources and heat sinks via the use of heat exchangers and reducing the amount of external heating and cooling required. A systematic design procedure has been developed to provide the final energy reduction design of the system. The method has further been developed to specify the source of heating and cooling required (e.g. steam, hot water, cooling water) and also the potential of power production in the form of shaftwork or electrical production. More details are available elsewhere [4-9]. This methodology is based on the analysis and understanding of heat exchange between process streams through the use of a temperature-enthalpy diagram. The specific steps for drawing the curves in this diagram are presented in Figs. 1 - 3. The methodology first identifies sources of heat (termed hot streams) and sinks of heat (termed cold streams) in the process flowsheet. Tab. 1 presents a simple example.

Table 1 Sources (Hot) and Sink (Cold) streams

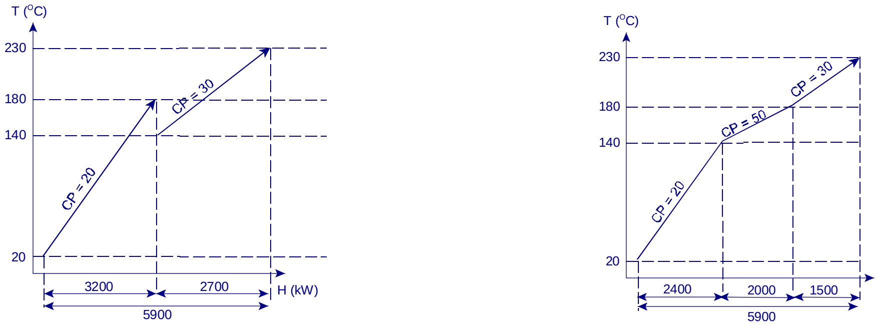
Stream	**Type**	**Supply Temp.** T_S (^oC)	**Target Temp.** T_T (^oC)	Δ**H** (kW)	**Heat Capacity Flowrate CP** (kW/^oC)
Fresh Water	Cold	20	180	3200	20
Hot Product 1	Hot	250	40	-3150	15
Juice Circulation	Cold	140	230	2700	30
Hot Product 2	Hot	200	80	-3000	25

Sources of heat can be combined to construct the composite hot stream (Fig.1) and sinks of heat can likewise be combined to construct the composite cold stream (Fig. 2).



(a) The hot streams plotted (b) The composite hot stream

Figure 1. Composing hot streams to create a hot composite curve



(a) The cold streams plotted (b) The composite cold stream

Figure 2. Composing cold streams to create a cold composite curve

The relative location of these curves on the temperature-enthalpy diagram is dependent on the allowable temperature difference for heat exchange. The next step is to select a minimum permissible temperature approach between the hot and cold streams, ΔT_{min}. The selection of the optimum ΔT_{min} is a result of an economical assessment and trade-off between the capital and operating costs (mainly for energy usage) of the process. A large ΔT_{min} implies higher energy use and costs and lower capital costs. For increasing energy cost the optimum ΔT_{min} is reduced, meaning the heat exchanger system is allowed to recover more energy, but at the expense of more capital to pay for the greater heat transfer area. This issue has been discussed in greater detail elsewhere – [10], [8], [11]. In this example a ΔT_{min} of 10 °C was selected for simplicity. Plotting the composite curves (CC) in the same graphical space (Fig.3) allows values to be derived for maximum heat recovery and minimum hot and cold utilities. These are known as targets. In this particular case of ΔT_{min} = 10 °C, the minimum hot utility requirement is 750 kW and minimum cold utility requirement is 1,000 kW.

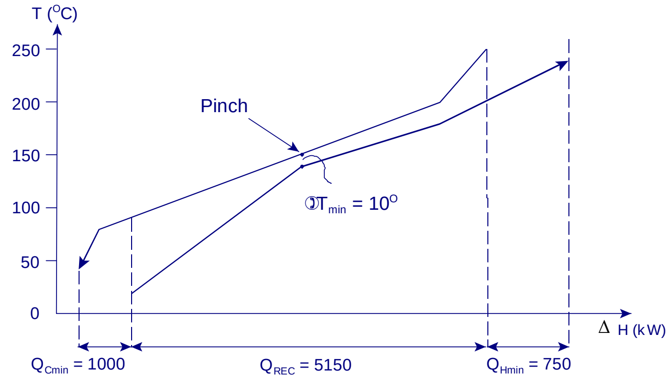


Figure 3. Plotting the hot and cold Composite Curves

In Fig.3 we can also determine the position of the Pinch. The Pinch represents the position where the hot composite and cold composite curves are at their closest (for a ΔT_{min} >0). The Pinch has provided the name for the Heat integration / Pinch Technology and has important features which make a substantial contribution to the design of maximum energy recovery systems and the design of economically efficient heat exchanger networks.

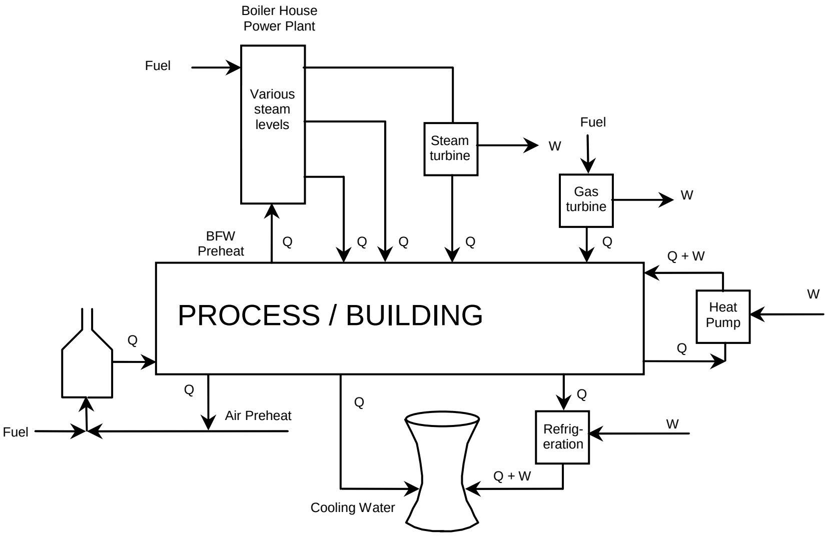


Figure 4. Potential for the choice of hot and cold utilities

Various design methods have been developed which allow these targets to be achieved in practice for both grass roots designs [4], and more importantly, for the retrofit of existing plants [12-14]. These methodologies are supported by process integration software which provides both design and retrofit support and automated design [15, 16]. In most cases there are more than one hot and one cold utility potentially providing heating and cooling requirements after energy recovery. In these situations we have to find and evaluate the cheapest and most desirable combination of the potential utilities that are available (Fig.4). To assist with this choice and to further enhance the information derived from the hot and cold CC, an additional graphical construction has been developed. This is known as the Grand Composite Curve (CC) and provides clear guidelines for the optimum placement and scaling of hot and cold utilities. The GCC together with the Balanced Composite Curves (the CC with the utilities selected added) provides a convenient tool for the optimum placement and selection of hot and cold utilities. An example of selection of utilities and its placement is shown in Fig. 5.

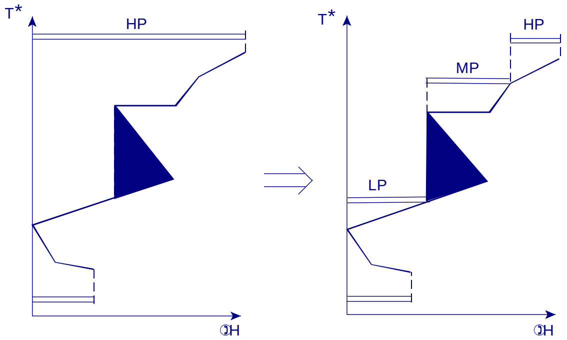


Figure 5. Placement of utilities with the help of GCC

The GCC is also a useful tool for targeting the cooling requirements in sub-ambient processes (such as air conditioning) which require some form of chilling or compression refrigeration. The GCC provides a target for the heat that has to be removed by a refrigeration process, and the temperature at which the refrigeration is needed. However, the overall process/utility system can be improved by using the heat rejected by the refrigeration system to provide low level heating to the process above ambient, thereby saving heat supplied by another utility source (such as hot water). The more detailed description has been provided elsewhere [17].

Traditional Heat Integration assesses the minimum practical energy needs for a process through a systematic design procedure involving five steps: (i) collection of plant data; (ii) setting targets for minimum practical energy requirements; (iii) examination of process changes that contribute to meeting the target; (iv) obtaining the minimum energy design that achieves the target and (v) optimisation which allows a trade-off between energy costs and capital costs.

EXAMPLES – CASE STUDIES

Hospitals are an example of building complexes which are important energy users, especially that of thermal energy. Although considerable research effort has been done to minimise the energy consumption in this sector, there are relatively few studies which apply Heat Integration (Pinch Technology) as a tool to evaluate potential energy savings and thereby reduce emissions.

Herrera et al [18] presented a study of a hospital complex which included an institute, a general hospital, a regional laundry centre, a sports centre, and some other public buildings. The use of diesel as a fuel represented 75% of its total energy consumption and 68% of its total energy cost which was 396,131 US$ in 1999. The hospital complex process diagram is shown in the Fig. 6. In the hospital complex, the heat demand is met by producing steam in boilers fuelled by a high price diesel fuel. There is no heat recovery between the existing heat sources and heat sinks. The hot streams were identified as the soiled soapy water from the laundry and the flow of condensed steam not recovered in the condensation network. The stream data are presented in Tab. 2.

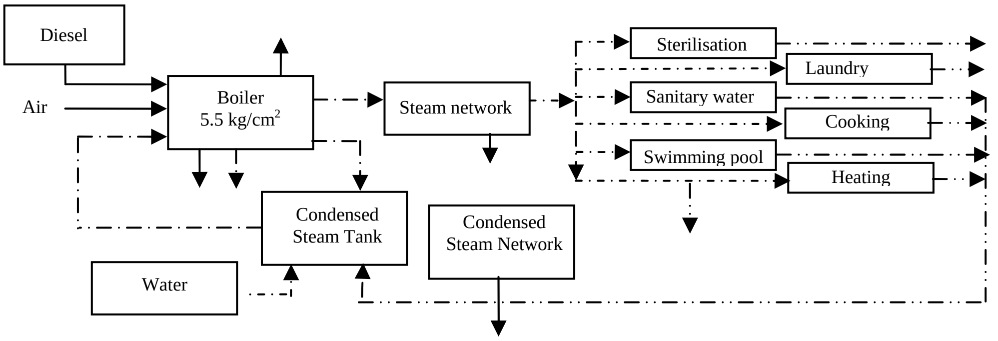


Figure 6. Hospital heat flow block diagram [15]

Table 2 presents the input data extracted from Fig 6.

Streams	**ΔH [kW]**	**CP [kw/°C]**	**Tin [°C]**	**Tout [°C]**
Hot Streams				
Soapy water (1)	23.7	0.53	85	40
Condensed steam (2)	96.32	2.41	80	40
Cold streams				
Laundry sanitary water (LS)	17.60	0.59	25	55
Laundry (L)	77.12	2.20	25	60
Boiler feed water (BF)	7.13	0.24	30	60
Sanitary water (SW)	77.12	2.20	25	60
Sterilisation (S)	12.50	0.14	30	121
Swimming pool water (SP)	151.67	50.56	25	28
Cooking (CO)	59.63	0.85	30	100
Heating (H)	100.82	14.40	18	25
Bedpan washers (B)	4.94	0.05	21	121

It needs to be noted that the CP represents mass flow m multiplied by the specific heat capacity Cp and in this case are considered constants. As can be seen from the CC (Fig. 7) the amount of external heating required, or the hot utility target, of this hospital complex is 388.64 kW. The GCC has been employed to determine the temperature levels of the utilities necessary to satisfy this requirement. This graphical method allows a more precise analysis to be undertaken in order to integrate the thermal utilities considered for the process heating and cooling requirements (Fig.8). This GCC indicates that the required heating of complex should be 388.64 kW. This means a yearly energy requirement of 12.26 TJ. The actual amount of heating provided is in fact 625.28 kW which represents the heat services that are currently transferred to the complex. This results in a potential energy savings of 38 % equivalent to saving 246,000 L of diesel/y (100,000 US$). To reduce energy demands in the form of heating to the value targeted by the analysis, the Heat Integration based analysis suggests that four extra heat exchangers should be added to the network. Two in the laundry to cover part of the heat demand, a third in the machinery rooms which help to heat boiler feed water, and the final one in the condensation tank area that heats the sanitary water. Several other issues could also have been considered to further refine the analysis, such as fouling, pressure drop and non constant heat demand.

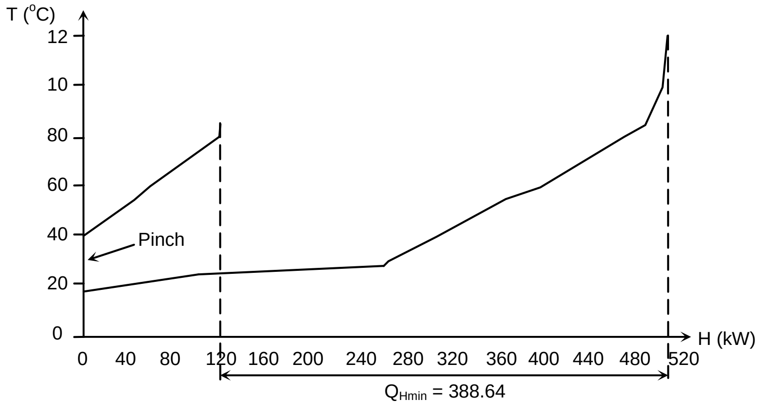


Figure7. CC for the hospital complex process streams

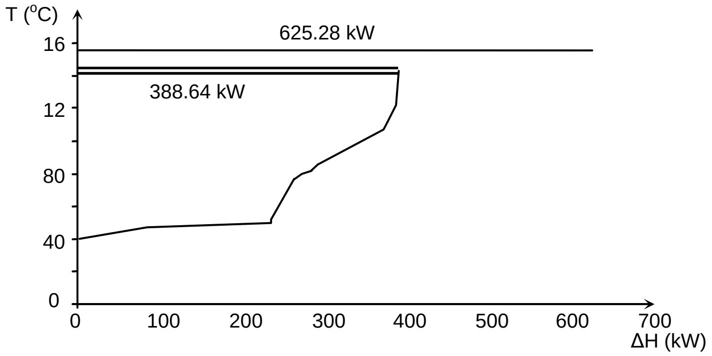


Figure 8. GCC of the hospital [15]

Kemp [9] presented a further more detailed case study of a hospital complex. The main energy demands were found to be space heating, air systems, general hot water supplies and other uses in the laundry and the incinerator. The main part of the complex was fully air conditioned. Central heating water was supplied at 80 °C, and returned at 71 °C and then reheated in a gas-fired calorifier. Tap hot water was also provided.

Table 3 Heat requirements and time distribution required during winter

Stream details and locations	No of streams	Hot streams total		Cold streams total		Times of operation
		Temp (°C)	Heat load (kW)	Temp (°C)	Heat load (kW)	
Main air supply	35	20-15	43	5-37	780	24 h: Day
	33	20-15	27	2-37	681	24 h: Night
Space heating	2			71-80	709	24 h: Day
	2			71-80	665	24 h: Night
Domestic hot water	1			5-60	244	24 h: Day
	1			5-60	48.5	24 h: Night
Autocalves	1			162	13	24 h
Kitchen	1			5-30	101	0530-0200
Laundry	3	37-30	67	18-26, 162	797	0700-1630
Incinerator	1	600-217	650			0900-1630
Boilers	1	235-60				24 h
Summary						
Maximum load			760		2,644	0900-1630
Minimum load			27		1407	0200-0530

In some areas (e.g. kitchens) the heat use varied considerably between day and night time. The identified streams are shown in Table 3. Energy use in winter for day time conditions was found to be 2534 kW (all hot utility) whereas in summer this value dropped to 1030 kW (hot utility) and 207 kW (cold utility) as space heating was replaced by air conditioning and the use of some refrigeration. Kemp [9] presented the GCC for the peak demand during winter (7− 9am period). Heat integration analysis of these different time periods provided various schemes for improvement. The first involved rescheduling. This took into consideration the possibility of changing the periods of high utility demand. Suggestions were (i) Moving a cold stream active in 7-9am period to a different time; (ii) Moving a hot stream not operating in 7-9am period to operate during this period. As it was not possible to shut down the central heating or air conditioning systems for this high demand 2 h period, an alternative was that laundry operations could be rescheduled to start 2 h later but finish at the usual time. This would result in the installation of new machines at a high capital cost. For the second suggestion is would be possible to start the incinerator at 7am and run it for a further 2 hours. Retaining the current waste disposal value would result in a reduced exhaust flow rate and heat recovery rate. The daytime total heat recovery would be the same, but one less boiler would be required. It was also found that additional municipal waste could be delivered and that the incinerator could be run at full power over 24 hours. The Heat Integration methodology also investigated the benefits of introducing CHP. The GCC shows that the hospital is represented by four different temperature ranges which were the laundry and autoclaves (160-170 ^{o}C), space heating (80-85 ^{o}C), domestic hot water (up to 70 ^{o}C), and air heating (10-40 ^{o}C). The heat from the jacket cooling water and exhaust gases could be recovered and be suitable for the space heating system. Standby diesel generators already installed to supply emergency power would be a cheaper option to convert than to provide heat and power from a new diesel generator. These would then provide about 50 % of the peak heat demand. Further options would be to install a micro gas turbine of around 1.5 MW. This would provide all power requirements and the majority of the peak demands. Maintenance for a single source heat and power supplier would leave the hospital complex in a vulnerable state.

Several other case studies have been reported by Linnhoff March Ltd. [19]:
a) A study with the code name BRECSU/BDP was an attempt to define the energy-efficient hospital of the future. LM Ltd looked at all aspects of hospital heating including space heating, ventilation air heating, hot water heating and sterilisation. For hot streams available for heat recovery LM looked at ventilation extraction air, drainage and incinerator flue gas. The major opportunities on an existing building were be in the utility area. There was much detail in the study, including heat generated by the patients in the day (active) and night (sleeping). The work demonstrated that, for a complex new building like a hospital, potential existed for heat recovery between extract and inlet air systems and for heat pumping from the drainage system. The most economic form of heat recovery was from the incinerator exhaust and they also concluded that the optimum utility system would be CHP.
b) Eastbourne Hospital. The largest saving found was in the laundry where dryer exhaust could heat water and fresh air for the dryers and hot dirty wash water could heat fresh water (with storage). A heat engine-based CHP scheme was recommended but this would affect the laundry recommendations because it would provide the necessary hot water.

CONCLUSIONS

Heat Integration (or Pinch Technology) has been used for 20 years in industry throughout the world to increase energy efficiency of any processing plants that have heating or cooling requirements, and also have needs for power to provide electricity or directly drive machinery. Energy savings of over 30% have been recorded, and the methodologies developed have been incorporated into the design offices of all major producing companies. The same methodologies and design rules can also be applied in buildings or their complexes. Examples of two complexes have been given. It is clear that as energy efficiency in buildings and the reduction of emissions becomes a standard issue in existing and new complexes, further examples of heat integration application will be carried out.

ACKNOWLEDGEMENT

The support from EC TREN/05/FP6EN/S07.54455/020114 Project "Network for promotion of Eco-building technologies, small Polygeneration, and renewable heating and cooling technologies for buildings – ProEcoPolyNet" (PEPNet) has been gratefully acknowledged.

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