CHEMICAL ENGINEERING TRANSACTIONS

VOL. 29, 2012

A publication of AIDIC

The Italian Association of Chemical Engineering

Online at: www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš

ISBN 978-88-95608-20-4; **ISSN** 1974-9791

DOI: 10.3303/CET1229011

Potential of Total Site Process Integration for Balancing and Decreasing the Key Environmental Footprints

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Process Integration allows for the optimising of those industrial processes integrated within other sectors, such as residential, business, service, and even agricultural. In general, the multiple goals involved within the optimisation of Total Site system design are: thermodynamic, economic, technical, and environmental criteria. As a result of growing concerns about environmental problems over recent years, the design criteria for modern Total Sites and other systems need to consider, besides the economic or technical, those environmental requirements from the life-cycle perspective. This paper presents the potential of Total Site process integration in order to reflect the key environmental footprints, including carbon, water, and nitrogen footprints. It is illustrated using a case study of locally integrated energy sectors.

1. Introduction

The reductions in the amounts of energy and water within various, not only industrial sectors, provide significant potential for optimisation (Siemens AG, 2012). The majority of industrial plants throughout the world use up to 50 % more energy than necessary (Alfa Laval, 2011). Water-saving measures and the reuse of water could reduce groundwater consumption by as much as 25 – 30 % (Klemeš et al., 2010). Most processes operate within Total Sites (TSs) where they are usually integrated within certain levels via common central utility system and power systems, and many also by other carriers such as pressurised air. TS integration maximises the energy recovery between processes by reducing fuel and other natural resources' consumption, greenhouse gas emissions, and other negative environmental impacts. The sustainability of TSs can also be considerably improved by using renewable energy sources (Klemeš et al., 2010).
The standard design criteria for modern TS systems so far has been economic in nature, however, it should now also deal with environmental requirements. Not only the annualised capital and operating costs (total annual cost), but also the corresponding direct and indirect waste has to be minimised (Chang and Hwang, 1996). Recently, the indicators for sustainable development (footprints) and their combinations have attracted attention and are being presented elsewhere (Čuček et al., 2012a). They are predominately defined on a life cycle basis (De Benedetto and Klemeš, 2009), and can provide evaluation and, in some cases, even measurement units of environmental, social, and economic impacts (Čuček et al., 2012a). Some of them, as e.g., carbon (CF) and nitrogen footprints (NF), can even form adversarial relationships between them (Čuček et al., 2012b). CF is defined as the amount of C emitted over the full life cycle of a process, product or activity, and causes an imbalance within the C cycle (Čuček et al., 2012a). Excessive N emissions cause an imbalance within the N cycle, and NF

Please cite this article as: Čuček L., Varbanov P. S., Klemeš J. J. and Kravanja Z., (2012), Potential of total site process integration for balancing and decreasing the key environmental footprints, Chemical Engineering Transactions, 29, 61-66

is defined as a measurement of the amount of reactive N released into the environment as a result of human activities (Leach et al., 2012) and has been reviewed in Čuček et al. (2012b). Water footprint (WF) represents the total volume of direct and indirect fresh water used, consumed, and polluted. It consists of blue, green, and grey WFs. Blue WF represents the consumption of surface and ground water, green WF the consumption of rainwater, and grey WF the volume of water required to dilute pollutants to water quality standards (Mekonnen and Hoekstra, 2010; Klemeš et al., 2009).

2. Analysis of footprints on the heating side

Process heat is generated in steam boilers, directly-fired heaters, gas turbines, or furnaces. Steam and hot water are the common media for conveying heat energy. Boilers can generate steam or hot water by using fuels (natural gas – NG, fuel oil, coal, biomass, and waste), air, water, and electricity. They all require fuel for heating the pre-treated water and generating steam, and the electricity for operating the mechanical equipment (Kim et al., 2010). The pollution problems associated with the combustion of fuels can be mainly attributed to gas emissions (CO_2, CO, NO_x, N_2O, CH_4, and SO_x) and ashes.

CF and NF mainly relate to direct emissions during the operation of a boiler, and are more or less proportional to the fuel consumption. Waste heat recovery often leads to significant fuel savings, and thus emissions are generally reduced. CF and NF are also associated with the exploration, extraction, transportation, refining, purification, regional distribution of fossil fuels, and leakages during production and transportation. WFs are connected to the used energy carriers. NG has a relatively small WF of 0.11 m^3/GJ, the WF of coal is 0.16 m^3/GJ, and that of crude oil is 1.06 m^3/GJ (Gerbens-Leenes et al., 2008). Biomass shows a larger difference in its WF. The WF of biomass is 70 to 400 times greater compared to coal, crude oil, NG or uranium (Gerbens-Leenes et al., 2008). Blue WF on the heating side is also related to boiler feed water, whilst grey WF is connected with impure water (boiler blow-down, water-side boiler cleaning). Boiler blow-down is required to prevent the build-up of solids in the boiler that would otherwise cause fouling and corrosion within the boiler (Smith, 2005). In order to calculate the blow-down, the cycles of concentration for the boiler (and the cooling tower) are used. In industrial practice they normally range from three to seven (Ahmetović et al., 2010).

3. Analysis of footprints on the cooling side

Process heat is usually rejected in cooling towers, air-cooled heat exchangers, chilled water systems, refrigeration systems (closed-loop cooling systems), etc. Another way of rejecting heat is through the use of water in once-through cooling systems (open-loop cooling) (Smith, 2005). The once-through cooling systems (open-loop) demand the largest share of freshwater withdrawal from amongst all the cooling systems. However, with increased freshwater conservation efforts, the selection of open-loop cooling for new utility plants is unlikely (Wu and Peng, 2011). Recirculating cooling water systems is the most common method used for heat rejection regarding the environment (Smith, 2005). Many plants have environmental constraints in terms of how much cooling water can be taken from a river, and/or the temperature limitations of the returned water (Alfa Laval, 2012).

The freshwater requirements for closed-loops regarding cooling water consist of evaporation, drift and windage losses, and blow-down in cooling towers. Reduced needs for cooling water means reduced needs for water treatment chemicals (Alfa Laval, 2012). Adopting techniques for minimising both water consumption and wastewater discharge can considerably reduce the demand for freshwater, and also the amount of effluent generated during processing (Klemeš et al., 2010).

4. Additional footprints for Total Site Analysis

Additional footprints within TSs are related to fluid (steam, hot water, hot oil...) distribution systems. The fluid distribution system is an essential link between the central fluid source (boiler house, cogeneration plant) and the fluid users. It consists of a boiler unit, thermal energy accumulators, pipelines, insulation, fittings, valves, pumps, heat emitters, a control system, and water treatment units. The quality and pressure of the fluid is supplied to the fluid-using equipment in the correct capacity. Steam pressure and pressure losses should be taken into account. The pump has to compensate for

any loss of pressure in the system. The installation and maintenance of the steam system are also important issues.
Footprints are associated with the manufacturing and transporting of a TS utility system (boiler, cooling tower, and fluid distribution system), the manufacture of machinery, excavation of ditches, and human labour. In addition, the consumption of electricity for pumping, fans, and conveyors, adds significantly to various footprints, depending on the source of electricity production. However, they were not considered during the simplified case study, as shown in the subsequent section.
CF and NF are almost certainly mainly related to carbon and nitrogen emissions relating to electricity consumption for pumps, and they strongly depends on the source of electricity production. The specific CO_2 emissions for electricity mixes vary considerably, and within the range of 9 – 1,100 kg/MWh. Also cumulative NO_x emissions vary considerably, from 50 to 4,700 g/MWh (Dones et al., 2007; PE LBP, 2012). The electricity required for operating equipment is also a major contributor to WFs. The highest WFs are for electricity from biomass (24 – 143 m^3/GJ) and from hydropower (22.3 m^3/GJ), whilst the WF for electricity from wind energy is negligible (Gerbens-Leenes et al., 2008). There is also a freshwater requirement that consists of steam and condensate losses.

5. Demonstration case study

The key environmental footprints, CF, NF and WF were evaluated during a demonstration case study of TS consisting of industrial, service, and domestic sectors. It was assumed, that only thermal energy was generated from the utility system (heat-only boiler). The heat was assumed to be transferred from one process to another via a carrying medium, steam or hot water. A TS analysis for fixed demand and supply was assumed, as in Perry et al. (2008).

5.1 Description

A case study of Locally Integrated Energy Sectors - LIES (Perry et al., 2008) based on TS methodology (Klemeš et al., 1997), was applied to illustrate the footprint-based evaluation of the various environmental impacts within TS. In LIES, heat sources and sinks can be derived from small-scale industrial plants, large building complexes (such as hospitals), offices, and residential dwellings. Two small-scale industrial processing plants (Plants A and B), a hospital complex (Plant C) and a group of residential complexes (Plant D) were included within the case study. The data for the LIES were taken from Perry et al. (2008). Without integration the LIES would need to dispose of around 6.2 MW of heat via cooling water. Around 17.5 MW of heat would have to be supplied from external fuel combusted within a boiler. The scenario for integration (Scenario α by Perry et al. (2008)) is shown in Figure 1.

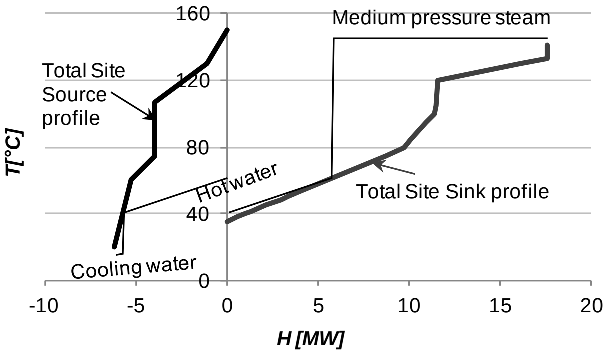

Figure 1: TS Composite Curves (after Perry et al., 2008)

In this scenario, hot water at a temperature of 60 – 40 °C (see Figure 1) was provided for extracting heat from the TS Source Profile and supplying heat to the TS Sink Profile, as in Perry et al. (2008). The integration enabled heat reduction of 5.5 MW. The external heat required (about 12 MW) at around 150 °C was provided by a boiler, and waste heat (about 0.7 MW) was disposed of either by using a cooling tower or once-through cooling water. In the case of the TS heat integration, the supplier of hot water was Plant A, and the recipients of the heat are Plants C and D.

5.2 Footprint evaluation

CF, WF, and NF for TS non-heat integrated (NTSI) and TS heat integrated (TSI) LIES were evaluated. Different energy sources, fossil and renewable, that provided the required external heat, were evaluated in terms of key environmental footprints. Also, two different cooling systems were taken into account, the open-loop (once-through cooling) and the closed-loop cooling system (cooling tower). It should be noted, that the footprint-evaluation during the demonstration case study focused on the heating and cooling sides. Additional footprints for TS analysis have not presently been evaluated. The energy losses were outside the boundaries of the system. The data relating to energy and water use are presented in Table 1. The data relating to fuels used for heating the TS are shown in Table 2.

Table 1: Data relating to heating and cooling needs

	NTSI	TSI
Site utility and its temperature levels (°C)	MP steam (150) Cooling water (15-30)	
Required heat (MW)	MP steam: 17.5	MP steam: 12.1
Disposed heat (MW)	Cooling water: 6.2	Cooling water: 0.7
MP steam (kg/s)	8.28	5.72
Cooling water (CW) (kg/s)	98.65	11.14
Boiler make-up water (kg/s)	2.07	1.43
Cooling tower make-up water (kg/s)	3.03	0.34

Table 2: Characteristics of fuels and their required flow-rates

	Coal	Natural gas (NG)	Fuel oil	Wood
Calorific value (MJ/kg)	28	52	40	14.4
Boiler efficiency (%)	90	90	90	90
Fuel required (kg/s) – NTSI	0.694	0.374	0.486	1.350
– TSI	0.480	0.259	0.336	0.933

This simplification assumed that there were no steam and condensate system losses, that there were five cycles of concentration, and the drift and windage losses were of 0.2 %. Evaporation loss in the cooling tower was estimated using empirical correlation:

$$0.00085 \cdot q_{m_{CW}}\,(\mathrm{m^3/h}) \cdot (T_{in} - T_{out}) \cdot 1.8 \quad \text{(Perry et al., 1997)}$$

Water leakage, reuse of treated water, and grey WF for boiler and cooling tower makeup water had not been assumed during this simplified case study. Footprints relating to materials, the constructions of the process equipment (boiler, cooling tower, heat exchangers, pumps, pipes, water treatment units, etc.), were assumed to be relatively small, since they are used over an entire life-time, 35 y (Shah et al., 2008) or more. Pipelines and buildings were assumed by Peters and Rouse (2005) to last 100 y, concrete tanks 150 y, and reservoirs 200 y. However it was rather doubtful whether the related process would be operational, and the need for the pipelines and buildings would continue for some considerable time. Footprints associated with human labour, transportation, and disposal were omitted for reasons of simplification.

5.3 Results and discussion

CF, NF, and WF originating from the heating of LIES are presented in Figure 2a for NTSI, and in Figure 2b for TSI. It can be seen that TSI performed significantly better than NTSI in terms of CF, NF, and WF. Also, the closed-loop system using a cooling tower was preferable. It can be seen that NG showed the lowest NF and WF, whilst wood the lowest CF, considerably lower than other fuels. On the cooling side, the WF for the NTSI amounted to 98.65 kg H_2O/s for an open-loop alternative, and 3.03 kg H_2O/s for a closed-loop alternative, whilst for the TSI WF was 11.14 kg H_2O/s for open-loop, and 0.34 kg H_2O/s for closed-loop alternatives. It can be seen that WF could be significantly reduced when TSI and closed-loop cooling systems were applied. CFs were within the range of 0.02 – 0.84 kg C/s, NFs within the range of 0.19 – 1.28 g N/s, and WFs from 0.34 to 98.65 kg H_2O/s.

As during this simplified case study, only footprints on heating and cooling sites were evaluated, the overall conclusions could be different if also additional footprints were taken into account.

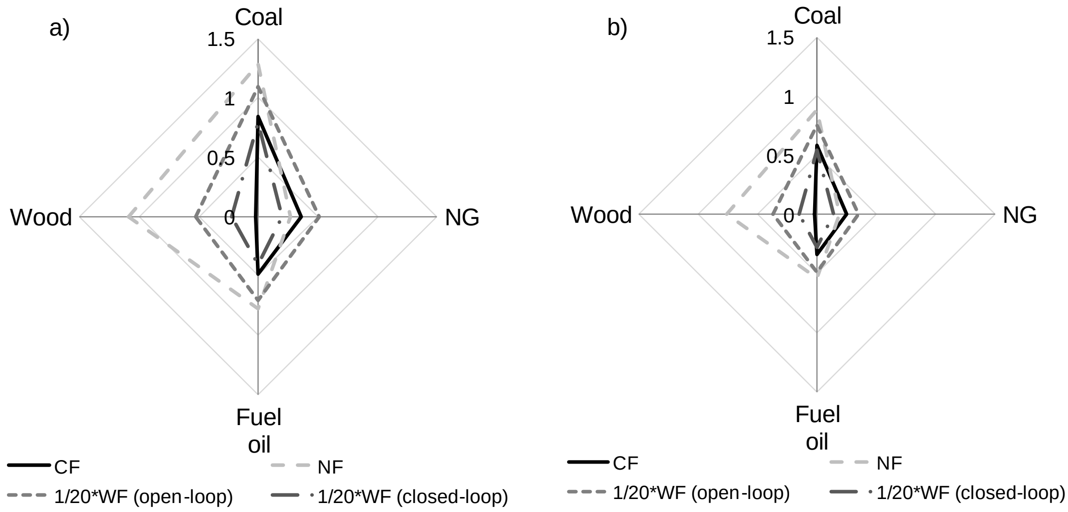

Figure 2: Trade-offs between footprints for a) NTSI and b) TSI

6. Conclusions and future work

In the presented contribution, a procedure was formulated for evaluating the key environmental footprints – CF, NF, and WF for heating and cooling sites, and heat distribution systems.
The demonstration case study showed the potential for evaluating and reducing footprints' magnitudes when applying TSs. However, in order to be able to achieve appropriate trade-offs between the NTSI and TSI alternatives, all footprints relating to energy, water, equipment use, etc., should be taken into account. The presented paper has been a first step in this direction - towards balancing and reducing key environmental footprints within TSs. Using the obtained indicator values, engineers can more easily decide on the directions of potential improvements to the sites – within various site processes as well as in the utility system.
For future work, additional footprints originating from TSI need to be evaluated. The other renewable technologies will then be included within case studies, such as solar water heating, heat pumps, and geothermal heat, and accounting for the temporal variations in their supplies. Also, fluctuation of energy demand, especially on the service and residential sites, will be taken into account (Varbanov and Klemeš, 2011). In order to achieve even more environmentally-friendly designs, combined heat and power (CHP) production plants would be tested, and compared with heat-only boiler systems.

Acknowledgement

The financial support is gratefully acknowledged from the EC FP7 project "Design Technologies for Multi-scale Innovation and Integration in Post-Combustion CO_2 Capture: From Molecules to Unit Operations and Integrated Plants" – CAPSOL, Grant No. 282789, from the Hungarian project Társadalmi Megújulás Operatív Program (TÁMOP) 'Tudományos képzés műhelyeinek támogatása' TÁMOP-4.2.2/B-10/1-2010-0025, and from the Slovenian Research Agency (No. P2-0032).

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