Journal of Cleaner Production 18 (2010) 848–856

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A graphical representation of carbon footprint reduction for chemical processes

Wendy Tjan [a], Raymond R. Tan [b], Dominic C.Y. Foo [a,*]

[a] Department of Chemical and Environmental Engineering, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia
[b] Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines

A R T I C L E I N F O

Article history:
Received 28 August 2009
Received in revised form
2 December 2009
Accepted 3 December 2009
Available online 21 December 2009

Keywords:
Carbon footprint
Cleaner production
Pinch analysis
Process integration

A B S T R A C T

Climate change has recently become a major focus for industry and government agencies. Some recent works have been reported on the use of pinch analysis techniques for carbon-constrained energy planning problems. This paper discusses a new application of graphical technique based on pinch analysis for company-level visualization and analysis of carbon footprint improvement. The technique is based on the decomposition of total carbon footprint into material- and energy-based components, or alternatively, into internal and external components. The decomposition facilitates the evaluation and screening of process improvement alternatives. Two industrial case studies on the production of phytochemical extracts and bulk chemicals are used to illustrate the new extension.

1. Introduction

In recent years, public concern about climate change has grown significantly. Emissions of greenhouse gases such as carbon dioxide, methane and nitrous oxide from industrial activities have long been known to be major contributors to global warming. This trend has led to significant interest in the increased use of energy technologies with inherently low-carbon footprints (e.g., renewable energy sources such as wind, solar or biomass) as well as in retrofitting of existing ones (e.g., via carbon capture and storage) to reduce greenhouse gas emissions. At the same time, there has been increased research on the development of new modelling techniques to analyse and simulate the effects of these technologies on carbon emissions, and furthermore to optimise the deployment of appropriate technologies in order to meet environmental goals while simultaneously considering technical and economic constraints.

A number of papers have recently been published on the use of *pinch analysis* techniques for such applications. Pinch analysis techniques date back to early work in the 1970's on the systematic design of heat recovery systems (Linnhoff et al., 1982; Smith, 1995). Even though these early applications focused on the economic implications of energy savings, the enhanced energy efficiency also contributes significantly to the emission reduction of process plants. Further applications were demonstrated also on the analysis of emissions for total sites (Dhole and Linnhoff, 1992; Linnhoff and Dhole, 1993; Klemeš et al., 1997). In the late 1980's, mass integration techniques were developed based on the analogies between heat and mass transfer (El-Halwagi and Manousiothakis, 1989; El-Halwagi, 1997, 2006). The work concept was later extended to water and hydrogen network synthesis (Wang and Smith, 1994; El-Halwagi et al., 2003; Manan et al., 2004; Prakash and Shenoy, 2005; Ng et al., 2007a,b) and property integration (Kazantzi and El-Halwagi, 2005; Foo et al., 2006). These various pinch analysis techniques include graphical and algebraic approaches. While the former provides good insight for system analysis, the latter is powerful in determining rigorous solution rapidly.

More recently, pinch analysis concepts were extended to applications involving management of CO_2 emissions from industrial systems. Tan and Foo (2007) developed the first approach on the use of pinch analysis technique for carbon-constrained energy sector planning, or in short *carbon emission pinch analysis* (CEPA). The method assumes that within the system, there exists a set of energy sources, each with a specific carbon intensity that is a characteristic of the fuel or the technology; and a set of energy demands, where each demand has a specified carbon footprint limit. Under the assumption that the various energy sources are fully interchangeable, the original problem was to minimise the amount of zero-carbon energy sources (i.e., renewable energy or non-combustion based sources such as nuclear or geothermal power) needed in order to satisfy the specified carbon footprint limits. The original technique made use of the *energy planning composite curves* similar to those used for water recovery

* Corresponding author. Tel.: +60 3 8924 8130; fax: +60 3 8924 8017.
E-mail addresses: wendy.tjan@gmail.com (W. Tjan), raymond.tan@dlsu.edu.ph (R.R. Tan), dominic.foo@nottingham.edu.my (D.C.Y. Foo).

0959-6526/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jclepro.2009.12.002

(El-Halwagi et al., 2003; Prakash and Shenoy, 2005) to determine the minimum amount of zero-carbon energy sources (Tan and Foo, 2007). The basic technique has then been applied for energy planning purposes in Ireland and New Zealand (Crilly and Zhelev, 2008a; Atkins et al., 2010). The latter work (Atkins et al., 2010) presents an interesting extension that takes into account the growth in energy demand within a sector over time.

The next development in CEPA was the use of an equivalent algebraic approach to solve similar problems (Foo et al., 2008). The extension is based on the established equivalence between graphical techniques (El-Halwagi et al., 2003; Prakash and Shenoy, 2005) and numerical ones (Manan et al., 2004). Furthermore, it was soon recognised that the assumption of zero-carbon technologies had to be relaxed, as even non-combustion based technologies had small carbon footprints when life cycle considerations are taken into account. Hence, a subsequent paper published recently (Lee et al., 2009) accounts for such low-carbon technologies by allowing the composite curves to be shifted diagonally along a shallow locus, rather than horizontally as in the original method (Tan and Foo, 2007). At the same time, two other new elements were proposed in Lee et al. (2009). The authors reformulate the CEPA targeting technique as a linear programming model that minimise the amount of zero- or low-carbon sources in an automated way. Furthermore, the concept of *segregated targeting* was introduced, in which not all energy sources can be used interchangeably by the demands (Lee et al., 2009). Recently, a new decomposition algorithm was also developed to solve the segregated targeting problem (Bandyopadhyay et al., in press). These methodologies have all been developed based on the concept of carbon intensity as the "quality" index for energy streams. Alternative applications have also been proposed using different quality indices for biomass-based energy, including land area (Foo et al., 2008) and water footprint (Tan et al., 2009a), as well as emergy (Bandyopadhyay et al., in press; Crilly and Zhelev, 2008b). Another recent extension in this area is for the planning of minimal retrofit of power plants for carbon capture and storage (Tan et al., 2009b), whereby pinch analysis is used to determine the minimum extent of retrofit needed across regional power plants in order to meet an overall carbon footprint target.

This work presents an extension of the CEPA approaches for evaluating and visualizing carbon footprint reduction options in chemical processes. Different strategies may be available to a given company to achieve the desired reduction in carbon footprint, ranging from management-based (e.g., material selection or selective procurement of inputs from suppliers based on carbon footprint) to technology-based solutions (e.g., process retrofits for energy conservation, heat recovery, on-site combined heat and power generation, etc.). In practice, it is essential to be able to identify the most promising approaches to prioritise for implementation. In the following section, the general methodology to allow for visualization of carbon footprints to facilitate such decision-making is outlined. The technique is then demonstrated using two industrial examples.

2. New application of CEPA for carbon footprint reduction in chemical processes

This section briefly outlines a novel application of CEPA to determine strategies in reducing carbon footprints in chemical processes. The latter measures the total emissions generated, taking into account an *internal* component (generated within the company itself) and an *external* one (generated upstream of the company by its supply chain). Alternatively, the total footprint may be segregated into a *material-based* component (embedded in the raw materials used by the process plant) and *energy-based* component (arising from various energy inputs of the plant, including fuels and electricity). The concept is closely linked to life cycle assessment (LCA) and may be viewed as a simplified form of the latter (De Benedetto and Klemes, 2009; Weidema et al., 2008). A graphical technique has been proposed for visualizing carbon footprints of companies (Tahara et al., 2005) that resembles the appearance of the energy planning composite curves (Tan and Foo, 2007), but which does not explicitly make use the principles of pinch analysis. A revised methodology is proposed here to combine these prior concepts using the *carbon footprint composite curves*.

The total carbon footprint of a company consists of components which can be segregated depending on the purpose of the analysis. For some applications, it may be useful to base the segregation into the internal and external components, while in other cases it may be more suitable to use the material-based and energy-based components instead. At the same time, the value of goods produced in an industrial process consists of the value of the inputs (raw material), plus the value added internally by the plant itself. The ratio of the carbon footprint to the economic value is termed as the *carbon intensity*. In general, the carbon intensities of the internal

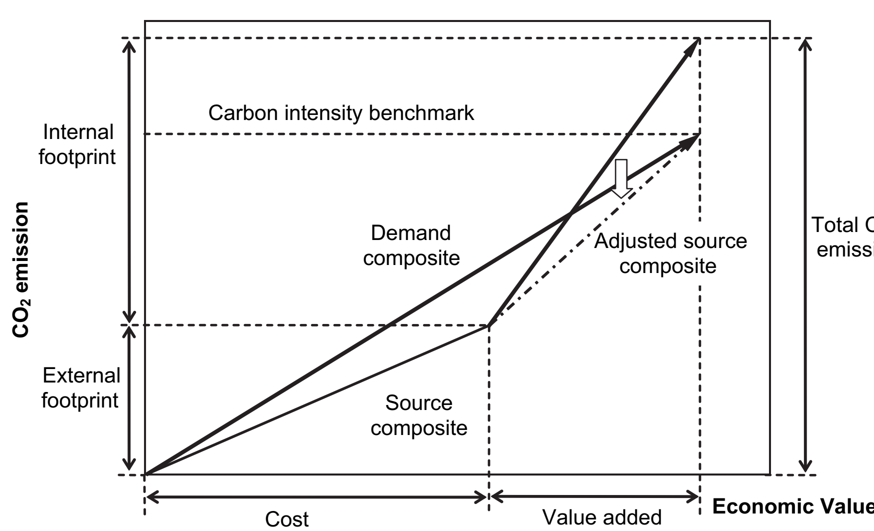

Fig. 1. Carbon footprint composite curves (Scenario 1).

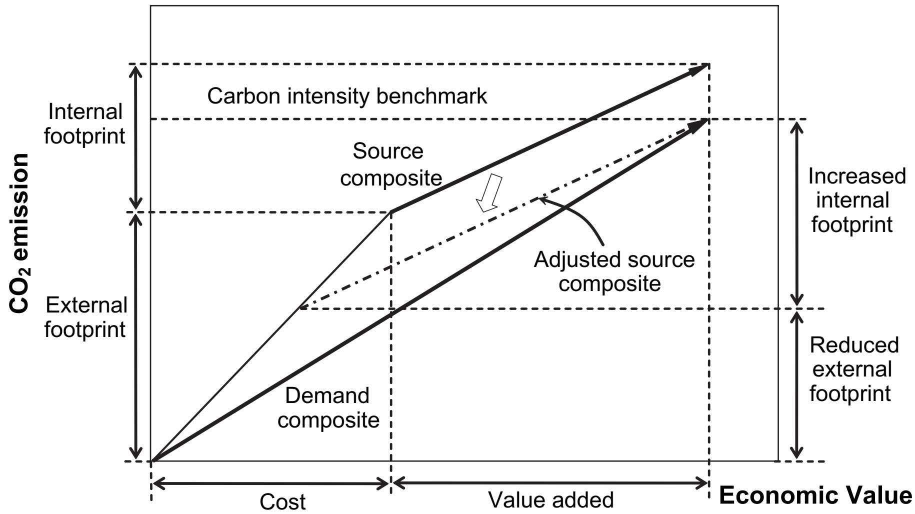

Fig. 2. Carbon footprint composite curves (Scenario 2).

and external components (or material- and energy-based) need not be the same. These components can thus be plotted as the *source composite curve* in Fig. 1, using the same approach as in the original CEPA technique (Tan and Foo, 2007), with economic value along the horizontal axis and CO_2 emissions on the vertical axis. Note that we apply the convention of plotting the external component first, as shown in Fig. 1. If a diagonal line is drawn from the origin to the terminal point of the source composite curve, the slope of the line is equivalent to the overall carbon intensity of the process, combining both internal and external component (Tahara et al., 2005). Note also that the composite curves will look similar if material- and energy-based components are plotted.

Next, it is assumed that a benchmark carbon intensity goal is set, which is lower that the current total carbon intensity of the plant. This goal may be based on industry standards, competitive benchmarking, or internal company choices (i.e., based on ad hoc management decisions), and may act as a *demand composite curve* (Fig. 1). The problem is for the company to determine general strategies to reduce its carbon intensity from the current level to the desired value.

Two scenarios are considered here, using the carbon footprint composite curves plotted based on internal and external components. In Scenario 1, if the external carbon intensity (represented by its slope of the segment) is lower than the internal one, such as that shown in the carbon footprint composite curve in Fig. 1, the appropriate strategy is to reduce the internal carbon footprint of the plant. Graphically, the result is a reduction in the slope of the internal footprint segment of the source composite curve, until it touches the demand composite curve. Thus, it is possible to see how much the internal carbon intensity needs to be reduced to meet the benchmark level.

In Scenario 2, the external carbon footprint has a much higher intensity than the internal one (Fig. 2). The source composite curve now lies completely above the demand composite curve that denotes the benchmark value for carbon intensity. In this case, the appropriate strategy for the plant is to reduce the length of the external footprint segment. This is equivalent to shifting the internal footprint component diagonally, along the external footprint segment of the source composite curve. The shifting is done until the tip of the composite curve touches the carbon intensity benchmark, as shown in Fig. 2. As a result, the external footprint of the product is reduced, corresponds to the increase of the internal footprint (see Fig. 2). In practical terms, this implies that companies with low internal carbon footprints can best reduce their carbon intensity simply by reducing the use of external inputs per unit of product, as these inputs contain embedded carbon footprints that become part of the overall footprint of the plant. It can easily be seen that these principles still apply equally well if the total carbon footprint is decomposed into material- and energy-based components instead. However, in some cases, the carbon footprint reduction goals cannot be easily achieved with the proposed simple strategies, hence hybrid strategies that involve the modification of both segments are needed. This will be illustrated in one of the following case studies.

3. Industrial case studies

Two industrial case studies are considered in this paper, which involve the production of Tongkat Ali extract and chlor-alkali chemicals, respectively. The former case study is based on the pilot plant production in a university research centre (Athimulam et al., 2006; Kuan et al., 2007), while the latter is taken from an industrial chlor-alkali plant located in Malaysia. As per request of the company, the details of the processes are kept confidential. However, the relevant features of the process used here are sufficiently realistic to be applicable in similar facilities. The total economic values used in the case studies are based on operating costs, that are in turn computed from average purchase costs and quantities of major process inputs (i.e., energy and raw materials) from existing plant records.

The carbon footprint of each plant in the case studies is first categorised into material- and energy-based components. For the former, an estimation aggregate carbon intensity of 2 kg of CO_2 generated for every US$1 worth of inorganic chemical input is used. This value is estimated using an online LCA tool accessible

Table 1
Carbon footprint of Malaysian power mix (Lim, 2009).

Energy source	Contribution (%)	Carbon intensity (kg CO_2/kWh)	Overall carbon footprint (kg CO_2/kWh)
Natural gas	50	0.5	0.25
Coal	35	1	0.35
Hydropower	14	0.1	0.014
Oil	1	0.8	0.008
Overall mix	100	0.662	0.662

via http://www.eiolca.net/ (Hendrickson et al., 2006). Although both of the plants are not situated in the United States, the technology used is presumed to be sufficiently similar to allow the use of this approximation throughout the case study. Thus, the values based on such life cycle data provide a representative approximation for aggregated inputs into the plants, even though in practice these chemicals are imported from different countries. Such data limitations are common in life cycle assessment (De Benedetto and Klemes, 2009; Tan, 2008). This approximation is also a necessary aspect of the graphical approach used here, while for detailed analysis a numerical approach may be used instead (Hendrickson et al., 2006). Nevertheless, uncertainty analysis techniques such as fuzzy numbers, sensitivity analysis or Monte Carlo simulation may also be utilised to assess how data assumptions affect the final solution found using the aggregated data (Tan, 2008). However, these are beyond the scope of this work, and hence are not considered here.

On the other hand, the energy-based footprint can be further segregated into two different subcomponents, i.e., internal and external footprints. Internal footprint is contributed mainly by fuel combustion for steam generation (within the plant premises), while the external footprint is contributed mainly by electricity,

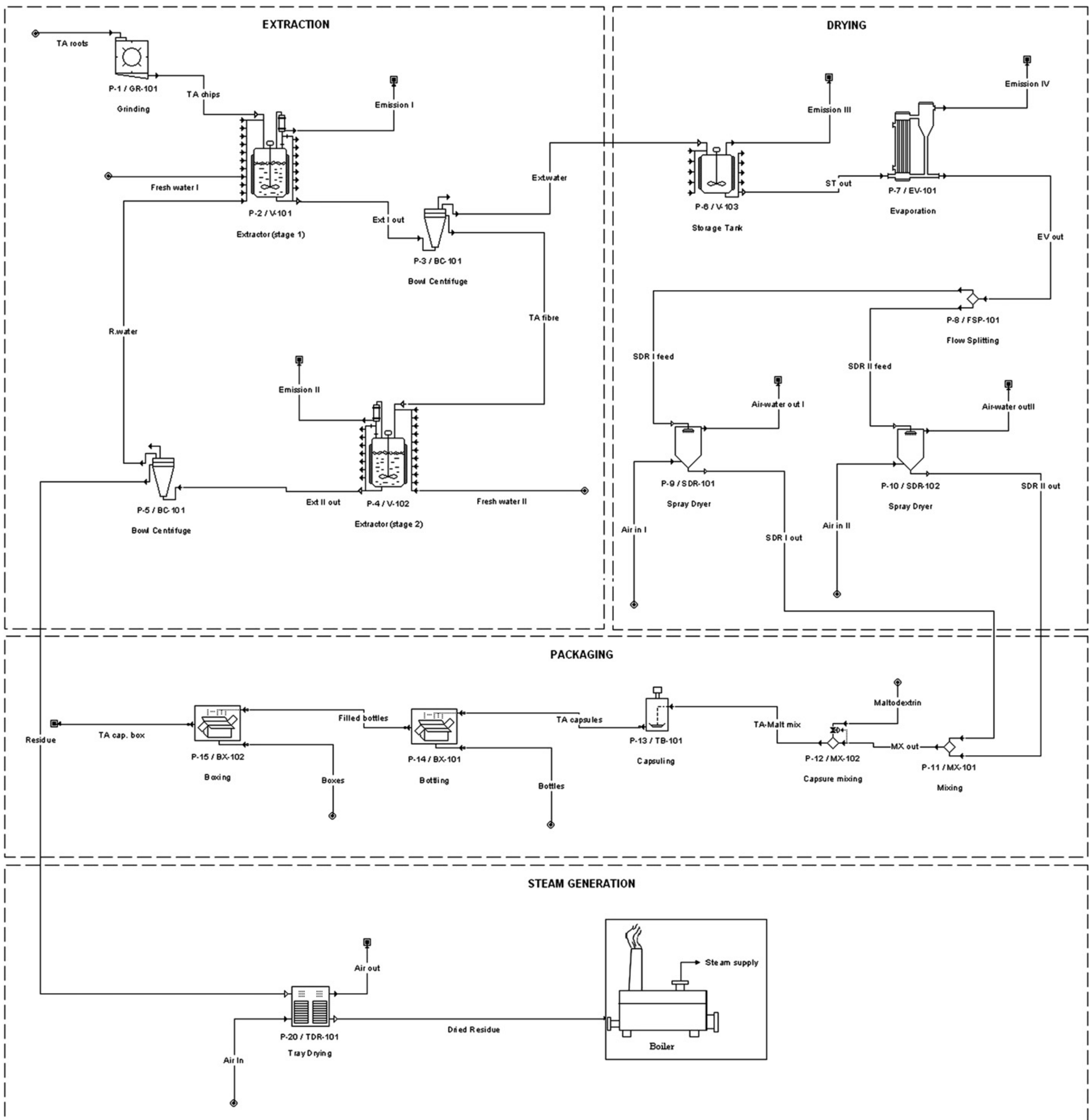

Fig. 3. Process flow diagram for TA extract production (Case Study 1).

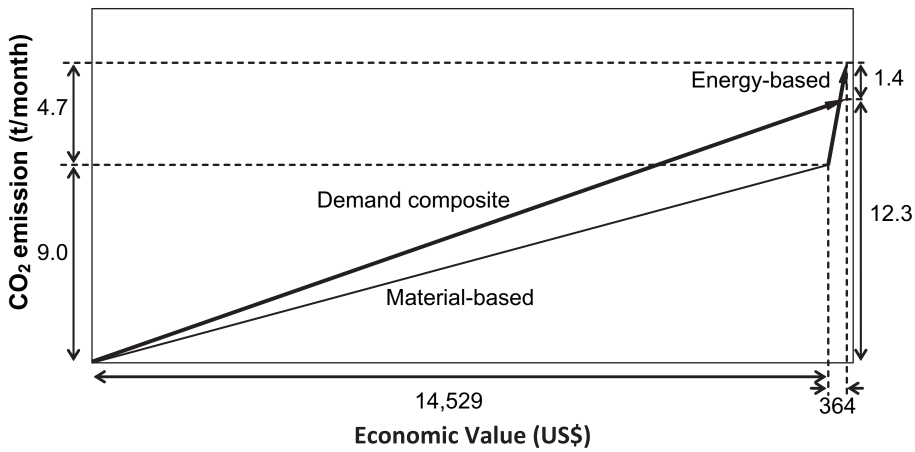

Fig. 4. Carbon footprint composite curves for Case Study 1.

which is provided by external utility supplier. For steam production, carbon footprint of 0.17 kg CO_2/kg steam (Wang, 1999) (based on typical industrial boiler efficiency and fuel compositions) is used in this study. In the Malaysian power generation sector, four main energy sources contribute to the overall power generation mix, i.e., natural gas, coal, hydropower and oil, with the contribution of 50, 35, 14 and 1%, respectively (Lim, 2009). Since each type of power generation sources has different carbon intensity, the overall carbon footprint of Malaysian power mix is calculated from the weighted average of the different energy sources. This is determined as 0.622 kg CO_2/kWh (see calculation in Table 1). The overall carbon footprint is used for both case studies.

4. Case Study 1 – Tongkat Ali extract production

In Case Study 1, production of Tongkat Ali (TA) extract (Athimulam et al., 2006) was analysed. The process flow diagram for the production scheme is shown in Fig. 3. As shown, the process involves a two-stage counter-current leaching of phytochemicals from TA root chips. In the first stage of extraction, TA chips are extracted using extract water recycled from the second extraction stage (denoted as “R.water” in Fig. 3), with a bit of fresh water make up. The phytochemicals in the chips are leached into water. In the second extraction step, the residual TA fibre from the first extraction stage is leached again with fresh water. Finally, the solid residue from the second stage of extraction is removed from the system. The liquid extract from the extraction process is then passed through a series of volume reduction operations, i.e., evaporation and spray drying before it is finally turned into the dried TA powder. The dried powder is then sent for packaging section to produce the final product in capsulated form. A monthly production of 80 batches is anticipated (Athimulam et al., 2006). Due to the relatively low process yield of 3 wt%, a significant quantity of solid residues is produced from the process. In a latter work, it is found that these residues can be further utilised as process fuel (Kuan et al., 2007).

The carbon footprint composite curves are next used to analyse the total carbon footprint of the overall process. Initially, the material- and energy-based footprints were plotted against the

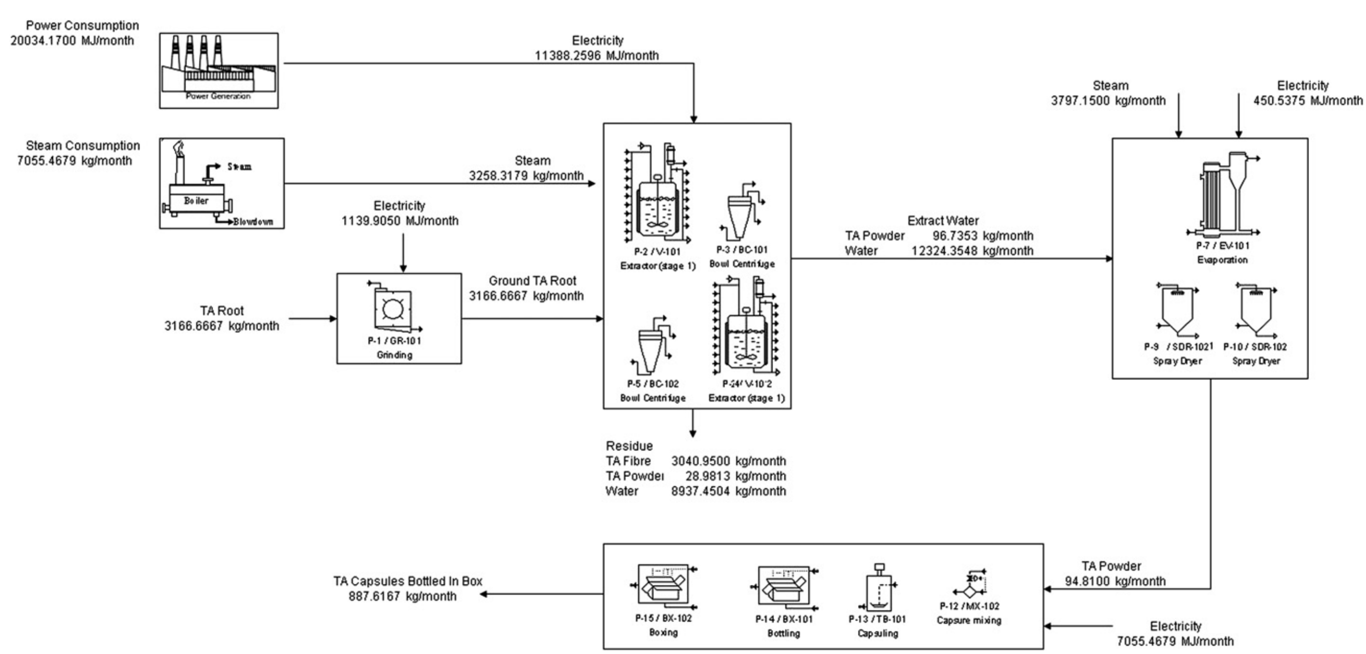

Fig. 5. Sectional electricity and steam input for Case Study 1 (Kuan, 2005).

Table 2
Monthly usage of steam and electricity for industrial case studies.

	Case Study 1 (Kuan, 2005)	Case Study 2
Steam usage – boiler (kg)	7055	2,609,075
Electricity usage (kWh)	5565	5,900,000

corresponding costs as the source composite curve in Fig. 4. The raw material carbon footprint was contributed by two components, i.e., TA as organic material, and other auxiliary inorganic materials used in the packaging section (e.g., bottles and boxes). The footprint contributed by TA was based primarily on the estimated fuel consumption from transporting the harvested TA to the plant site. For the latter, the footprint for heavy duty vehicle transportation is taken as 92 g CO_2/t-km (European Environment Agency, 2003). For a distance of 600 km (from the plantation to production site) and a monthly consumption of TA chips of 3167 kg, the monthly footprint was calculated as 0.2 t CO_2. With a unit cost of $3.20, the monthly purchase cost for this raw material is estimated as $10,133. On the other hand, the monthly footprint contributed by the auxiliary inorganic material inputs was based on their economic value, i.e., given by the product of the raw material cost of US$4396 (Kuan et al., 2007) with its aggregate carbon intensity (2 kg of CO_2/US$) to yield a value of 8.8 t CO_2. The monthly total material-based footprint was hence added as 9.0 t CO_2, with a monthly material cost of $14,529 (Fig. 4).

On the other hand, the energy segment of the carbon footprint comes from the external (electricity generation) and internal sectors (steam generation using an oil-fired boiler). From a simulation study (Kuan, 2005), the total monthly electricity consumption for the process is determined as 20,034 MJ (equivalent to a monthly consumption of 5565 kWh), while its steam consumption is 7055 kg, as shown in Fig. 5 and Table 2. Carbon footprint for the external sector was then determined by multiplying the total power consumption with the overall carbon intensity of Malaysian power mix (0.622 kg CO_2/kWh), and found to be 3.5 t/month. With the unit costs for electricity of $0.06/kWh, its monthly cost is calculated as $334. On the other hand, the monthly carbon footprint contributed by the steam generation was determined by the product of the corresponding carbon intensity (0.17 kg CO_2/kg steam) with the steam produced, and found to be 1.2 t/month. Hence, the energy segment contributes a total of 4.7 t CO_2/month (Fig. 4). Finally, adding the footprint from both material and energy segment gives a total of 13.7 t CO_2/month. With the unit costs of $0.0042/kg, the monthly steam cost is determined as $30, which leads to a total utility cost of $364/month.

A goal of 10% reduction from the total carbon footprint was then set, which corresponds to a reduction of 1.4 t CO_2/month. The latter was then plotted as the demand composite curve in Fig. 4. As shown in the source composite curve in Fig. 4, although the carbon footprint emitted by the material-based (9.0 t CO_2/month) is much higher compared to the energy-based footprint (4.7 t CO_2/month), the carbon intensity of the energy-based segment is much higher as compared to that of the material-based segment, represented by their respective slopes. Hence, a detailed study should focus on the energy-based segment. For the next step, a new source composite curve is plotted for the energy-based footprint in Fig. 6. The source composite curve consists of the earlier calculated steam and electricity consumption of the process, which are plotted as internal and external segments respectively. Note also that the total vertical and horizontal distances of this source composite curve match those of the original energy-based segment in Fig. 4. To identify the “hot-spot” of the electricity consumption, the external segment is further segregated into sub-segments that represent the processing sections of the plant. As shown in Fig. 6, the biggest electricity consumer corresponds to the extraction (section 1), followed by the packaging (section 3) and drying (section 2). For the demand composite curve, only the portion that lies in the energy-based section in Fig. 4 is extracted. From Fig. 6, it can be seen that the whole source composite curve lies above the demand composite curve. However, shifting the internal segment (strategy illustrated in the earlier section) will not help in achieving the carbon intensity goal. This is due to the external carbon footprint that is even higher than the carbon intensity goal. The only possible strategy is to reduce the slope of the external section. In practice, the slope reduction of the external segment can be achieved by utilising cleaner electricity. The conventional usage of non-renewable energy sources produces high carbon footprint. This can be avoided if the TA residues from the process are used as the energy sources.

In order to meet the targeted carbon footprint, the amount of electricity supply by the municipal has to be reduced. As mentioned earlier, to satisfy the carbon footprint reduction of 10%, a total carbon footprint reduction of 1.4 t CO_2/month is required (see Figs. 4 and 6). This means that the maximum footprint that can be contributed by the electricity sector is to be reduced to 2.1 t (Fig. 6) and the corresponding electricity supply is found to be 12,147 MJ (determined from carbon intensity of 0.622 kg CO_2/kWh). Since the overall process requires electricity supply of 20,034 MJ, and the maximum external supply is only 12,147 MJ, the balance of 7887 MJ

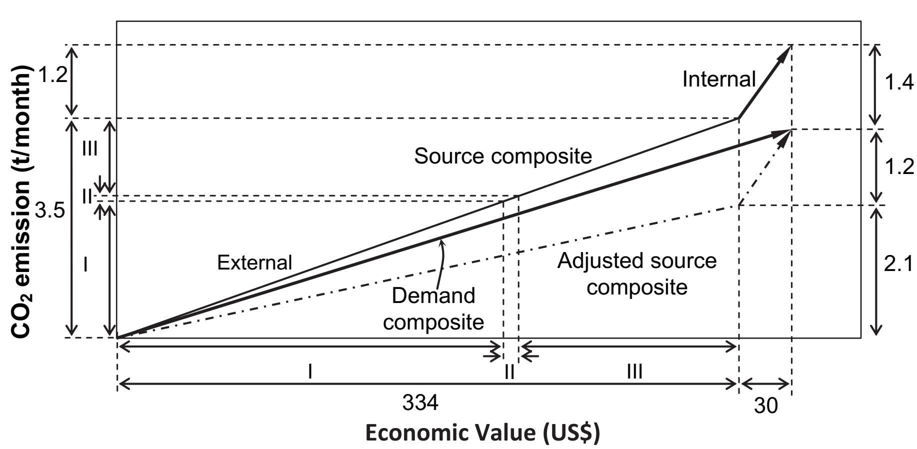

Fig. 6. Energy-based footprint composite curves for Case Study 1 (I: extraction, II: drying, III: packaging).

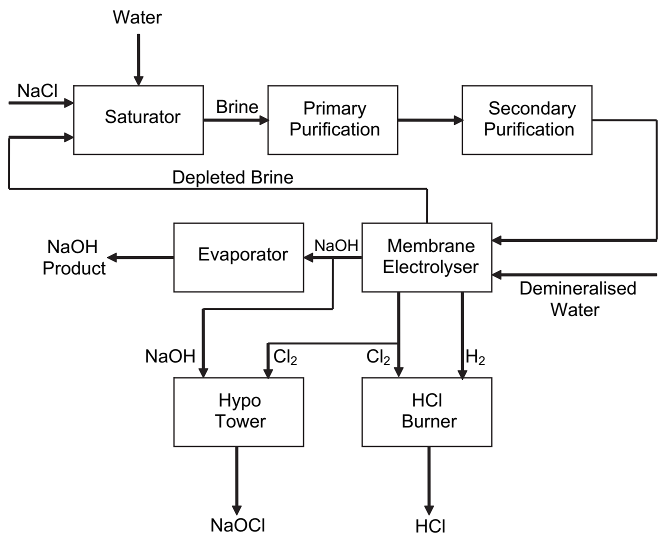

Fig. 7. Process flow diagram for chlor-alkali plant (Case Study 2).

has to be generated by utilising the biomass as the energy sources. It is assuming that the biomass has a calorific value of 15 MJ/kg (Erol et al., 2010) and moisture content of 50%. Besides, the biomass-fired electricity generation is assumed as 40% efficiency (Daugherty, 2001). In this case, based on the total available solid residue of 3041 kg/month (Kuan, 2005), a total of 9122 MJ/month of electricity can be generated. This indicates that the available biomass residue is more than sufficient to reduce the overall carbon footprint by 10%. However, this option might not be feasible due to the fact that this option will involve significant investment in purchasing a new power generator for the plant. Hence, a further analysis based on the economic consideration has to be performed.

If the power generation option is not feasible due to economic considerations, another option available is to replace the steam produced by the oil-fired boiler. Given that the efficiency of biomass-fired boiler of 70% (Prasad, 1995) and heat content of steam as 2 MJ/kg, the maximum amount of steam can be produced from 3041 kg/month of solid residue (with calorific value of 15 MJ/kg and 50% moisture content) is 7982 kg/month. This means that the whole internal segment of the energy composite curve can be removed. However, the targeted footprint reduction of 10% will not be achieved. The maximum carbon footprint reduction is 1.2 t, which is 8.8% of the total carbon footprint of the overall process.

5. Case Study 2 – chlor-alkali plant

In Case Study 2, a chlor-alkali production plant was analysed. A simplified version of its process flow diagram is shown in Fig. 7. First, the raw material of sodium chloride (NaCl) is mixed with water to form brine, which is then passed through a series of purification processes before being sent to the membrane electrolysers to form its main product, i.e., caustic soda (NaOH). The other effluents of the electrolysers are chlorine (Cl_2), hydrogen (H_2) gases and depleted brine. The NaOH produced is then sent for water evaporation to produce concentrated NaOH product that meet industrial standard. The chlorine and hydrogen gases are then burned to produce hydrochloric acid (HCl). This process is highly exothermic, and the some of the excess heat from the HCl burner is recovered to generate steam (not shown). Some portion of NaOH is also used to produce sodium hypochlorite (NaOCl), by reacting with Cl_2 gas inside the Hypo Tower, as shown in Fig. 7.

The material-based footprint was calculated based on the raw material economic value, i.e., by multiplying the raw material cost with the aggregate carbon intensity of 2 kg CO_2/US$. Since the total monthly raw material cost is approximately US$500,000, the corresponding footprint was found to be 998.4 t CO_2. However, it has to be noted that one of the raw material is transported from a place that has a distance of approximately 5000 km, thus with the carbon intensity of 13.9 g CO_2/t-km (sea transportation) (Hendrickson et al., 2006), the resultant footprint for 3500 t of raw material consumed monthly is 243.3 t CO_2. Hence, the total monthly carbon footprint for the raw material is 1242 t.

The monthly electricity consumption of the process is determined as 5,900,000 kWh (Table 2). With a unit cost of $0.07/kWh, the monthly electricity expenses are estimated at $425,500. This results in a large external carbon footprint of 3671 t/month (carbon footprint = 0.17 kg CO_2/kg steam). Among the many processes in the plant, membrane electrolysis consumes nearly 90% (5,000,000 kWh) of the total electricity consumption of the plant. Meanwhile, the internal energy footprint is contributed mainly by fuel use for steam generation. There are two sections that produce steam in the plant, i.e., the oil-fired boiler and the HCl burner. For the former, boiler feed water and recycled steam condensate are heated and converted into high pressure steam by burning light fuel oil. On the other hand, feed water and steam condensate are vaporised in the HCl burner to form low pressure steam. This reaction is known to be highly exothermic and the heat generated is potentially enough to generate high pressure

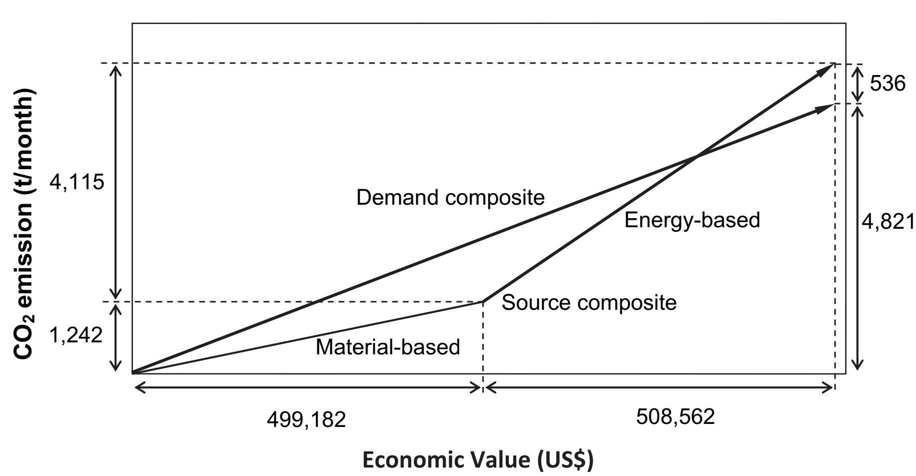

Fig. 8. Carbon footprint composite curves for Case Study 2.

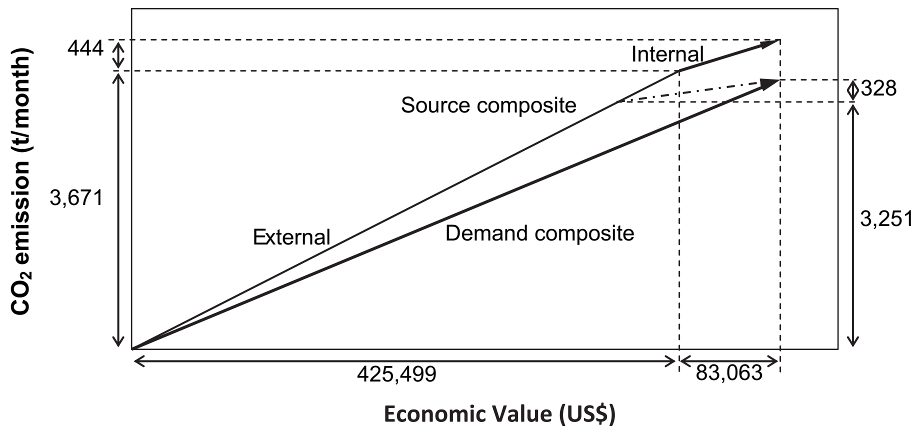

Fig. 9. Energy-based footprint composite curves for Case Study 2.

steam. However, due to the limitations of the existing facility, only low pressure steam is produced at present. This low pressure steam produced does not generate carbon footprint, since it utilised the waste heat generated from HCl burner. Thus, the only contributor to the internal carbon footprint is the oil-fired boiler. Through heat balance calculations, the steam produced by the boiler (with efficiency of 85%) was calculated to be 2,609,075 kg per month, which corresponds to the internal carbon footprint of 444 t/month (carbon footprint = 0.17 kg CO_2/kg steam). Thus, the total energy-based carbon footprint was found to be 4115 t/month, which is contributed by external sector (3671 t CO_2/month from electricity) and internal sector (444 t CO_2/month from steam generation). With the unit costs of $0.03/kg, the monthly steam cost is determined as $83,063, which leads to the total monthly utility cost of $508,562.

The same graphical technique was used as in the previous problem, as shown in Fig. 8. A goal of 10% reduction (i.e., 536 t, see Fig. 8) of the total carbon footprint was set, and was plotted as the demand composite curve. From Fig. 8, it can be seen that the energy-based segment contributes more to the total footprint. Hence, an additional source composite curve on energy-based footprint is plotted to investigate its footprint contribution, as shown in Fig. 9. From Fig. 9, it can be seen that the source composite curve lies above the demand composite curve. As described in the earlier section that the source composite curve has to be adjusted until its tip touches the demand composite curve in order to fulfil the footprint reduction target. However, doing this alone will not achieve targeted goal, as the external footprint is higher than the 10% reduction goal. A dual approach is thus adopted here, where the slope of the internal source composite curve segment was reduced; while the segment is simultaneously shifted down along the external source composite curve segment. In practice, the reduction of the slope can be achieved by utilising cleaner energy sources in the steam generation section. Alternatively, some of the steam can be produced by the HCl burner due to its excess heat produced. Note that the latter option requires the existing equipment to be retrofitted or replaced in order to increase thermal efficiency, thus potentially displacing some of the plant's fuel oil demand. However, this is not possible with the current design of the equipment. On the other hand, the option for shifting along the external source composite curve segment means the reduction of the external carbon footprint. In practice, this can be achieved by more efficient use of electricity, particularly through retrofit or replacement of the electrolytic cells, which are the largest power consumer in the plant. Another possible solution is to utilise more renewable energy with lower carbon footprint, such as biomass, hydro power, etc., in countries where companies have the option to selectively purchase "green electricity". However if one of the above-proposed solutions is able to sufficiently reduce the carbon footprint to the goals set by the company, the other approaches might not be necessary. The result of these proposed options is reflected in Fig. 9. The external carbon footprint is now reduced from 3671 to 3251 t/month, while the internal carbon footprint is reduced from 444 to 328 t/month. By doing so, the chlor-alkali plant will be able to achieve the desired carbon footprint reduction of 10%.

6. Conclusion

A novel application has been developed here on the use of graphical pinch analysis for determining strategies to meet carbon footprint reduction goals for a chemical process. The approach decomposes the footprint into material- and energy-based components, and also into internal and external components. The use of graphical display on the carbon footprint composite curves facilitates the analysis of potential process changes and allows for evaluation and screening of cleaner production options. The graphical approach allows clear visualization of key contributors to the carbon footprint of the process plant, which is an advantage inherent to pinch analysis techniques. Industrial case studies involving phytochemical extract and chor-alkali production illustrate how this new analysis approach enhances decision-making by identifying priority strategies for carbon footprint reduction. The simplicity of this methodology also provides an added advantage, since in practice process engineers and plant managers may not be keen to adopt excessively complex or data-intensive analysis techniques. The methodology developed here can be extended further by applying techniques such as sensitivity analysis, which have long been used in LCA to deal with data uncertainties encountered in practical applications.

Acknowledgements

The financial support from the Malaysian Ministry of Science, Technology and Innovation (MOSTI) through Science Fund is gratefully acknowledged. The partial support of the De La Salle University Science Foundation is also deeply appreciated. The assistance of Ir Shyam Lakshmanan, Wei Loon Phan and colleagues are highly appreciated.

References

Athimulam, A., Kumaresan, S., Foo, D.C.Y., Sarmidi, M.R., Aziz, R.A., 2006. Modelling and optimization of *Eurycoma longifolia* water extract production. Food and Bioproducts Processing 84 (C2), 139–149.

Atkins, M.J., Morrison, A.S., Walmsley, M.R.W., 2010. Carbon emissions pinch analysis (CEPA) for emissions reduction in the New Zealand electricity sector. Applied Energy 87, 982–987.

Bandyopadhyay, S., Foo, D.C.Y., Tan, R.R., 2009. Segregated targeting for multiple resources using decomposition principle. AIChE Journal (in press, doi:10.1002/aic.12050).

Crilly, D., Zhelev, T., 2008a. Emissions targeting and planning – an application of CO_2 emissions pinch analysis (CEPA) to the Irish electricity generation sector. Energy 33, 1498–1507.

Crilly, D., Zhelev, T., 2008b. An emergy-based targeting technique for treatment and utilisation of greenhouse gas emissions. In: Novosad, J. (Ed.), Paper Presented in the 18th International Congress of Chemical and Process Engineering (CHISA) – Summary 4: PRES 2008 and System Engineering, Vol. 4, pp. 1214–1215.

Daugherty, E.C., 2001. Biomass energy systems efficiency: analyzed through a Life Cycle Assessment. Unpublished thesis (M.Sc.), Lund University.

De Benedetto, L., Klemes, J., 2009. The environmental performance strategy map: an integrated LCA approach to support the strategic decision making process. Journal of Cleaner Production 17 (10), 900–906.

Dhole, V.R., Linnhoff, B., 1992. Total site targets for fuel, co-generation, emissions, and cooling. Computers and Chemical Engineering 17, S101–109.

El-Halwagi, M.M., 1997. Pollution Prevention Through Process Integration: Systematic Design Tools. Academic Press, San Diego, USA.

El-Halwagi, M.M., 2006. Process Integration. Elsevier Inc., Amsterdam.

El-Halwagi, M.M., Manousiothakis, V., 1989. Synthesis of mass exchange networks. AIChE Journal 35 (8), 1233–1244.

El-Halwagi, M.M., Gabriel, F., Harrel, D., 2003. Rigorous graphical targeting for resource conservation via material reuse/recycle networks. Industrial and Engineering Chemistry Research 42, 4319–4328.

Erol, M., Haykiri-Acma, H., Küçükbayrak, S., 2010. Calorific value estimation of biomass from their proximate analyses data. Renewable Energy 35 (1), 170–173.

European Environment Agency, 2003. Overall Energy Efficiency and Specific CO_2 Emissions for Passenger and Freight Transport, Indicator Factsheet. TERM. 27 EEA 31.

Foo, D.C.Y., Kazantzi, V., El-Halwagi, M.M., Manan, Z.A., 2006. Surplus diagram and cascade analysis technique for targeting property-based material reuse network. Chemical Engineering Science 61, 2626–2642.

Foo, D.C.Y., Tan, R.R., Ng, D.K.S., 2008. Carbon and footprint-constrained energy sector planning using cascade analysis technique. Energy 33, 1480–1488.

Hendrickson, C.T., Lave, L.B., Matthews, H.S., 2006. Environmental Life Cycle Assessment of Goods and Services. An Input–output Approach. RFF Press. 2006.

Kazantzi, V., El-Halwagi, M.M., 2005. Targeting material reuse via property integration. Chemical Engineering Progress 101 (8), 28–37.

Klemeš, J., Dhole, V.R., Raissi, K., Perry, S.J., Puigjaner, L., 1997. Targeting and design methodology for reduction of fuel, power and CO_2 on total sites. Applied Thermal Engineering 17 (8-10), 993–1003.

Kuan, C.K., 2005. Life Cycle Analysis of Tongkat Ali (Eurycoma longifolia) Water Extract Manufacturing Process. Final Year Research Project Report (B.Eng.), Universiti Teknologi Malaysia.

Kuan, C.K., Foo, D.C.Y., Tan, R.R., Kumaresan, S., Aziz, R.A., 2007. Streamlined life cycle assessment of residue utilization options in Tongkat Ali (*Eurycoma longifolia*) water extract manufacturing process. Clean Technology Environment Policy 9, 225–234.

Lee, S.C., Ng, D.K.S., Foo, D.C.Y., Tan, R.R., 2009. Extended pinch targeting techniques for carbon-constrained energy sector planning. Applied Energy 86, 60–67.

Lim, C., 2009. TNB awaits government decision to commission first nuclear power plant by 2025. accessed 27 June 2009 Available from. http://www.bernama.com.my/bernama/v5/newsindex.php?id=413588 May 2009,.

Linnhoff, B., Dhole, V.R., 1993. Targeting for CO_2 emissions for total sites. Chemical Engineering and Technology 16, 252–259.

Linnhoff, B., Townsend, D.W., Boland, D., Hewitt, G.F., Thomas, B.E.A., Guy, A.R., Marshall, R.H., 1982. A User Guide on Process Integration for the Efficient Use of Energy. Institute of Chemical Engineers, Rugby.

Manan, Z.A., Tan, Y.L., Foo, D.C.Y., 2004. Targeting the minimum water flowrate using water cascade analysis technique. AIChE Journal 50, 3169–3183.

Ng, D.K.S., Foo, D.C.Y., Tan, R.R., 2007a. Targeting for total water network – Part 1: waste stream identification. Industrial and Engineering Chemistry Research 46 (26), 9107–9113.

Ng, D.K.S., Foo, D.C.Y., Tan, R.R., 2007b. Targeting for total water network – Part 2: waste treatment targeting and interactions with water system elements. Industrial and Engineering Chemistry Research 46 (26), 9114–9125.

Prakash, R., Shenoy, U.V., 2005. Targeting and design of water networks for fixed flowrate and contaminant load operations. Chemical Engineering Science 60, 255–268.

Prasad, S.B., 1995. Biomass-fired steam power cogeneration system. A theoretical study. Energy Conversion Management 36 (1), 65–77.

Smith, R., 1995. Chemical Process Design. McGraw Hill, New York.

Tahara, K., Sagisaka, M., Ozawa, T., Yamaguchi, K., Inaba, A., 2005. Comparison of CO_2 efficiency between company and industry. Journal of Cleaner Production 13, 1301–1308.

Tan, R.R., 2008. Using fuzzy numbers to propagate uncertainty in matrix-based LCI. International Journal of Life Cycle Assessment 13 (7), 585–593.

Tan, R.R., Foo, D.C.Y., 2007. Pinch analysis approach to carbon-constrained energy sector planning. Energy 32, 1422–1429.

Tan, R.R., Foo, D.C.Y., Aviso, K.B., Ng, D.K.S., 2009a. The use of graphical pinch analysis for visualizing water footprint constraints in biofuel production. Applied Energy 86, 605–609.

Tan, R.R., Foo, D.C.Y., Ng, D.K.S., 2009b. Pinch analysis approach to carbon-constrained planning for sustainable power generation. Journal of Cleaner Production 17 (10), 940–944.

Wang, M., 1999. GREET 1.5 – Transportation Fuel Cycle Model. Final Report. Argonne National Laboratory ANL/ESD-39.

Wang, Y.P., Smith, R., 1994. Wastewater minimisation. Chemical Engineering Science 49 (7), 981–1006.

Weidema, B.P., Thrane, M., Christensen, P., Schmidt, J., Lokke, S., 2008. Carbon footprint: a catalyst for life cycle assessment. Journal of Industry Ecology 12, 3–6.