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Recent Trends in Pinch Analysis for Carbon Emissions and Energy Footprint Problems

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Climate change has recently become a major focus of industry and government agencies. Pinch analysis techniques have now been extended to various carbon and environmental-constrained problems. The first applications were meant to determine the minimum amount of zero- or low-carbon energy sources needed to meet regional or sectoral emission limits. The concept was later extended to segregated targeting with regions using unique sets of energy sources, and for targeting retrofits for carbon sequestration in the electricity sector. Furthermore, the pinch analogy was used for energy planning in scenarios involving land and water footprints. Graphical, algebraic and automated targeting variants have been developed for these problems. This paper discusses the historical evolution of recently developed pinch analysis techniques for the various emission- and footprint-related problems, along with their contributions and limitations. Some recent applications in Ireland and New Zealand are also reviewed. Finally, a new application of the use of composite curves for company-level analysis of carbon footprint improvement options is described

1. Introduction

In recent years, public concern about climate change has grown significantly. Emissions of greenhouse gases such as carbon dioxide (CO_2), 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 the 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 modeling techniques to analyze and simulate the effects of these technologies on carbon emissions, and furthermore to optimize the deployment of appropriate technologies in order to meet environmental goals while simultaneously considering technical and economic constraints.

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A number of papers have recently been published on the use of pinch analysis methods 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 to 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 network synthesis (Wang and Smith, 1995; El-halwagi et al., 2003; Manan et al., 2004; Prakash and Shenoy, 2005; Foo et al., 2006a; Ng et al., 2007) and property integration (Kazantzi and El-Halwagi, 2005; Foo et al., 2006b). These various pinch analysis techniques include graphical and numerical approaches.
More recently, pinch analysis concepts were extended to applications involving management of CO_2 emissions from industrial systems. The development of these techniques is discussed in the next section.

2. Brief Review of Carbon Emission Pinch Analysis (CEPA)

Tan and Foo (2007) developed the first approach on the use of pinch analysis technique for carbon constrained energy sector planning, 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 characteristic of the fuel or the technology. At the same time, the system also contains a set of energy demands, and that each demand has a specified carbon footprint limit. Alternatively, a total carbon footprint limit may be specified for all of the demands combined. Under the assumption that the various energy sources are fully interchangeable, the original problem was to minimize 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 *energy planning composite curves* similar to those used for water recovery (El-Halwagi et al., 2003; Prakash and Shenoy, 2005) using energy as the horizontal axis and CO_2 emissions as the vertical axis (Figure 1). The basic technique has since been applied for energy planning purposes by researchers in Ireland (Crilly and Zhelev, 2008a) and New Zealand (Atkins et al., 2008). The latter work 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 numerical 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; Foo et al., 2006a). Furthermore, it was soon recognized 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 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 (Lee et al., 2009). At the same time, two other new elements were proposed in the work of Lee et al. (2009). The authors reformulate the CEPA targeting technique as a linear programming model that minimize 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., 2009). 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 (Crilly and Zhelev, 2008b; Bandyopadhyay et al., 2009).

The most recent application of pinch analysis in this area is for the planning of minimal retrofit of power plants for carbon capture and storage (Tan et al., 2009b). In this work, pinch analysis is used to determine the minimum extent of retrofitting needed across a region's power plants in order to meet an overall carbon footprint target. Note that retrofitting in general is undesirable as it entails capital costs for retrofitting as well as energy losses due to the power requirements for carbon capture and storage processes. The approach assumes that compensation for such power losses is accomplished by installing additional zero-emission plants using renewable energy.

3. New Application of CEPA for Carbon Footprints Reduction

This section briefly outlines a novel application of carbon pinch analysis for companies to determine strategies to reduce their carbon footprints. Note that the carbon footprint is a life cycle based concept that measures the total emissions generated, taking into account an internal component (generated by the company itself) and an external one (generated upstream of the company by its supply chain). The concept is closely linked to life cycle assessment (LCA) and may be viewed as a simplified form of the latter (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 of pinch principles. Here, a revised methodology is proposed to combine these prior concepts.

In general, the total carbon footprint of a company consists of internal and external components. At the same time, the value of goods produced in an industrial process consists of the value of the inputs, plus the value added internally by the firm itself. The ratio of the carbon footprint to the economic value is termed as the *carbon intensity*. Note that, in general, the carbon intensities of the internal and external components need not be the same. These components can thus be plotted as the *source composite curve* in Figure 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. We apply the convention of plotting the external component first, as shown in Figure 1. Note that 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 company, combining both internal and external component.

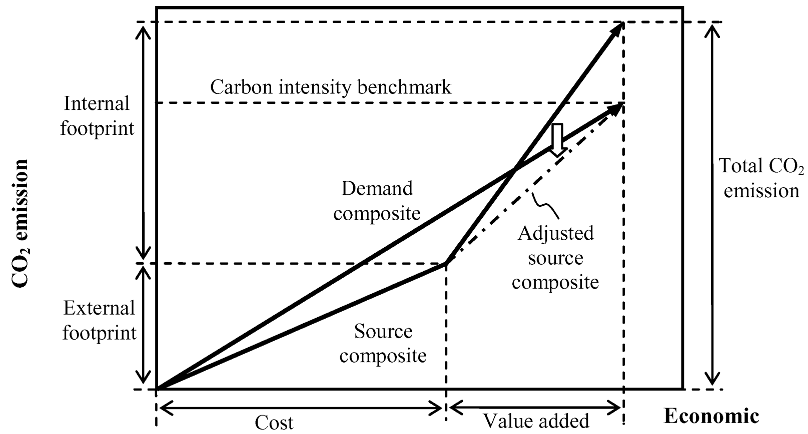

Figure 1. Carbon Footprint Composite Curves (Scenario 1)

Next, it is assumed that a benchmark carbon intensity level is set, which is lower that the company total carbon intensity. This benchmark may be based on industry standards, competitive benchmarking, or internal company choices, and may act as a *demand composite curve* (see Figure 1). In any case, 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 may be considered. 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 Figure 1, the appropriate strategy is to reduce the internal carbon footprint of the company. 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 (Figure 2). Note that 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 company 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 Figure 2. As a result, the external footprint of the product is reduced, corresponds to the increase of the internal footprint (see Figure 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 company footprint.

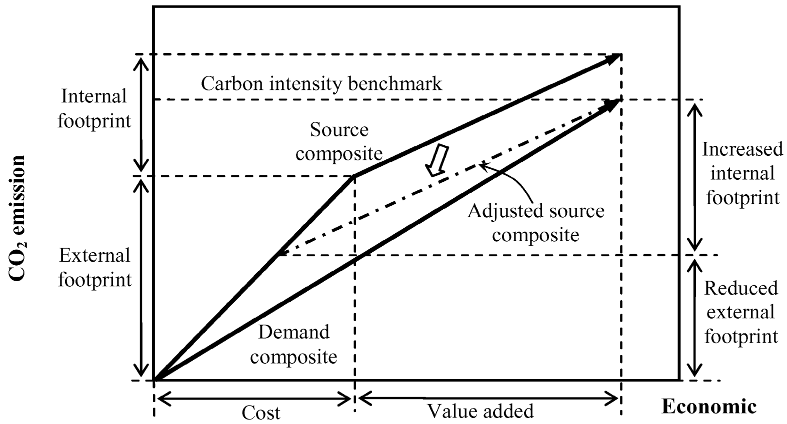

Figure 2. Carbon Footprint Composite Curves (Scenario 2)

4. Conclusion

Pinch analysis techniques have recently been extended for various applications involving management of carbon emissions in response to climate change issued. Several methodological (graphical and numerical) approaches have been developed to such problems as energy allocation, segregated targeting, and retrofit planning. At the same time, similar applications for considering emergy, land and water footprint issues in energy and biofuel systems have been developed. These methodologies and recent applications have been reviewed here. Finally, a novel application has also been developed on the use of graphical pinch analysis for determining strategies to meet corporate carbon intensity benchmarks.

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