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Carbon Sources Diagram - A Tool for Carbon-Constrained Energy Sector Planning

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Climate change is increasing as an effect of human activities around the world. The reduction of CO_2 emissions by human activities would be the most important measure to reduce this negative effect. Recently, many countries around the world have committed to reduce his CO_2 emissions over time. In this context, the world has been struggling to balance the growth in energy requirement and environment conservation for a sustainable future, mainly due the adverse environmental, social and economic impacts of global warming that are associated with greenhouse gas emissions. In the last decade, some methodologies based on Pinch Analysis (Linnhoff et al., 1982) were developed as a tool for carbon emission reductions and planning. Thus, the concepts of Pinch Analysis were applied to solve carbon transfer, maximum carbon recovery, minimum carbon targets and the design of carbon exchange networks. Focusing in planning for the power generation sector, a new methodology is presented based in the Water Sources Diagram - WSD (Gomes et al., 2013). This new methodology is called Carbon Sources Diagram - CSD. In this work, the Carbon Sources Diagram is used to locate the rigorous targets for both low and zero-carbon energy sources for carbon-constrained energy planning. The results using the CSD are similar to the ones obtained in the literature with other procedures for the same problems. However, the Carbon Sources Diagram method is easier to be applied and presents a smaller number of steps when compared with the methodologies employed in these works, graphical and algebraic, respectively.

1. Introduction

Recently it has been observed a progressively increase on global energy demand (AEO, 2012) driven by industrial growth which is connected with the substantial economic growth. The industrial activities are seen to be a major contributor to global warming, because of the high level of greenhouse gases emissions, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (NO_x). The industrial growth substantially increases the total demand for energy in general and electricity, in particular. As is known, the major source for electricity generation is carbon intensive fossil fuels (coal, oil and natural gas), which are the main contributors of carbon dioxide (CO_2) emissions. In this context, it has been increased research activities on fuel substitution, technology substitution, efficiency improvements and increased use of low carbon (e.g., natural gas) or renewable energy (e.g., wind, solar, biomass, hydro, etc…) for the generation of cleaner electricity (Varun et al., 2009).

Unfortunately, even with the broad public awareness of climate changes, fossil energy still dominates the power generation sector due to three reasons: 1) Coal is prevalent in developing countries because has a relatively low cost; 2) recent trends in the production of fossil fuels from nonconventional reserves (e.g., shale gas, tar sands, Venezuelan heavy oil), and ; 3) replacing fossil fuels with renewable energy (which is constrained by various limitations such as cost and low availability) is often an unpopular decision. At the same time, in many parts of the world, fossil fuel is still more socially accepted by the general public than low-carbon nuclear energy because of the 2011 Fukushima disaster.

On the other hand, increasing public concerns about climate change in industry and governmental bodies along with stricter environmental protection norms for sustainable development have created new challenges for these industries to reduce their CO_2 emissions and meet the emission targets set by

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environmental legislation (Al- Mayyahi et al., 2013). As a result, studies involving planning to reduce greenhouse gas emissions at regional and national levels have been developed. The planning involves minimize the CO_2 of the energy used, whilst simultaneous meeting the CO_2 emission target (carbon footprint or emission load limits), and simultaneously fulfilling the energy demands of different economic or geographic sectors, taking into account all the associated constraints.

Much researches have already been published on management of CO_2 emission to meet environmental targets, whilst simultaneously meeting economic constraints. Mainly of these researches create methodologies based on Pinch Analysis (Linnhoff et al., 1982), in which a tool for carbon emission reductions and planning has been proposed.

These methodologies carried out the principle of pinch analysis to target the CO_2 emissions associated with energy and utility systems. The first work using this concept was presented by Dhole and Linnhoff (1992, 1993), where the Total Site Approach is used to optimize the utility system and target the CO_2 associated emissions in the site. However, this approach was restricted to the optimization within industrial facilities, and not to regional or national energy sectors. Lately, a new application developed by Tan and Foo (2007), which was denominated as CO_2 Emissions Pinch Analysis (CEPA), introduced the first approach on the use of pinch analysis technique for carbon-constrained energy sector planning. This technique, a graphical approach, uses energy planning composites curves to determine the minimum amount of zero-carbon energy sources needed to satisfy the specified carbon footprint limits (Tan and Foo, 2007). Crilly and Zhelev (2008) extended the work of Tan and Foo (2007) by including time constraints and energy power demand forecasting. Newly, Crilly and Zhelev (2010) extended his previous work by including the division of renewables in non-zero (biomass and biogas) and zero (wind, hydro and landfill gas) emission factors and dealing with combined disturbance induced by new emission factor of fossil fuels energy resources and pinch jump provoked by the use of new Kyoto limits for energy demand, making the methodology more flexible, more robust and more resilient to the disturbances of the energy sector. They use this approach within a larger energy-planning framework in this work.

Nevertheless, graphical pinch analysis has as limitation the accuracy of the solution, which depends on visual resolution. To overcome this limitation some algebraic approaches was developed Foo and Tan (2007) which developed a tabular and algebraic approach, based on a sequential analysis, called Cascade Analysis Technique that locate precise targets for both low and zero-carbon energy sources needed to meet a national or a regional energy demand quickly and more accurate, while not violating the CO_2 emission limits. Lee et al. (2009) constructed Emission Interval Tables to locate the minimum CO_2-neutral and low-carbon sources for energy sector planning. Shenoy (2010) developed a two stage approach based on an algorithmic procedure associated with graphical representation, called limiting composite curve, to obtain the target of the minimum clean energy resources and synthesize energy allocation networks to meet the already established targets.

Afterward, several works have been presented to show the application of the developed tools, based on CEPA, with CO_2 emission constraints in the Irish electricity generation sector (Crilly and Zhelev, 2008) and New Zeland electricity center (Atkins et al., 2010), determining emissions targets and making energy planning (Jia et al., 2009), show the applications of CEPA in China for eco-industrial parks indicating potential Carbon Footprint reductions of 10 % and 30 %. Liang and Zhang (2011) proposed urban energy planning using the CEPA methodology together with energy input-output model. A review of these methodological developments divides them in graphical, algebraic and automated techniques (Tan and Foo, 2009). The concepts of Pinch Analysis have been applied to solve carbon transfer, maximum carbon recovery, minimum carbon targets problems and to design carbon exchange networks (CENs).

Focusing in planning for the power generation sector, a new methodology is presented in the present paper based in the Source Diagram Concept (see, for example, the WSD in water system studies with single contaminant - Gomes et al. (2007), the extended WSD in water systems with multiple contaminants - Gomes et al. (2013), and the HSD for hydrogen studies in petroleum refineries - Borges et al., (2012)), which is a heuristic-algorithmic procedure. This new methodology is called Carbon Sources Diagram (CSD). The CSD was developed to locate the rigorous targets for both low and zero-carbon energy sources for carbon-constrained energy planning. In other words, this methodology has the objective of determining the optimal energy resource mix, for national or regional level, based on demand/emissions targeting including economic constraints, such as the cost of generation and carbon prices.

2. Methodology

This section describes the methodology Carbon Source Diagram applied for energy sector planning with emissions constraints. Equal to the work of Tan and Foo (2007), this methodology identify 1) the minimum quantity of zero-emission energy resource necessary to meet the specified energy requirements and emissions limits of different sector or regions, and; 2) identify the energy allocation scheme to meet the specified emission limits using the minimum quantity of zero-emission energy resource.

The Water Source Diagram is a method that was developed to determine the minimum flowrate of pure water in management of water networks. In this work, this method is extended to set the minimum clean source target and simultaneously provide de carbon emission network (named in this work as scenario). To show this new tool one example taken from Tan and Foo (2007) is utilized. In Table 1, the data of the Case Study (Example) are shown. In this case, a low-carbon source of biodiesel is assumed to be in service with a small value of emission factor, i.e. 25 t CO_2/TJ.

The left side of the table shows the emission factor ($C_{k,i}$) and the different energy source (S_i) available. These resources are assumed to be available for the horizon planning. The right side of the table shows three distinct geographic regions that represents the demands (D_j) for the Case Study – Example, each one with its own expected consumption and emissions limit ($D_jC_{in,j}$). From these data it is possible achive the desired goals.

The following six steps are used to perform the Carbon Source Diagram:

Step 1) Determine all the emissions factors for source and demand. It is observed that for the resources the emission factor is given, on the other hand for the demand is only informed the emission limit. To obtain the respective emission factor for each region it is necessary divide the emission limit by the expected consumption for each region. The results can be seen in Table 2.

Step 2) This step is similar to the step in WSD where it is used the definition of a concentration interval. In CSD instead of concentration the emission factors are arranged in increasing order to create the intervals. If there are more than one emission factor with the same value, only one is represented in the intervals.

Step 3) Represent all the demands in the diagram by arrows, which are delimited by their respective emission factor and the highest emission factor on the data set. The respective expected consumption is indicated in a column on the left side of the diagram (see Figure 1).

Step 4) Determine the amount of energy transferred in each interval. It is calculated using the following expression (Eq(1)).

$$\Delta E_{transf,j,t} = D_j * \left(C_{kfinal,t} - C_{kinitial,t}\right) \quad (1)$$

where $\Delta E_{transf,j,t}$ is the amount of energy transferred by the demand j in interval t; D_j is the energetic demand; $C_{kfinal,t}$ is the emission factor upper limit in interval t, $C_{kinitial,t}$ is the corresponding emission factor lower limit in interval t; and j = 1 …. N_d, and t = 1….N_{int} (N_d is the number of demands (regions) in Table 1 and N_{int} is the number of emission factors intervals in the CSD). All $\Delta E_{transf,j,t}$ are written in the CSD in parenthesis over the respective arrow.

Step 5) Represent the sources in the diagram. The sources are represented above their respective emission factor. The results of Table 1 and Table 2 are presented in the diagram shown in Figure 1.

Table 1: Data for Case Study – Example (Tan and Foo, 2007)

Energy resource	Emission factor, $C_{k,i}$ (t CO_2/TJ)	Available resource, S_i (TJ)	Energy demand	Expected consumption, D_j (TJ)	Emission limit, $D_jC_{in,j}$ (10^6 t CO_2)
Coal	105	600,000	Region I	1,000,000	20
Oil	75	800,000	Region II	400,000	20
Natural gas	55	200,000	Region III	600,000	60
Others	0	>400,000			
Total		>2,000,000	Total	2,000,000	100

Table 2: Emission factor for demands

Energy demand	Emission factor, $C_{k,j}$ (t CO_2/TJ)
Region I	20
Region II	50
Region III	100

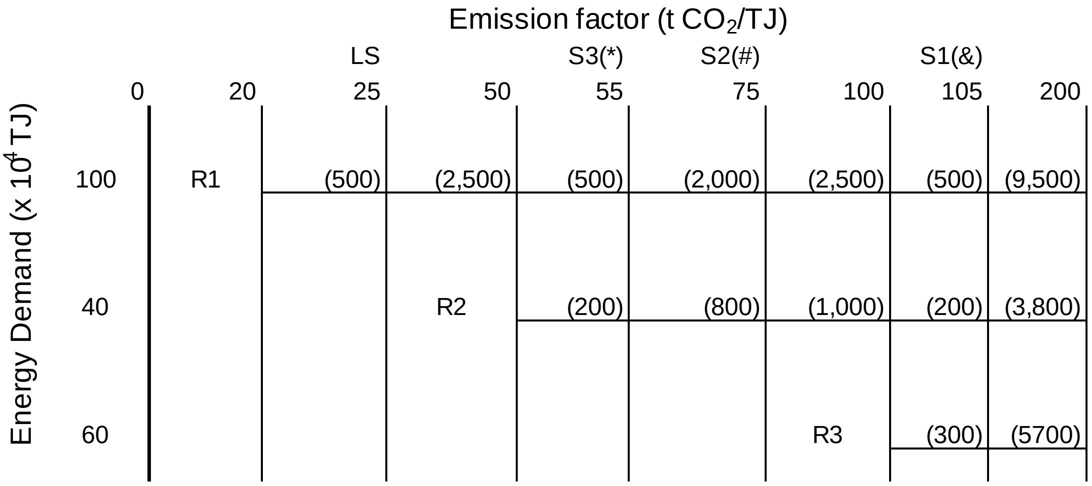

Figure 1: Initial CSD for the data of Study Case - Example

Step 6) In this step the synthesis of the carbon emission network is effectively started, following three rules:

Rule 1: Always use a source with the highest carbon emission factor, when this same is available. This will generated a scenario with lower use of a low-carbon source, but not environmental friendly.

Rule 2: If more than one source is available and an environmental friendly scenario is necessary, use the source with lower emission factor.

Rule 3: Use low-carbon source only when the others sources are not available.

Using these rules in each interval it is possible to calculate the respective low-carbon source consumption. In some intervals it is possible to choose more than one source and depending on the source used, different carbon emission networks can be obtained. Note that this CSD feature enables the simultaneous analysis of different scenarios and the consideration of constrains along the procedure.

With the diagram created, the allocation of carbon sources in each interval can be started. The algorithm analysis is made on each interval, from the lower emission factor to the higher ones. Performing the algorithm it is possible to obtain two scenarios presented in Figure 2 and Figure 3.

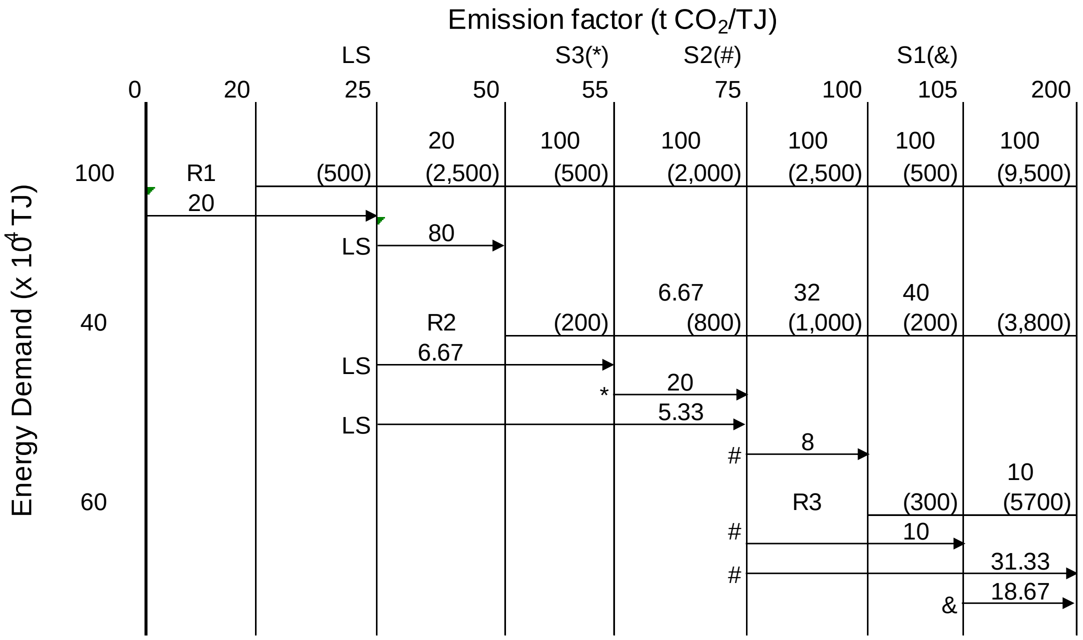

Figure 2: Final CSD for the Case Study – Environmental friendly scenario

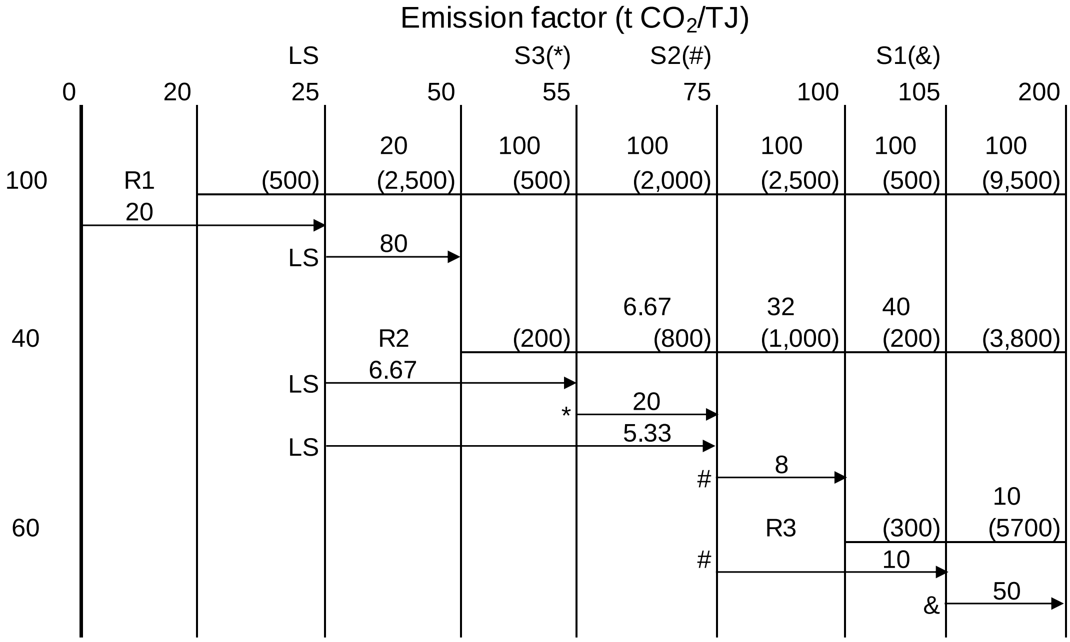

Figure 3: Final CSD for the Case Study – Lower cost scenario

Based on the CSDs obtained in Figure 2 3, the minimum zero-carbon and low-carbon energy source are targeted as 20 × 10^4 TJ and 92 × 10^4 TJ, respectively. An excess energy source of 41.34 × 10^4 TJ and two pinch points at 25 and 75 t CO_2/TJ, for both scenario, are also determined. The pinch points are indicated by the higher emission factor of the last interval where zero-carbon and low-carbon source are used in CSD. The scenario in Figure 2 privileges the use of oil instead coal, for this reason this scenario represent higher total cost when compared with scenario in Figure 3, where is privileged the use of coal instead oil. However, in environmental terms, scenario in Figure 2 is "cleaner" than scenario in Figure 3 because uses energy sources with lower carbon emission factor. The same target of zero-carbon energy source was obtained by Tan and Foo (2007a) using a graphical method; by Foo and Tan (2007) using the Cascade Analysis (algorithm technique) and; Shenoy (2010) adopting a two stage approach.

When assessing the possibility to generate different scenario, only the approach of Shenoy (2010) allows this possibility, however using two stages, one to obtain the target and other to generate the scenarios. The methodology here presented has only one stage and others scenarios can be obtained with the introduction of some restrictions, for example: in region 3 coal energy source cannot be used. If one or more low-carbon source or higher carbon source is available it is easier to use these sources in the CSD, being only necessary to add another interval with the respective value of carbon emission factor and recalculate the value of energy transferred in each interval. This tool can also deal with problems involving segregated planning and fixed zero-carbon energy supply.

3. Conclusions

An algorithmic-heuristic procedure, using the Source Diagram Concept, for planning energy sectors with emission constraints has been developed, and presented using a case study where the targets for the minimum quantity of zero- and low-carbon energy resources needed to meet a set of energy demand with corresponding emission limits were found. The results found by CSD algorithm in the case study-example show equal values when compared with those obtained by others methodologies proposed in the literature. However, CSD algorithm has the simplicity to obtain, at the same time, target and carbon emission network at the same diagram. In others words, only one approach is necessary. The CSD can easily generate another scenario when solving the energy allocation problem or when some constrains are imposed. So, the CSD can be seen as an excellent tool to decision-makers. Due to the available space other examples and the application of the CSD algorithm to another type of problems involving carbon emissions were not discussed in the present text.

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