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Targeting for Minimum Low and Zero-Carbon Energy Resources in Carbon-Constrained Energy Sector Planning Using Cascade Analysis

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This work presents targeting techniques for energy sector planning with carbon (CO_2) emission constraints. In general it is desirable to maximize the use of low-carbon or zero-carbon energy sources. However, such technologies are either more expensive (as with renewable energy) or more controversial (as in the case of nuclear energy or carbon capture and storage) than conventional fossil fuels. In addition, in the short term it is often necessary to manage the transition to increased low-carbon energy utilization to minimize disruptions in energy supply or price. Thus, in many planning scenarios there is some interest in identifying the minimum amount of low- or zero-carbon energy sources needed to meet national or regional CO_2 emission limits. That quantity can be identified through the targeting step of pinch analysis. Algebraic technique called the cascade analysis technique that was originally developed for material recovery network is extended to locate the minimum amount of low- and zero-carbon energy sources.

1. Introduction

Pinch analysis was originally developed based on thermodynamic principles to identify optimal energy utilization strategies for process plants (Linnhoff *et al.*, 1982; Shenoy, 1995; Smith, 1995, 2005). The basic concept is to match available internal heat sources with the appropriate heat sinks to maximize energy recovery and thus minimize the need to make use of external heat sources such as purchased fuels. Analogies between heat and mass transfer led to the field of mass pinch analysis, which is concerned primarily with the efficient use of industrial solvents (El-Halwagi, M. M., Manousiouthakis, 1989; El-Halwagi, 1997, 2006). This field also led to the specialized areas such as water recovery (Wang and Smith, 1994; El-Halwagi *et al.*, 2003; Manan *et al.*, 2004) and hydrogen integration (Alves and Towler, 2002). More recently, novel applications of pinch analysis for emergy analysis (Zhelev and Ridolfi, 2006) and production planning (Singhvi and Shenoy, 2002; Singhvi *et al.*, 2004) have been reported in the literature. In all cases, the common underlying principle is that pinch analysis makes use of information about stream quantities in conjunction with data about quality. Depending on the application, stream quality can be defined by variables e.g. temperature, concentration, emergy or time of occurrence.

Emission targeting by pinch analysis has been previously reported by in the framework of total site analysis (Dhole and Linnhoff, 1992; Linnhoff and Dhole, 1993). Total sites in their work refer to factories incorporating several processes which are serviced by a central energy utility system. Although emissions targeting by pinch analysis was introduced in those studies, the early applications were limited specifically to optimization within industrial facilities, and not to regional or national energy sectors. The latter application covers broader geographic and temporal scales, and also includes different energy demand sectors, such as residential consumption, transportation and industry. More recently, Tan and Foo (2006) addresses this latter application by utilizing the composite curves to locate the minimum amount of zero-carbon energy source during energy planning. However in this early work, the low-carbon sources are treated as zero-carbon source, and hence lead to an approximate target. Further more, the graphical targeting approach has always been associated with inaccuracy and being cumbersome. In this work, the algebraic targeting approach of cascade analysis is proposed to set the exact targets for both low and zero-carbon energy sources. Procedure will be outlined firstly for zero-carbon source, and is extended in the next section to cases when low-carbon source is used.

2. Cascade Analysis For Targeting Zero-Carbon Source

Cascade analysis tool that was developed to locate minimum flowrate targets for a material recovery network (Manan *et al.*, 2004) is extended here to set the minimum clean source targets. To demonstrate the approach, a literature example taken from Tan and Foo (2006) will be utilized, with the data tabulated in Table 1. To conduct a cascade analysis, all energy demand and non-zero carbon sources are firstly located at their respective levels of emission factor. This is shown in the first four columns of Table 2, with the levels of emission factor (C_k) being arranged in an ascending order (column 1). Note that in columns 3 and 4, the total demand (D_j) and source (S_i) are summed at their respective levels of emission factor k. Column 5 represents the net surplus or deficit of energy, obtained via the net between the energy demands and sources at level k, i.e. $\Sigma_i S_i - \Sigma_j D_j$. Hence, a positive value indicates energy surplus, and vice versa. Next, the net energy surplus/deficit is cascaded down the different levels of C_k to yield the cumulative energy cascade ($F_{C,\ k}$) in column 6 with an assumed zero clean source ($F_{CS} = 0$). As shown, negative values are observed in the entire energy cascade. This indicates that the the carbon sources are insufficient in supplying to the energy demands, which is indeed true with an inspection on the data in Table 1.

Table 1. Data for example

Energy Resource	Emission Factor, $C_{\text{out},\,i}$ (t CO_2/TJ)	Available Resource, S_i (TJ)	Energy Demand	Expected Consumption, D_j (TJ)	Emission Limit, $D_jC_{\text{in},\,j}$ (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
Zero-carbon source	0	>400,000			
Total		>2,000,000	Total	2,000,000	100

Table 2. Infeasible cascade

C_k	ΔC	ΣD_j	ΣS_i	ΣS_i - ΣD_j	F_C	$\Delta m_k = F_C \Delta C_k$	Cum. Δm_k	$F_{CS,k}$
					0			
0				0				
	20				0	0		
20		1,000,000		-1,000,000			0	0
	30				-1,000,000	-30,000,000		
50		400,000		-400,000			-30,000,000	-600,000
	5				-1,400,000	-7,000,000		
55			200,000	200,000			-37,000,000	-672,727
	20				-1,200,000	-24,000,000		
75			800,000	800,000			-61,000,000	-813,333
	25				-400,000	-10,000,000		
100		600,000		-600,000			-71,000,000	-710,000
	5				-1,000,000	-5,000,000		
105			600,000	600,000			-76,000,000	-723,810
	4895				-400,000	-1,958,000,000		
5000							-2,034,000,000	-406,800

The subsequent step in performing the cascade analysis is to determine the CO_2 emission load resulting from the assumed zero clean source. The emission load at each C_k is obtained from the product of cumulative energy surplus/deficit ($F_{C,\ k}$) and the emission factor difference across two C_k levels ($C_{k+1} - C_k$). Cascading the CO_2 load load down the C_k levels of column 8 yields the cumulative CO_2 load (Cum. Δm_k). A feasible cascade is characterized by all positive Cum. Δm_k in column 8. As such, Table 1 is an infeasible cascade due to its negative Cum. Δm_k values. In column 9, an interval clean source demand ($F_{CS,\ k}$) is calculated by dividing Cum. Δm_k by the difference between the emission factor at level k (C_k) and that of the clean source (C_{CS}) i.e.,

$$F_{CS,\,k} = \frac{\text{Cum.}\,\Delta m_k}{C_k - C_{CS}} \tag{1}$$

Table 3. Minimum clean source targeting utilizing cascade analysis

C_k	ΔC	ΣD_j	ΣS_i	ΣS_i - ΣD_j	F_C	$\Delta m_k = F_C \Delta C_k$	Cum. Δm_k
					F_{CS} = 813,333		
0				0			
	20				813,333	16,266,667	
20		1,000,000		-1,000,000			16,266,667
	30				-186,667	-5,600,000	
50		400,000		-400,000			10,666,667
	5				-586,667	-2,933,333	
55			200,000	200,000			7,733,333
	20				-386,667	-7,733,333	
75			800,000	800,000			**0**
	25				413,333	10,333,333	
100		600,000		-600,000			10,333,333
	5				-186,667	-933,333	
105			600,000	600,000			9,400,000
	4895				**F_{ES} = 413,333**	2,023,266,667	
5000							

The absolute value of the largest negative $F_{\mathrm{CS},\ k}$ will then replace the earlier assumed zero clean source in the energy cascade (column 6) to obtain a feasible cascade (Table 3). The magnitude of the largest $F_{\mathrm{CS},\ k}$ value represents the minimum clean source demand (F_{CS}) of the energy system; while the final row in column 6 represents the excess energy source (F_{ES}) after the carbon sources are utilized to their maximum limits in all the energy demands. A pinch is observed at C_k level with zero Cum. Δm_k.

2. Cascade Analysis For Targeting Low and Zero-Carbon Sources

To extend the targeting tool in handling low-carbon sources, the targeting approach for impure fresh feed by Foo (2007) may be adapted. The main assumption of the approach is that, the low-carbon source has a much lower cost as compared to the zero-carbon source. Hence the overall strategy will be to utilize the low-carbon source before the zero-carbon source is utilized. A three-step approach presented by Foo (2007) may be readily applied for this case, i.e.:

i. Determination of minimum demand of the low-carbon source,
ii. Determination of minimum demand of the zero-carbon source; and
iii. Adjustment for the low-carbon source

To demonstrate the approach, the earlier example is used. In this case, a low-carbon source of biomass is assumed to be in service. Even though biomass may be viewed as a potentially carbon-neutral or zero-carbon source in the life cycle analysis perspective, its production and use can still generate small amounts of net CO_2, or other greenhouse gases (CH_4 or N_2O) which can be expressed in terms of CO_2 equivalents, which leads to a hypothetical small value of emission factor, i.e. 25 t CO_2/TJ. Table 4 shows the first step of the targeting approach. The minimum demand of the low-carbon source is obtained via the largest negative value in the $F_{\mathrm{CS},\ k}$ column of Table 4. Utilizing this low-carbon source obtain another infeasible cascade in Table 5.

Table 4. Step 1 – targeting for low-carbon source (infeasible cascade)

C_k	ΔC	ΣD_j	ΣS_i	ΣS_i - ΣD_j	F_C	$\Delta m_k = F_C \Delta C_k$	Cum. Δm_k	$F_{\mathrm{CS},\ k}$
					0			
0				0				
	20				0	0		
20		1,000,000		-1,000,000			0	
	5				-1,000,000	-5,000,000		
25				0			-5,000,000	
	25				-1,000,000	-25,000,000		
50		400,000		-400,000			-30,000,000	-1,200,000
	5				-1,400,000	-7,000,000		
55			200,000	200,000			-37,000,000	-1,233,333
	20				-1,200,000	-24,000,000		
75			800,000	800,000			-61,000,000	-1,220,000
	25				-400,000	-10,000,000		
100		600,000		-600,000			-71,000,000	-946,667
	5				-1,000,000	-5,000,000		
105			600,000	600,000			-76,000,000	-950,000
	4895				-400,000	-1,958,000,000		
5000							-2,034,000,000	-408,844

Table 5. Step 2 – targeting for zero-carbon source

C_k	ΔC	ΣD_j	ΣS_i	ΣS_i - ΣD_j	F_C	$\Delta m_k = F_C \Delta C_k$	Cum. Δm_k	$F_{CS,k}$
					0			
0				0				
	20				0	0		
20		1,000,000		-1,000,000			0	
	5				-1,000,000	-5,000,000		
25			**1,233,333**	1,233,333			-5,000,000	-200,000
	25				233,333	5,833,333		
50		400,000		-400,000			833,333	16,667
	5				-166,667	-833,333		
55			200,000	200,000			0	0
	20				33,333	666,667		
75			800,000	800,000			666,667	8,889
	25				833,333	20,833,333		
100		600,000		-600,000			21,500,000	215,000
	5				233,333	1,166,667		
105			600,000	600,000			22,666,667	215,873
	4895				833,333	4,079,166,667		
5000							4,101,833,333	820,367

The negative value in the Cum. Δm_k column of Table 5 indicates a zero-carbon source is needed. The minimum demand of this zero-carbon source is again determined by the largest negative value in the $F_{CS,\ k}$ column. Utilizing this amount of energy source results in an excess of the low-carbon source (bio-diesel). The excess amount of low-carbon source may be identified by another cascade analysis which is similar to Step 1, with the final results shown in Table 6.

Table 6. Cascade analysis after Step 3

C_k	ΔC	ΣD_j	ΣS_i	ΣS_i - ΣD_j	F_C	$\Delta m_k = F_C \Delta C_k$	Cum. Δm_k
					F_{CS1} = 200,000		
0							
	20				200,000	4,000,000	
20		1,000,000		-1,000,000			4,000,000
	5				-800,000	-4,000,000	
25			**F_{CS2} = 920,000**	920,000			**0**
	25				120,000	3,000,000	(PINCH)
50		400,000		-400,000			3,000,000
	5				-280,000	-1,400,000	
55			200,000	200,000			1,600,000
	20				-80,000	-1,600,000	
75			800,000	800,000			**0**
	25				720,000	18,000,000	(PINCH)
100		600,000		-600,000			18,000,000
	5				120,000	600,000	
105			600,000	600,000			18,600,000
	4895				F_{ES} = 720,000	3,524,400,000	
5000							3,543,000,000

3. Conclusion

Algebraic approaches for targeting minimum low and zero-carbon sources is presented in this work. The approach sets rigorous targets by eliminating the cumbersome step of graphical targeting tool. Possible extensions of the procedure to similar applications can be envisioned, for example in allocating energy sources to the production of chemical products for which there are benchmark CO_2 intensities.

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