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Pinch analysis approach to carbon-constrained energy sector planning

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

[a]Chemical Engineering Department, De La Salle University-Manila, 2401 Taft Avenue, 1004 Manila, Philippines
[b]Faculty of Engineering and Computer Science, University of Nottingham-Malaysia Campus, Jalan Broga, 43500 Semenyih, Selangor Darul Ehsan, Malaysia

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Abstract

Pinch analysis techniques have been developed for a wide range of applications ranging from process plant thermal or water integration to financial and supply chain management. This paper presents a new application of pinch analysis. A scenario is assumed wherein energy sector planning takes place with carbon emission constraints arising from an effort to reduce climate change effects. A procedure for identifying the minimum amount of zero-carbon energy resource required to achieve the overall emissions target for a country or region, given that the amount of fossil energy resources available are already known. The pinch analysis method can be used for a single overall emissions target, or for cases wherein separate sectors or geographic regions have distinct targets but share a common energy resource. For the latter case the procedure allows the allocation of the energy resources to meet both the overall emissions limit and the individual targets of the different sectors or location. Numerical examples are provided to illustrate the technique, which is intended for use as a preliminary energy sector-planning tool.

Keywords: Pinch analysis; Energy planning; Emissions; Carbon constraints

1. Introduction

Pinch analysis was originally developed based on thermodynamic principles to identify optimal energy utilization strategies for process plants [1,2]. 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 [3,4]. This field also led to the specialized application of pinch analysis tools to industrial water utilization [5–16], decentralized effluent treatment [17], cooling water network design [18,19], oxygen integration for wastewater treatment [20–22] and hydrogen integration in refineries [11,23,24].

More recently, novel applications of pinch analysis for emergy analysis [25], financial management [26], production planning [27,28] and reuse/recycle system design based on material properties [29,30] 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 process variables such as temperature, concentration, emergy, time of occurrence or material properties.

It is notable that the conceptual or graphical techniques applied in pinch analysis have persisted despite the fact that mathematical programming techniques can also be used to solve similar problems [4,11,31]. This shows the value of the intuitively appealing pinch approach in solving real-life problems. They are also useful for communicating results visually to decision-makers and stakeholders. Nowadays, pinch analysis is used in conjunction with rigorous mathematical modeling as part of an integrated approach to problem solving in order to take advantage of the useful features of each approach [32–35].

Emission targeting by pinch analysis has been previously reported by Linnhoff and Dhole [36,37] in the so-called total site analysis concept. Total sites in their work refer to

*Corresponding author. Tel.: +632 536 0257; fax: +632 524 0563.
E-mail address: tanr_a@dlsu.edu.ph (R.R. Tan).

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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. This work addresses the latter application.

2. Problem statement

The application of pinch analysis for energy sector planning with emission constraints is presented. Specifically, the problems addressed by the proposed methodology can be stated as follows:

- Identification of the minimum quantity of zero-emission energy resource needed to meet the specified energy requirements and emission limits of different sectors or regions in a system.
- Identification of the energy allocation scheme to meet the specified emission limits using the minimum quantity of zero-emission energy resource.

Such problems now arise, for example, in planning energy utilization subject to carbon (or carbon dioxide (CO_2)) emission constraints due to climate change considerations. In general it is desirable from purely environmental considerations to maximize the use of low-carbon or zero-carbon energy sources. Since most CO_2 emissions result from combustion processes, some technologies generate inherently low levels of this gas. These technologies include:

- Non-combustion-based technologies such as nuclear, wind, hydroelectric or solar power.
- Biomass energy, for which CO_2 emissions during operation are largely offset by carbon fixation during feedstock photosynthesis.
- Fossil fuel combustion with CO_2 capture and storage.

On the other hand, 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 pinch analysis. Thus, energy planners will be able to identify the feasible range of utilization of low-carbon technologies, with the upper limit being derived from resource availability data and the lower bound being identified through the proposed pinch technique. Alternatively, the same procedure can be used to identify the feasible CO_2 emissions limit for a given amount of available zero-carbon energy resource base. Finally, the pinch analysis procedure can be used for determining how the different energy resources should be allocated among different energy demands in order to meet the specified emission limits.

3. Methodology

To illustrate the pinch analysis method for energy planning, consider the data for a hypothetical case shown in Table 1. The left side of the table shows the emission factors and availability of different energy sources. For simplicity, low-carbon or zero-carbon energy sources are lumped together as a single category. In practice this group will include non-combustion sources such as wind, solar, hydroelectric or nuclear energy, as well as CO_2-neutral combustion-based systems using biomass. It is assumed that the quantities given represent the available resource for the planning horizon. The demands or sinks are already given in primary energy equivalents, which means that conversion efficiencies of different processes have already been implicitly factored into the quantities.

The right side of the table shows the hypothetical energy demand for the case study. The energy demand is spread out over three geographic regions; each with its own expected energy usage and CO_2 emissions limit. The first

Table 1
Data for case studies

Energy resource	Emission factor, $C_{out,i}$ (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[a]	0	>400,000			
Total		>2,000,000	Total	2,000,000	100

[a]Refers to energy sources with zero or near-zero CO_2 emissions.

problem is to determine the minimum amount of zero-carbon energy resource needed to meet the specified emissions limits. This energy resource is to be used as sparingly as possible due to its relatively high cost (as in the case of renewable energy) or due to risk factors and public acceptability (as in the case of nuclear energy). In pinch analysis, this phase is usually referred to as "targeting." The second problem is to determine how the energy sources should be allocated to meet the different demands while complying with the emission limits. In the literature of pinch analysis, this procedure is known as "network synthesis." It can be noted that this problem can also be solved by linear programming (LP). However, graphical displays in pinch analysis provide decision-makers with a more intuitive grasp of the planning problem than does mathematical modeling.

The mathematical formulation for the energy-planning problem is

Subscripts:

i index for energy source
j index for energy demand

Parameters:

$C_{\mathrm{out},i}$ emission factor of energy source i
$C_{\mathrm{in},j}$ emission factor of energy demand j
S_i quantity of energy source i
D_j energy demand j

Decision variables:

F_j zero-emission energy supplied to demand j
W_i unused portion of energy source i
$F_{i,j}$ energy supplied from source i to demand j

3.1. Crisp LP model

The objective function is to minimize the total amount of zero-emission energy resource used in the system:

$$\min \quad \sum_j F_j. \tag{1}$$

The problem is subject to several constraints. The energy balance for each energy source is given by

$$W_i + \sum_j F_{i,j} = S_i \quad \forall i. \tag{2}$$

The energy balance for each demand is given by

$$F_j + \sum_i F_{i,j} = D_j \quad \forall j. \tag{3}$$

The emissions limit, a product of D_j and $C_{\mathrm{in},j}$, of each energy demand must be met by the energy mix supplied to it:

$$\sum_i C_{\mathrm{out},i} F_{i,j} \leqslant D_j C_{\mathrm{in},j} \quad \forall j. \tag{4}$$

All variables in the system are non-negative:

$$F_i, \quad W_j, F_{i,j} \geqslant 0 \quad \forall i,j. \tag{5}$$

It should be noted that this model is similar in overall structure to the synthesis of water and hydrogen networks to derive the graphical method for industrial material reuse and recycle. Hence, that graphical pinch approach can be readily adapted to the energy sector-planning problem. Details of the mathematical proof of the technique can be found in many water network papers [4,10,11].

The pinch analysis procedure used here makes use of composite curves where cumulative emissions and cumulative energy flows are plotted on the vertical and horizontal axes, respectively. The general procedure for the pinch analysis approach proposed is as follows:

- Tabulate the energy source and demand data. The resulting table must contain the quantity of the energy sources (S_i) and demands (D_j) and their respective emission factors ($C_{\mathrm{out},i}$ and $C_{\mathrm{in},j}$).
- Arrange the energy sources and demands in order of increasing emission factors.
- Calculate the emission levels ($S_i C_{\mathrm{out},i}$) or limits ($D_j C_{\mathrm{in},j}$) of the energy sources and demands.
- Plot the demand composite curve with the energy quantity (D_j) as the horizontal axis and the emissions limit ($D_j C_{\mathrm{in},j}$) as the vertical axis. As a result the slope of the composite curve at any given point corresponds to the emissions factor ($C_{\mathrm{in},j}$).
- Plot the source composite curve in the same manner as with the demand composite, but using the quantities S_i and $S_i C_{\mathrm{out},j}$. In this curve, the slope at any given point is given by the emissions factor $S_i C_{\mathrm{out},j}$.
- Superimpose the two composite curves on the same graph.
- Shift the source composite curve horizontally to the right so that it does not cross the demand composite. The final position should be such that the former lies diagonally below and to the right of the latter. The two curves must touch each other tangentially without crossing; this point of contact is known as the pinch point. This step of the procedure corresponds to finding the smallest quantity of zero-carbon energy (Eq. (1)) while still satisfying the emissions limit of each demand (Eq. (4)).
- Note the distance from the origin of the graph to the leftmost end of the source composite curve. This distance gives the minimum amount of zero-carbon energy needed to meet the system's specified emissions limits.
- The identification of the pinch point provides valuable insights to decision makers. Its primary value is that it identifies the system bottleneck. Thus, the "golden rule" of pinch analysis can be applied to this problem—in

order to meet all the specified emission limits in the system, the zero-carbon energy resource must be supplied only to the energy demands below the pinch point. Allocation of this resource above the pinch point will lead to an infeasible solution, or will require more zero-carbon energy than the minimum quantity identified by pinch analysis. The general procedure can be more clearly illustrated with the aid of the examples in the next section.

4. Case studies

From the data in Table 1, the composite curves for the energy demands and sources can be generated as shown in Figs. 1 and 2, respectively. To generate the demand composite curve, the energy demands of the sinks are first arranged in order of increasing emission factors. These emission factors can be found by dividing the emission limits for each region by the corresponding energy consumption. The resulting factors are 20, 50 and 100 t CO_2/TJ for Regions I, II and III, respectively. The overall emission factor for the three regions combined is 50 t CO_2/TJ, obtained by dividing the total emissions limit by the total energy demand across all regions. Each region can then be plotted as in Fig. 1, with the horizontal axis representing cumulative energy and the vertical axis representing cumulative emissions. The regions are then represented by a series of segments arranged end-to-end starting at the origin of the graph. The procedure of constructing composite curves is similar to the addition of two-dimensional vectors. The slope of each segment is equal to its emission factor; since the demands or sinks have been arranged in ascending order; the resulting composite curve curls upwards. Note that the three regions can be taken as a single demand without regard to their individual, disaggregated emission limits, resulting in the composite curve indicated by the broken line in Fig. 1. The composite curve for energy sources is constructed in a similar manner, except that initially the zero-carbon energy sources are initially excluded; this condition corresponds to setting $F_j = 0$ in Eq. (3). The resulting curve is shown in Fig. 2.

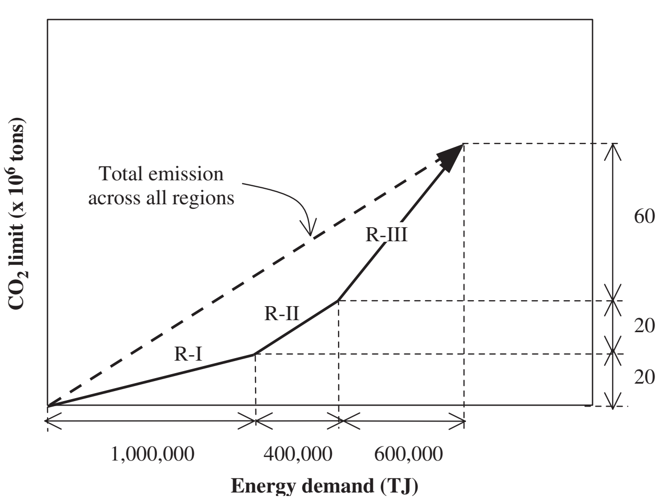

Fig. 1. Generating the energy demand composite curve.

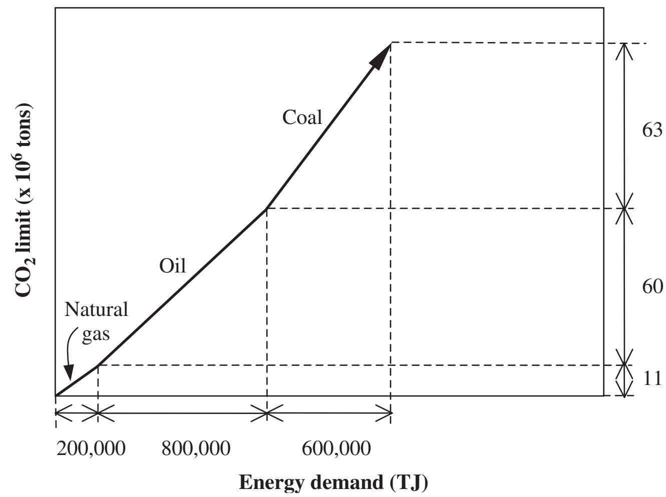

Fig. 2. Generating the energy supply composite curve.

It can be seen that the composite curves have been constructed in such a manner that their geometry reflects the cumulative nature of both energy and emissions. These quantities can be read directly from the graphs as horizontal and vertical distances, respectively. Three different energy-planning scenarios are given as follow and the use of composite curves will be demonstrated for each of these cases.

4.1. Case 1—aggregated planning with overall emission limits

Suppose that initially the individual emission limits of the three regions are disregarded, with only the total CO_2 emissions being of concern to the planners. The result is a trivial example, which can serve to illustrate the basic principle of pinch analysis, prior to proceeding to a more complicated example. In this case, the energy demand composite curve will be the broken line in Fig. 1. Combining the two composite curves gives the pinch diagram in Fig. 3. In order to supply the necessary energy sources to the sink, the source composite curve is shifted horizontally to the right, until the two curves touch at the pinch point. The horizontal distance by which the source composite has to be moved away from the origin is the quantity of zero-carbon energy needed in the system—in this case, about 720,000 TJ.

In Fig. 3, the coordinates of the pinch point are 2,000,000 TJ and 100 million tons of CO_2, which correspond to the total energy demand and combined emissions limit, respectively, specified in the problem. In addition, these coordinates also represent the cumulative energy supplied and emission generated by the sources, as indicated by the source composite curve crossing the

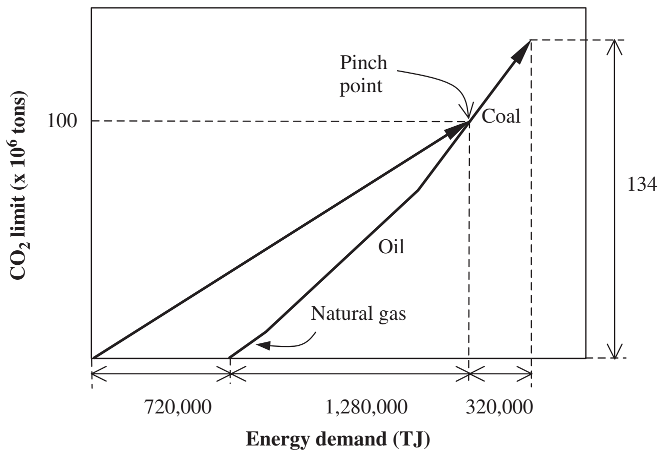

Fig. 3. Targeting demand for zero-carbon energy by shifting the source composite curve (Case 1).

Table 2
Energy allocation for Cases 1 and 2

	Energy resource				
	Coal	Oil	Natural gas	Others	Total
Case 1					
Quantity (TJ)	280,000	800,000	200,000	720,000	2,000,000
Emissions (10^6 t CO_2)	29.4	60.0	11.0	0	100.4
Case 2					
Quantity (TJ)	90,000	800,000	200,000	910,000	2,000,000
Emissions (10^6 t CO_2)	9.5	60.0	11.0	0	80.5

demand composite at this point. The procedure thus identifies the energy mix needed to meet both the energy demand and emissions limit simultaneously.

The portion of the source composite that extends beyond the demand composite is the excess energy, which cannot be utilized in view of the emission limits. If all of the available energy resource is used, a total of 134 million tons of CO_2 emissions will be generated; however, in order to meet the specified limit, some of these resources will be replaced with zero-carbon energy sources. In this case, the unusable energy is 320,000 TJ of coal. In other words, the emission targets can only be achieved by leaving this portion of the coal unutilized. While it is possible to use more coal and instead leave the oil or natural gas unutilized, more zero-carbon energy will have to be used in such a case in order to compensate for the increased emissions generated from coal combustion. This is equivalent to the situation in which higher fresh water is consumed when "dirtier" instead of "cleaner" water sources are used in water networks. The resulting energy allocation is given in Table 2. Note that the exact total emissions level is slightly higher than the tabulated value, due to the small error incurred in reading the graph containing the composite curves. Such minor errors commonly arise in graphical pinch methods [12], but their presence has not detracted from their over-all usefulness.

4.2. *Case 2—targeting emissions with fixed zero-carbon energy supply*

Suppose that the 910,000 TJ of zero-carbon energy is available, and the objective is to determine the lowest level of CO_2 emissions that can be achieved. In this case, the specified quantity of zero-carbon energy results in the source composite curve being separated from the original demand composite curve from Case 1. The gap between the two composite curves can then be removed by moving the demand composite curve downwards, as shown in Fig. 4 so that its uppermost point is at the new emission limit. The overall emission limit for the three regions combined can then be reduced by 20%, to about 80 million tons of CO_2.

In Fig. 4, the coordinates of the shifted pinch point are 2,000,000 TJ and 80 million tons of CO_2, respectively. Once again, these coordinates represent the cumulative energy supplied and emission generated by the sources, as well as the total energy and total emissions generated by the energy sources used. The amount of unusable coal increases to about 510,000 TJ, corresponding to 85% of the total available supply of coal. While coal utilization can be increased by leaving either oil or natural gas unused instead, in such a case more zero-carbon energy must be consumed as well to compensate for the higher emission factor of coal. The energy allocation for this case is also shown in Table 2. As in Case 1, a slight error is incurred in reading the exact quantity of emissions generated in the system. This effect is not considered a major concern, as more precise readings can be made simply by magnifying the graph or improving resolution quality; the appearance of similar errors occurs in other pinch analysis applications but has not prevented their widespread use.

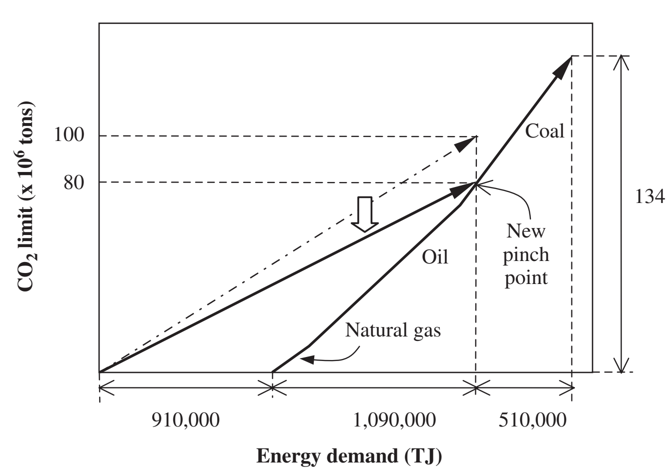

Fig. 4. Effect of reduced emission limit on zero-carbon energy demand (Case 2).

4.3. Case 3—disaggregated planning with individual emission limits

In some cases, it may be necessary to meet emission limits for each individual demand, instead of the aggregate limit for all demands combined. Note that this problem is more complicated than the previous cases. When an overall target is specified, emissions in excess of the local limit in one sector or region can be offset when another sector or region generates emission below its corresponding limit; in other words, low emission levels in some energy demands compensate for high ones elsewhere. Some scenarios, however, may require complying with each of the emission limits of the different sectors or regions.

If the emission limits for the individual regions are to be met, the original, disaggregated composite curve in Fig. 1 must be used in the pinch analysis. The new pinch diagram is shown in Fig. 5. Note that the new location of the energy source composite fall between that of Case 1 and Case 2, due to the downward facing curvature of the demand composite. A total of about 810,000 TJ of zero-carbon energy is required to meet all three regional emission limits. At the same time, 410,000 TJ of coal, the fuel with the highest emission factor, remains unusable. The shift also results in a new pinch point, which separates the demand composite curve into two segments. Regions I and II evidently fall to the left and below the pinch point, while Region III is to the right and above the pinch.

The significance of the pinch point is as follows. The optimal solution is possible by supplying the zero-carbon energy source to the demands that fall below the pinch—Regions I and II, in this case. The energy demands above the pinch (Region III) does not require and should not be supplied with this zero-carbon energy source. This will be evident in Fig. 5. Note that the energy flows are plotted cumulatively, like two-dimensional vectors, and that the slopes of the segments are equivalent to the emission factors. On the left-hand side of the pinch diagram, the supply and demand composite curves begin at the same point (the origin) and also meet at a common point (the pinch). This geometry indicates that the quantity of energy (measured as horizontal distance) and emissions (measured as vertical distance) are exactly the same for the sources and demands below the pinch point. On the other hand, above the pinch point the overall slope of the source composite curve is lower than that of the corresponding segment of the demand composite curve. This relationship indicates that the emission factors for the energy resources above the pinch are much lower than what is required by the corresponding demands, thus making it possible to meet all the emission limits even without any further use of zero-carbon energy sources. This is analogous to the so-called ‘‘golden rule’’ of pinch analysis mentioned above, in which the demand for the external, high-quality resource (in this case, the zero-carbon energy source) should be used only in the demands occurring below the pinch point [1–12]. Of course, this result does not preclude the use of additional zero-carbon energy to generate additional reductions in CO_2 emissions.

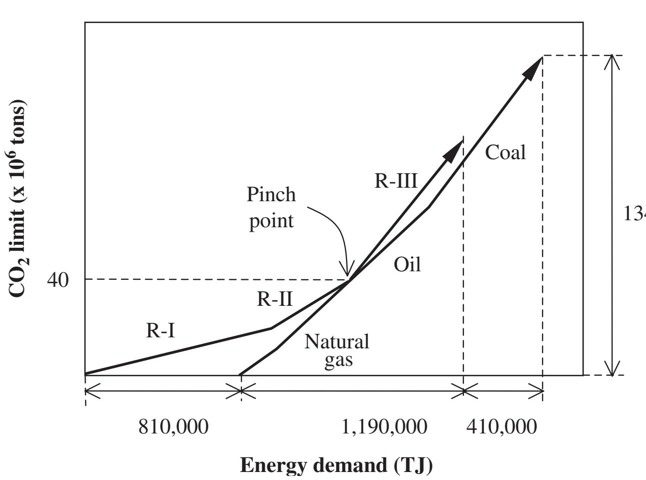

Fig. 5. Effect of disaggregated emission limits on zero-carbon energy demand (Case 3).

Another problem is the identification of the optimal energy allocation to the different sinks in order to meet their individual emissions limits. This objective can be achieved by considering each energy demand individually, and using the available energy resource with the lowest emissions factor (other than the zero-carbon energy source) to meet the requirement. The procedure was repeated for each energy demand, utilizing the available energy resources in order of ascending emissions factor. Finally, the zero-carbon resource was allocated only to the energy demands for which emission limits had already been saturated by the previously assigned conventional energy sources. The new diagram has two pinch points—the original one, as found in Fig. 5, and a new pinch point occurring at coordinates 1,000,000 TJ and 20 million tons of CO_2. The optimal allocation of energy sources can be found from this adjusted diagram. About 680,000 TJ of zero-carbon energy must be supplied to Region I. The balance of the energy demand of Region I amounts to 320,000 TJ and is met by using all of the available natural gas and 120,000 TJ of oil. These quantities are shown by the lengths of the segments of the source composite immediately below Region I. Note that, by using Fig. 5, it has been determined that 810,000 TJ of zero-carbon energy is required by the system. Hence, an excess of 130,000 TJ of zero-carbon energy remains after meeting the demand of Region I. This balance is supplied to Region II. This region also requires an additional 270,000 TJ of oil to meet the rest of its energy demand. Finally, the demand of Region III can be met using the remainder of the oil (410,000 TJ) and the amount of coal that can be utilized (190,000 TJ). The amount of unusable coal is shown in Fig. 6 to be 410,000 TJ. No zero-carbon energy needs to be supplied to Region III. The results have been confirmed by comparing with the solution found using the mathematical model given in the previous section; the two methods give similar allocation results. The optimal energy allocation that allows all regional emission limits and energy demands to be met, using the smallest amount of zero-carbon energy resource, is summarized in Table 3. The actual emissions for generated from this allocation scheme are also shown. Again, slight errors do arise from the inherent lack of visual resolution in the graphical displays.

It should be noted also that the amount of emissions actually generated from this energy mix is somewhat lower than the 100 million tons limit set for the total system. The figure is 91 million tons of CO_2, as indicated in Fig. 6. The reason for this is that the bottleneck or pinch for meeting carbon emission limits occurs in the regions with lower (more stringent) targets. In comparison, the solution to Case 1 assumes that any excess emission in Region I or II can be compensated for by emission savings in Region III.

It must be emphasized that, in general, the energy allocation solution derived by the above procedure is not unique. Depending on the specific numerical figures involved in the problem, more than one alternative feasible network may be possible. However, mathematical programming techniques are better suited to identifying the details of network variations. Such design methodologies can also take into account various additional constraints in addition to emissions limits. The pinch approach provides a useful supplement, particularly in the initial planning stages, when an overview of potential energy allocation to meet emission constraints may be more valuable than detailed modeling results.

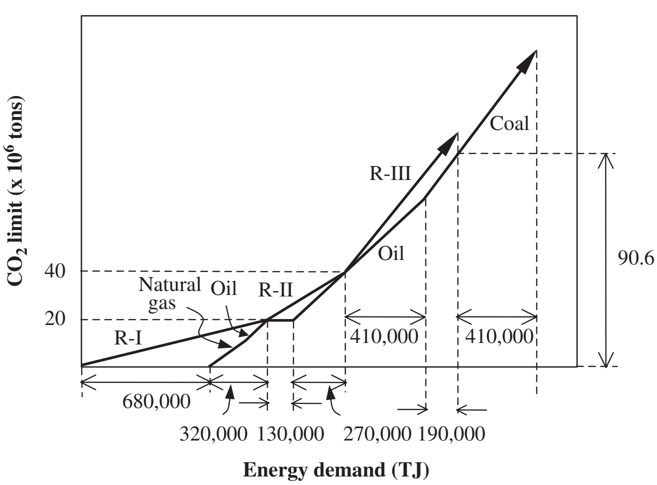

Fig. 6. Determining allocation of energy resources by pinch analysis (Case 3).

5. Conclusions

A graphical procedure for energy sector planning with emission constraints has been developed, and demonstrated with a case study on energy allocation with carbon emission limits. The technique is based on pinch analysis, which has been used for various applications with similar mathematical structure. Solutions to three simple case studies were found using the pinch technique. The same solutions can be found using linear programming, but the graphical displays of pinch analysis provide human decision-makers with a more intuitive grasp of the problem than is possible with mathematical programming. On the other hand, the pinch analysis approach is limited to relatively simple problems with highly aggregated energy sources and demands, and it cannot account for the constraints encountered in detailed planning. Furthermore, it can only be used for cases wherein a single emission, as in the case of CO_2 shown here, is of primary concern. Also, the precision of the results is dependent on the quality of resolution of the graphical displays, so that modified pinch approaches based on tabular techniques may have to be developed if more precise results are desired [12–14]. However, for the envisioned purpose of preliminary planning, such errors may be negligible as shown by the widespread use of graphical pinch applications that share similar shortcomings.

Table 3
Energy allocation for Case 3

	Energy resource (TJ)				
	Coal	Oil	Natural gas	Others	Demand total
Region I					
Quantity (TJ)	0	120,000	200,000	680,000	1,000,000
Emissions (10^6 t CO_2)	0	9.0	11.0	0	20.0
Region II					
Quantity (TJ)	0	270,000	0	130,000	400,000
Emissions (10^6 t CO_2)	0	20.3	0	0	20.3
Region III					
Quantity (TJ)	190,000	410,000	0	0	600,000
Emissions (10^6 t CO_2)	20.0	30.8	0	0	50.8
Supply total					
Quantity (TJ)	190,000	800,000	200,000	810,000	2,000,000
Emissions (10^6 t CO_2)	20.0	60.1	11.0	0	91.1

Pinch analysis can be used in energy management in conjunction with more sophisticated mathematical models, particularly as a tool for a preliminary planning. In addition, the same technique can be used for energy planning under other constraining conditions. For example, emission factors can be replaced with specific costs to allow the pinch technique to be used for planning problems with cost limits. These applications will be investigated in future work.

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