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ORIGINAL RESEARCH PAPER

Extended Graphical Technique for the Evaluation of Carbon Dioxide Emission Reduction Projects

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Abstract In recent years, many industrial companies are moving towards energy conservation initiatives, as a mean for cost reduction as well as to achieve a sustainability goal. In this work, a recently developed graphical technique based on *pinch analysis* is extended to perform selection among various CO_2 reduction and energy conservation projects, to be implemented for an industrial site. The extended technique performs project selection with the priority on CO_2 reduction, rather than economic criteria. The technique is elucidated with two case studies to demonstrate its applications.

Keywords Process integration · Pinch analysis · Graphical technique · CO_2 reduction

Introduction

It is now widely accepted that climate change is being one of the most critical environmental issues in the modern world (Rockström et al. 2009; Steffen et al. 2015). Note however that, despite the various international efforts such as the United Nations Climate Change Conference (COP 21) (Goldberg et al. 2015), fossil fuels will remain as the main energy source in the global market in the short term. This also includes the utilization of fossil fuel as the main energy source in many industrial processes. Fortunately, with the advances of technology, many new technologies have been reported to enhance the efficiency of those processes, which leads to

reduced cost and emissions. Hence, the key challenge remained on the selection of appropriate technologies for implementation, in order to ensure business sustainability apart from achieving a sustainable development goal.

Concurrently, various *process integration* tools have been developed in the past four decades to address various resource conservation problems. Process integration may be formally defined as "a holistic approach to design and operation that emphasises the unity of the process" (El-Halwagi 1997). Many of the developed tools are now widely accepted as standard design methodologies that are easily found in textbooks, such as those for the synthesis of heat-exchanger network (Linnhoff et al. 1982), heat-integrated processes (Smith 2016; Kemp 2007), and material resource conservation (El-Halwagi 2011; Foo 2012). Many industrial applications were also reported (El-Halwagi 2006; Klemeš 2013).

In the past decade, process integration methodologies have also been extended to various non-conventional applications, such as those for environmental footprint reduction and production planning. For the formal, some of the important works include the seminal work of Tan and Foo (2007) on *carbon-constrained energy planning*, as well as their subsequent works on water footprint (Tan et al. 2009; Jia et al. 2015) and production carbon footprint reduction (Tjan et al. 2010). In these works, process integration techniques were utilized to maximize the various resources but subject to the maximum footprint constraint. Some recent reviews summarized the state of the art in this area of research (Foo and Tan 2016; Tan and Foo 2017). On the other hand, various process integration tools were also developed for the optimum use of production resources such as equipment (Foo et al. 2007), human resource (Foo et al. 2010), and financial (Bandyopadhyay et al. 2016; Roychaudhuri et al. 2017). For the latter in particular, *financial pinch analysis* was used to evaluate the selection of various energy conservation projects, in order to fulfill the minimum requirements of available funds, such as the

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annual revenue (Bandyopadhyay et al. 2016), or net present value (Roychaudhuri et al. 2017). Note however that in both of these works, the attention is more towards energy conservation. Even though carrying out the energy conservation project will also lead to CO_2 emission reduction, the main aim of such implementations is on financial benefit rather than CO_2 emission reduction. The latter is hence the main objective of this work.

In this paper, graphical financial pinch analysis technique (Bandyopadhyay et al. 2016; Roychaudhuri et al. 2017) is extended for the selection of various CO_2 reduction conservation projects. The paper is structured as follows: in the following section, the problem statement is first given. The newly extended tool is described, with its procedure outlined. Two case studies are then used to illustrate the newly extended tool.

Problem Statement

The problem to be addressed may be formally stated as follows:

Given a set of CO_2 reduction projects ($j \in J$), each with CO_2 reduction intensity target (C_{Pj}) and requires an amount of investment (P_j), and also given a set of financial resources ($i \in I$), each with a maximum amount (F_i), and with minimum expected CO_2 reduction intensity (C_{Fi}) and/or expected payback, it is desired to determine which CO_2 reduction projects are to be selected for implementation, in order to maximize the CO_2 reduction goal.
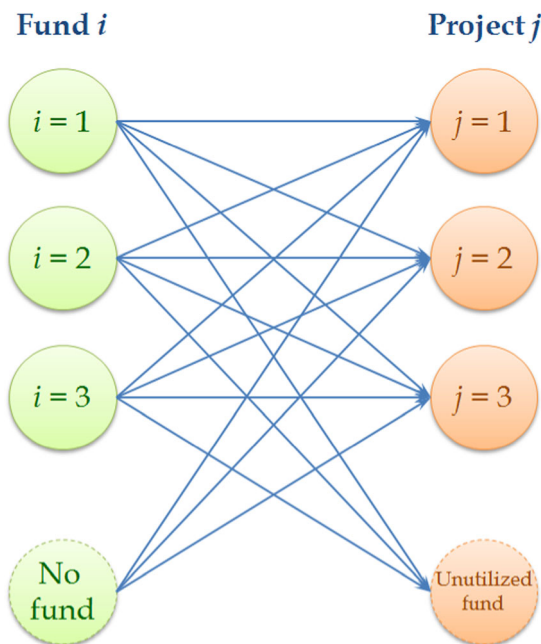

Fig. 1 Superstructure representation for CO_2 reduction project selection

Figure 1 shows the superstructure for this problem. Its associated model is shown in Appendix 1.

Extended Graphical Tool for CO_2 Reduction Project Selection

Figure 2 shows the newly extended graphical tool known as the *CO_2 reduction pinch diagram*, extended based on the financial pinch diagrams, originally proposed by Bandyopadhyay et al. (2016) and later improved by Roychaudhuri et al. (2017). Procedure to generate the CO_2 reduction pinch diagram is given as follows:

1. All CO_2 reduction projects are arranged in ascending order of CO_2 reduction intensity; the latter is a ratio of CO_2 reduction to financial expenditure for the given projects.
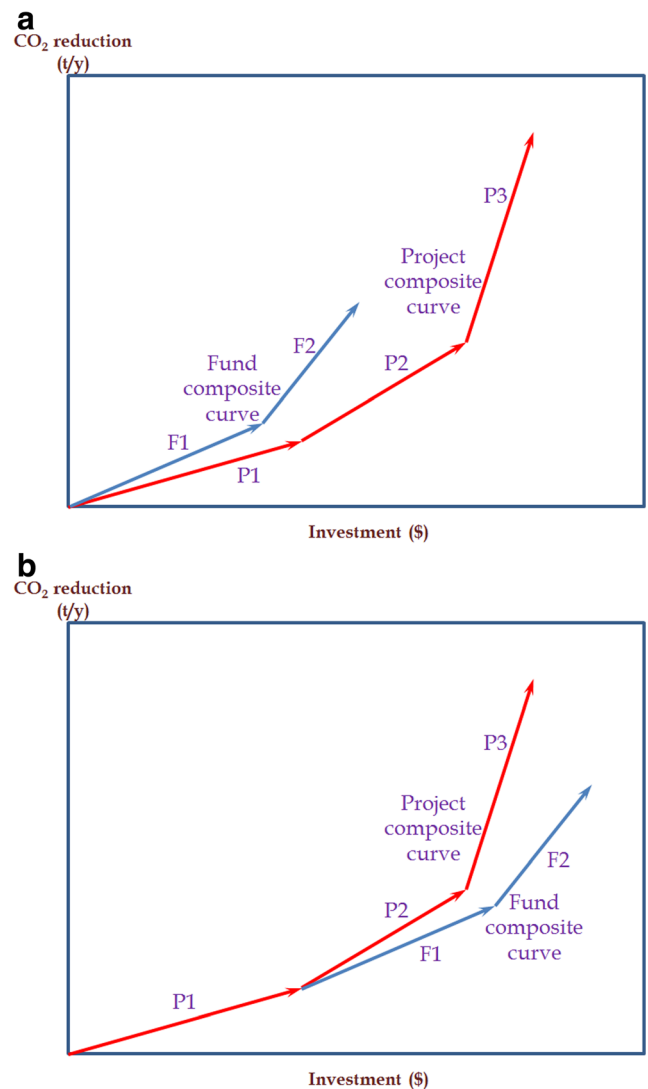

Fig. 2 CO_2 reduction pinch diagram: (**a**) infeasible investment and (**b**) feasible investment
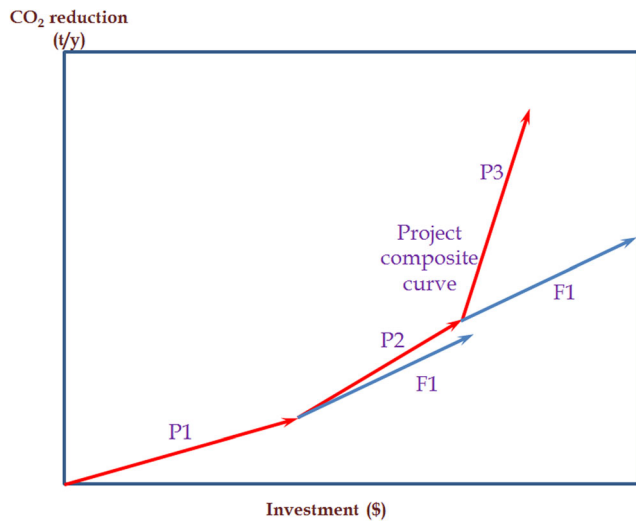
Fig. 3 CO_2 reduction pinch diagram for single fund and multiple project candidates

2. The CO_2 reduction projects are plotted on a CO_2 reduction versus financial expenditure diagram, one after another, to form the *project composite curve*. The segment with the lowest CO_2 reduction intensity (corresponds to the slope of the segment) is plotted from the origin, followed by segment of higher CO_2 reduction intensity (i.e., steeper slope).
3. All funds are arranged in ascending order of CO_2 reduction intensity. Note that in most cases, the CO_2 reduction intensity for the funds has to be set by funders, based on the desired CO_2 reduction that is anticipated.
4. The *fund composite curve* is next plotted at the origin of the same CO_2 reduction versus financial expenditure diagram, following the ascending order of CO_2 reduction intensity.

If part of the fund composite curve is located to the left of the project composite curve, the CO_2 reduction pinch diagram is considered as infeasible (Fig. 2a), as the anticipated CO_2 reduction of the fund has not been achieved. The fund composite curve has to be moved to the right along the fund composite curve, until it completely stays on the right and below the project composite curve; the latter case results with the feasible pinch

diagram (Fig. 2b). Note that the fund composite curve can only be moved segmental along the project composite curve, indicating that the project has to be implemented or rejected entirely (i.e., no partial implementation of the project), following the same practices in Bandyopadhyay et al. (2016) and Roychaudhuri et al. (2017). Also note that in the feasible pinch diagram, the CO_2 reduction intensities of the fund segments (indicated by its slope) are always lower than those of the project segment. In other words, the funded projects have fulfilled the minimum CO_2 reduction requirement of the funds.

There are also cases where a single fund is available and may be used to fund more than one project candidate. Figure 3 illustrates an example for such a case, where fund F1 may be used to fund project P2 or P3; note however that its amount is insufficient to fund both projects. Hence, decision has to be made to decide which fund is to be spent for either of the project candidates. For CO_2 reduction and cost effectiveness perspective, it is always advisable to fund the project with higher CO_2 reduction intensity (e.g., project P3 in Fig. 3).

In the following sections, two case studies are demonstrated to show how the CO_2 reduction pinch diagram is useful for project selection.

Case Study 1—CO_2 Reduction Initiatives for Palm Oil Refinery

Being the most important edible oil in the world market, the palm oil industry however has always been associated with some sustainability issues, e.g., deforestation, CO_2 debt, etc. In the past decades, with the growth of sustainability awareness among the consumers, various steps have been taken to improve the sustainability aspect of the palm oil industry.

In this section, an operating palm oil refinery in Pasir Gudang, Malaysia is analyzed for its effort towards energy saving and CO_2 reduction initiatives. The refinery produces more than one million tonnes of refined palm oil and speciality chemical products annually. In order to stay competitive, the company initiated several energy conservation projects, with the aim to reduce operating cost and to cut CO_2 emission. A total of four projects were under study, each with different financial commitment and payback, as well as CO_2 reduction

Table 1 Financial details for four projects

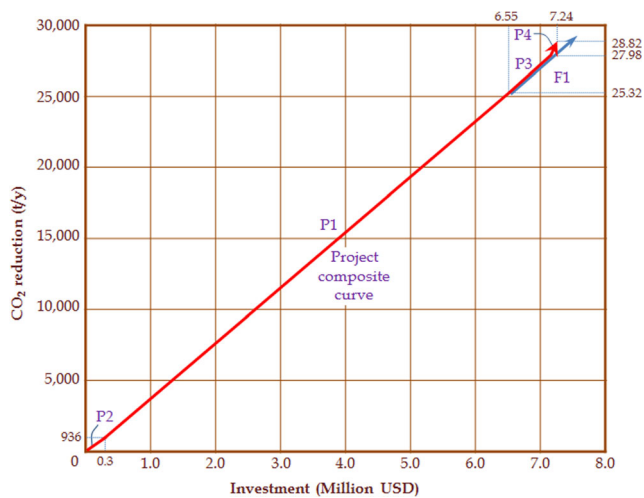| Projects	CO_2 reduction (t/year)	Saving ($/year)	Investment ($)	Payback period (year)
Project 1 (P1) Cogeneration	24,384	3,546,000	6,250,000	1.76
Project 2 (P2) Vapor absorption chiller	936	146,361	300,000	2.05
Project 3 (P3) High pressure boiler installation	2664	253,002	625,000	2.47
Project 4 (P4) Economizer installation	840	67,026	62,500	0.93

Fig. 4 CO_2 reduction pinch diagram for Case Study 1

target summarized in Table 1 (see details for project P1 in Appendix 2). It is assumed that the company had an internal fund of $1 million (F1), which may be used for investment. It is further assumed that the company hoped to reduce a total CO_2 emission of 4000 t/year. The latter may be used to calculate the CO_2 reduction intensity of this fund, i.e., 0.004 (= 4000 t/year CO_2/$1000,000). Decision is to be made to decide which of the project(s) among the four candidates is to be funded.

Following the step outlined, the feasible CO_2 reduction pinch diagram is plotted in Fig. 4. As shown, the internal fund is to be invested on projects P3 (high pressure boiler installation) and P4 (economizer installation). These projects have higher CO_2 reduction intensity (2664 t/year $CO_2/$625,000 = 0.0043$ for P3 and 840 t $CO_2/$62,500 = 0.0134$ for P4) than that of the fund. Since projects P3 and P4 will consume a total investment of

$687,500 (= $625,000 + $62,500), a total of $312,500 of the fund is left unutilized. Note also that implementing projects P3 and P4 will reduce 3504 t/year (= 2664 + 840 t/year) of CO_2 emission.

It is also worth considering project selection using the financial pinch diagram. One of such diagram based on the work of Bandyopadhyay et al. (2016) is shown in Fig. 5, in which project saving is plotted versus the investment. Note that the arrangement of the segments in the project composite curve is slightly different from that in Fig. 4. For this case, the expected payback period for the internal fund is assumed as 2 years. From Fig. 5, it can be observed that the internal investment of $1 million can only be used to fund project P4, with an investment of $62,500. Even though the payback period of projects P1 (1.76 years) and P4 (0.93 years) are both shorter than that of the fund, the fund is however insufficient to cater for project P1 which needs a huge investment of $6.25 million (see Appendix 2 for its utility cost). Even though this project has a huge CO_2 reduction potential of 24,384 t/year, its high capital investment renders its implementation. By implementing project P4, the company will only achieve a CO_2 reduction of 840 t/year, which is much lower than having projects P3 and P4 combined (i.e., 3504 t/year); however, P3 has not been selected due to its long payback period (2.47 years). This proves the importance of using the CO_2 reduction pinch diagram for CO_2 reduction project selection.

It is also worth noting that in some cases, both financial and CO_2 reduction goals are to be considered simultaneously. In these cases, the recently established multi-dimensional pinch analysis techniques (Jia et al. 2016; Patole et al. 2017) may be adopted.
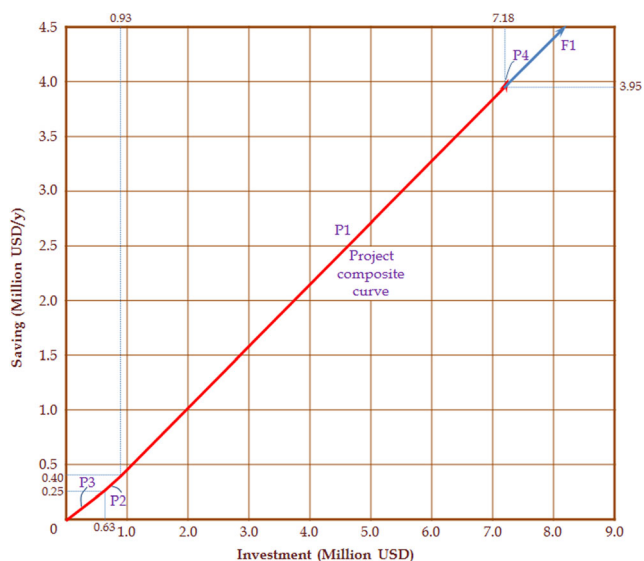

Fig. 5 Financial pinch diagram for Case Study 1

Table 2 CO_2 reduction and investment for different NETs

| Projects	CO_2 reduction (MM t/year)	Investment (MM $/year)
P1—Wet calcination	10,000	3,800,000
P2—Supported amines	10,000	1,700,000
P3—Biochar	2000	320,000
P4—BECCS—combustion	6000	960,000
P5—Ocean liming—electrochemical	1000	140,000
P6—Ocean biomass burial	2200	162,800
P7—Forest restoration	2200	132,000
P8—Ocean liming—calcination	3000	174,000
P9—BECCS—ethanol	48	2160
P10—BECCS—black liquor	310	13,950
P11—Soil mineralization	1000	30,000
P12—Biomass burial	2000	56,000
P13—Wetland restoration	300	4500
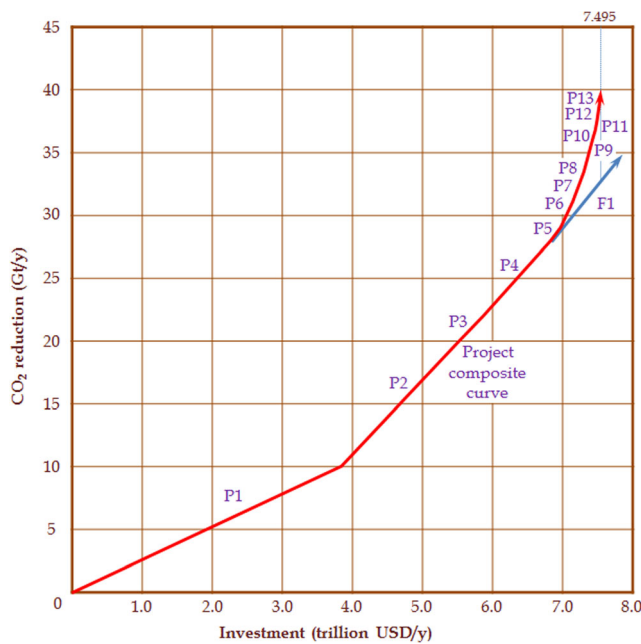
Fig. 6 CO_2 reduction pinch diagram for Case Study 2

Case Study 2—Assessment of Negative Emissions Techniques (NETs)

McLaren (2012) reported a comparative assessment of 30 prospective negative emissions techniques (NETs) that are potentially useful in achieving negative greenhouse gas (GHG) emissions globally. These NETs may be broadly categorized according to their storage mechanism, i.e., mineral, pressurized, oceanic and biotic storage. Mineral storage binds CO_2 in mineral form in the rocks or soil. For pressurized storage, the captured CO_2 are compressed and injected into geological storage reservoir. On the other hand, CO_2 are bound with chemicals naturally occurring in the oceanic storage. Lastly, CO_2 are held in relatively stable organic form (e.g., soil, construction timber, or buried biomass) for biotic storage.

Among the 30 prospective NETs, 13 of them were analyzed in detail for their technology readiness, capacity, and costs. The latter two are the main focus of this work, with their data summarized in Table 2. An annual fund of $1 million (F1) is assumed to be available for investment, further assuming that the fund should have a CO_2 reduction intensity of 0.007 Gt/trillion USD. Decision is to be made to select the appropriate project(s) to be funded.

The feasible CO_2 reduction pinch diagram in Fig. 6 shows that the fund is to be invested on projects P5–P11. Data in Table 2 indicates that a total of 12,058 MM t/year of CO_2 will be removed by implementing these projects. A close inspection also reveals that these projects have higher CO_2 reduction intensity values as compared to that of the fund. Note however

that a total of $284,590 of the fund is left unutilized since projects P5–P11 will only consume a total investment of $715,410.

Conclusion

A graphical technique has been proposed for project selection that emphasizes on CO_2 emission reduction. The technique was extended based on the recently established financial pinch analysis technique. Instead of selecting the project based on financial criteria, the CO_2 reduction pinch diagram emphasizes on CO_2 reduction. The case studies solved show that good projects can be selected to maximize the CO_2 reduction goal. Future works may consider the analysis of CO_2 reduction projects that have simultaneous reduction of other environmental footprints.

Appendix 1

The project selection model can also be solved using the following model, adapted from Roychaudhuri et al. (2017). The objective is given in Eq. A1.

$$\text{Maximize} \sum_j F_{i,j} C_{Pj} \tag{A1}$$

subject to,

$$F_i = \sum_j F_{i,j} + F_{U,i} \quad \forall i \tag{A2}$$

$$P_j = \sum_j F_{i,j} + P_{NF,j} \quad \forall j \tag{A3}$$

$$\sum_i F_{i,j} C_{Pj} \geq \sum_i F_{i,j} C_{Fi} \quad \forall j \tag{A4}$$

$$\sum_i F_{i,j} \leq I_j M \quad \forall j \tag{A5}$$

$$P_{NF,j} \leq I_{NF,j} M \quad \forall j \tag{A6}$$

$$I_j + I_{NF,j} = 1 \quad \forall j \tag{A7}$$

$$I_j I_{NF,j} = 0 \quad \forall j \tag{A8}$$

where $F_{i,j}$ and $F_{U,i}$ denote the allocation amount from fund i to project j and the amount of fund i that is left unutilized, respectively; $P_{NF,j}$ indicates the amount for the non-funded project j; binary variables I_j and $I_{NF,j}$ indicate if a project is funded or otherwise, respectively; and M is an arbitrary large value.

Constraint in Eq. A2 indicates that the available fund i may be allocated to project j or left unutilized. Eq. A3 indicates that project j may be funded by fund i or not funded at all. Eq. A4 indicates that when a project is to be allocated by fund i, its CO_2 reduction intensity should be larger than the minimum value of the fund. Eq. A5–A8 are used to forbid project from being funded partially. Note that the model is a mixed-integer non-linear program (MINLP) due to the bilinear term in Eq. A8.

Appendix 2

Cost and CO_2 emission calculation is shown here for Project 1 (cogeneration). The calculation for conventional system (with external utility supplier) is summarized in Table 3, while that for cogeneration is shown in Table 4. Details for other projects are found in Kumar (2011).

Table 3 Utility cost and CO_2 emission for conventional system (monthly basis)

Details	Specification	
Power generation		
Consumption	3,639,600	kwh
CO_2 emission at 0.45 kg/kWh	1638	t
Cost at \$0.073/kW	263,871	\$
Steam generation		
Average steam consumption/month	28,800	t
Natural gas	2160,000	sm^3
Cost at \$0.145/sm^3	313,200	\$
CO_2 emission at 1.81 kg/sm^3	3910	t
Total CO_2 emission	5547	t
Total utility cost	577,071	\$

Table 4 Utility cost and CO_2 emission for cogeneration system (monthly basis)

Details	Specification	
Power generation		
Power produced by cogeneration	3,465,360	kwh
Natural gas consumption	1,185,120	sm^3
CO_2 emission at 1.81 kg/sm^3	2145	t
Steam generation		
Steam produced for heat recovery	8892	t
Steam produced fr. supplementary fixing	19,908	t
Natural gas required fr. supplementary fixing	757,440	sm^3
CO_2 emission at 1.81 kg/ sm^3	1371	t
Total natural gas requirement	1,942,560	sm^3
Total CO_2 emission	3516	t
Total utility cost (natural gas at \$0.145/sm^3)	281,671	\$

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