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Optimal Electricity Trading with Carbon Emissions Pinch Analysis

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Many countries face the challenge of cutting greenhouse gas (GHG) emissions from electricity generation while coping with increasing demand. This problem is especially pronounced in developing countries with growing energy consumption. Commitments to cut GHG emissions can be met by increasing the share of low-carbon sources such as renewable and nuclear energy, but rapidly scaling up the capacity of such sources can be difficult. In a region of contiguous countries with heterogeneous levels of GHG intensity, electricity trading can be used to reduce the need for new power generation capacity. A country with a low-carbon power mix can export to its neighbours and thus reduce the need for new generation capacity in those countries. In this work, a variant of Carbon Emissions Pinch Analysis (CEPA) is developed for optimizing regional electricity trading to meet GHG emissions cuts. The method is demonstrated with the case of the Association of Southeast Asian Nations (ASEAN).

1. Introduction

Due to the clear urgency of climate change as a global environmental problem, the optimization of Carbon Management Networks (CMNs) has become an important emerging sub-area of Process Integration (PI) (Tan and Foo, 2018). The potential of PI, and specifically Pinch Analysis (PA), for determining emissions reduction potential in Total Sites (TS) was recognized in the early 1990s before climate change became widely recognized as a cause for concern (Dhole and Linnhoff, 1993). Although PI was originally motivated primarily by the need to reduce costs associated with energy consumption, sustainability issues have become increasingly important considerations as PI diversified through four decades of development. This trend can be seen in the scope of issues addressed by contributions in a handbook dedicated to the topic (Klemeš, 2013), and more recent developments are surveyed in a review article (Klemeš et al., 2018).
Carbon emissions pinch analysis (CEPA) was first proposed by Tan and Foo (2007) for energy planning with greenhouse gas (GHG) emissions constraints. The original methodology used a graphical PA approach, but subsequent contributions developed algebraic (Foo et al., 2008) and Automated Targeting Method (ATM) variants (Lee et al., 2009). The temporal aspect was introduced by Atkins et al. (2010) to allow the use of CEPA for long-term planning. Related approaches based on Mathematical Programming (MP) (Pękala et al., 2010) and P-graph (Tan et al., 2017) have also been developed. Francisco et al. (2014) proposed the Carbon Sources Diagram technique that allows the generation of an optimal CMN without the need to establish the target beforehand. Tan et al. (2018) combined economic input-output analysis and CEPA to allow carbon-constrained energy planning to be based on economic sectors. Variants of CEPA were also developed to account for other sustainability metrics, such as land footprint (Foo et al., 2008), water footprint (Tan et al., 2009a), emergy (Bandyopadhyay et al., 2010), and inoperability risk (Tan and Foo, 2013). The limitation of being able to deal with just one sustainability aspect at a time was addressed in recent efforts to develop multi-dimensional variants (Jia et al., 2016). Patole et al. (2017) proposed to use a weighted aggregate

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sustainability index to allow graphical PA to handle multiple dimensions simultaneously. Sinha and Chaturvedi (2018) developed a graphical bi-objective approach to minimize energy use and carbon footprint. Lee et al. (2019) proposed an MP model for multi-footprint energy planning problems.

CEPA and its variants has been used by different research groups to optimize energy systems in Ireland (Crilly and Zhelev, 2008), New Zealand (Atkins et al., 2010), India (Krishna Priya and Bandyopadhyay, 2013), the United States (US) (Walmsley et al., 2015a), China (Li et al., 2016), the United Arab Emirates (UAE) (Lim et al., 2018), the Baltic States (Baležentis et al., 2019), Nigeria (Salman et al., 2019), Taiwan (Lee et al., 2019), and the European Union (EU) (Su et al., 2020). It has also been used for specific sectors or subsystems, such as industrial parks (Jia et al., 2009), electricity generation with CO_2 capture and storage (CCS) (Tan et al., 2009), transportation systems (Walmsley et al., 2015b), negative emissions technologies (NETs) (Foo, 2017), chemical production (Qin et al., 2017), and municipal solid waste (MSW) management (Jia et al., 2018). Andiappan et al. (2019) discussed the potential of CEPA as a tool to guide the development of policies for low-carbon growth. The review article by Foo and Tan (2016) gives a detailed survey of key developments in CEPA and allied topics in the decade following the publication of the initial paper (Tan and Foo, 2007). A comprehensive tutorial on CEPA can be found in a recently published book (Foo and Tan, 2020).

In this paper, a variant of CEPA is developed for the novel problem of optimal planning of electricity trading among countries or regions. This strategy allows for export of low-carbon electricity to displace capacity in other countries with higher grid carbon intensity (Lopez et al., 2018); trade can also occur among regions in a single country (de Chalendar et al., 2019). The methodology finds the minimum target for the total zero-carbon electricity generation required by all the countries or regions in the system, and then determines the optimal electricity imports and exports to meet the target. The rest of this paper is organized as follows. Section 2 defines the formal problem statement. Section 3 describes the steps in the graphical procedure. Section 4 applies the methodology to a simple tutorial example, while Section 5 presents a more complex application to geographically contiguous countries in the Association of Southeast Asian Nations (ASEAN). Finally, Section 6 gives the conclusions and further prospects for future work.

2. Problem statement

The specific problem addressed by this work can be formally stated as follows. Given:

- A system consisting of m countries which at present do not trade electricity;
- For each country in the system, the current electricity generation/demand, the average CO_2 intensity, and the total CO_2 emissions from electricity generation;
- For each country in the system, the estimated future electricity demand (typically larger than the current level), the future average CO_2 intensity limit at the end user (lower than the current level), and the corresponding limit on the total CO_2 footprint of electricity;

The objective is to target the minimum amount of new zero-carbon electricity generation capacity to be shared by all the countries in the system, but allowing them to meet their future increased demand for electricity with reduced CO_2 intensity. By allowing countries with lower grid CO_2 intensity levels to export to their neighbours, the requirement for new zero-carbon electricity can be lower than if each country seeks to meet its demands in isolation from the others. Note that zero-carbon electricity, in this case, refers to sources such as renewables, whose emissions intensity levels are much lower than those of fossil-based electricity (Tan and Foo, 2007).

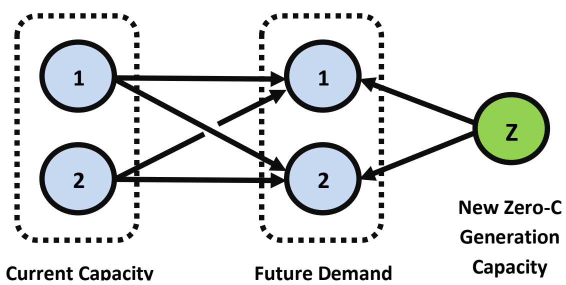

Figure 1: Electricity trading problem superstructure for two countries

The corresponding superstructure for this problem is shown in Figure 1. The current installed capacity in the different countries act as the sources, while future demands of the countries are as the sinks. Additional zero-carbon generation capacity may be needed in the system to meet increased demand or reduce CO_2 intensity, but is to be minimized through electricity trading.

3. Graphical procedure

The steps in the graphical procedure are similar to standard CEPA (Tan and Foo, 2007) and are as follows:

- Step 1. The sources are arranged in order of increasing CO_2 intensity.
- Step 2. The demands are arranged in order of increasing CO_2 intensity.
- Step 3. The sources are plotted in sequence to form the source composite curve (SCC), with cumulative electricity generation as the x-axis and cumulative CO_2 emissions as the y-axis.
- Step 4. The demands are plotted in sequence to form the demand composite curve (DCC) using the same coordinates as the SCC.
- Step 5. The SCC and DCC are superimposed and the relative orientations are inspected. A feasible solution occurs if the SCC is entirely below the DCC and if its horizontal span at least equals that of the DCC.
- Step 6. If the initial solution is infeasible, the SCC is shifted horizontally to the right until the conditions for feasibility are satisfied. The smallest horizontal shift needed to ensure feasibility is the target.
- Step 7. The electricity trading matrix may be determined from the final orientations of the SCC and DCC. Detailed steps are omitted here for brevity, but a full description can be found in the book by Foo and Tan (2020).

This procedure is illustrated with case studies in the next two sections.

4. Case study 1

This case study presents a simple example with three countries for illustrative purposes. The system data are given in Table 1. In the current state, all countries are assumed to be self-sufficient, so the capacity is equivalent to demand. It can be seen that the desired future state entails demand growth of 25 %, 0 %, and 25 % for the three countries, respectively. At the same time, the countries seek to reduce CO_2 intensity by 40 %, 50 %, and 10 %. The countries aim to meet the future conditions by supplementing the current electricity generation mix with new zero-carbon capacity in the form of renewables.

Table 1: System data for Case Study 1

Country	Current capacity (TWh/y)	Current CO_2 intensity (Mt/TWh)	Current CO_2 emissions (Mt/y)	Future demand (TWh/y)	Future CO_2 intensity limit (Mt/TWh)	Future CO_2 emissions limit (Mt/y)
1	60	0.40	24.00	75	0.24	18.00
2	40	0.70	28.00	40	0.35	14.00
3	20	0.90	18.00	25	0.81	20.25

Without electricity trading, each country will need to install new generation capacity for itself in order to reduce CO_2 intensity, meet the increased demand, or both. For example, Country 1 will need to phase out 25 % of its current generation capacity to reduce CO_2 emissions by the same factor. It is assumed that there is no differentiation of the components of the current energy mix. Country 1 will need 15 TWh/y (60 TWh/y x 25 %) of new capacity just to replace this lost output, and an additional 15 TWh/y to meet the incremental demand. Thus, a total of 30 TWh/y of zero-carbon electricity generation capacity will be needed to satisfy the future demand and emissions limit. Similar calculations for Country 2 will yield a requirement of 20 TWh/y. Finally, Country 3 can meet its new demand by installing 5 TWh/y of additional capacity without even reaching its emissions limit. Without electricity trading, the system needs a total of 55 TWh/y (30 TWh/y + 20 TWh/y + 5 TWh/y) of new zero-carbon electricity generation capacity.

If electricity trading is allowed, the amount of new capacity needed can be reduced. Application of Steps 1–5 of the procedure described in the previous section gives an infeasible solution, as shown in Figure 2a. Note that the SCC is above the DCC, and its horizontal span is shorter. Applying Step 6 gives an optimal result as shown in Figure 2b. The target is 43.6 TWh/y, which is 20.7 % lower than the requirement without electricity trading. Countries 1 and 2 are below the Pinch Point; the significance of this result is discussed later. It can be seen that Country 3 in the DCC is above the Pinch Point, which indicates that its emissions limit are not reached by this configuration.

The actual electricity trading scheme that satisfies this target can be found using Step 7. The allocation can be found by inspection in the case of this simple example, but can also be done algorithmically; details of this step are described elsewhere (Foo and Tan, 2020).

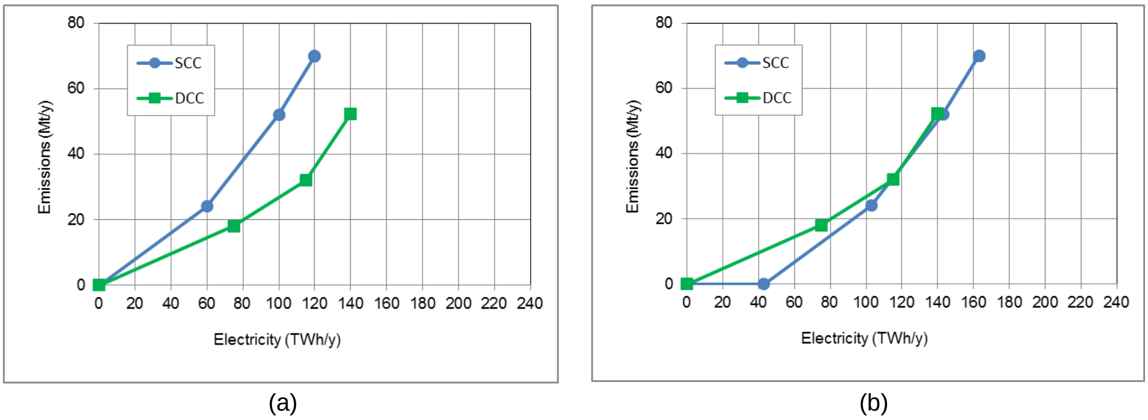

Figure 2: (a) Initial and (b) Optimal Pinch Diagrams for Case Study 1

The resulting electricity trading matrix is shown in Table 2. The total new capacity of zero-carbon electricity generation (43.6 TWh/y) is allocated only to Countries 1 and 2, which are below the Pinch Point. This result corresponds the Golden Rule of PA forbidding cross-pinch transfer of streams in an optimal system. Country 1 retains its current generation capacity, but uses only 75 % for itself, *and* exporting 25 % to Country 2. Country 2 uses 11.4 TWh/y of its capacity internally, exports enough electricity to supply the entire 25 TWh/y demand of Country 3, and an excess capacity of 3.6 TWh/y is unused. This excess capacity corresponds to power plants to be shut down or held in reserve. Country 3 shuts down all of its power plants and relies on imports from Country 2 to satisfy all of its requirements. It should be noted that the PA solution represents the physical limit based on energy and carbon balances, and does not account for non-physical aspects such as energy security. In practice, the solution to be implemented may lie between the two extremes of complete self-sufficiency (i.e., no electricity trading) and the physical optimum reported here.

Table 2: Optimal electricity trade matrix for Case Study 1 (values in TWh/y)

	Country 1	Country 2	Country 3	Excess
New zero-C capacity	30	13.6	0	0
Country 1	45	15	0	0
Country 2	0	11.4	25	3.6
Country 3	0	0	0	20

5. Case study 2

This case study applies this methodology to the case of six geographically contiguous countries in ASEAN. The system data is shown in Table 3. Final consumption energy data is used from IEA (2019). CO_2 intensity is obtained by calculating actual emissions based on the power generation mix. Future power demand and CO_2 emissions are estimated in the near term, considering the ASEAN Energy Outlook (ASEAN Centre for Energy, 2017) and the individual country renewable energy commitments (IEA, 2017).

Table 3: System data for Case Study 2

Country	Current capacity (TWh/y)	Current CO_2 intensity (Mt/TWh)	Current CO_2 emissions (Mt/y)	Future demand (TWh/y)	Future CO_2 intensity limit (Mt/TWh)	Future CO_2 emissions limit (Mt/y)
Vietnam	194.04	0.360	69.85	242.42	63.03	0.260
Myanmar	21.05	0.380	8.00	25.65	8.34	0.325
Singapore	50.24	0.440	22.11	58.07	16.85	0.290
Cambodia	8.09	0.520	4.21	9.41	4.33	0.460
Thailand	207.94	0.570	118.53	249.76	129.87	0.520
Malaysia	163.29	0.660	107.77	191.68	76.67	0.400

Table 4: Optimal electricity trade matrix for Case Study 2 (values in TWh/y)

	Vietnam	Myanmar	Singapore	Cambodia	Thailand	Malaysia	Excess
New zero-C capacity	67.3	2.7	17.4	1.1	15.8	75.4	0
Vietnam	175.1	19.0	0.0	0	0	0	0
Myanmar	0	4.0	17.1	0	0	0	0
Singapore	0	0	23.6	0	26.7	0	0
Cambodia	0	0	0	8.1	0	0	0
Thailand	0	0	0	0	207.3	0.7	0
Malaysia	0	0	0	0.2	0	115.6	47.5

Following the same steps as in the previous case study, it is possible to determine the target of 179.9 TWh/y of new zero-carbon electricity generation capacity, and an optimal electricity trading scheme for these six countries which meet their future requirements and emissions limits. Due to space constraints, the Pinch Diagram is not shown here. The resulting electricity trading matrix is given in Table 4. The results show that even with electricity trading in place, each country would still need to install some amount of zero-carbon generation capacity to meet its emissions target. It also suggests that Malaysia should shut down (or utilize as reserve) 47.5 TWh/y of its current capacity. In this scenario, the region would trade approximately 71.6 TWh/y of electricity.

6. Conclusions

This paper has developed a CEPA approach for planning optimal electricity trading. The new methodology can identify the optimal target and determine the corresponding electricity import and export matrix for a given set of countries or regions with self-defined emissions limits. Two case studies were solved to illustrate the procedure – one for tutorial purposes, the other to demonstrate applicability to a real data set from ASEAN. Future work can focus on the development of a multi-period or dynamic extensions, which will allow progressive emissions cuts and power plant phase-out to be dealt with.

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