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Process-to-Policy (P2Pol): Using Carbon Emission Pinch Analysis (CEPA) Tools for Policy Making in the Energy Sector

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Abstract

Global warming is a major international issue due to rising levels of greenhouse gases (GHGs) such as CO_2. Many countries now face the challenge to find cost effective ways to deploy low carbon technologies in order to meet commitments to the Paris Agreement. *Process systems engineering* (PSE) can play an essential role in supporting high-level policy decisions to help mitigate climate change. Within PSE, carbon-constrained planning will become increasingly critical for policy-making on provision of sustainable energy in electricity generation as well as other economic sectors. There are existing carbon-constrained planning tools but these often consider energy issues from limited perspectives at specific scales. In this perspective paper, we argue for a Process-to-Policy (P2Pol) framework that centres on carbon-constrained planning which includes various stakeholders at various scales for developing strategies to address global warming. There is an urgent need for research on the development of such tools at multiple scales to effectively allocate countermeasures such as negative emission technologies (NETs). We also discuss potential extensions for carbon-constrained planning in conjunction with other established tools.

[End of Abstract]

The rise in global CO_2 levels has prompted policy-makers to rethink energy initiatives for the future. In response to this, the Paris Agreement was adopted by 190 nations at the 21st Conference of Parties (COP21) in 2015. The agreement makes use of voluntary intended nationally determined contributions (INDCs) by signatory countries. Shortly after COP21, the 17 Sustainable Development Goals (SDGs) were agreed upon in the United Nations (UN). Among these SDGs, SDG 7 (Affordable and Clean Energy); SDG 9 (Industries, Innovation and Infrastructure); SDG 12 (Responsible Consumption and Production); and SDG 13 (Climate Action) are goals related to sustainable energy generation. However, national commitments to the Paris Agreement alone are not enough. It is essential to cascade these down to other decision-making levels as implementable actions to realize these high-level commitments. In this respect, many countries have worked towards formulating specific policies to reduce their emissions in the energy sector. Sustainable electricity generation will play a particularly important role for developing countries . Many government ministries have already set targets and started along this path, but there are many other factors to consider, such as other environmental impacts, social acceptability, economics, reliability, and scale.

To plan and evaluate sustainable energy generation opportunities, system analysis tools would be very useful for providing policy makers with additional insights when making decisions on environmental policy. With growing energy demands, these techniques are important tools to assist policy-makers and energy companies in designing (and planning operations) for sustainable energy generation systems of the future. In this respect, *process systems engineering* (PSE) has a unique role to play in developing strategic plans for sustainable energy generation. PSE is a field that focuses on developing systematic design approaches to identify the optimum type, design and interconnection of processing units in process and manufacturing systems (Stephanopoulos and Reklaitis 2011). Within PSE, there is a sub-domain known *process integration* (PI) which places emphasis on efficient use of resources through the optimization of linkages among system components. PI involves a wide range of methodologies developed for the design of networks that efficiently use energy and water (Linnhoff et al. 1982; Klemeš 2013). PI tools are essentially focused on process improvement. This is evidently pointed out in reviews by El-Halwagi and Foo (2014), Foo (2009) and Klemeš et al. (2018) respectively. In other words, these tools have been mainly used by process engineers at the process/manufacturing plant level. In one notable exception, Tan and Foo (2007) developed the *carbon emissions pinch analysis* (CEPA) for optimizing energy allocation in carbon-constrained systems based on the principles of PI. In CEPA, a graphical tool known as *energy planning pinch diagram* (EPPD, Fig 1) was proposed to analyse the minimum required renewable energy resources, while taking into account the maximum amount of conventional fossil fuel that can be used. EPPD was then extended by Lee et al. (2009) and Sahu et al. (2014). Lee et al. (2009) extended EPPD by incorporating it into an optimisation framework called *automated targeting model*. Meanwhile, Sahu et al. (2014) developed an alternative extension of EPPD, in the form of an algebraic technique. Since then, CEPA approaches have been developed and used to plan emission reduction strategies for several countries. A list of selected countries where CEPA approaches have used or developed for are shown in Table 1.

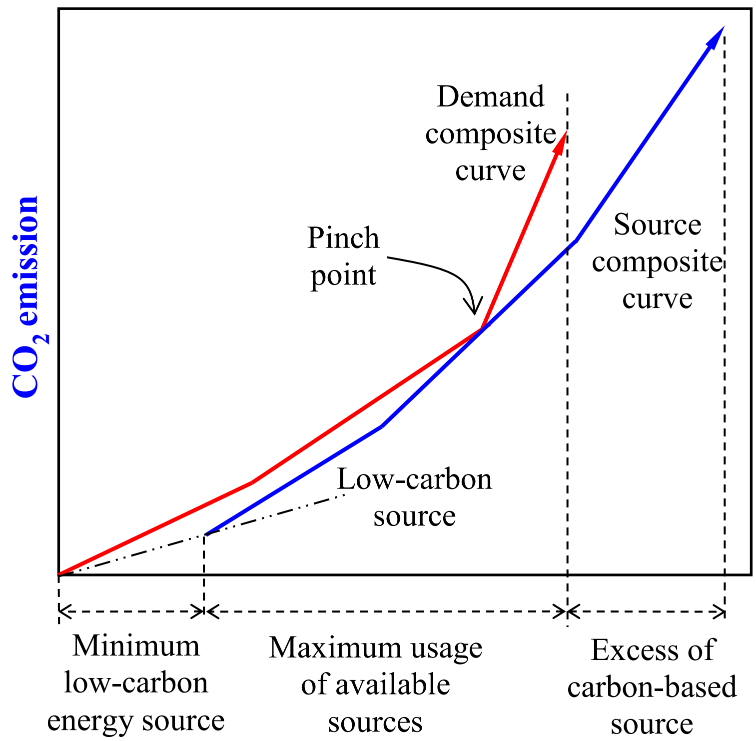

Fig. 1 Energy Planning Pinch Diagram for CEPA

Table 1 CEPA Approaches and Variants Developed based on Countries

Country	Reference
China	(Li et al. 2016)
New Zealand	Atkins et al. (2010), Walmsley et al. (2014)
Ireland	Crilly and Zhelev (2010)
India	Priya and Bandyopadhyay (2013)
Estonia, Latvia and Lithuania	Baležentis et al. (2019)
Malaysia	Leong et al. (2019), Ramli et al. (2018)
Nigeria	Salman et al. (2018)
Brazil	de Lira Quaresma et al. (2018)
United States of America	Walmsley et al. (2015)

The aforementioned works are essential to the development of future CEPA tools. However, many of these works take a decentralised perspective, and are not readily focused on the "big picture". CEPA approaches have significant potential to provide a basis for national and international policy-making. Thus, in this paper, we propose a Process-to-Policy (P2Pol) concept that is inspired by the multi-scale modelling framework known as Process-to-Planet (P2P) framework (Hanes and Bakshi 2015). Unlike P2P, P2Pol is presented in this paper to emphasise the importance of scaling up CEPA efforts to national and international policy-making in the energy sector.

P2Pol is a conceptual framework that features inclusivity, which is a key element in enabling a successful shift towards sustainable policies. In this respect, it is important to have an approach that is inclusive of every stakeholder involved in determining the direction of energy utilisation. Since CEPA originates from process systems thinking, it readily includes engineers and industrial practitioners into the conversation. However, CEPA can be more inclusive when it considers many other aspects that are crucial to policy-makers. As shown in Fig. 2, P2Pol is a multi-scale framework that uses CEPA to include stakeholders from different levels, ranging from local districts, to entire states, countries and regions. In practice, decisions made at different levels may not be properly synchronized towards overall goals unless proper measures are taken to cascade decision implications upwards and downwards through the hierarchy. Insights from each scale can be used to determine the feasibility at the next scale. For instance, if a nation intends to achieve a certain reduction target, the multi-scale CEPA framework would allow policy-makers to examine if the amount of available resources at the national level is sufficient to achieve the targets. Subsequently, based on the insights from the national level, policy-makers can determine if the efficiency and process challenges at the district and process levels permit such ambition. Eventually, the actual measures to reduce emissions will be implemented by decision-makers in industry, in response to top-down policy signals or directives. CEPA can be applied at multiple levels to allow such cascading to occur. This approach has been used in New Zealand via nested composite curves (e.g., Walmsley et al., 2014; 2019), and promises to be widely applicable in broader contexts.

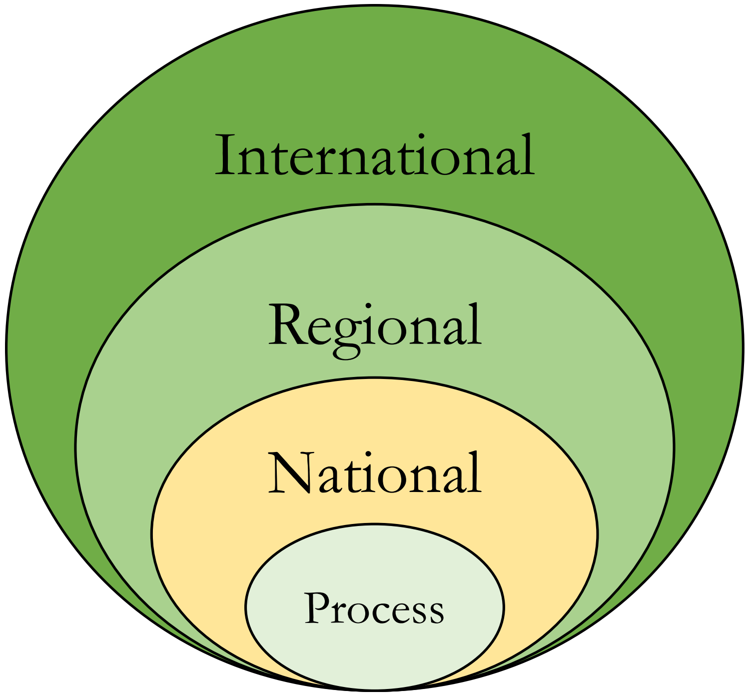

Fig. 2 Multi-Scale P2Pol Framework

At the national and international level, P2Pol facilitates discussion and negotiation among countries involved in reducing GHG emissions. This is a critical point, since equity issues have been a major stumbling block in the past, particularly between developed countries like the United States and emerging economies like China. With P2Pol, each country can have comprehensive measurement of their current CO_2 levels, an up-to-date CEPA which can be used a basis for negotiation with other countries. In particular, countries that intend to achieve a global CO_2 reduction by a certain target year, can negotiate commissioning schedules according to priority and current economic growth (Fig. 3). For instance, developing countries would not regard investing in new *negative emission technologies* (NETs) as the highest priority since their efforts need to be placed in other matters. As such, developing countries can postpone their deployment to a later date and allow developed countries with high economic growth to lead the way in reducing CO_2 emissions. At the same time, developed countries could share responsibility with developing countries to deploy these infrastructure.

Governments and policy-makers can also use this opportunity to explore and incorporate indigenous renewable energy resources into their future energy initiatives and trade with other nations. Countries with excess renewable energy resources (presumably after meeting internal reduction targets) can trade with countries that lack resources to achieve their individual targets. In the scenario envisioned here, the personnel using CEPA tools are not the politicians themselves, but technical experts and researchers providing advice to politicians. Policies should be formulated on the basis of comprehensive study, and the study is undertaken by those who are experienced in that given area. In addition, it is worth pointing out that CEPA, and particularly the EPPD, is also very user-friendly communication tool. As previously shown in Figure 1, EPPD visually displays the CO_2 emissions versus the energy content from each source. These are terms easily understood by policy-makers and government officials, which must be a prerequisite for making policy in climate change or energy related matters.

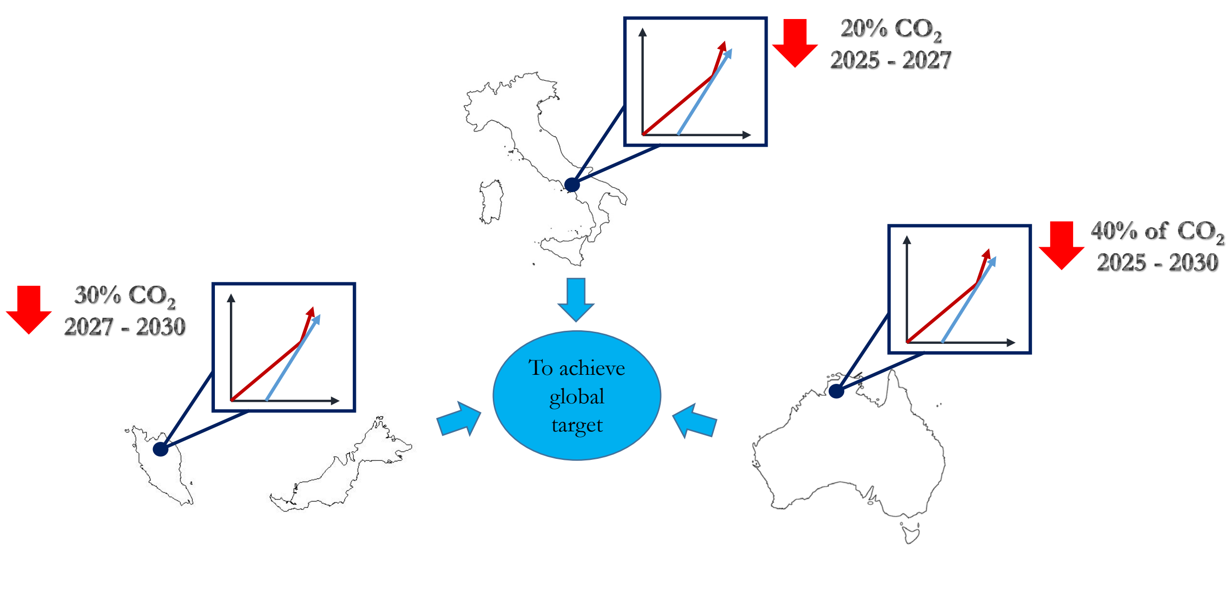

Fig. 3 CEPA as a basis for negotiation to achieve global CO_2 reduction targets

At each policy level, stakeholders will inevitably have their own self-interests and motivations. These motivations and interests may not always be evident, and could pose challenges in formulating an inclusive agreement. In this respect, CEPA tools could be coupled with approaches that consider conflicting interests from various stakeholders. In literature, there are several approaches available to address the conflicting interests. Among these approaches, some notable options are listed in Table 2, along with their potential application with CEPA;

Table 2 Notable approaches that can be coupled with CEPA

Approach	Potential Use with CEPA
Multi-objective optimisation	These approaches can be used to address several conflicting objectives simultaneously. For instance, Pareto optimal solutions can be generated and used as a basis for negotiation. Aside from this, multi-objective approaches can be used to balance carbon footprint with other conflicting factors such as water footprint, costs, reliability and social acceptability of energy policies. In the case of problems involving a small number of predefined options, the optimization problem reduces to multi-criterion decision analysis.
Multi-criterion decision analysis (MCDA)	MCDA approaches are suitable for cases where conflicting qualitative objectives are considered. These approaches use expert-based decisions to quantify qualitative objectives (e.g., quality of life, well-being, etc.) into indices that can be measured and used as decision support tools. An example of MCDA is Analytic Hierarchy Process (AHP). AHP allows decision makers to convert qualitative judgements into quantitative measures and is best known for determining the priorities of each objective.

Table 2 (Cont.)

Approach	Potential Use with CEPA
Game theory	Game theory can be broadly defined as optimal decision-making by multiple agents with potential conflicts of interest. Cooperative game theory approaches can be used to fairly allocate carbon reduction targets based on the contribution of each nation. The contribution here would refer to the size of each nation's energy consumption. This will provide an unbiased method of assessment that is transparent for decision-makers to analyse, discuss and negotiate. Moreover, cooperative game theory can be used to determine an equitable allocation of footprints (e.g., carbon budget shares) (Hiete et al. 2012). In fact, the dominance of agents can also be captured within this framework (e.g., via concepts such as weighted Shapley value). Dominant participants in this sense, refer to developed countries that may take the lead on the carbon reduction efforts. By doing this, the satisfaction of each (dominant and non-dominant) participants can be optimised to determine a realistic allocation of carbon reduction targets. Alternatively, disjunctive fuzzy optimisation could be used to maximise the satisfaction of each agent, providing the opportunity for them to opt out in the case where the cooperation is considered not favourable.
Decision theory	These approaches focus on facilitating quantitative decision-making by analysing the risk neutral decisions. In practice, uncertainty has to be factored into the decision-making process as an integral dimension, instead of being treated as an incidental complication. This can be used when stakeholders are doubtful of the long-term economic sustainability of the agreed carbon reduction targets. Therefore, a more risk neutral carbon reduction target can be established.

Table 2 (Cont.)

Approach	Potential Use with CEPA
Economic stability analysis	This approach will allow stakeholders to assess their respective economic stability after carbon emission targets have been assigned. By doing this, each stakeholder may analyse whether the amount of investment required to achieve the carbon reduction target outweighs the potential carbon credits or incentives received. Such assessment could function a quantitative basis for negotiation at the policy level.

Apart from conflicting interests, CEPA can be extended further to analyse disruptive scenarios where uncertainties can arise. Currently, CEPA studies have been presented based on a single operating scenario, where uncertainties are assumed to not occur. However, this assumption may not be an accurate representation, because uncertainties may arise in several forms. Uncertainties (e.g., variations in energy source availability, climate, fuel prices, etc.) may cause disturbances or disruptions on operations. In this respect, CEPA approaches can be coupled with scenario-based approaches, previously used for climate forecasts. Other approaches such as *economic input-output models* and *vulnerability analyses* can be considered to provide consequential CO_2 reduction estimations when disasters occur or when an industry/sector experiences slow growth. This will allow policy-makers to reallocate existing energy resources in the face of disruptions.

Aside from uncertainties, CEPA can be integrated with existing economic records such as gross domestic product (GDP). This is particularly crucial for CEPA tools to gain wide mainstream use. For instance, Tan et al. (2018) embarked on this direction by incorporating *input-output analysis* (IOA) into CEPA to analyse emissions based on industrial sectors. In their work, each segment of the composite curves represents an industrial sector within an economic system. This is particularly important for policy applications, as CEPA evidently illustrates its compatibility with standard economic statistics (i.e., GDP) that are compiled on a regular basis in most countries. This will allow policy-makers to easily understand the overall picture as the presented tool links familiar information such as GDP and carbon emissions within a single framework.

On top of combining with approaches mentioned in Table 2, CEPA tools can be linked with mathematical programming tools to CEPA tools to determine optimal renewable energy supply chains and analyse current CO_2 reductions. Although CEPA tools provide very useful and intuitive insights, they could benefit further with the advantages of automation offered by mathematical programming tools (e.g., superstructure models, etc.). Li et al. (2016) are the earliest to have attempted this direction by combining the consideration of supply chains with CEPA. More recently, Leong et al. (2019) developed a hybrid methodology to plan carbon reduction polices for both developed and developing countries. The work published by Li et al. (2016) and Leong et al. (2019) provides a basis for further extension. It is evident that more work can be placed in this area to consider uncertainties in energy resource availability and its impact on reductions. In addition, these works can be coupled with modern analytics, which have recently received increasing attention. Aside from this, since CEPA is visually simple to understand, it can be coupled with data analytics tools to help coordinate decision across multiple scales, and then to effectively communicate the results to stakeholders. This allows CEPA tools to provide an automated visualisation tool that provides a real-time decision support for engineers, environmentalists, policy-makers. Hybrid analytics like this can provide clearer understanding of the situation at hand (Tseng et al. 2018).

In a nutshell, it is clear that CEPA tools have the potential for wider and more international implications. It is imperative that PI scholars and practitioners work closely to elevate CEPA tools to the next level, which is sustainable energy policy-making. CEPA tools as well as its extensions and hybrid methods, are important to inform the debate on sustainable energy deployment, specifically on which energy resource should be used, on how much and where, and the overall impact on global CO_2 reduction efforts. As for the P2Pol framework, it can be extended to scale up water and material integration efforts to the policy-making stage. In fact, the proposed framework can be further improved to consider other important sectors, such as health and transportation.

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