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Towards a Low Carbon ASEAN: An environmentally extended MRIO optimization model

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Abstract

Background

Economic growth is dependent on economic activity, which often translates to higher levels of carbon emissions. With the emergence of technologies that promote sustainable production, governments are working towards achieving their target economic growth while minimizing environmental emissions to meet their commitments to the international community. The IPCC reports that economic activities associated with electricity and heat production contributed most to GHG emissions and it led to the steady increase in global average temperatures. Currently, more than 90% of the total GHG emissions of the ASEAN region is attributable to Indonesia, Malaysia, the Philippines, Thailand, and Vietnam. These regions are also expected to be greatly affected with climate change. To analyze how ASEAN nations can achieve carbon reduction targets while aspiring for economic growth rates, and in consideration of interdependencies between nations, this study develops a multi-regional input-output model for minimizing collective and individual carbon emissions. A high-level eight-sector economy is used for analyzing different economic strategies.

Results

This model shows that minimizing collective carbon emissions can still yield economic growth. Countries can focus on developing sectors that have growth potentials and lower carbon intensity-such as the services sector, agriculture, and food manufacturing sector. In addition, the simultaneous implementation of multiple

carbon emission reduction strategies provides the largest reduction in regional carbon emissions.

Conclusions

This model provides a more holistic view of how the generation of carbon emissions are influenced by the interdependence of nations. The emissions reduction achieved by each country varied depending on the state of technology and the level of economic development in the different regions. This current model can be used to help nations identify more appropriate and achievable carbon reduction targets and to develop more customized policies to target priority sectors in a country. This model is currently limited by the assumption of fixed technical coefficients in the exchange and interdependence of different regions. Future work can investigate modelling flexible multi-regional trade where regions have the option of substituting goods and products in its import or export structure. Other strategies for reducing carbon emission intensity can also be explored, such as modelling transport mode choices, or establishing sectors for waste management. Hybrid models which integrate the multi-regional input-output linear program model with data envelopment analysis can also be developed.

Background

An increasing trend in greenhouse gas (GHG) emissions has been observed since the 1900s and it has been linked primarily to fossil fuel combustion and industrial activities. In 2014, the Intergovernmental Panel on Climate Change (IPCC) reports that economic activities associated with electricity and heat production contributed most to these emissions (e.g. 25% of the global emissions), in which China was identified as the highest emitting country accounting for 30% of the global emissions (IPCC, 2014). The increase in atmospheric GHG concentration has led to the steady increase in global average temperatures. Projections indicate that a global average temperature rise of 2°C from the pre-industrial period is likely to occur by 2100 if no concrete actions to reduce GHG emissions are implemented (Collins et al. 2013). This scenario can lead to serious consequences such as sea level rise (ASEAN Cooperation on Climate Change 2012), water shortages, increased rainfall, and crop failure (Hijioka, Lin, and Jacqueline Pereira 2014) which will have a significant impact on livelihoods and economic performance.

The Association of Southeast Asian Nations or ASEAN was established in Bangkok in 1967. The ASEAN includes 10 countries namely Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. Though the region currently does not contribute significantly to GHG emissions, its role in climate change mitigation should be monitored and examined because of the region's recent rapid industrialization and economic growth (ASEAN Secretariat Community Relations Division 2021). Approximately 90% of the total GHG emissions of the

ASEAN region is attributable to five countries namely, Indonesia, Malaysia, the Philippines, Thailand, and Vietnam (Raitzer et al. 2015). In addition, the region is expected to be greatly affected with climate change with majority of its economic activities heavily reliant on agriculture and coastal activities.

Globally, countries have identified their Nationally Determined Contributions (NDC) towards reducing GHG emissions and have reaffirmed their commitment to the Paris Agreement in 2018 including ASEAN member states. However, achieving these targets based on identified strategies remains a question. (Pascual-González et al. 2016) examined the commitment of six ASEAN countries with particular focus on the strategies for the energy and transport sector. They found that though the countries have set forth several policies towards meeting the goal, few of them have been quantified or evaluated for their potential to succeed. Another challenge for the region is in maintaining the growth of the economy amidst emission reduction efforts. (J. Zhang et al. 2020) analyzed the driving forces behind the CO₂ emission using the log mean Divisia index (LMDI) and found that carbon density effect, per capita GDP effect, and the population effect are the main contributors towards increasing emissions, while energy intensity effect contributed towards reducing emissions in the ASEAN region. (Chontanawat 2019) on the other hand, examined the dynamic relationship between energy, CO₂ emissions, and economic growth of the ASEAN region. (Lopez et al. 2021) showed that an alternative approach through consumption-based accounting can yield different results compared to the traditional production-based approach.

Numerous approaches towards emission reduction have been adapted. Indonesia and the Philippines have implemented climate change budget tagging, wherein each branch of government, down to the local level indicates whether their expenditure contributes towards sustainability (Mutiarra et al. 2021; World Bank 2021). Indonesia's NDC has set an unconditional GHG emission reduction target of 29% and conditional reduction target of up to 41% from the business as usual (BAU) scenario by 2030 through finance, technology transfer, technology development, and capacity building which will cover among others the sectors of energy, agriculture, industry, waste, and forestry (Amheka & Higano, 2015; Government of Indonesia, 2016; Siagian et al., 2017). The Philippines' NDC is committed to reduce its GHG emissions by 75% in 2030 relative to its BAU scenario (Philippine Climate Change Commission, 2021) for the five leading sectors (i.e. energy, transport, waste, forestry and industry) (Government of Philippines 2015). The Philippine government mitigation strategy focuses on research and capacity development, while adaptation focuses on being more climate and disaster-resilient. External assistance is still necessary to support the development and adoption of most technologies to improve adaptive capacities and resilience. For Vietnam, its NDC commitment is to reduce its GHG emissions by 8% by 2030 with a potential increase to 25% compared to BAU if the initiative is supported through bilateral and multilateral cooperation (Shem et al. 2019). The efforts are expected to reduce the emission intensity per unit of GDP by 20% to 30% compared to 2010 levels. The intention is to increase the proportion of new and renewable energy (RE) in energy production and consumption. This strategy will cover and affect the

sectors of industry and transportation, agriculture, land use, land-use change, and forestry (LULUCF) and waste (Government of Vietnam, 2015; Nguyen et al., 2018c). Thailand's emissions represent around 0.84% of global emissions. Thailand's NDC is targeted to reduce its GHG emissions by 20% from the BAU level by 2030 (Government of Thailand 2015), and has the potential to be reduced beyond the target through technology development and financial resources while its adaptation action focuses on water resources management, agriculture, forest, and tourism (Government of Thailand 2015). For Cambodia, the INDC is set at 16% by 2030 which can be achieved through harnessing the renewable energy potential in power generation and promoting energy efficiency for end users. It has been identified that Cambodia is rich in renewable energy resources however, it lacks policies that will promote the development of such resources. Thus, the government has been exploring incentives such as feed-in tariffification, renewable portfolio standards and net metering to promote expansion in the sector (Ministry of Mines and Energy of Cambodia 2019). Malaysia and Singapore have NDC targets imposed on the same sectors, including energy, industry, agriculture, land use, and waste. For Malaysia, its GHG emission contributed around 0.6% to the global emissions, and its NDC unconditional reduction target for 2030 is at 35%, which can be increased to 45% if given international support (Sarkar, Al-Amin, and Filho 2019) focusing on climate finance, and technology development (Government of Malaysia 2016; Rasiah et al. 2016). Singapore, a developed country accounts for approximately 0.11% of global emissions and 2.2% of global trade. Singapore's NDC target is to reduce GHG emissions intensity by 36% by 2030 (Government of Singapore 2016). Singapore has designed a multi-sectoral plan to mitigate the carbon emissions not only in power generation but also tightening standards for household appliances, promoting green buildings and more efficient transportation (Singapore National Climate Change Secretariat n.d.)

Based on the description of the NDC targets of ASEAN countries, there are similarities on the economic sectors that are expected to contribute towards GHG emission reductions (i.e. energy, industry, waste, agriculture and forestry). This shows the similarities in characteristics of ASEAN countries being developing countries. The identified sectors have a major influence on the survival of the community as a basis for livelihood (Al Mamun et al. 2014).

With global energy policy trends directed towards addressing SDG 7 on affordable and clean energy, initiatives have focused on identifying strategies to improve energy efficiency, supporting low-carbon technologies, and increasing RE penetration. Similar strategies are being explored by the ASEAN region and will be focus of discussion in the case studies presented in this work. In 2019, the ASEAN reached a 24.4% reduction in energy intensity compared to 2005 levels, exceeding the 20% reduction target set for 2020. In 2017, the contribution of RE to the energy mix of total primary energy supply within the ASEAN reached 14.3% of the targeted 23% share in TPES by 2025 (APAEC 2019). However, there has been limited work on examining how the interactions between these countries can be exploited to help achieve carbon

emission reduction targets both collectively and individually in consideration of continued GDP growth rates.

This work thus develops a multi-regional input-output (MRIO) based optimization model to determine how a cluster of nations can collectively reduce their carbon emissions in recognition of the individual reduction targets and expected GDP growth rates. The input-output framework provides a structure for representing the interdependence between economic sectors while the MRIO model extends the analysis to account for interactions between the different countries. Transforming the traditional MRIO model into an optimization model helps identify the prescribed economic structure to achieve maximized carbon emission reductions which are useful for crafting policies to mitigate climate change. The rest of this paper is organized as follows. A review of recent literature on the use of input-output models particularly the MRIO model for assessing GHG emissions of countries is discussed in Section 2. Section 3 discusses the methodology used starting with a tutorial on the environmentally extended MRIO model. It is then followed by the development of the MRIO based optimization model which can be used for minimizing identified environmental impacts. A motivating example is then presented to illustrate how the model works using a simplified case study. The analysis is then extended to look at countries in the ASEAN region and their interactions with the rest of the world. Then discussion, conclusions, and recommendations for future work are provided.

Literature review

There are several strategies that can be implemented to achieve low-carbon targets, and these can be applied at various levels of the economy. Work on how to decarbonize specific industries such as iron and steel manufacturing have been reviewed recently by (Z. Fan and Friedmann 2021), deployment of smart energy systems at a regional or national level has also been proposed (Zhao et al. 2022; Amheka et al. 2015), while (Nabernegg et al. 2019) focused on analyzing national policies and how they relate to the emissions resulting from international supply chains. On a national level, the deployment of measures to lower GHG emissions may result in constraining the growth in economy of some countries especially if the most productive sectors are the most pollutive ones. Thus, it is necessary for governments and relevant stakeholders to evaluate how carbon emission reduction strategies influence economic growth (Oliveira, Coelho, and Antunes 2016). Early work on assessing the technological capability of ASEAN countries (Jones and Lall 1998) where ASEAN performance was benchmarked against more productive nations. The use of Data Envelopment Analysis (DEA) (Charnes, Cooper, and Rhodes 1978) which was developed for defining various forms of efficiency through the selection of appropriate input and output performance indicators, has also been used for examining the environmental performance of economies. Examples include relating environmental sustainability and economic growth (Bresciani et al. 2021) (and assessing carbon emissions efficiency for sectors of the economy (Zhao et al. 2022). Such approaches are useful for identifying empirically efficient examples (i.e. decision-making units (DMUs)) in the dataset and determining relevant factors which favor or deter efficiency. However, the DEA is unable to represent interactions

between DMUs which can potentially influence over-all performance of an economy. Such interactions can be modelled using input-output (IO) analysis (Leontief 1936). The national IO model provides a tool for capturing the interconnectedness among different economic sectors (Miller and Blair 2009). The national IO analysis can be extended to quantify other aspects within the economic system. For example, (Hoa et al. 2016) made use of inoperability input-output model introduced by (Haimes and Jiang 2001) coupled with the vulnerability indicators proposed by (Yu et al. 2014) to develop a multi-criteria framework for evaluating disaster vulnerability due to deployment of a biofuel regulation while (Amheka et al. 2021) examine prioritizing economic sectors for post-pandemic recovery in a country scale. The extended IO model that considers environmental burdens, has been applied for optimizing supply chains in consideration of water footprint constraints (Aviso et al. 2011) in optimizing multi-regional bioethanol supply chains with fuzzy multi-objectives (Tan et al. 2009); and in identifying the role of economic sectors as pollution producers (Nguyen, Aviso, Kojima, et al. 2018). Besides these, the national IO analysis was also extended to link with structural decomposition analysis to uncover the main socio-economic driving factors on the increase of CO₂ emission within the Vietnamese economy (Nguyen, Aviso, Le, and Tokai 2018) and on the decrease of toxic chemical releases in the Japanese economy (Nguyen et al. 2021). The national IO analysis has also been extended to MRIO analysis to allow for the examination of global or international supply chains. This model is useful to evaluate economic-environmental impacts embodied in international trade among nations because of the growth of globalized markets. For example, (Peters and Hertwich 2008) proposed a method using MRIO to estimate CO₂ emissions embodied in the trade among 87 countries. (Wiedmann 2009) provided a review on studies of MRIO on the basics of consumption-based emissions and resource accounting, while (Andrew and Peters 2013) estimated undated carbon footprint using global trade analysis project database (GTAP-MRIO). (Ali et al. 2017) used MRIO to quantify carbon and water footprint for both production-based and consumption-based emissions while (Osei-Owusu Kwame et al. 2020) made use of an economically extended model to track carbon emissions in Denmark also using production and consumption-based perspectives.

The capability of the IO model is further strengthened if it is coupled with systematic optimization tools such as linear programming (LP) (Vogstad 2009). A comprehensive review of IO-LP indicates the advantages of this hybrid approach in comparison to the conventional IO model (Oliveira, Coelho, and Antunes 2016). The IO-LP can identify the proper productivity of economic activities to find the optimal solutions for a given objective function (i.e., maximize gross domestic product) while maintaining the balance of sectoral productivity levels. Furthermore, IO-LP may provide a more comprehensive evaluation of effective production possibilities and economic impact from implementing potential regulations and allow for the study of trade-offs among conflicting objectives (Oliveira, Coelho, and Antunes 2016). For example, IO-LP has been used for quantifying the macroeconomic costs due to an implementation of CO₂ reduction policy (Y. Fan, Zhang, and Zhu 2010); and for evaluating the trade-offs among economic, environmental, and energy objectives for

Brazil's economy (De Carvalho et al. 2016). This approach was used to maximize the gross domestic output in the Greek economic system under constraints of GHG, energy and final demands (D. Hristu-Varsakelis et al. 2010); and then extended to couple with the impact of solid waste (Dimitrios Hristu-Varsakelis et al. 2012). (Cayamanda et al. 2017) developed an IO-LP based on fractional programming, which aims to minimize the carbon intensity in the Philippine economy in consideration of economic development and climate target as given in the Philippine's NDC. Similar works was also carried out by (Nguyen, Aviso, Le, Kojima, et al. 2018b) to minimize the total GHG emissions of the Vietnamese economy. Meanwhile, (Nguyen, Aviso, Le, Kojima, et al. 2018a) used IO-LP for mapping low-carbon scenarios and quantifying the reduction on human health damage by applying different technological improvement methods. However, the application of LP for MRIO models is still limited, a keyword search in the Scopus database using the keywords (TITLE-ABS-KEY (multi AND regional AND input-output)) AND ((optimization)) AND (linear AND program) only yielded 16 documents. Part of the difficulty results from data requirement and model complication. (Tan et al. 2012) applied MRIO-LP for optimizing a fuzzy multi-regional input-output model for biomass supply chain and trade under resources and footprint constraints. Meanwhile, (Pascual-González et al. 2016) used MRIO-LP for multi-objective optimization to minimize CO₂ emissions in US's economy while (Aviso et al. 2018) optimized virtual water trade flows between different regions of a country.

Methodology

Environmentally Extended Multi-Regional Input-Output Analysis

Multi-Regional Input-Output models provide a framework for analyzing the economic transactions between regions. The technical coefficient matrix for a 2 region MRIO model is given by Eq. 1 where A^{rr} represents the transactions between sectors in region R, A^{rs} contains the transactions from region R to region S, A^{sr} contains the transactions from region S that are used by region R and A^{ss} contains the transactions between sectors in region S. The entries in these matrices, which are of the form a_{ij} , represents the required inputs from sector i needed to generate a unit of output in sector j. Eq. 2 represents the over-all size of sectors in region R (x^r) and region S (x^s), the entries of these vectors are of the form x_j^k , and is equivalent to the total output of j in region k. Similar to the basic IO model, the final demand, (f) of regions can be obtained using Eq. 3 which can be expanded into Eq. 4. Adding the final demands of each economic sector in a region results in the GDP and represents the amount of goods consumed by households as final goods. Typically, the final demand for products and services are known and the objective is to determine the over-all size of economic sectors so that final demand will be satisfied. In this case, Eq. 5 can be used to solve for matrix x .

$$A = \begin{bmatrix} A^{rr} & A^{rs} \\ A^{sr} & A^{ss} \end{bmatrix} \quad (1)$$

$$x = \begin{bmatrix} x^r \\ x^s \end{bmatrix} \quad (2)$$

$$(I - A)x = f \quad (3)$$

$$\left(\begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} - \begin{bmatrix} A^{rr} & A^{rs} \\ A^{sr} & A^{ss} \end{bmatrix} \right) \begin{bmatrix} x^r \\ x^s \end{bmatrix} = \begin{bmatrix} f^r \\ f^s \end{bmatrix} \quad (4)$$

$$x = (I - A)^{-1}f \quad (5)$$

The MRIO model can be integrated with the environmental IO model to take into consideration the interaction of the economic system with the environment. An optimization model can then be developed to identify potential strategies that can be used to reduce the environmental impact of regions. Eq. 6 can be utilized to quantify the over-all environmental impact of the economic system where **B** is the environmental intervention matrix (or direct impact coefficient matrix) and **g** contains the total environmental impact of the system. Eq. 6 can be expanded to Eq. 7 to clearly illustrate how each region contributes to the over-all environmental impact.

$$Bx = g \quad (6)$$

$$\begin{bmatrix} B^r & B^s \end{bmatrix} \begin{bmatrix} x^r \\ x^s \end{bmatrix} = g \quad (7)$$

Due to the interdependency between economic sectors and between regions, it is expected that meeting the demands of one region will also influence the economic activities of other regions. In a similar way, this will also affect the environmental burden placed on the resources of each region either for meeting their own needs or the need of others. It has been argued that the environmental burden in a region may be reduced by importing resource intensive products rather than utilizing local resources (C. Zhang and Anadon 2014). However, this will obviously shift the environmental burden to another region. A balance must then be made between the environmental impact generated by one region against those generated by another. In this regard, the environmentally extended MRIO model can be formulated into a multi-objective optimization problem where each objective represents the goal of each stakeholder or each region.

Development of the MRIO Optimization Model

The MRIO model may be translated into an optimization model to address the given problem statement. The following model assumptions are considered.

- Given N number of regions with M economic sectors, the interaction between these sectors and between regions is known
- Given K number of relevant environmental emissions, the amount of environmental emission generated corresponding to a level of economic productivity per sector is known
- Given that each region has a target economic growth

- Given that each region has a target reduction in environmental emission
- The objective of the model is to determine the final output and final demand of economic sectors which will minimize environmental emissions

It must be ensured that the MRIO model has degrees of freedom within the system such as the possibility of differentiated sector growth (Cayamanda et al. 2017). The objective function can be represented by Eq. 8 which in this case intends to minimize one specific environmental impact, g_1 . The optimization model will then be subject to equality constraints as defined by the MRIO model (Eq. 9), environmental impact constraints (Eq. 10) and target growth for each region (Eq. 11 and 12) which must be within reasonable lower ($F^{r,L}, F^{s,L}$) and upper ($F^{r,U}, F^{s,U}$) limits.

$$\min g_1 \quad (8)$$

$$(I - A)x = f \quad (9)$$

$$Bx = g \quad (10)$$

$$[f^r]^T \mathbf{1} \leq F^{r,U}, [f^s]^T \mathbf{1} \leq F^{s,U} \quad (11)$$

$$[f^r]^T \mathbf{1} \geq F^{r,L}, [f^s]^T \mathbf{1} \geq F^{s,L} \quad (12)$$

Motivating Example

The motivating example used here was taken from the multi-region IO example provided in (Miller and Blair 2009) which was amended with matrix **B** to account for the environmental impacts associated with the economic activities between regions R and S. Note that this is a hypothetical example intended to demonstrate the model developed in this work. Using this framework, it is possible to determine the associated environmental impact from the consumption activities of a region in contrast to environmental impacts resulting from production activities. In this example, region R has 3 sectors while region S has 2. Furthermore, 2 different emissions are considered (e.g. CO₂ emissions, solid waste). The technical coefficient matrices are given in (13) to (16), these matrices indicate the required input from sector i needed to generate a 1 USD output from sector j . The final demands for regions R and S are shown in (17) and (18), respectively, these reflect the total amount of products consumed as final goods from sector i in region r . The associated emission intensity matrices are given in (19) and (20) and represent the amount of emission k generated per 1 USD of output from sector j .

$$A^{rr} = \begin{bmatrix} 0.1500 & 0.2500 & 0.0500 \\ 0.2000 & 0.0500 & 0.4000 \\ 0.3000 & 0.2500 & 0.0500 \end{bmatrix} \quad (13)$$

$$A^{ss} = \begin{bmatrix} 0.1667 & 0.3125 \\ 0.1250 & 0.1250 \end{bmatrix} \quad (14)$$

$$A^{rs} = \begin{bmatrix} 0.0208 & 0.0938 \\ 0.1667 & 0.1250 \\ 0.0500 & 0.0500 \end{bmatrix} \quad (15)$$

$$A^{sr} = \begin{bmatrix} 0.0750 & 0.0500 & 0.0600 \\ 0.0500 & 0.0125 & 0.0250 \end{bmatrix} \quad (16)$$

$$f^r = \begin{bmatrix} 200 \\ 1000 \\ 50 \end{bmatrix} \quad (17)$$

$$f^s = \begin{bmatrix} 515 \\ 450 \end{bmatrix} \quad (18)$$

$$B^r = \begin{bmatrix} 0.2 & 0.3 & 0.1 \\ 0.1 & 0.4 & 0.3 \end{bmatrix} \quad (19)$$

$$B^s = \begin{bmatrix} 0.3 & 0.2 \\ 0.2 & 0.5 \end{bmatrix} \quad (20)$$

Taking this example, the matrices can be combined into an MRIO coefficients table as that shown in Table 1 and an emission intensity table as shown in Table 2. The emission intensity is expressed as the number of units of emission generated per monetary output of an economic sector (e.g. kg CO₂/million USD). It is possible to determine vector $\mathbf{x}$ which will satisfy the final demands for regions R and S using Eq. 5. The final demands are satisfied through internal production (e.g. produced within the region) or imports (e.g. produced from another region). Furthermore, the accompanying environmental load can also be obtained using Eq. 6. The results are given below where matrix $\mathbf{x}$ is shown in (21) while vector $\mathbf{g}$ is in (22). It is important to note that the resulting $\mathbf{g}$ accounts for the environmental burden of satisfying demands in both region R and S. However, it is possible to disaggregate how the resources are allocated across the different sectors and how each sector contributes towards the environmental burden which can be used to integrate and analyze more localized information (Monsalve et al. 2020). This disaggregation is shown in Table 3. This type of allocation does not reflect the environmental burden associated with the demand for goods of Regions R and S, which is considered as consumption-based environmental impact. To account for the environmental impact resulting from the demand of the individual regions, the result can be obtained by solving Eq. 9 while using the demand of Regions R and S separately.

$$\mathbf{x} = \begin{bmatrix} 1000 \\ 2000 \\ 1000 \\ 1200 \\ 800 \end{bmatrix} \quad (21)$$

$$\mathbf{g} = \begin{bmatrix} 1420 \\ 1840 \end{bmatrix} \quad (22)$$

Table 1. Multi-regional Coefficients Matrix.

		Region R			Region S		Demand
		1	2	3	1	2	
Region R	1	0.1500	0.2500	0.0500	0.0208	0.0938	200
	2	0.2000	0.0500	0.4000	0.1667	0.1250	1,000
	3	0.3000	0.2500	0.0500	0.0500	0.0500	50
Region S	1	0.0750	0.0500	0.0600	0.1667	0.3125	515
	2	0.0500	0.0125	0.0250	0.1250	0.1250	450

Table 2. Emission Intensity of Economic Sectors (in units of emission/USD).

		Region R			Region S	
		1	2	3	1	2
Emission 1		0.2	0.3	0.1	0.3	0.2
Emission 2		0.1	0.4	0.3	0.2	0.5

Table 3. Baseline scenario.

		Region R			Region S		Demand	x
		1	2	3	1	2		
Region R	1	150	500	50	25	75	200	1,000
	2	200	100	400	200	100	1,000	2,000
	3	300	500	50	60	40	50	1,000
Region S	1	75	100	60	200	250	515	1,200
	2	50	25	25	150	100	450	800
Total								
Emission 1		200	600	100	360	160		1420.00
Emission 2		100	800	300	240	400		1840.00

For example, if the interest is in finding the environmental impact associated with the demands for products of Region R, vector $\mathbf{f}$ will then be reduced to $\mathbf{f}^r$, with the values for $\mathbf{f}^s$ all equal to zero. This results in the allocation indicated in Table 4. In a similar manner, it is also possible to obtain the environmental impact associated with the consumption of Region S, this is summarized in Table 5. For Table 4, the results obtained for $\mathbf{x}^s$ represents the contribution of production-based activities of Region S while the results obtained for $\mathbf{x}^r$ in Table 5 represents the contribution of production-based activities in Region R. The production-based environmental impact of Region R is thus equal to the generated emissions of the sectors in Region R when it produces products to supply the requirements of Region S and vice-versa. These results clearly show the interdependence between the two regions. In this regard, we can expect that minimizing the environmental impact of one region might result in the increase in impact from the other region due to a potential increase in the amount of traded goods. To demonstrate that reducing the environmental impact of one region does not necessarily reduce the impact of another, we look at the following scenarios, Scenario A considers minimizing Emission 1 of Region R, Scenario B considers minimizing Emission 1 of Region S while Scenario C considers minimizing Emission 1 of the system. In all 3 scenarios, we consider that Region R has a target growth rate between 5 % to 10 % while Region S has a target growth rate of 3 % - 8 % for their respective

GDPs and that each individual economic sector cannot grow more than 10 % from its baseline. Solving for Eq. 8 subject to the constraints given in Eq. 9 – 12, the results of the different scenarios are shown below.

Table 4. Consumption-based transactions and environmental impact for Region R.

		Region R			Region S		Demand	X
		1	2	3	1	2		
Region R	1	114.67	396.03	36.57	5.49	11.70	200	764.45
	2	152.89	79.21	292.54	43.89	15.60	1,000	1584.12
	3	229.34	396.03	36.57	13.17	6.24	50	731.34
Region S	1	57.33	79.21	43.88	43.89	39.01	0	263.31
	2	38.22	19.80	18.28	32.91	15.60	0	124.83
Emission 1		152.89	475.24	73.13	78.99	24.97		805.22
Emission 2		76.45	633.65	219.40	52.66	62.41		1044.57

Table 5. Consumption-based transactions and environmental impact for Region S.

		Region R			Region S		Demand	x
		1	2	3	1	2		
Region R	1	35.33	103.97	13.43	19.51	63.30	0	235.55
	2	47.11	20.79	107.46	156.11	84.40	0	415.88
	3	70.66	103.97	13.43	46.83	33.76	0	268.66
Region S	1	17.67	20.79	16.12	156.11	210.99	515	936.69
	2	11.78	5.20	6.72	117.09	84.40	450	675.17
								Total
Emission 1		47.11	124.76	26.87	281.01	135.03		614.78
Emission 2		23.55	166.35	80.60	187.34	337.59		795.43

The summary of the results for Scenario A can be found in Table 6, while those for Scenario B are in Table 7 and that of Scenario C is in Table 8. A summary of the total emissions generated by each region in each of the scenarios presented are shown in Table 9. For all three scenarios, Region R achieved a growth rate of 5% while Region S achieved a growth rate of 3%. However, the individual sectors did not grow proportionately, for scenarios A and C, Sectors 1 and 3 achieved the highest growth in Region R at 10% with Sector 2 growing only by 3.75% while Sector 1 of Region S grew by 5.6% and its Sector 2 remained at the baseline level. For scenario B, Region R achieved 10% growth in Sector 3 and 5.75% growth in Sector 2 while for Region S it was Sector 2 that achieved a 6.4% growth with its Sector 1 remaining at the baseline level.

Results show that reducing the emissions for one region does not only affect the productivity of that region but also impacts other regions connected to it. Furthermore, when comparing the total output of each sector in the three scenarios against the baseline, we can see variations with respect to Scenarios A and C, Sector 1 in Region R had the highest growth rate at 5.3% while Sector 2 in Region S had the lowest growth rate of 1.6%. Alternatively, for Scenario B it was Sector 2 in Region S that had the highest growth rate of 5.2% and Sector 1 in Region S had the lowest growth rate of 2.4%.

With regards to emissions, reducing emissions in one region can potentially increase the emission in another as demonstrated in the results between Scenarios A and B. Awareness of this may help global communities understand how the targets set in one country can potentially affect the targets set by another.

Table 6. Scenario A (minimizing Emission 1 for Region R).

		Region R			Region S		Demand	x
		1	2	3	1	2		
Region R	1	157.94	520.32	52.34	26.10	76.22	220.00	1052.92
	2	210.58	104.06	418.73	208.77	101.63	1037.5	2081.28
	3	315.88	520.32	52.34	62.63	40.65	55	1046.82
Region S	1	78.97	104.06	62.81	208.77	254.08	543.95	1252.64
	2	52.65	26.02	26.17	156.58	101.63	450	813.04
Total								
Emission 1		210.58	624.38	104.68	375.79	162.61		1478.05
Emission 2		105.29	832.51	314.05	250.53	406.52		1908.90

Table 7. Scenario B (minimizing Emission 1 for Region S).

		Region R			Region S		Demand	x
		1	2	3	1	2		
Region R	1	155.55	524.60	52.33	25.59	78.94	200.00	1037.01
	2	207.40	104.92	418.62	204.72	105.25	1057.5	2098.41
	3	311.10	524.60	52.33	61.42	42.10	55	1046.55
Region S	1	77.78	104.92	62.79	204.72	263.12	515	1228.33
	2	51.85	26.23	26.16	153.54	105.25	478.95	841.98
Emission 1		207.40	629.52	104.65	368.50	168.40		1478.48
Emission 2		103.70	839.36	313.96	245.67	420.99		1923.69

Table 8. Scenario C (minimizing total Emission 1).

		Region R			Region S		Demand	x
		1	2	3	1	2		
Region R	1	157.94	520.32	52.34	26.10	76.22	220.00	1052.92
	2	210.58	104.06	418.73	208.77	101.63	1037.50	2081.28
	3	315.88	520.32	52.34	62.63	40.65	55.00	1046.82
Region S	1	78.97	104.06	62.81	208.77	254.08	543.95	1252.64
	2	52.65	26.02	26.17	156.58	101.63	450.00	813.04
Emission 1		210.58	624.38	104.68	375.79	162.61		1478.05
Emission 2		105.29	832.51	314.05	250.53	406.52		1908.90

Table 9. Summary of Emission Results.

	Scenario A		Scenario B		Scenario C	
	R	S	R	S	R	S
Emission 1	939.64	538.4	941.57	536.9	939.64	538.4
Emission 2	1251.85	657.05	1257.02	666.66	1251.85	657.05

Case Study

This case study investigates how the interaction of 12 different regions impact each region's goal in achieving their nationally determined contributions based on the Paris Agreement. The evaluation aggregates the IO tables into 8 different sectors. Primary focus is given to the ASEAN region. The 12 regions and 8 sectors considered are summarized in Table 10.

Table 10. Regions and Sectors considered in the Case study.

Regions		Sectors	
R01	Brunei	S1	Agriculture
R02	Cambodia	S2	Coal, Oil, Gas and Oil Products
R03	Indonesia	S3	Food
R04	LaoPDR	S4	Transport
R05	Malaysia	S5	Energy intensive industries
R06	Philippines	S6	Non-energy intensive industries
R07	Singapore	S7	Services
R08	Thailand	S8	Electricity
R09	Vietnam		
R10	Rest of South East Asia		
R11	East Asia		
R12	Rest of the World		

The multi-regional IO table was obtained from the GTAP 10 database and carbon emissions from the use of coal, oil, gas, and other oil products were obtained from the GTAP-E database (Aguiar et al., 2019) and with the relevant information summarized in the supplementary file.

Table 11. Target growth rates and NDCs for 2030.

		Average annual growth in GDP from 2021 – 2030 (in %)	Carbon emission Reductions by 2030 from BAU (in %)
R01	Brunei	2.60	
R02	Cambodia	7.16	
R03	Indonesia	5.36	29.00
R04	LaoPDR	5.62	
R05	Malaysia	5.96	45.00
R06	Philippines	6.66	70.00
R07	Singapore	3.04	
R08	Thailand	4.14	20.80
R09	Vietnam	6.96	9.00
R10	Rest of South East Asia (RoSEA)	4.06	
R11	East Asia	5.12	74.00
R12	Rest of the World (ROW)	4.06	45.00

Business-as-usual (BAU) scenario

Using BAU scenario with the target annual growth rates identified in Table 11, the resulting carbon emissions for the different regions by fuel type is illustrated in Figure 1 with the relative contributions of the fuel types to over-all carbon emissions shown in Figure 2. Indonesia has the highest carbon emissions for the countries in Regions 1 to 9, with its emissions almost equally contributed by coal and other oil products. Emissions from coal use had the highest contribution over-all which comprised about 56% of the total. Analysis of the carbon footprint of regions based on their consumption and production patterns are illustrated in Figures 3. Results show that if we look at the consumption pattern of the regions, Regions 1 and 7 relied heavily on imports such that carbon emissions generated to support their demand were primarily (i.e. more than 50%) generated in another region. The carbon emissions of the remaining regions were generated primarily (i.e. more than 50% of emissions) from their own economic activities. Alternatively, looking at the production-based emissions, Region 7 had the highest carbon emission proportion associated with activities meant to support the demand of other regions.

Figure 1. CO₂ emissions by 2030 for Regions 1 to 10 in gigagrams (BAU scenario).

Figure 2. Contribution of energy source to emissions.

Figure 3. Consumption and Production based contribution of carbon emissions for BAU

Scenario 1 – Differentiated growth

We now considered the scenario wherein differentiated sectoral growth is allowed in each region if the over-all national growth rate was still greater than the target average annual growth as indicated in Table 11. This contrasts with the assumption that all economic sectors will grow at the same rate. Such a scenario can be realized by infusing more funds into priority sectors. Each sector in the regions could contract or grow by $\pm 10\%$ from the target rate. Solving Eqs. 8 – 12, the resulting growth rate for the individual sectors per region considered is shown in Table 12. Entries which have been marked with red downward arrows indicate that the annual growth rate of the associated sector in each region is below the average target growth rate of the region. A green upward arrow indicates that the sector had a higher growth rate compared to the average target growth rate of the region. Sector 7 (Services Sector) in almost all regions grew more than the target growth rate except in the case of Cambodia and the Philippines. For Cambodia and the Philippines, the service sector has the largest share of their gross domestic product at 36.60% and 61.42% respectively (World Bank n.d.). Sectors 2, 4, 5, 6 and 9 mostly had growth rates below the regional target growth rates indicating that these sectors should not be prioritized if the intention is to meet carbon reduction targets, since these sectors had higher carbon intensity.

Table 12. Annual growth rates of different sectors across the different regions.

			S01	S02	S03	S04	S05	S06	S07	S08	Regional
			Agr	Coal++	Food	Transp	Energy	Non Int	Services	Electricity	Target
							Int				
R01	Brunei	↑	2.86%	↓ 2.34%	↓ 2.34%	↓ 2.34%	↓ 2.34%	↓ 2.34%	↑ 2.64%	↓ 2.34%	2.60%
R02	Cambodia	↑	7.88%	↓ 6.44%	↑ 7.88%	↓ 6.44%	↑ 7.88%	↓ 6.44%	↓ 6.82%	↓ 6.44%	7.16%
R03	Indonesia	↑	5.90%	↓ 4.82%	↑ 5.90%	↓ 4.82%	↓ 4.82%	↓ 4.82%	↑ 5.50%	↓ 4.82%	5.36%
R04	LaoPDR	↓	5.06%	↓ 5.06%	↓ 5.06%	↓ 5.06%	↓ 5.06%	↓ 5.06%	↑ 5.65%	↓ 5.06%	5.62%
R05	Malaysia	↓	5.36%	↓ 5.36%	↓ 5.36%	↓ 5.36%	↓ 5.36%	↓ 5.36%	↑ 6.09%	↓ 5.36%	5.96%
R06	Philippines	↑	7.33%	↓ 5.99%	↑ 7.33%	↓ 5.99%	↓ 5.99%	↓ 5.99%	↓ 6.20%	↓ 5.99%	6.66%
R07	Singapore	↓	2.74%	↓ 2.74%	↓ 2.74%	↓ 2.74%	↓ 2.74%	↓ 2.74%	↑ 3.33%	↓ 2.74%	3.04%
R08	Thailand	↓	3.73%	↑ 4.55%	↓ 3.73%	↓ 3.73%	↓ 3.90%	↓ 3.73%	↑ 4.55%	↓ 3.73%	4.14%
R09	Vietnam	↑	7.66%	↑ 7.66%	↑ 7.66%	↓ 6.26%	↓ 6.29%	↓ 6.26%	↑ 7.66%	↓ 6.26%	6.96%
R10	RoSEA	↑	4.47%	↓ 3.65%	↑ 4.47%	↓ 3.65%	↓ 3.65%	↓ 3.65%	↑ 4.20%	↓ 3.65%	4.06%
R11	East Asia	↑	5.63%	↓ 4.61%	↓ 4.61%	↓ 4.61%	↓ 4.61%	↓ 4.61%	↑ 5.43%	↓ 4.61%	5.12%
R12	ROW	↓	3.65%	↓ 3.65%	↓ 3.63%	↓ 3.65%	↓ 3.65%	↓ 3.65%	↑ 4.31%	↓ 3.65%	4.06%

Figure 4. Contribution of fuel source to emissions (Scenario 1).

Figure 5. Consumption and Production based contribution of carbon emissions for Scenario 1

This differentiated growth achieved almost a 2% over-all reduction in carbon emissions in comparison to the BAU scenario with the contribution of each region illustrated in Figure 4. Figure 5 on the other hand shows how the emission for each region is accounted for using a consumption based and production-based perspective. Figure 6 illustrates the reduction in CO₂ achieved in each region and where the reductions were realized with regards to the fuel used. All regions were able to reduce their emission levels while meeting the desired GDP growth rates. If only individual countries were analyzed, Region 2 achieved the highest reductions in carbon emissions at 4.13%, the reductions were from the decrease in emissions of other oil products and of coal which arose from reduced growth of sectors reliant on these types

of fuel. Region 1 had the lowest reductions in emissions. It can be noted that Region 1 (Brunei) does not have coal-fired power plants, however, Brunei also has to exert much effort in harnessing renewable energy in the electricity generation aspect as the solar energy remains to be their sole renewable energy resource (IRENA n.d.). None of the countries achieved the target carbon emission reductions as indicated in Table 11. Customized regional strategies can be developed based on the results shown in Table 12 to ensure that the reductions obtained from the model results are indeed achieved. In the Philippines for example, policies which support the growth of the agricultural and food industry which were recommended to have higher growth rates of 7.33%, should be strengthened.

Figure 6. Change in CO₂ emissions from BAU to differentiated growth.

Scenario 2 Reduced Carbon Intensity in the Electricity Sector

The next scenario couples differentiated growth rates with a 20% reduction in carbon intensity of the electricity sector, this scenario is possible if a country decides to increase renewable energy penetration in its national grid. The ASEAN economies have developed their programs to reduce their dependence on non-renewable resources and shift towards renewable energy into their primary energy mix. For example, the Indonesia Energy Law of 2007 was enacted to reduce the import dependence on refined oil. In the Philippines, the Renewable Energy Act of 2008 seeks to promote the development of the renewable energy sector of the country. In Malaysia, the Renewable Energy Act of 2011 is also in place. While these legislations have been in place for quite some time, it is only recently that the technological innovations have made it more efficient to invest in the sector. Results suggest that it is possible to reduce the carbon footprint further to 11.6 %. The reductions for each region in comparison to the BAU scenario are illustrated in Figure 9. In this case, Region 6 (Philippines) achieved the highest reduction in carbon footprint while Region 1 (Brunei) achieved the least. Figure 7 also shows that various countries efforts in veering away from coal, Region 07 (Singapore) will have a significant reduction in its

gas consumption as a result, given that 95% of their electricity is generated using natural gas (Singapore Energy Market Authority n.d.).

Figure 7. Change in CO₂ emissions from BAU to reduced carbon intensity of the electricity sector.

Discussion and Policy Implications

The scenarios presented for the MRIO model which consisted of 9 individual countries, rest of Southeast Asia, East Asia, and the rest of the world demonstrates how individual carbon emissions reductions of nations are linked with each other. Differentiated sector growth rates and reductions in the carbon intensity of the electricity sector are some strategies which can be considered to achieve carbon emission reductions. In both cases, carbon emission reductions were achieved both collectively and for individual regions (e.g. countries) without greatly varying the current level of interdependence between regions. This means that the production structure of each economic sector remains the same. It can be seen however, that certain countries achieved higher reductions therefore compensating for lower reductions achieved in other nations. These results were influenced by the existing economic structure of individual nations. In this regard, more customized policies can be developed in each country to realize higher carbon emission reductions while maintaining target GDP growth rates. Crafting of international policies should take these in consideration especially in a globalized economy. For example, based on the results of the case study, the agricultural sector should be encouraged only for certain countries (e.g. Brunei, Cambodia, Indonesia, Philippines, Vietnam) and that other sectors should be encouraged in other countries. Such changes can initiate other transformations such as developing competencies and establishing new trade agreements. In addition, the developments from the Conference of Parties 2026 (COP26) held in Glasgow highlights the importance of climate financing that can extend the benefits of reducing the carbon emissions of a region to reduced carbon emissions across the supply chain.

Conclusions

A multi-regional IO-based optimization model for reducing global carbon emissions has been developed in this work. This model can be utilized for assessing the potential carbon emission reductions that can be achieved given the adoption of certain strategies. This model provides a more holistic view of how the generation of carbon emissions are influenced by the interdependence of nations. The results obtained from the different scenarios considered minimized the collective carbon emissions for the 12 different regions used in the analysis. However, the reductions achieved by the regions varied between each other which reflects the state of technology and the level of economic development in the different regions. This approach can thus be used to help nations identify more appropriate and achievable carbon reduction targets as well as develop more customized policies to target priority sectors in a country. However, one of the limitations of the model is that it made use of fixed coefficients to represent the exchange and interdependence of different regions. As a result, the structure for multi-regional trade is not flexible. Future work can thus investigate modelling flexible multi-regional trade where regions have the option to select where to import or export goods from or to consider substitutability of goods and products. More complex models which make use of non-linear relationships between economic parameters can be developed using computable general equilibrium (CGE). Other carbon reduction strategies can also be considered in the scenarios such as reductions in the carbon emission intensity within the transport sector. Finally, hybrid models which integrate the MRIO – LP model with DEA can be explored in the future.

Declarations

Availability of data and materials

The datasets used in this study are publicly available taken from official sources. The data used in the manuscript together with the models developed in LINGO may be accessed at https://github.com/kbaviso/ASEAN_MRIO/tree/main.

Competing interests

The authors declare that they have no competing interests

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Authors' contributions

Following is the authors contribution,

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Model implementation was carry out by KB Aviso

The case study development and analysis are done by KB Aviso, KD Yu, and V Andiappan.

Article writing and verification conducted by A Amheka, KB Aviso, KD Yu, HT Nguyen, V Andiappan, VJ Dacanay, RM Noach

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Abbreviations

GHG	: Greenhouse Gas
IPCC	: Intergovernmental Panel on Climate Change
ASEAN	: Association of Southeast Asian Nations
NDC	: Nationally Determined Contributions
CO ₂	: Carbon dioxide
LMDI	: Log Mean Divisia index
GDP	: Gross Domestic Product
BAU	: Business As Usual
RE	: Renewable Energy
LULUCF	: Land Use, Land-Use Change, And Forestry
MRIO	: Multi-Regional Input-Output
DEA	: Data Envelopment Analysis
DMUs	: Decision-Making Units
IO	: Input-Output
GTAP	: Global Trade Analysis Project
LP	: Linear Programing
COP26	: Conference of Parties 2026
CGE	: Computable General Equilibrium

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