Doctor of Philosophy

Assessment of national and industrial park-level economic growth, resource metabolism, and sustainability transition in Vietnam by industrial ecology approaches

The Graduate School of the University of Ulsan

Department of Civil and Environmental Engineering

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Assessment of national and industrial park-level economic growth, resource metabolism, and sustainability transition in Vietnam by industrial ecology approaches

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Abstract

Material and energy are the essential components of industrialization and economic revolution. These momentous factors will define the success of an industrial ecology system in any region. The study of the flows of materials and energy in industrial and consumption activities, along with the social and environmental factors can be utilized to initiate changes in the economies as stated in industrial ecology. The primary goal of industrial ecology is to promote sustainable development at the local, regional, national, and global levels which is necessary for each economy. Industrial ecology and sustainable development are a dynamic system-based framework that enables management of human activitiy on a sustainable basis by: (1) minimizing energy and materials usage; (2) ensuring acceptable quality of life for people; (3) minimizing the ecological impact of human activity to levels in which the natural system can sustain; (4) maintaining the economic viability of systems for industry. However, there is an ambiguity and an absence of studies related to these fields, leading to a lack of awareness about energy and material flow, and sustainable development in systematic perspectives. Mainly, developing countries have rarely studied and understood this fundamental field that is the core of sustainability. Hence, this study aims to develop and apply industrial ecology tools, and systematic approaches to promote ambitious green growth targets in developing countries such as Vietnam.

In chapter 1, the concept and definition of industrial ecology, circular economy, an overview of Vietnam’s condition, then research question, and objectives were described. Industrial ecology and sustainable development pursue an equilibrium among the triple line variables: social equity, economic efficiency, environmental responsibility through circular economy which can be broadly defined as a system solution framework that tackles global challenges and biodiversity loss together, while addressing important social needs. Furthermore, they aim to inform decision-making parties about the impacts of industrial activities and affluence on the environment by tracking and investigating physical resources and energy flows through innovative environmental assessment tools. Vietnam exhibits patterns of resource consumption similar to a typical fast-growing economy with an increase in the use of primary resources (metals and non-metallic minerals). It is a dilemma that is faced by many emerging economies which is struggling to balance between economic growth and sustainable resource consumption. Therefore, an investigation from a transitional perspective and

an identification of key drivers is crucial. Thus, a necessity to research in these fields focused on Vietnam and its neighboring countries has emerged. In order to address this need, this research developed an industrial ecology approach including economic growth, resource metabolism and sustainability with an emphasis on how to harmoniously integrate industrial activity into ecological systems to assess sustainability transition in Vietnam.

In chapter 2, the picture of resource metabolism in Vietnam was drawn under the economy-wide material flow accounting approach from 1978 to 2017. Besides, several typical economies that represent different levels of development (fast developing country: China; primary developed country: South Korea) were also explored with the intention of to compare with Vietnam's case. Trends in resource efficiency, bilateral trade dynamics, and progress regional economic and environmental policy are analyzed in order to improve the condition of Vietnam and streamline its path to sustainability. South Korea and Japan which is in their post-industrial economy phase has already attained its environmental efficiency whereas Vietnam is yet to reach its peak. However, Vietnam's issue has been continued a stable climb with the slight acceleration of technological advancements. Malmquist data envelopment analysis denotes that all the indicators in this test in Vietnam have improved and are closer with comparative countries. However, Vietnam is still material-intensive and has low material productivity. Therefore, Vietnam is highly recommended to strengthen technology innovation and efficiency enhancement with closely coordinated policies on sustainable resource consumption, carbon reduction, economic growth for sustainable development goal 2030.

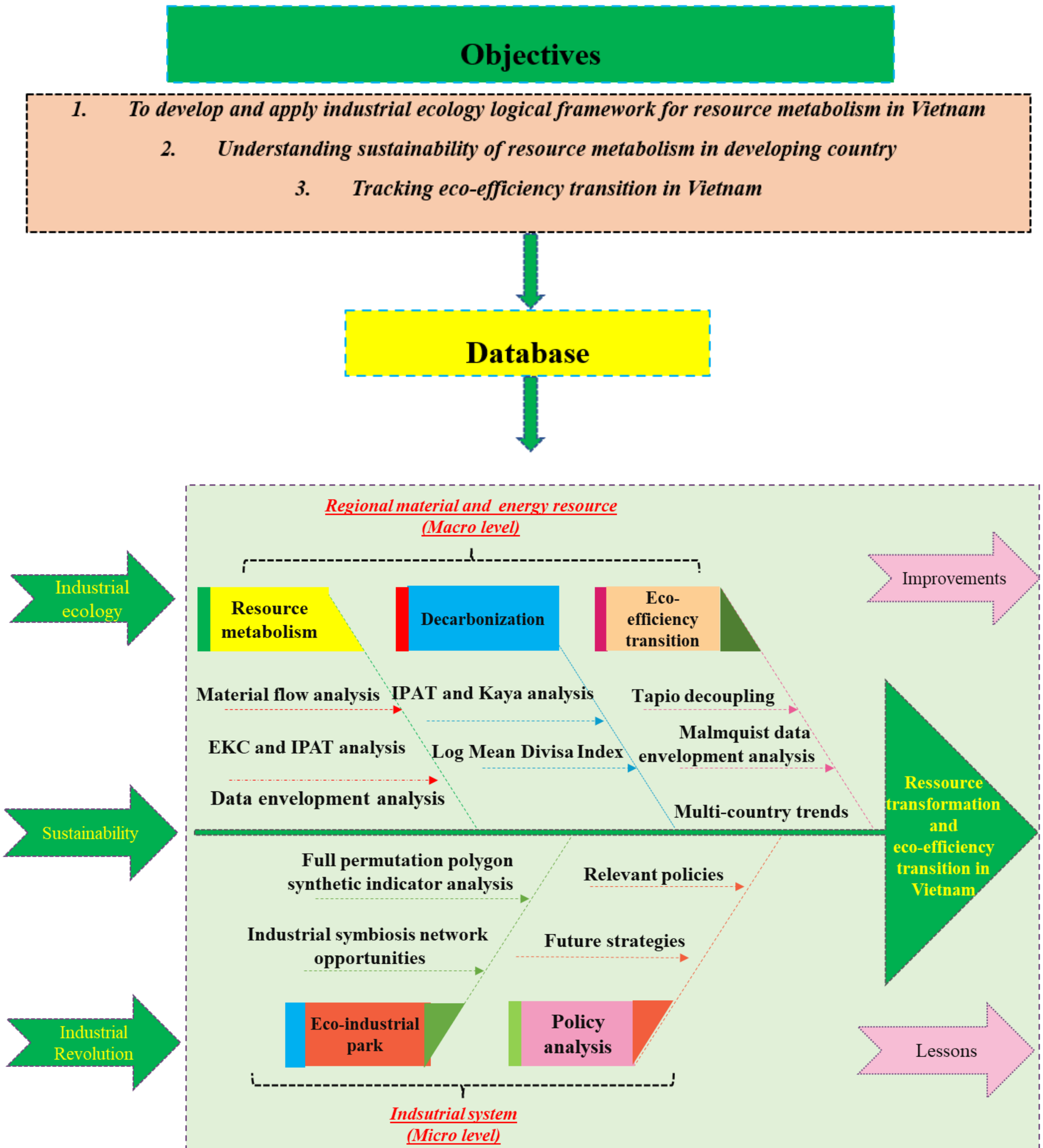
The chapter 3 aims to analyze the key factors contributing to carbon emissions between 1990 and 2016 using the expanded IPAT/Kaya framework and logarithmic index (LMDI) method. The carbon emissions impacts were decomposed to population affluence, energy intensity, fuel mix, and emission intensity factor. As per the results, CO_2 emissions during 1990-2016 were mainly driven by the affluence of higher income levels (58.5%) and changing fuel mix (33.2%) that have resulted from enhanced living standards and growing fossil fuel consumption. However, the population (13.8%) and emission intensity (3.1%) exhibit a relatively lower impact on CO_2 emissions. Interestingly, the energy intensity factor has prevented emissions from rising to a certain extent with (-8.7%) – indicating the ratio between domestic energy consumption and GDP. Based on the analysis of energy policy development, the share of renewable energy consumption was still relatively low in the national energy mix (higher reliance observed on non-renewable fossil fuel resources). Therefore, to make a transition towards low-carbon economic growth, significant improvements in energy efficiency and emission intensity are necessary, together with national energy mix restructuring for low-carbon economic growth. Through insight, the policy and country's context indicate that the equitization of the energy sector and technological innovation along with promoting investment in renewable energy is an essential element for sustainable development.

The eco-efficiency transition in Vietnam is being analyzed in chapter 4 under Malmquist data envelopment analysis. The results reveal that eco-efficiency performance has had some improvement starting from the 2000s. The eco-efficiency trend has shown a variety of trends, such as weak, expansive, and strong decoupling. However, this change is not remarkable. Malmquist productivity index has only grown slightly (only 0.6% during 1990-2016), while multi-country eco-efficiency has exhibited better performances for most Malmquist indexes. At the same time, pure efficiency change and efficiency change indicators in Vietnam slightly reduced, while technical efficiency changes and scale efficiency indexes have increased. It means that the eco-efficiency transition in Vietnam has not yet achieved an optimal result; even these results forecast the unstable change.

Chapter 5 aims to examine the EIPs performance from the viewpoint of the integrative mathematical model, such as the full permutation polygon synthetic indicator analysis (FPPSI) to normalize the values of the performance indices in an industrial park (enterprise and park level). In detail, the FPPSI analysis for enterprise-level showed that most of the food, beverage, and paper companies dominate with outstanding performance under moderate to excellent ratings. At the park level, Ninh Binh and Can Tho stand out with many remarkable successes (5 out of 13 indicators reaching the optimal value "1"). Specifically, these EIPs saved 51% of fuel LGP, 67.1% of coal, 78.16% of wastewater reduction in Ninh Binh compared to the total value for each indicator; while saved 77% of fresh water, more than 66.8% of electricity saving, 77% of COD reduction, and 56% of cost-saving at Can Tho pilot project. In addition, many potential and reasonable opportunities have been revealed and practiced during the first step. Energy recovery, green energy, reusable waste (metals, paper, and woods), utilizing heat-steam, and wastewater treatment in the whole EIP pilots have been centralized and emerged in EIP symbiosis networks. However, as a recommendation, this country needs to promote the participation of companies in the heavy industry sector. On the other hand, maintaining and expanding current successful symbiosis networks, parallelly, all stakeholders and the Vietnamese government should create new innovative symbiosis networks to deal with hazardous wastes and acquire knowledge for all industrial zones in the nation.

Based on the results, the dissertation can contribute to environment engineering/management and industrial ecology in several ways. Firstly, by developing industrial ecology approaches to analyse sustainability transition in Vietnam, the thesis provides important insights into the process of materialization and carbonization in developing nations, thus extending the application of industrial ecology to previously under-studied regions. Secondly, the thesis identifies "regional ecosystems" based on industrial ecology thinking and documentation systems. Also, material flow accounting results were extended further into environmental policy, regional trade dynamics, and economic development. Thirdly, the thesis develops an ecological efficiency assessment process that could be used as a reliable assessment of ecological industrial development and sustainability transformation of industrial ecosystems. Fourth, with the help of some empirical industrial symbiosis, the thesis presents the application of waste valuation in industrial ecosystems. On this basis, critical technical, environmental, and policy understanding of the considerations in urban-industrial symbiosis can be developed.

Graphical abstract – The brief framework for this dissertation



Outline of the research work

Chapter 1 Introduction	Introduction for research background and overview of studied country
Chapter 2 Material analysis	Resource metabolism and with technical efficiency in Vietnam by Data Envelopment Analysis in macro level for material field during 1978-2017
Chapter 3 Energy analysis	Decarbonization analysis in Vietnam during 1990-2016 – Macro level for energy field
Chapter 4 Eco-efficiency	Eco-efficiency in Vietnam through Malmquist data envelopment analysis during 1990-2017
Chapter 5 EIP assessment	Assessment of Eco-industrial park (EIP) performance and industrial symbiosis cases in UNIDO EIP project in Vietnam
Chapter 6	Contribution, discussion, conclusion, and future recommendation

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CHAPTER 1

Introduction

1.1. Background and literature review

1.1.1. Industrial ecology

Our environment currently faces up many severe problems that seem to be getting worse over time. It pushes us into an environmental crisis. Therefore, awareness of existence of environmental problems becomes urgent. Several vital issues include pollution, global warming, overpopulation, waste disposal, ocean acidification, loss of biodiversity, deforestation, ozone layer depletion, resource security, and human – ecosystem health, etc. Hence, ecological efficiency and sustainable development emerged as an important field to solve environmental problems and get long-term benefits (Sakr et al., 2011; Weisz and Schandl, 2008). In addition, the correlation among economic growth, socio-activities, and environment (ecology) is the key to sustainable development. It is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In which material and energy are the fundamental of industrial activities and economic growth by principles of which they become essential elements defining industrial ecology and sustainability. This field also requires interdisciplinary, usually related to the environment, economy, and technology that helps examine sustainable problems through multiple innovative environmental assessment tools (Subramanian et al., 2018; Wang et al., 2015). Since many historical references indirectly mentioned this concept in the early 1970s. It was developed by Ehrenfeld in 1997 with several rules:

- Close material loops
- Use energy in a thermodynamically efficient manner; employ energy cascades.
- Avoid upsetting the system’s metabolism; eliminate materials or wastes that upset living or inanimate components of the system.
- Dematerialization; deliver the function with fewer materials.

Industrial ecology aims to inform decision-making processes about the impacts of industrial activities and affluence on the environment by tracking and investigating physical resources and energy flows through innovative environmental assessment tools. For instance, tracking elements, substances, compounds, chemicals, and materials, etc. that take through the natural or economic system, it is known as material flow analysis (MFA) (Daniels and Moore, 2002; Oldfield et al., 2016). To assess the environmental aspects associated with a product over its life cycle, the life cycle assessment method (LCA) is an ecological tool that could be evaluated the impacts of a product (Oldfield et al., 2016). Besides, environmentally extended input-output analysis (EEIO) is an integrating IO method with LCA in drawing the holistic picture of product processing on environmental impacts (Guo et al., 2017; Thi et al., 2006). In addition, the relationship between affluence and environmental pressure are understood by various analytical methodologies such as the Environmental Kuznets Curve hypothesis (EKC), Eco-efficiency approach, Tapio decoupling analysis, etc.

1.1.2 Circular economy

The traditional linear economy development has become a stagnant trend. In which raw materials and resources have transformed into commodities and disposal. However, recently, the circular economy model has become a spotlight in narrowing the gap between economic growth and the natural system. Under the perspective of Ellen McArthur: "Looking beyond the current take-make-dispose extractive industrial model, a circular economy aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from consuming finite resources and designing waste out of the system. Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital. It is based on three principles: design out waste and pollution; keep products and materials in use; regenerate natural systems." Ultimately, one of the purposes of a circular economy is to optimize resource output by circulating products, components, and materials used at their highest utility at all times of the year between engineering and biological cycles (Figure 1.1).

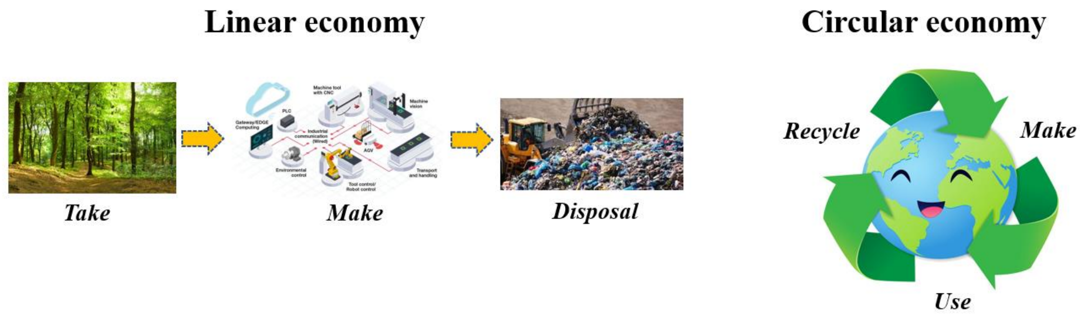


Figure 1.1. Transformation linear economy to become a circular economy.

1.2. Overview of Vietnam

1.2.1. Geographical location

Vietnam locates on the eastern coast of mainland Southeast Asia, covering 331,699 square kilometers, and shares borders with China to the north, two vicinity countries to the west include Laos and Cambodia, the Gulf of Tokin and South China Sea to the ease, and the Gulf of Thailand to the south (Fig 1.1). Vietnam has been experiencing rapid demographic and social change. Its population reached 96.5 million in 2019 (up from about 60 million in 1986), making it the world's sixteenth most populous country, and is expected to expand to 120 million by 2050. However, the population is rapidly aging, and Vietnam's emerging middle class, currently accounting for 13 percent of the population, is expected to reach 26 percent by 2026 (Bass et al., 2009). Overview of economic development, resource consumption, and sustainable development challenges are described below.

Figure 1.2. Map showing Vietnam and neighboring countries.
Modified by author: Orginal source: Mapchart.net.
(https://mapchart.net/world.html?fbclid=IwAR1Cvs-5UdingXrRIPTsXSiI6PyUsPCa20sh4pFcxH9oDuUi7We-7L7vBk8, access date)

1.2.2. Economic development status

Due to a long period of suffering from catastrophic wars, Vietnam faced many difficulties such as poverty, epidemics, a backward economy, and high illiteracy. The country's per capita income was among the poorest in the world (<200 USD) before 1980. Only after 1986, the country's reform "Đổi Mới (renovation or new changes)" gradually revive Vietnam's economy, culture, politics, and society (Revilla Diez, 2016). Vietnam had achievedan annual GDP growth rate of 7.9% during 1990-2000 – making it one of the emerging performance in the world (Perkins and Anh, 2009). The country grew even more rapidly in subsequent periods; the Socio-Economic Development Plan for 2006-2010 continues the growth strategy, with expected exports to increase 16% annually (the Socialist Republic of Vietnam, 2016). Vietnam also had witnessed many regional and world economic fluctuations during this period. In recent years, the country has well performed with the real gross domestic product (GDP) in 2017 equal to 223.78 billion USD (constant 2010-dollar prices) and annual GDP growth 6.8%, surpassing the target 6.7% set by the National Assembly (Konrad Adenauer Stiftung, 2017), which put Vietnam to be one of the fastest-growing economies in the world at that time. Looking into the industrial structure in 2017, the service sector was the highest contribution with over 42.7% of GDP, followed by industry and construction (32.5%), while manufacturing & processing and agriculture; forestry and fishery sectors accounted for 15.3% and 14.7%, respectively (Harker, 2018). From an export perspective, recently, Vietnam has driven the industrial growth with a large share of phones and components commodities on the top export (45.1 billion USD in 2017). In parallel, textiles, electronics, computers, and component ingredients were also substantially shared in exports. However, these industrial advancement has brought Vietnam new challenges to deal with a large number of materials required for the manufacturing and processing industry (91.4% of import turnover in 2017) (Konrad Adenauer Stiftung, 2017; Report, 2018).

1.2.3 Resource consumption patterns

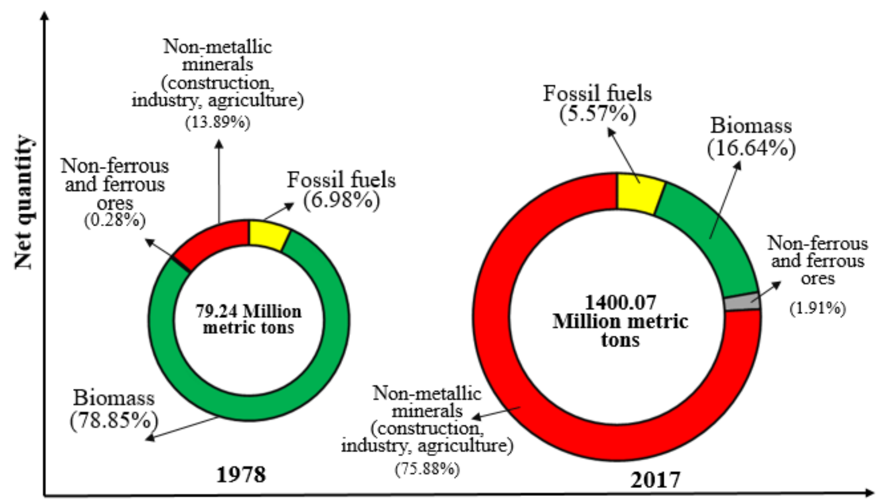
The domestic material consumption (DMC) by material type during 1978 and 2017 in Vietnam (Fig 1.3) confirms the fact that resource consumption increases steadily with the level of economic development (Schandl and Turner, 2009). As shown in Fig 1.3, total DMC was increased over 17.6 times from 79.24Mt in 1978 to 1400.07 Mt in 2017, and composition was changed, which presents rapid economic development, shifting from a centrally planned economy to a new, more open market economy with industrial advancement, urbanization, and enhanced living standard during last 4 decades (The World Bank, 2017).

In detail, consumption of non-metallic mineral (construction, industry, and agriculture) was sharply increased from 13.9% to 75.9% in the total DMC during 1978-2017. In the non-metallic mineral category, construction material was dominant and increased 119 times from 8.88 Mt (1978) to 1054.6 Mt (2017), which is due to the infrastructure construction for industrialization and urbanization. In contrast, biomass consumption in total DMC was increased ~ 4 times from 62.6Mt (1978) to 233.1Mt (2017), while the share sharply plummeted from 78.9% to 16.6%, which was due to the overwhelming increase of other materials. These material consumption transition trendsalign with this country's policy of transforming the agricultural economy into an industrialized and modernized economy (Barker and Üngör, 2019).

Coming to fossil fuels, although the share in DMC was decreased from 7.0% in 1978 to 5.6% in 2017, the total amount of fossil fuel consumption was increased 12.5 times from 5.53 Mt in 1978 to

69.36 Mt. In metal ores, the share in DMC was increased from 0.3% (1978) to 1.9% (2017), while the mass was increased 121.7 times from 0.22 Mt (1978) to 26.77Mt (2017).

Considering the material consumption trends shown in Fig.2, construction material consumption, fossil fuels, biomass, and metal ore in Vietnam are expected to surge continuously in line with economic growth, industrialization, urbanization, and improved living standards. However, if domestic extraction of specific material resources is insufficient to meet DMC demand, resources must be imported from other countries, which can seriously impact the national exchequer and quality of economic growth (Shah and Park, 2020). Thus, informed resource management strategies and policies based on resource flow and productivity efficiency transition in Vietnam seem to be highly required.



Detail information (Figure 3)		1978	2017
Biomass (Mt)	Crop Residues	15.1	77.4
	Crops	25.3	123.9
	Grazed biomass and fodder crops	4.0	15.7
	Wild catch and harvest	0.5	1.8
	Wood	17.7	14.3
Non-metallic minerals (Mt)	Non-metallic minerals - construction dominant	8.88	1054.60
	Non-metallic minerals - industrial or agricultural dominant	2.13	8.16
Fossil fuels (Mt)	Oil shale and tar sands	0.00	0.00
	Petroleum	0.93	23.65
	Coal	4.60	45.70
Metal ores (Mt)	Ferrous ores	0.00	18.03
	Non-ferrous ores	0.22	8.74

Figure 1.3. Resource consumption (DMC) by material type during 1978-2017 (proportional donut size to the value of DMC, DMC values are in million metric tons).

1.2.4. Sustainable development polices and challenges

Before the “Đổi Mới” period, Vietnam had not mentioned and paid no attention to policies related to sustainable development. Because in that period, reviving the economy after the wars was the most urgent task, in line with poverty reduction. It was not until the 2000s that the concepts of cleaner, eco-friendly, and efficient production and environmental conservation were rekindled through the first law on Environmental Protection issued in 2005. This is considered as a first step to mark regulations and provisions from an environmental point of view. As well as, it was the initial effort in the legal framework to protect ecosystems and precious resources (Nickerson, 2008). However, pollutants such as solid waste and wastewater were continuously increased. CO_2 emissions were also sharply increased approximately 4 times from 2000 to 2017. Hence, relevant policies and strategies have been formulated, such as Green industry (in 2008) – striving for green growth and encouraging environmentally responsible investment (Massard et al., 2018); Cleaner production and resource efficiency (in 2009). The main purposes of these policies and strategies were to promote production efficiency and reduce emissions in production processes. In addition, the sustainable development strategies during 2011-2020 not only focus on resources and the environment but also protect national sovereignty through political, cultural, and social stability (Republic et al., 2020). Among sustainable development strategies, the eco-industrial park initiative for sustainable industrial zones from 2015-2019 (Shem et al., 2019) marks a significant turning point in the awareness of resource efficiency, cleaner production, and industrial symbiosis in industrial activities, together with the community to create sustainable industrial parks that are an integral part of a modern - environmentally friendly city.

However, economic development and environmental management have been treated separately in Vietnam as in most developing countries (Bass et al., 2009). Separate institutions, policies, budgets, and programs have been established to work with each objective alone. Thus, the challenges of sustainable development in Vietnam are integrating environmental management and economic development, which is based on the knowledge of the economy-wide material flow and efficiency of the economic system.

1.2.5. Summary of eco-efficiency transition in Vietnam

After removing the cultural barriers, Vietnam has been interconnected with many countries and became an ideal incubator for foreign investments. It led to Vietnam's economic development has been remarkably accelerated. However, Vietnam also must face upheavals for climate change. To be aware of the consequences of unmitigated climate change, Vietnam vulnerably becomes one of the pioneers in part of reducing greenhouse gases through ratifying several international commissions (such as the Paris Agreement on Climate Change, the United Nations Framework Convention on Climate Change) (Bank, n.d.). To implement GHG reduction, the country should understand comprehensively about material flows, resource consumption, along with challenges in resource circularity and current policy. While resource circularity can be understood as utilizing wastes be inputs, which create new valuables in other manufacturers. It is a part of the circular economy.

Vietnam lacks relevant research in the area. Before transforming and improving the economic pathway, the country needs to have an insight into the picture of development in the past. In which physical flows accounting – presents economy-wide data on material consumption. In addition, its indicators such as material intensity and resource productivity can be translated to environmental impact. It is the stark transition from the linear economy that is mainly based on material extraction, consumption, and disposal. Besides, an overview of sustainable development programs is also fundamental to figure out strategies in long-term solutions. Hence, the thesis aims to investigate Vietnam's circular economy, as well as examine three industrial parks (Ninh Binh, Da Nang, and Can Tho) to investigate industrial transformation.

The speed of industrialization in Vietnam must face a shortage of natural resources, and it is the driving force for the study. The research has been established a quantitative method for national resource performance, along with evaluation of environmental performance and eco-industrial transition. Particularly, the objectives of the research include: (1) develop and apply industrial ecology analytical framework for resource metabolism in Vietnam; (2) understanding sustainability of resource metabolism in developing countries likes Vietnam; (3) identify key policy instrument for a sustainable transition. Besides, it helps answer the major issues: (1) What is the regional resource metabolism in developing countries? (2) How does materialization & carbonization affect a typical developing economy? (3) Are industrial ecosystems capable of changing environmental issues?

1.3. Research background

Material resources can be understood as a physical foundation of an economy. Since material consumption directly drives economic growth (Schandl and Turner, 2009). Recently, many mature developed countries, primary developed countries and developing countries, have been analyzed their material and resource consumption for many decades to find out the process chains, metabolism, and natural ecosystems. It is vital for the sustainable metabolism of urbanization and industrial economies (Daniels and Moore, 2002; Giljum et al., 2014a). In addition, the repercussion of imbalances between economic growth and resource overexploitation leads to an imbalance in Vietnam's growth trajectory. The correlations among affluence (economic growth), urbanization, industrialization, environmental quality, quality of life, and adversarial impacts from resource depletion and environmental degradation are complicated, and it is paramount to acknowledge this connection. The traditional development shows that economic growth in developing countries is based on the pure background such as resources, matter, and energy. It has only brought a vast number of massive landfills, deforestation, diseases, and man-made-catastrophic. Since it requires experts, managers, and policymakers to figure out the way to deal with the issue.

Furthermore, industrial activities are famous for economic development in a region, however, they also play a key role in material and energy consumption, as well as contribute to increasing GHG and environmental issues. The material intensity and resource productivity represent the technological level in countries and regions. On the other hand, each type of economic sector demands a different input intensity. Since economic innovation and transformation need to derive from significantly changing the major indicators (Krausmann et al., 2011; Wang et al., 2012). As a result, prior to transforming the economic pathway, several definitions related to sustainable development should be clearly understood. Firstly, sustainable development definition, which is a future key. It was officially reaffirmed at the Rio+20 conference: “Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs.” This is a long-term development in the global with three core pillars: economic development; social development; and environmental protection (Najam and Cleveland, 1992). Secondly, circular economy: the economy has a set of practices about built and rebuilt economic-social and material-energy systems (Zhao et al., 2012). Besides, one of the important definitions, which is industrial ecology is often mentioned at many international conferences. The picture of goods and services is drawn under the view of nature, with an eye toward finding innovative solutions for the upcoming future (Schandl and West, 2012).

Hence, many mathematical equations have been established to express the interrelationships among core indicators in making sustainable development. A simple model was built by Ehrlich and Holdren in 1972 (Ehrlich et al., 2007; Ehrlich and Holdren, 1971) intending to present the link of three key factors: Population (P); Affluence (A); and Technology (T). They are known as three major factors that have directly or indirectly affected environmental impact (I). Besides, the expanded IPAT model is known as Kaya identity. It analyzes energy intensity, energy efficiency and shows the scenario of stabilizing atmosphere greenhouse gases (Li et al., 2018; Thi and Anh, 2012, 2012). On the other hand, conducting a decoupling analysis aiming to interact between economic growth and environmental impact, the analysis is known as Environmental Kuznets Curve (EKC). It is famous for "Inverse U-shaped" hypothesis (Stern, 2004). With two stages, at the first stage, economic development is in line with environmental degradation, until reaching the optimal value (turning point – Fig 1), the trend of flourish jumps further, while environmental degradation drops to a low of value (Fig 3) (Mensah et al., 2018). All the economies are being pursuit the trend.

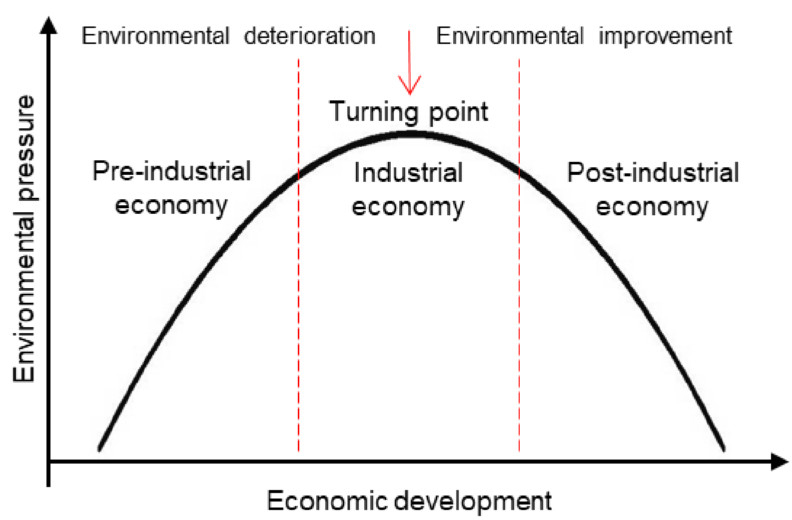


Figure 1.4. The diagram of environmental Kuznet curve (EKC) (https://www.economicshelp.org/blog/14337/environment/environmental-kuznets-curve/)

1.4. Research objective and questions.

In this dissertation, I try to develop methodological approaches to harmoniously track and integrate industrial activity into socio-ceconomic systems in Vietnam. A number of industrial ecology tools were developed and synchronized to understand the resource transformation of material flows, energy uses, waste generation, and final output. The goal is to contribute knowledge in this area and broaden the boundaries of industrial ecosystems and environmental management for developing countries to view resource sustainability perspective.

This thesis comprehensively addresses the following questions:

(1) What are the fundamental features of resource metabolism (exploitation, consumption, and trading market) in Vietnam at the macro-scale? How to accelerate resource productivity and reduce the physical intensity of materials for sustainable economic development in Vietnam?

(2) What are the drivers of energy-based CO_2 emissions in Vietnam based on the time-series data? What is the impact share of each factor (population, affluence, energy intensity, substitution, and emission intensity) and how these factors have varied in influence over time? and from a policy perspective, what potential hotspots could be targeted for low-carbon economic growth in Vietnam as well as other emerging economies?

(3) How has material consumption evolved in fast-growing Vietnam during the last four decades? Which factors are driving material consumption in the economy? How do material and carbon efficiencies vary temporally at the national level, in comparison with Japan, Korea, and China?

(4) How has Vietnam's Eco-industrial program (EIP) been implemented, including its performance? How to standardize the values of multiple indicators that can be described at the enterprise level and the park level performances? Which EIP pilot project is practical?

1.5. Structure of dissertation

The dissertation has been organized into 6 chapters. Chapter 2 is denoted the urban metabolism under the study of material flow analysis (MFA) during over 3 decades (from 1978 to 2017) in line with typical indicators domestic material consumption (DMC), domestic extraction (DE), and physical trade balance (PTB). To understand the status of industrialization and resource consumption with resource security in the manufacturing nation, some critical indicators include material intensity (MI) and resource productivity, were investigated. Based on these indicators, the environmental Kuznet curve (EKC) was also presented for drawing the picture of economic growth and environmental pressure. In the end, the efficiency of resource management and relevant policy at the macro-level were evaluated to show the strong and weak points for making a better economic transition. Furthermore, in this section, neighboring countries (fast-growing country as China, also primary developed countries such as South Korea, Japan) are also conducted to highlight Vietnamese issue compared with surrounding nations.

Chapter 3, the interrelationship of quantitative energy consumption and carbon-emission was conducted under the extended Kaya and IPAT applications combined with Logarithmic Mean Divisia Index (LMDI) decomposition model in Vietnam from 1990 to 2016. Under the foundation factors comprise population growth, affluence, technology, and three additional factors that are centralized to energy issue: fuel mix (substitution), energy intensity, and emission intensity.

The eco-efficiency transition in Vietnam is being analyzed in chapter 4 under Malmquist data envelopment analysis and Tapio decoupling analysis. The Malmquist productivity index values were measured based on the input-orientated Malmquist DEA under the hypothesis of constant returns to scale. Tapio decoupling analysis reflects separation among variables and time frame under eight levels: recessive decoupling, recessive coupling, weak negative decoupling, strong negative decoupling, expansive negative decoupling, expansive coupling, weak decoupling, and strong decoupling

Chapters 5 cover the contents of industrial activities and eco-transformation. The assessment for enterprise and industrial park level, decision-making unit with data envelopment analysis presented for the feasibility performance in implementing eco-industrial program in the selected pilots (Ninh Binh, Da Nang, and Can Tho). On the other hand, the key role of sustainable development throughout the eco-industrial park transition and circular economy has been shown. Besides, some typical industrial symbiosis models have been dedicated in some projects. In addition, strategies and fortune plans have been presented to consult and examine the upcoming future picture in the country. Finally, chapter 6 showed the comprehensive conclusion, some contributions of the dissertation on this field, and several limitations with the future recommendation.

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Chapter 2

Assessment of resource metabolism with technical efficiency in Vietnam by Data Envelopment Analysis[1]

Abstract

The picture of resource metabolism in Vietnam was drawn in this chapter under the economy-wide material flow accounting approach during 1978-2017. Besides, several typical economies that represent levels of development (fast developing country: China; primary developed nation: South Korea) were also explored in some sides to compare and polish Vietnam's case. Trends in resource efficiency, bilateral trade dynamics, and progress regional economic and environmental policy are shown. Consumption of raw materials has been decomposed into economic dynamics, and dematerialization has been tested. As a result, domestic material consumption (DMC) significantly increases in Vietnam from 79.24Mt in 1978 to 1400.07 Mt in 2017 under vastly changing types of material consumption. Although the nation has not reached the turning point in EKC analysis, South Korea and Japan have met this point early. However, Vietnam's issue has been continued a stable climb with the slight acceleration of technological advancements. Through Malmquist data envelopment analysis denotes that all of the indicators in this test in Vietnam have improved and are closer with comparative countries. However, Vietnam is still material-intensive and has low material productivity. Therefore, Vietnam is highly recommended to strengthen technology innovation and efficiency enhancement by closely coordinated policies on sustainable resource consumption, carbon reduction, economic growth for sustainable development goal 2030.

2.1. Introduction

Rapidly rising resource extraction and its consumption (Aoki-Suzuki et al., 2012; Krausmann et al., 2009) brings a multitude of environmental and socio-economic problems (Milner-Gulland, 2012; Weisz and Schandl, 2008) where developing economies are expected to suffer the most due to poor material efficiency and production technologies. Market-oriented production also often aims to increase population growth, and improve standard living standards, which is the dominant condition,

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leading to increased productivity and increases resource consumption. This increases the risk of resource imbalance and non-renewable resources with low efficiency because the increase in input often exceeds the productivity increase. The consequence is an ecological imbalance (Caiado et al., 2017; Ferronato et al., 2019). Although rising resource consumption can be driven by a multitude of factors, including population, urbanization patterns, social lifestyles, industry structure, production technologies, price, or abundance of resources etc., the impact of economic development becomes more important, especially in the context of an entire economic system bounded by geographical boundaries. It, thus, becomes imperative to mitigate environmental damage caused by extensive natural resource consumption driven by existing national and global level economic policies. A pathway to inhibit such a global material use trajectory is to understand resource metabolism across different regions and diverse ecosystems (Guo et al., 2017). The role national policy in transboundary material flows, domestic material intensity (MI) and productivity is also an important area of concern to materialize sustainable use of natural resources. Among various approaches used for examining human use of natural resources, material flow analysis (MFA) has become an important methodological approach for environmental accounting and to better understand material metabolism from an ecological perspective (Dai and Liu, 2018; Daniels and Moore, 2002; Eisenmenger et al., 2016; Wiedenhofer et al., 2019) with economy-wide MFA incorporating an economic dimension to this approach (EUROSTAT, 2013). Economy-wide MFA can be used to understand flows and consumption of natural resources within the boundaries of an economic system such as a country or a region (EUROSTAT, 2017; Pratt et al., 2016) and analyze resource exploitation, trade in resources, and the nexus between nature and economic growth (Hezri and Dovers, 2006; Lee et al., 2014; Mancini et al., 2015).

Vietnam has been recognized as one of the rapidly developing countries with remarkable achievement in economic reformation. The country performed well under the outstanding GDP growth of 6.4 percent in 2017. Meanwhile, global GDP growth at that time was only expected at about 3 percent (Update and Opment, 2012). However, Vietnam has been facing emerging challenges of huge resource requirements and carbon emissions, which can be confirmed by the fact that total Domestic Material Consumption (DMC) increased from 16.06 Mt in 1990 to 61.41 Mt in 2016, and emission intensity rose from 4.75 to 5.12 Mt CO_2 per ktoe of fossil fuels (Huong et al., 2020). Furthermore, according to the Ministry of Natural Resources and Environment of Vietnam, the nation would sharply increase greenhouse gases emissions around 5 times and 20% carbon intensity per GDP, which could result in adverse consequences of material-resource depletion by 2030 (Dinh, 2013; Massard et al., 2018; Report, 2018; UNDP, 2012).

These numbers confirm that Vietnam's pro-growth policy, which sacrifices environmental assets such as resources and a clean environment (Bass et al., 2009) that has resulted in rapid resource depletion and environmental degradation with weak resource and environmental management institutions. However, to our knowledge, there have been few studies on material flow and productivity in Vietnam until now. Therefore, research on material flows and resource efficiency to understand Vietnam's transition characteristics of economic growth, resource consumption, efficiency, and pollution emissions is needed to derive sustainable development policy insights integrating environmental and development objectives together.

With these backgrounds, this study investigates the sustainability of resource flow and productivity transition in Vietnam during 1978-2017 using economy-wide material flows analysis and DEA-based Malmquist Productivity Index approach (stands for DEAM). As per our knowledge and the literature review, no published studies exist on this topic with similar methods. Through this work, this paper aims to answer the following research questions: 1) how material consumption does have been evolved in fast-growing Vietnam during the last 4 decades, 2) which factors are driving material consumption in the economy; 3) how material and carbon efficiencies vary temporally at the national level, in comparison with Japan, Korea, and China. This study intends to address research questions and derive key policy suggestions for Vietnam's material consumption, productivity, and sustainable development from a historical and macro-policy perspective.

2.2. Materials, methods, and data

2.2.1. Methodological framework

Fig 2.1 presents the research framework and detailed data used in this study. Thirteen material types are classified into four resource categories: metal ores, fossil fuels, non-metallic minerals, and biomass. The first step is to conduct Vietnam's MFA based on EW-MFA guidelines using the most recent long-time series data covering four decades, from 1978 to 2017. The second step is to identify the drivers of resource consumption by decomposition analysis and apply the EKC hypothesis.

Finally, economic performance is analyzed by the DEA-based Malmquist productivity Index approach (DEAM). As material metabolism depends on economic development stages, Vietnam is investigated compared to top trade partners: China (middle-developing country) and South Korea (primary developed country). The starting and ending points are based on the longest term and data availability.

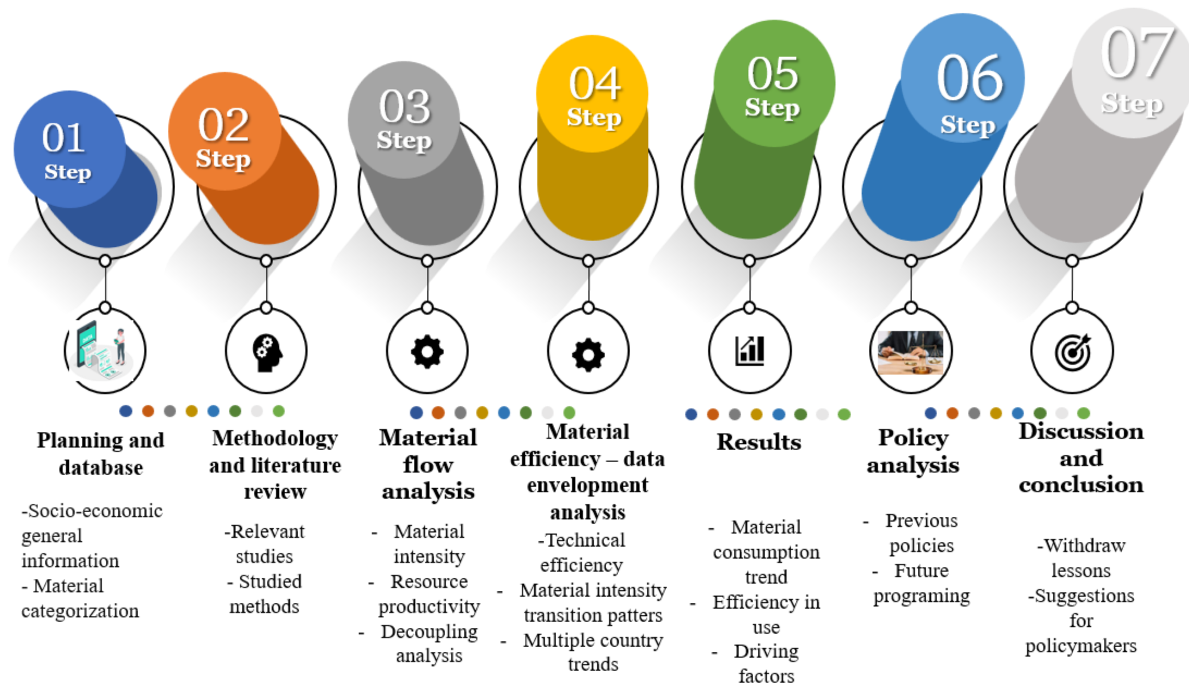


Figure 2.1. The research framework and data for MFA and DEA.

2.2.2. Material flow analysis

This chapter has mainly adhered to the EW-MFA framework and methodological guidelines in EUROSTAT (Eurostat, 2001; EUROSTAT, 2013, 2007). The MFA indicators used in this study are summarized in Table 2.1. As shown, the indicators such as DE, DMC, and PTB are expressed in physical units (Mt), while intensity and efficiency indicators such as MI, EI, and RP are in mixed units' DMC/capita and/or DMC/GDP; CO_2/capita and/or CO_2/GDP, and GDP/DMC, respectively. These MFA indicators are used to explore the dematerialization/decoupling trends and resource productivity (Kósi and Torma, 2005; Pivnenko et al., 2016). This study uses GDP as an economic performance indicator and is reported in the United States dollar (USD) based on 2010 constant prices (or otherwise stated).

Table 2.1. Material flow and efficiency indicators applied in this study		
Indicator	Abbreviation	Description
Domestic extraction	DE	Extracted resources from natural environment used as an input for an economy (except water and air).
Domestic material consumption	DMC	DMC = DE +import – export
Physical trade balance	PTB	The trade surplus or deficit of material resources within an economy. (PTB = import -export)
Material intensity	MI	The total amount of material directly used in an economy, represented by DMC per capita and DMC per GDP
Emission intensity	EI	Total CO_2 emissions/capita or Total CO_2 emissions/GDP
Resource productivity	RP	Evaluation the level of efficiency in using resources, which is calculated on the ratio between GDP and DMC, GDP/DMC.

2.2.3. IPAT Decomposition analysis

IPAT decomposition analysis is done to investigate further the drivers for the resource consumption with the results of MFA; IPAT is a fundamental equation postulating that environmental impacts are the multiplicative product of three socio-economic drivers of the population (P), affluence (A), and technology (T) (Nakicenovic and Swart, 2000; York et al., 2003). In this study, DMC was taken as the environmental impact (I) driven by three major factors under the IPAT assumption as given in Equation (1):

$$DMC = P \; X \; A \; X \; T = P \times \frac{GDP}{P} \times \frac{DMC}{GDP} \qquad (1)$$

Where population ‘P’ is (number of persons), affluence ‘A’ (GDP per capita), and technology ‘T’ (DMC per GDP). To quantitatively measure the contributions of the three drivers, the Log-Mean Divisia Index (LMDI) method (Ang and Liu, 2001) was used to decompose the change in DMC from ‘time=0’ (the start year) to ‘time=t’ (the end year).

Based on the LMDI method, the change of DMC from ‘time=t^0’ to ‘time=t’ can be expressed as the following equation:

$$\Delta \mathrm{DMC} = \mathrm{DMC}_t - \mathrm{DMC}_{t0} = \Delta \mathrm{P} + \Delta \mathrm{A} + \Delta \mathrm{T} \qquad (2)$$

$$\Delta \mathrm{P} = \sum \frac{\mathrm{DMC}_{(t)} - \mathrm{DMC}_{(0)}}{\mathrm{Ln}(\mathrm{DMC}_{(t)}/\mathrm{DMC}_{(0)})} \times \mathrm{Ln}\frac{\mathrm{P}_{(t)}}{\mathrm{P}_{(0)}} \qquad (3)$$

$$\Delta \mathrm{A} = \sum \frac{\mathrm{DMC}_{(t)} - \mathrm{DMC}_{(0)}}{\mathrm{Ln}(\mathrm{DMC}_{(t)}/\mathrm{DMC}_{(0)})} \times \mathrm{Ln}\frac{\mathrm{A}_{(t)}}{\mathrm{A}_{(0)}} \qquad (4)$$

$$\Delta \mathrm{T} = \sum \frac{\mathrm{DMC}_{(t)} - \mathrm{DMC}_{(0)}}{\mathrm{Ln}(\mathrm{DMC}_{(t)}/\mathrm{DMC}_{(0)})} \times \mathrm{Ln}\frac{\mathrm{T}_{(t)}}{\mathrm{T}_{(0)}} \qquad (5)$$

Where ΔP, ΔA, and ΔT describe the contribution of population, affluence, material intensity, respectively.

2.2.4. Data envelopment analysis-based (DEA) approach

Data envelopment analysis (DEA) is known to be one of the most effective mathematical tools in evaluating and supporting performance results for a given job, also support decision-making units (DMUs) (Charnes et al., 1978). In the study, the application of DEA was based on two inputs and one output, as previously reported (Zhu and Shan, 2020). Among the DEA inputs, DMC was selected as it well represents economic, urban, and agro-industrial development at the national level (Waheed et al., 2019), and the stream accounts for economy-wide raw materials are also available (Department of Environmental Affairs, 2019). At the same time, CO_2 emissions were used as undesired outputs that are to be minimized (Mardani et al., 2017). Though several inputs and outputs could be used in DEA, they must not be excessive (i.e., not exceed the number of DMU_s) in order to guarantee the method’s discriminatory power (Boussofiane et al., 1991). This means that the number of inputs and outputs needs to be small relative to the number of DMU_s in order for the DEA to effectively distinguish between the DMU_s under consideration (Boussofiane et al., 1991). In this study, the number of inputs and outputs was considered adequate (2 and 1) respectively because the same size was not large enough (e.g., 7 DMU_s in the national efficiency analysis and 5 in the multinational effect analysis (i.e., 4 top trading economies plus Vietnam).

In the DEA analysis part, the solution drives from Charnes, Cooper, and Rhodes (CCR) resolve the reliability measurement problem for DMUs with a considerable number of inputs-outputs (Masternak-Janus and Rybaczewska-Błażejowska, 2017), we investigated representatively during 1978-2017 for Vietnam. The model proposes constant returns to scale (CRS) in terms of input and size assumptions. The CRS assumption makes sure that "best practice benchmark units" be reliable results by judging inputs on the DEA model (Deilmann et al., 2018). The input-oriented CCR model was reported as an efficient model to measure the capabilities at the regional level (Masternak-Janus and Rybaczewska-Błażejowska, 2017). Hence, the study is to apply the "efficient" (Pedraja-Chaparro et al., 1997; Shah and Park, 2020) as a DEA standard, which is referred to as expressed in DEA results.

$$\text{Max}_{\lambda,\theta}\ \theta$$

$$\text{With } n = 1, 2, \ldots$$

$$\theta X_{n1} \leq X_{11}\lambda_1 + X_{12}\lambda_2 + \ldots + X_{n1}\lambda_n$$

$$\theta X_{n2} \leq X_{12}\lambda_1 + X_{22}\lambda_2 + \ldots + X_{n2}\lambda_n$$

$$Y_n \geq Y_1\, \lambda_1 + Y_2\lambda_2 + \ldots + Y_n\lambda_n$$

$$\text{Where, } \lambda \geq 0$$

Where X inputs, including two inputs of material consumption (Mt) and carbon emissions (Mt); Y is the output (GDP – unit billion USD constant price in 2010). Besides, θ is a score for efficiency for the n-th DMU, respectively. Its values are ≤ 1 if the value is 1 – it denotes that the optimal frontier and technical efficiency are obtained. For λ is a constant vector NX1. The DEA – CRS analysis is tested on DEAP software.

2.2.5. Data collection

The general information for socio-economic and environmental issues was gathered from the World Bank (The World Bank, 2017; World Bank, 2019) and the International Energy Agency's database (IEA, 2017). For material categorization, consumption statistic was taken from the International Resource Panel's database – based on the EUROSTAT framework (Eurostat, 2001; EUROSTAT, 2013, 2007). Besides, the official national reports and Statistical Yearbooks of Vietnam (Department of Environmental Affairs, 2019; Dinh, 2013; Jung Eun et al., 2019) were used to complement the missing data and ensure data reliability. For the policy analysis, publicly available policy documents were accessed and analyzed.

2.3. Overview of Vietnam and some comparative countries.

Notably, developing economies are receiving international attention and support in increasing the efficiency of resource consumption and cleaner production. Through the application of successful models across developed countries and the funding of economic potentials are creating favorable conditions for developing countries to improve their environmental status through following a frog-leap approach and innovative resource management policies (Dong et al., 2017). As of now, the rapid material consumption is taking place in the East Asia-Pacific region, including China and South Korea (Hashimoto and Moriguchi, 2010), while countries, such as Vietnam, are also showing impressive growth both in material use and economy (Barker and Üngör, 2019). South Korea, China, and Vietnam belong to disparate economic stages where South Korea is a mature developed economy, China is rapidly developing, and Vietnam is a typical low to middle-income country. South Korea is an industrialized country with considerable dependence on imported virgin resources and exported final goods. China, sometimes referred to as the world factory, has shown tremendous resource consumption in recent decades fueled by rapid economic growth (Chiu et al., 2017), while Vietnam is an emerging economy with large economic development witnessed during the last three decades. After years of unrest and wars, the unification of Vietnam (1976) paved the way for rapid development that strengthened their economic, social, and trade ties with South Korea and China. Despite significant economic growth by Vietnam, material flow accounts have never been studied nor analyzed to characterize its domestic resource metabolism, and the role of regional economies remains unclear. This becomes highly relevant when developing countries such as Vietnam tend to follow the footsteps of China's economic development model (Schellekens, 2013). Moreover, Vietnam receives large monetary assistance from South Korea, and both remain important trading partners to date – indicating a huge potential for knowledge and technology transfer among them. The geographical proximity of China, South Korea, and Vietnam makes them important trade partners of primary resources and finished products and services, as shown in Fig 2.2.

Figure 2.2. The map of China, South Korea, and Vietnam

Table 2.2 presents the current socio-economic status of China, South Korea, and Vietnam. Among them, China is the largest and most populous country, followed by Vietnam and South Korea. From 1978 to 2017, the population in China and South Korea increased by about 45% and 39%, respectively, while that in Vietnam grew by nearly 84%, indicating a considerable human resource available for national economic development. In terms of nominal GDP, as of 2020 estimates by International Monetary Fund World Economic Outlook 2020, China is expected to be the second-largest economy in the world while South Korea will rank at 10th number and Vietnam at 37th number. However, the per capita GDP among the three countries is the highest in South Korea followed by China and Vietnam. Although China's annual GDP growth rates have been very high during the last two decades, Vietnam has also achieved rapid GDP growth in recent years, and with rapidly rising per capita GDP, resource consumption in these countries is also expected to increase (Hashimoto and Moriguchi, 2010).

Table 2.2. General socio-economic data for subject countries, as of 2017

	China	South Korea	Vietnam
Population, million	1,386	51.47	95.54
GDP, billion USD*	10,161.0	1,345.9	175.3
GDP/capita, USD	7,329	26,152	1,835
Average GDP growth (ages 15-64) (1978-2017), %	1.52	1.33	2.26
World rank in exports	1st	5th	26th
World rank in imports	2nd	8th	23rd
Total CO_2 emissions (Mt)	9258	600	191

*Based on constant 2010-dollar prices

Source: World Bank Indicators; UN COMTRADE and ITC statistics (2017).

The World Factbook; International Energy Agency (IEA)

With a focus on examining current material consumption trends in China, South Korea, and Vietnam, and identifying a transition towards innovative regional resource management from a policy perspective, this study aims to characterize their distinct yet connected material use patterns using MFA methodology. Although economy-wide MFA is a conventional approach (Calvo et al., 2016; Giljum et al., 2014b; Krausmann et al., 2011; Moriguchi, 2001), yet the novelty of this work lies in the undertaken supra-national comparison of economies at the different developmental stage. According to World Bank GNI (Gross National Income) per capita Operational Guidelines & Analytical Classifications – World Development Indicators in 2017, income country is classified into four categories – including low income, lower-middle income, upper-middle income, and high income. Starting from a low-income country in 1987, China has risen remarkably and steadily to become an upper middle income. In comparison, South Korea's performance has been presented an upper- middle income until 1995. However, during 1998-2000, South Korea was considered as an upper-middle income because of undesirable effects from the East Asia Crisis; after that, the country has been quickly recovered as a high-income country. About Vietnam, the country was reported as a low-income country for a long time, and it has been transformed to become a lower-middle income nation starting from 2009 (Word Bank Indicators, n.d.). The idea is, based on the material flow accounts within the three countries, to analyze resource use efficiency and productivity based on important MFA indicators and regional environmental development. With the help of extensive pan-regional policy analysis, this study also discusses structural policy changes over time to better understand the nexus of economic development and environmental policy evolution in these countries.

2.4. Results and discussions

This section will present some significant outcomes of this work. With the help of material flow analysis, key policy implications will also be exhibited. In parallel, the driving factor and assessment of metabolism under Malmquist data envelopment analysis will also be drawn to track material used in Vietnam and subject countries.

2.4.1. Domestic extraction (DE)

Fig 2.3 presents per capita domestic extraction for (a) China, (b) South Korea, and (c) Vietnam, while total DE results are presented in Fig 2.3 (d) for the period 1978-2017. Results showed that DE trends and shares of each material type varied significantly among the three countries. Moreover, DE per capita increase during 1978-2017 was highest in Vietnam (869%), followed by China (599%), while that in South Korea was lowest (58%). During the 40 years, total DE in South Korea first increased during the 1978-1997 period; however, it then started to decline after 2005, making the overall per capita DE increase from 4.8 t in 1978 to 7.6 t in 2017. On the contrary, total DE in China has increased by 914% during 1978-2017, making the per capita DE sharply increase from 3.4 t in 1978 to 23.9 t in 2017. Similarly, the increase in total DE for Vietnam has been the highest among the three countries (1,680%), making the per capita DE increase from 1.5 t in 1978 to 14.6 t in 2017. Interestingly, per capita DE back in 1978 was highest for South Korea (4.8 t) followed by China (3.4 t) and Vietnam (1.5 t); however, in 2004, China’s per capita DE (12.1 t) overtook that of South Korea (10.8 t) while Vietnam was still at the third place (6.9 t). In 2008, Vietnam’s per capita DE (10.4 t) surpassed that of South Korea (9.6 t) while China still maintained the first spot (15.3 t).

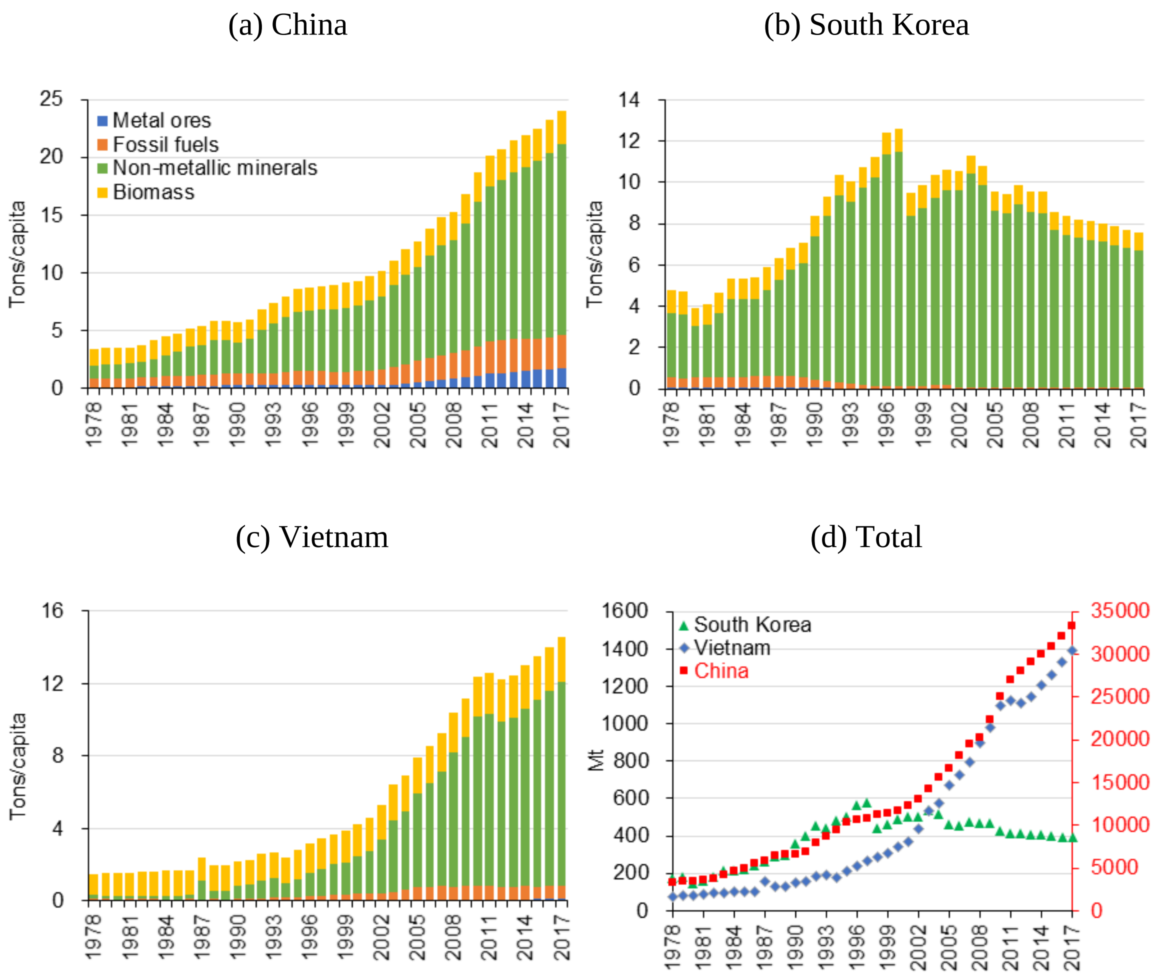


Figure 2.3. Domestic extraction in subject countries during 1978-2017

Note: Fig 2.3 (d), the second y-axis represents the total DE in China.

For China, in 1978, non-metallic minerals for construction had a share of 32.2% in total DE which almost doubled to 67.1% in 2017, indicating large-scale extraction of mineral resources for construction and infrastructure development. Similarly, for South Korea, the share of construction minerals in total DE increased from 63.6% in 1978 to 85.9% in 2017, indicating its significant share in domestic resource extraction. For Vietnam, the share of construction minerals in total DE increased significantly from 11.4% (1978) to 76.9% (2017), indicating higher extraction of construction-based materials. Thus, as of 2017, construction minerals were the largest domestically extracted resource and showed the highest growth during 1978-2017 in all three countries. On the other side, the share of biomass and fossil fuels resources in total DE reduced in all three countries, over the study period, mainly due to the overwhelming increase in the share of construction materials. Although, absolute quantities for most of the resource categories had increased over time, yet the extraction of construction minerals was significantly higher than the rest - making it the biggest shareholder in total DE.

Fossil fuels are essential energy resources, especially for industrialization, urbanization and for meeting other energy demands. For the study countries, fossil fuel extraction increased considerably in China and Vietnam, while South Korea plummeted sharply. In China, fossil fuel extraction increased from 732 million tons (Mt) in 1978 to 4,019 Mt in 2017, showing a growth of 449%. Similarly, in Vietnam, fossil fuel extraction increased from 6.0 Mt in 1978 to 69.7 Mt in 2017, representing nearly a ten-fold increase. Nevertheless, local fossil fuel extraction has somehow stabilized in Vietnam, especially after 2009, making the country more dependent on resource import to meet the increasing demand for energy resources. However, in South Korea, fossil fuel extraction reduced from 18.1 Mt in 1978 to 1.6 Mt in 2017, showing a decline of 91% during the study period. For both China and Vietnam, rapid industrial development and availability of domestic energy resources helped in the expansion of fossil fuel extraction, including coal, oil, and natural gas. In contrast, in South Korea, depleting fossil fuel reserves coupled with alternate energy policies caused such a decline (Saling et al., 2002).

2.4.2. Domestic material consumption (DMC)

Fig 2.4 presents per capita domestic material consumption for (a) China, (b) South Korea, and (c) Vietnam, while total DMC results are presented in Fig 2.4 (d) for the period 1978-2017. Like DE results, trends in DMC and shares of each material type varied among the three countries. DMC per capita in 1978 was highest for South Korea (5.9 t), followed by China (3.4 t) and Vietnam (1.5 t). However, in 2009, China's per capita DMC (17.6 t) overtook that of South Korea (15.9 t) while Vietnam was still in third place (11.1 t). As of 2017, per capita DMC was highest in China (25.4 t), followed by South Korea (15.7 t) and Vietnam (14.7 t) – highlighting the importance of per capita DMC and national population in absolute resource use. As far as total DMC increase in concerned, from 1978 to 2017, it was highest for Vietnam (1,668%) followed by China (974%) and South Korea (271%), indicating rigorous consumption growth taking place in developing countries as opposed to developed countries – mainly arising from economic and urban expansion.

The ratio of DMC over DE can indicate resource consumption concerning locally extracted or imported resources. In 1978, DMC/DE ratio was 1.0, 1.2, and 1.0 for China, South Korea, and Vietnam, respectively, demonstrating a relatively higher self-dependency. Especially China and Vietnam, as domestically extracted resources were sufficient to meet the local resource demand. However, in 2017, DMC/DE ratio was 1.1, 2.1, and 1.0 for China, South Korea, and Vietnam, respectively, indicating a relative dependence on imported resources, particularly in South Korea, where DMC/DE ratio has almost doubled during the 40 years. Country-wise in 2017, China's DMC/DE ratio was 1.5, 1.2, 1.1 for metal ores, fossil fuels, and biomass, respectively, thus, indicating substantially higher local consumption as compared to local resource availability. In Vietnam, as of 2017, DMC/DE ratio was higher for metal ores (2.5) and fossil fuels (1.1). However, the gross number of imports was considerably lower than China's. In South Korea during 2017, DMC/DE ratio was extremely high for fossil fuels (186.6) and metal ores (40.5), thus, indicating severe dependency on imports of these two material categories and indigenous resource scarcity. The increasing dependence on imported resources also indicates future global resource supply-chain dynamics, resource price fluctuations, and potential competition among importing countries.

As the construction minerals are dominated in the non-metallic mineral category, their DMC in China and Vietnam almost identically increased as with their DE trends; however, in South Korea relative share of construction mineral DMC reduced from 50.6% in 1978 to 41.3% in 2017, mainly because fossil fuel consumption had increased 6-folds during this time - making their relative share equal to 37.4% in 2017 as compared to 19.8% in 1978. In South Korea, fossil fuel resources are critical to meet the energy demand, and nearly all of them are imported and consumed mainly by the industrial and transport sectors (KEEI, 2017).

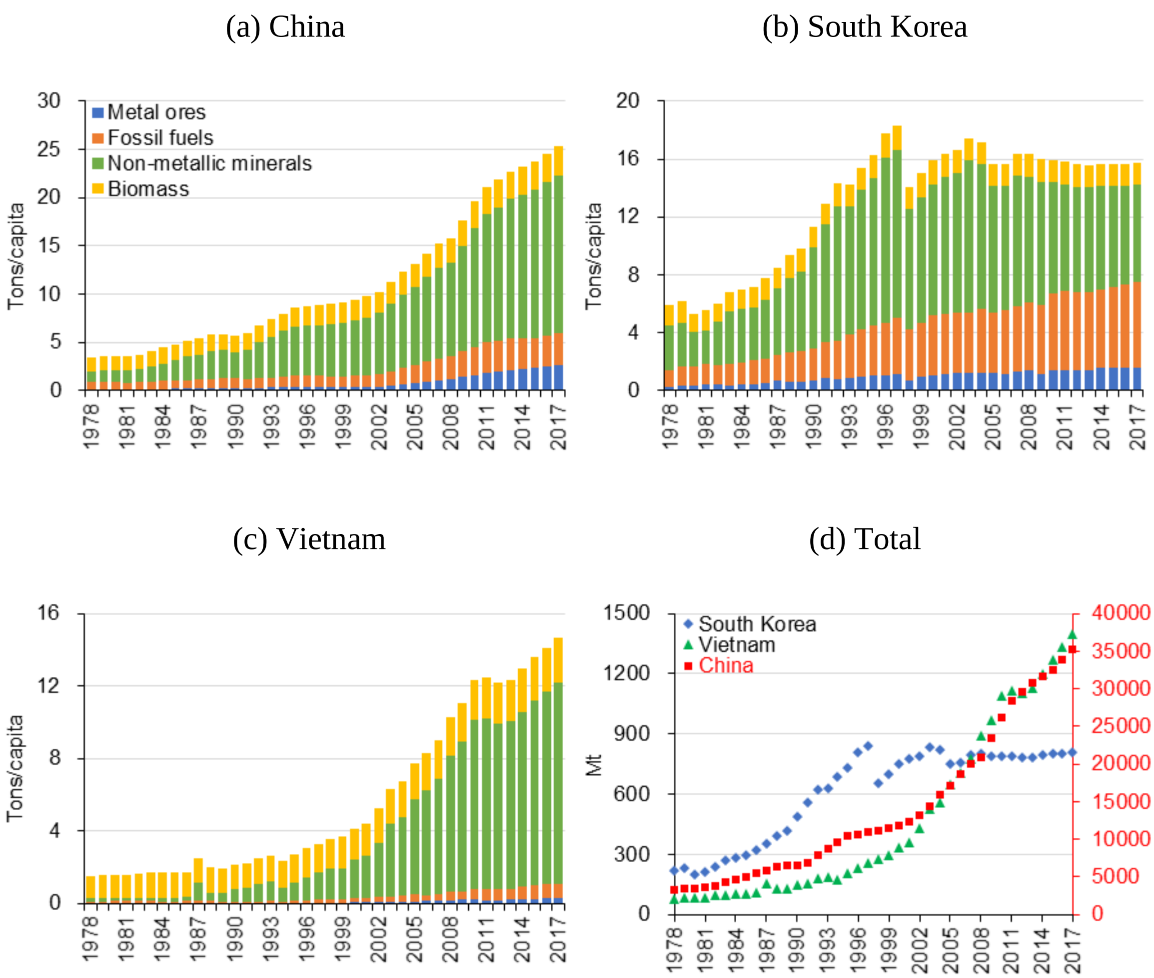


Figure 2.4. Domestic material consumption in subject countries during 1978-2017

Note: Fig 2.4 (d), the second y-axis represents the total DMC in China.

2.4.3. Physical trade balance

Fig 2.5 presents the net physical trade balance for (a) China, (b) South Korea, and (c) Vietnam while total PTB results are shown in Fig 2.5 (d) for the period 1978-2017. The PTB is different for each country, with China and South Korea both having considerable inflows of imported resources while Vietnam has an almost balanced PTB profile. As for China's PTB, there are two distinct phases – before and after 2000. In 2000, China's net traded resources (imports minus exports) amounted to 89.1 Mt, comprising imports of metal ores (85.7 Mt), biomass (27.9 Mt) and fossil fuels (4.2 Mt), and exports of non-metallic minerals (for construction and industrial or agricultural dominant) (28.7 Mt). However, in 2017, China's net imported resources equaled 1948.6 Mt (~22 times higher than that in 2000), comprising imports of metal ores (1175.3 Mt), fossil fuels (679.9 Mt) and biomass (206.2 Mt), and exports of non-metallic minerals (112.9 Mt). Therefore, from a net exporter of resources during 1978 to one of the top importers of global resources during 2017, China's economic miracle during the last few decades can be partly attributable to the resource inflow from other countries.

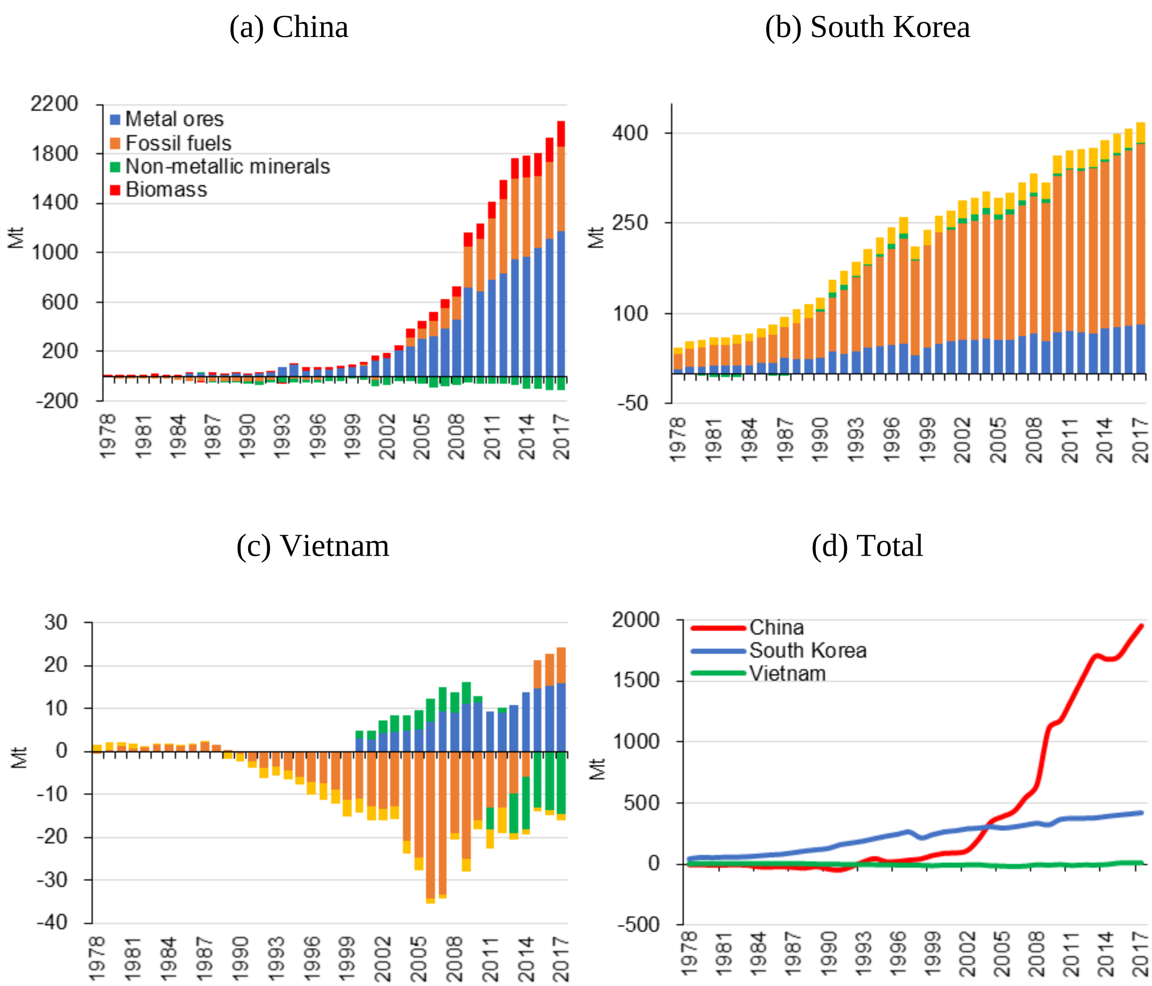


Figure 2.5. Physical trade balance in subject countries during 1978-2017

In South Korea, the material trade balance has been dramatically inclined towards imported primary resources, including metal ores, fossil fuel, non-metallic minerals, and biomass. Back in 1978, South Korea's net resource import equaled 40.6 Mt comprising imports of fossil fuels (25.1

Mt), biomass (10.8 Mt), and metal ores (6.8 Mt) and exports of non-metallic minerals (2.2 Mt). However, in 2017, their net resource import was 417.4 Mt (~10 times higher than that in 1978, but ~5 times lower than that of China in 2017) with imports of fossil fuels (300.4 Mt), metal ores (80.8 Mt), biomass (33.3 Mt) and non-metallic minerals (2.9 Mt). Therefore, by 2017, South Korea became heavily reliant on imported materials which explain how resource mining and extraction have moved to other countries, causing a lower per capita DE as compared to per capita DMC. During 1978-2017, the share of fossil fuels in total resource trade increased from 61.8% to 71.9%, and biomass reduced from 26.7% to 7.9%, indicating both higher aggregate fossil fuel consumption and its increased relative share in net resource trade.

There are three interesting phases in Vietnam concerning PTB: 1978-1988, 1989-2014, and 2014-2017. From 1978-1988, Vietnam's net resource import remained relatively low and only increased from 1.0 Mt to 1.5 Mt, with mainly fossil fuel imports (1.5 Mt). By 1989, fossil fuel imports reduced significantly due to domestic resource availability while biomass exports rose. From 1989 onwards, Vietnam's fossil fuel exports increased significantly, reaching their peak in 2006 when 34.3 Mt of fossil fuels were exported. However, a sharp decline in fossil fuel exports was seen after 2006, mainly due to increasing local demand until 2014, after which Vietnam began to import fossil fuels. The phenomenon presents a situation where a country can surpass domestically available energy resources within a couple of decades and, therefore, must develop policies ensuring its energy security in the long run. On aggregate levels, Vietnam's net resource trade during 1989 equaled -1.4 Mt with exported biomass (1.8 Mt) and imported fossil fuels (0.29 Mt). As of 2014, their net resource export was 5.5 Mt with exports of non-metallic minerals (12.1 Mt), fossil fuels (6.1 Mt), biomass (1.1 Mt), and imports of metal ores (13.8 Mt). However, the situation has changed since 2014, and by 2017, Vietnam's net resource trade was equal to 8.3 Mt comprising exports of non-metallic minerals (14.7 Mt) and biomass (1.1 Mt) while imports of metal ores (15.9 Mt) and fossil fuels (8.4 Mt), indicating a shift towards increasing demand of imported energy resources and metallic ores. This is in contrast with South Korea and China, where net resource trade has reached 417.4 Mt and 1,948.6 Mt, respectively – much higher than Vietnam.

2.4.4. Intensity and efficiency trends

Based on the basic material flow indicators, intensity, and efficiency trends of Vietnam, and top three trade partners comprising China, South Korea, and Japan are investigated during 1978-2017 (Fig 2.6). Inthis figure, economic growth is represented by GDP per capita; resource productivity, DMC tons per capita; resource productivity, GDP per DMC, and environmental impact, CO_2 per capita, respectively. As Vietnam is a fast-growing developing country, China (upper-middle-developing country), South Korea (primary developed country) are selected as top Vietnam trading partners at different stages of economic development to compare the material and efficiency indicators trends (Dong et al., 2017).

As for economic growth, GDP per capita continuously increased 4.9; 7.7; and 23.9 times in Vietnam, Korea, and China, respectively, for 4 decades (Fig 2.6a). However, material intensity (DMC per GDP) has reduced 65.5, 64% in Korea, China, respectively (Fig 2.6b), while in Vietnam, its trend has fluctuated; decreasing 64.25% from 0.012 tons/USD in 1978 to 0.0043 tons/USD in 1994, then increased 84% to 0.07991 tons/USD in 2017. This shows that, despite some improvement, Vietnam remains highly material intensive as a whole and results in the lowest productivity.

Resource and material productivity are expressed as the economic output per unit of total DMC, an important indicator of computing economic contribution per unit of material consumed. For example, material productivity presented in Fig 2.6c shows that material productivity has increased 3.2; and 2.9 times in China and South Korea, respectively, while 1.5 times increased from 82.4 USD/ton to 125 USD/ton in Vietnam during that time. As of 2017, the material productivity of Korea and China is 14, and 2.3 times higher than that of Vietnam.

As per carbon intensity, ton CO_2 per capita has continuously increased 6.75 times in Vietnam during 1978-2017, as illustrated in Fig 9d, while South Korea and China rose 3.8 and 4.36 times, respectively, during that time. Though the increasing rates of the carbon intensity of South Korea and China are lower than Vietnam, those of South Korea and China were 11.66; and 6.69 tons CO_2 per capita, respectively, in 2017. Thus, they must strengthen climate countermeasures: circular economy, green growth, and sustainable development policy drive and its implementation. However, in Vietnam, the carbon intensity is very low, which is continuously increasing. Therefore, Vietnam is highly recommended to make a transition towards low-carbon economic growth by significant improvement in energy efficiency and emission intensity with national energy mix restructuring (Huong et al., 2020).

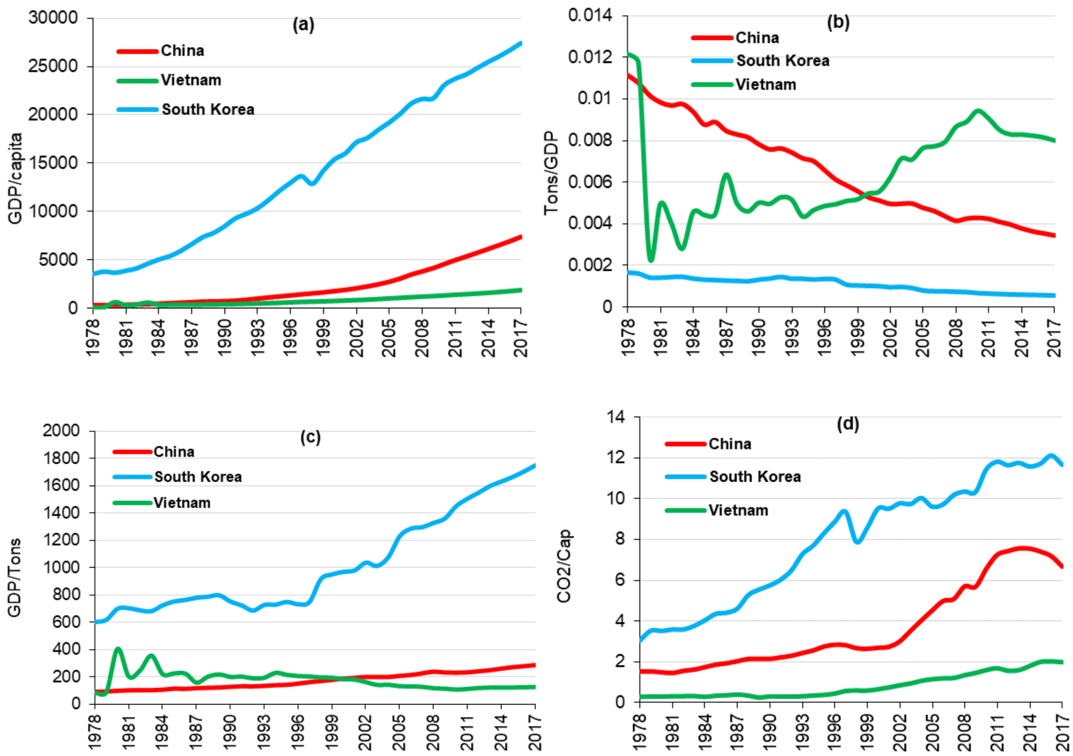


Figure 2.6. Characteristics of economic growth, resource consumption and emissions in Vietnam, China, and South Korea during 1978-2017. (GDP is in constant dollar prices of 2010). (a) Economic growth (GDP/capita); (b) Resource intensity (DMC/GDP); (c) Resource productivity (GDP/DMC), and (d) environmental impacts (CO_2 emissions/capita).

In summary, intensity and efficiency trends confirm that resource consumption and economic development patterns are different based on country situations such as resource condition, economic development stage, industrial structure, and the position in the global supply chains (Daniels and Moore, 2002). Thus, country-specific MFA is essential to draw critical policies insights on sustainable resource management for the target country (Schandl and West, 2012; Wang et al., 2012).

2.4.5. Coupling trends and drivers of resource consumption

With the material intensity and economic indicators calculated from MFA, the Environmental Kuznets Curve approach analyzed decoupling trends. As shown in Fig 2.7, Vietnam and China had been in the surging upswing stage, both GDP per capita and resource consumption, being in the first half of the inverse "U" curve and presenting a strong coupling trend between DMC per capita and economic growth during last 4 decades. However, South Korea reached the EKC inversion point with a per capita GDP of ~ 20,000 USD/capita in 2007. Those OECD countries clearly show the decoupling of material intensity from economic growth. These results clearly show that China and Vietnam need to strengthen resource efficiency, green growth, and circular economy policy and implement strong actions to enhance the material intensity and material productivity. Although Vietnam is still far behind in reaching the EKC inversion point, considering the contribution of a technical factor on material consumption, they are strongly recommended to strengthen technical innovation (negative driver) customized to local conditions to decouple resource consumption from economic growth.

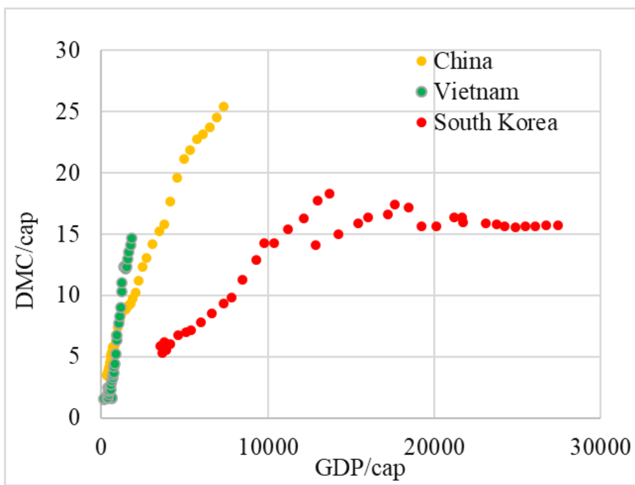


Figure 2.7. EKC curve of Vietnam in comparison with South Korea and China during 1978-2017.

After this phase, Vietnam has returned to stable economic, social, and political status. It is easily observed through three factors' contributions in Table 2. The next stage (1988-1998) shows that a significant setback in technology (6.48 %) has resulted in a loss of control over resource use reduction. At the same time, the economy decreased significantly (69.53 %) in a period of global hardship due to the economic crisis of 1998 [60]. The economic recovery in the following periods shows that the influence of economic development always has a direct impact on material consumption (Table 2.3). Since Vietnam's GDP has grown at a relatively stable growth rate in 2008-2017, ΔDMC were 238.79 and 269.3 during 2008-2013, 2013-2017, respectively. Affluence and population also contribute to the increase of DMC in these periods. This DMC are essential for the expansion of transport infrastructure, industries, business, and household buildings resulted from rapid urbanization and industrialization.

Table 2.3. Driver factors of material consumption in Vietnam under intervals.

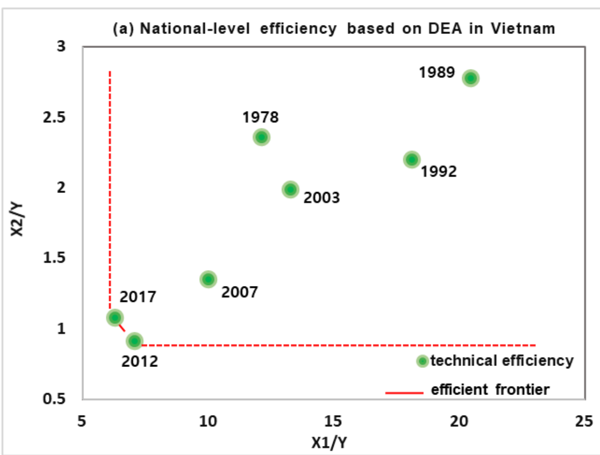
Change in impact (DMC)		Change in impact (DMC)			Attribution to drivers using log transform			
1978–1988								
	ΔI %	ΔI (Mt)	ΔP	ΔA	ΔT	P	A	T
China	94%	3074.79	1052%	126%	-93%	369%	123%	-392%
South Korea	80%	174.61	14%	107%	-53%	120%	682%	-702%
Japan	6%	85.84	7%	44%	-31%	13%	74%	-76%
Vietnam	63%	50.19	26%	219%	-59%	46%	237%	-183%
1988–1998								
	ΔI %	ΔI (Mt)	ΔP	ΔA	ΔT	P	A	T
China	77%	4866.27	13%	122%	-29%	21%	140%	-61%
Korea	66%	258.24	10%	75%	-13%	19%	108%	-27%
Japan	0%	-5.68	3%	18%	-18%	-72%	22%	-27%
Vietnam	115%	148.39	20%	75%	2%	24%	73%	3%
1998–2008								
	ΔI %	ΔI (Mt)	ΔP	ΔA	ΔT	P	A	T
China	87%	9711.80	7%	147%	-29%	10%	145%	-55%
South Korea	23%	149.40	6%	68%	-54%	-29%	-260%	389%
Japan	-9%	-138.87	1%	9%	-18%	1%	8%	-17%
Vietnam	221%	614.78	11%	71%	70%	9%	46%	45%
2008–2013								
	ΔI %	ΔI (Mt)	ΔP	ΔA	ΔT	P	A	T
China	47.40%	9920.32	2%	50%	-4%	6%	105%	-12%
South Korea	-2.02%	-16.16	3%	15%	-25%	-23%	-114%	237%
Japan	-9.86%	-136.83	0%	2%	-12%	-2%	10%	-52%
Vietnam	26.75%	238.79	6%	26%	-4%	23%	96%	-19%
2013–2017								
	ΔI %	ΔI (Mt)	ΔP	ΔA	ΔT	P	A	T
China	14.08%	4344.92	2%	29%	-13%	16%	191%	-107%
South Korea	3.00%	23.52	2%	11%	-12%	-249%	-1237%	1586%
Japan	-8.68%	-108.55	-1%	5%	-12%	-2%	22%	-62%
Vietnam	23.80%	269.31	4%	23%	-4%	20%	97%	-17%
1978–2017 (Whole period)								
	ΔI %	ΔI (Mt)	ΔP	ΔA	ΔT	P	A	T
China	974%	31918.10	1350%	2292%	-97%	113%	134%	-146%
South Korea	269%	589.61	39%	675%	-88%	112%	691%	-703%
Japan	-21%	-304.09	10%	100%	-64%	3%	24%	-36%
Vietnam	1668%	1321.46	84%	1375%	-35%	21%	94%	-15%

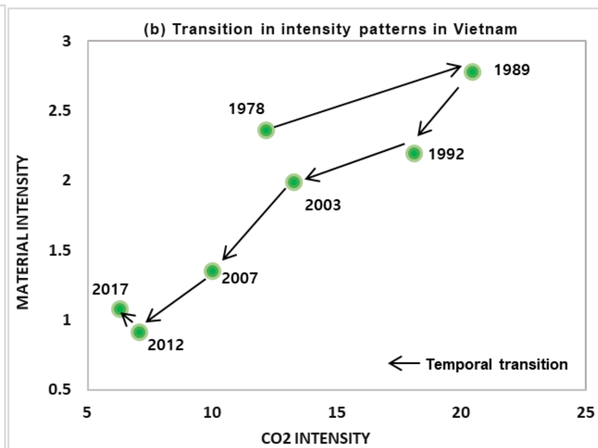
(*Where ΔP: Population; ΔA: Affluence; and ΔT: Technology factor*)

2.5. Transition material intensity in Vietnam and multiple countries.

Over the past decades, a comprehensive assessment of economic and environmental problems in Vietnam has been reported in numbers, not analyzed by effective mathematical methods with a wide range of inputs and outputs. Therefore, applying DEA analysis is an essential step in evaluation and monitoring. The results of the DEA – CRS input-oriented analysis for Vietnam from 1978-2017 are presented in Fig 2.8(a). Under the 7 temporal points selected, it indicates 2012 and 2017 were lied on the frontier curve, while most of the years presented the weakness in material consumption performance, or excessive GHG emissions occurred in the period. It shows the weakness in planning strategies and management for a long time, being affected to a greater degree on the environmental problem in Vietnam. However, it is worth noting that the distances between inefficient points and the optimal efficiency frontier (from 1978 to 2007) were relatively broad. There is no denial that resource consumption performance was inadequate with higher CO_2 emissions.

(a) (b)





(c)

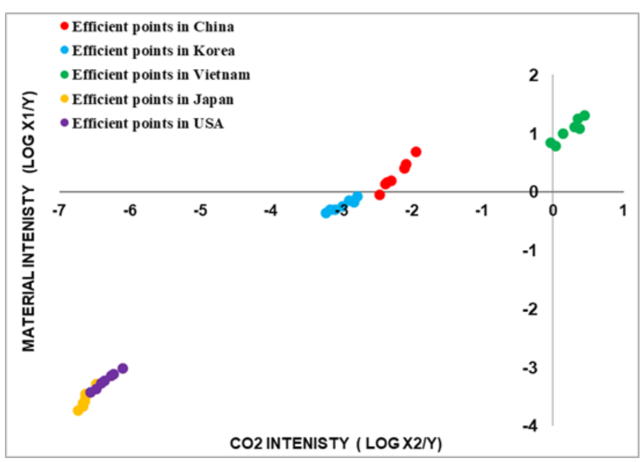


Figure 2.8. (a) National-level efficiency based on DEA analysis result in Vietnam (where: x1: domestic material consumption (Mt); x2: CO_2 emissions (Mt); y: GDP – billion USD constant price

2010); (b) Transition in intensity patterns and technical efficiencies in Vietnam; (c) Transition in intensity patterns and technical efficiencies in Vietnam and several top trade economies from 1978 - 2017 (China, South Korea, Japan, and USA) under logarithmic scale.

The relationship between carbon intensity and material intensity was highlighted in Fig 2.8(b) in relation to technical efficiency in Vietnam. The overarching trends were reported with a drop to low of material intensity from 1978 to 2017. Besides, CO_2 intensity was also significantly plummeted during the period. Repeatedly, industrialization and economic transition (GDP average growth was around 6.4% over the last 20 years from 1997 to 2017) ("The Future of ASEAN:," n.d.) in Vietnam have played a key role in improving both indicators. On the other hand, shifting Vietnam's economy became open, market oriented-global, diverse property, encouraged with simulated private and individual organizations growth, accelerated foreign investments. Especially, administrative reform and innovation in manufacturing with reinforce in management, these upraised and overcame backward poverty in the country (Bui Tat Thang, 2000). On the other hand, technical efficiency values have improved in recent years. It is consistent with the technology factor that has contributed significantly to the improvement of raw material consumption in Vietnam (-131% in the period 2008-2013 and -23% for the whole period 1990-2017). However, the conversion process is still unsatisfactory, with high raw material intensity and low resource productivity during the study period.

Comparison of the transition between Vietnam and some typical countries (fast-growing country: China; primary developed country: South Korea; and mature developed countries: Japan and USA) (Dong et al., 2017) was presented in Fig 2.8(c) under the logarithmic scale. Overall, from 1978-2017, the intensity of materials consumption and carbon emissions per GDP has tended to decrease markedly in the studied countries.

Three levels of transition are clearly constituted, which quite corresponds to the economic development levels of the five countries compared (Fig 2.8c). Japan and USA are far ahead of the other three in technical efficiency. This is entirely consistent with EKC results - early economic transformation leading to a sustainable development trend was also recognized early. The CO_2 and DMC per capita indicators were recorded to a negligible extent. Meanwhile, South Korea and China are recorded at the average conversion level (in terms of both time and value). Korea still shows as a country that achieves high efficiency over 63.6% and 48% reducing these indicator values (compared between 1978 and 2017), respectively - along with a very close year-to-year gap. A good signal for sustainable economic development for this country. It indicates that technological innovation, economic potential, and reasonable policies have remarkably contributed to a decelerating environmental problem and lifting the economic transition in South Korea in over 3 decades. From a policy viewpoint, South Korea has greatly implemented and utilized its strong points and efficiency in resource management, also mitigated the effects of materialization and carbonization.

China has emerged as a recent phenomenon, not only in terms of rapid urbanization and economic development in a short period, but also recognized for its bold strategies in solving the problem of resource shortage. China has emerged as the "World factory" and large importer and exporter (Sakr et al., 2011). In detail, 68.8% and 81.7% of the material and CO_2 intensity change in China from 1978 to 2017. Although China has performed less efficient economy compared with best performers (such as the United Kingdom, France, Italy, Germany, and Spain), the country has renovated expressly to decrease its material intensity and carbon intensity during 1971-2015 (Shah and Park, 2020). Especially, starting from 2003 to 2017, these indexes have quickly narrowed down the distances.

For Vietnam, its index value is the highest among the five countries selected in the section (Fig 2.8(c)). Therefore, it is classified as the slow transition. In 1978-1989 and 2012-2017, the efficiency trend over time tended to be negative (Fig 2.8b). Therefore, the country needs to remind and adjust related policies and management strategies for the near future. However, the overall transition picture shows a better way of improving economic transition in the country with reductions in material and CO_2 intensity exceeding 48% and 54% between 1978 and 2017, respectively.

Basically, Vietnam has not been able to close the gap with these two countries gradually. However, this country is also gradually improving the situation in the process of economic transformation. Based on the development path of China and Korea, some lessons can be considered as some orientations for Vietnam such as: firstly, gradually apply developed technologies with renewable energy and innovation-promoting capabilities into industrial activities and institutions, and at the same time provide financial support for technology acquisition and dissemination with synchronous way. Secondly, the upgrading of human resources and training should be focused on. Ultimately, thinking for long-term development, as well as building a sound institutional framework with sustainability, are key roles in promoting development.

2.6. Policy perspectives and future recommendations

Before 1980, Vietnam paid little attention to the provisions, programs, and policies of environmentally friendly and resource-saving development. Because the country's situation was not completely stable after long brutal wars. Back in 1986, Vietnam began to have a historic turning point in economic development and socio-political improvement, through a policy called “Doi Moi” (standard translation: Đổi mới) (Revilla Diez, 2016) by encouraging investors to invest and produce to serve the immediate needs, then contribute to the accumulation and improvement of the national face. In particular, the mechanism to open the economy to the world is one of the main factors to promote the economy and at the same time restructure the state economy. It has brought about many significant changes, such as: leading to an annual GDP per capita growth rate of 5.6% in the period 1986-2014 while achieving an average annual GDP growth rate. Around 8% in 1990-1997. It has made this country being one of the most developed countries, attracting foreign investment during that time (Hoang et al., 2017; Largo, 2002).

Moreover, the United States' economic sanctions were officially lifted in 1994, opening the way for Vietnam to develop in the following years with a constant growth rate (Fig 2.9). Besides, the impact of the Asian financial crisis in 1997 was significantly less in Vietnam than in other countries. Meanwhile, most countries with great economic potential have slowed down or partially declined during this challenging period. The country remained resilient even during the global economic downturn from 2000 to 2010, with a high GDP growth rate of 7% per year.

Vietnam's industrial sectors mainly comprised manufacturing plants, technology-based products, and petroleum fuels industries by this time. From 2008 onwards, several green industry developments and cleaner production programs have been initiated by Vietnam’s government, including the industrial park development plan and cleaner production and resource efficiency program. Although resource conservation programs and sustainable development policies launched during 2011-2017 have helped improve the national economy, the apparent cost seems to be amplified resource intensity. By 2030, Vietnam plans to make a concrete foundation for sustainable and efficient growth. The strategy approaches in protecting and preserving natural resources, improving the status of the environment, making energy and material use efficiently, as well as adapting to the global climate change. The scenario follows international trends and meets the commitments signed by Vietnam and many countries. They are firstly, cutting down emissions to the air while meeting the growing demand for energy in the context of the higher urbanization rate. In addition, solving land degradation while modernizing agriculture, forestry, and fisheries, which also plays an important task. However, a big concern about chronological programs that have not yet bent over backward to rise resource and environmental status in this country for a while. On the other hand, overlapped and vicious strategies maintaining that are proportionate with technological factors behind the times. It is also a weakness for development due to the overlapping and vicious programs these have not yielded adequate results. Furthermore, future strategies have not yet been built on a scientific basis, such as evaluation and heuristic models (ecological assessment tools: material flow analysis; analytical hierarchy analysis; optimization model; life cycle assessment; etc.) to provide realistic and feasible plans.

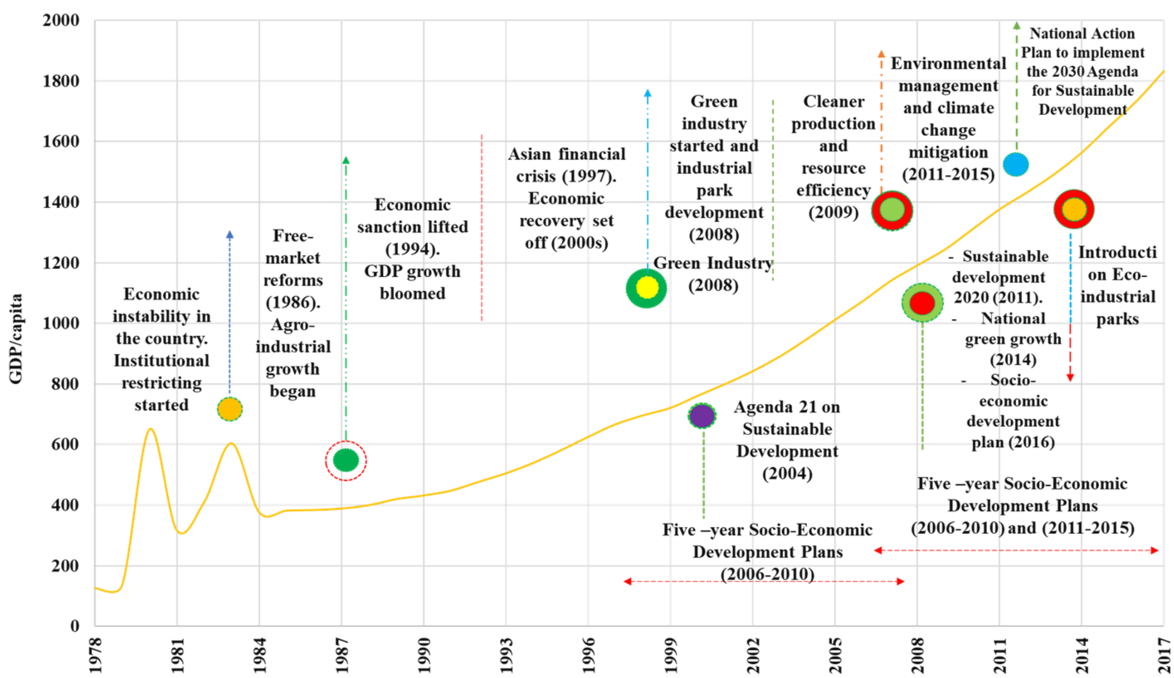


Figure 2.9. Economic and environmental policy development in Vietnam during 1978-2017.

2.7. Conclusion

The material flows in Vietnam along with its indicators over a span of four decades have been displayed, reflecting the reciprocal relationship between material consumption and environmental impact. Through the input and output indicators of the MFA analysis, the consumption of raw materials has increased rapidly. It has led to an imbalance in import and export in Vietnam, and a resource deficit is alarming soon. Besides, affluence and technological factors have significantly promoted the dynamic resource transformation in the country. In recent years, technological progress has contributed significantly to improving the problem of material consumption and bringing higher benefits to the product. On the other hand, through the Malmquist-DEA efficiency index, Vietnam has made strides in improving the value of natural resources, along with controlling environmental issues at a stable level. Although the trend has not been able to catch up with the rest of the countries, it has also recorded the efforts of this economy over the past time. Therefore, Vietnam needs to continuously follow the trends of countries that have been on the right track in sustainable development, such as Japan and South Korea. In addition, policymaking and programs towards sustainable natural resource consumption based on reducing the material intensity and increasing resource productivity should be considered, evaluated, and forecasted its performance before its application. Vietnam should early adjust and tighten development policies while reducing the burden on reserve resources.

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Chapter 3

Carbonization of Vietnam's economy: Decomposing the drivers for low-carbon growth[2]

Abstract

Vietnam is facing enormous decarbonization pressure from rapid urbanization, economic and industrial growth rely on fossil fuels. Therefore, this research aims to analyze the key factors contributing to carbon emissions between 1990 and 2016 using the expanded IPAT/Kaya framework and logarithmic index (LMDI) method. The carbon emissions impacts were decomposed to population affluence, energy intensity, fuel mix, and emission intensity factor. As per the results, CO_2 emissions during 1990-2016 were mainly driven by the affluence of higher income levels (58.5%) and changing fuel mix (33.2%) that have resulted from enhanced living standards and growing fossil fuel consumption. However, the population (13.8%) and emission intensity (3.1%) exhibit a relatively lower impact on CO_2 emissions. Interestingly, the energy intensity factor has prevented emissions from rising to a certain extent with (-8.7%) – indicating the ratio between domestic energy consumption and GDP. Based on the analysis of energy policy development, the share of renewable energy consumption was still relatively low in the national energy mix (higher reliance observed on non-renewable fossil fuel resources). Therefore, to make a transition towards low-carbon economic growth, significant improvements in energy efficiency and emission intensity are necessary, together with national energy mix restructuring for low-carbon economic growth. Through insight, the policy and country's context indicates that the equitization of the energy sector and technological innovation along with promoting investment in renewable energy is an essential element for sustainable development.

Key words: Carbon emissions, Decarbonization, Decomposition analysis, IPAT identity, Kaya identity, Sustainable economic growth, Vietnam.

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3.1. Introduction

Changes in carbon dioxide (CO_2) levels are affected by population growth, economic activity, technological advances and the carbon cycle itself (Liu et al., 2019). Although natural ecosystems are resilient and slowly adapt to environmental change, however, an industrial revolution based on the extensive consumption of fossil fuels has caused irreversible environmental damage (Wood and Roelich, 2019). The existing global socioeconomic model has thus led to a rapid rise in CO_2 levels, has interrupted the global carbon cycle, and led to global warming effects (Conard, 2013; Shah and Zeeshan, 2016). In response to rising carbon levels, global actions through the United Nations Framework Convention on Climate change (UNFCCC), Kyoto Protocol, and the Paris Agreement have been implemented in Vietnam by setting-up several national emission reduction targets. However, as with most developing countries, Vietnam has been unable to fulfill its carbon mitigation commitments for several reasons. Firstly, Vietnam's economy is in transition by itself and is among the fastest-growing regional economies. Table 1 presents some essential socioeconomic statistics for Vietnam. Secondly, Vietnam has developed a strong export-oriented industry for trade with global markets, leading to higher consumption of energy resources by the industrial and agricultural sectors. Thirdly, technological advancement in the country has not been at par with other regional economies such as Japan and Korea – leading to the inefficient use of energy resources and consequently higher atmospheric emissions per unit generation of gross domestic product (GDP). More recently, Vietnam's foreign trade has greatly expanded thanks to important regional trade deals such as the Free Trade Agreement (2015), which provides free market access to the European Union and other developed countries. This, in return, is expected to facilitate the expansion of energy-intensive and export-oriented industries and, therefore, higher energy use and their corresponding emissions.

Table 3.1. General socioeconomic statistics for Vietnam during 1990-2016

(Source: World Bank 2019)

Year	1990	1995	2000	2005	2010	2016
Population (million)	67.99	74.91	79.91	83.83	87.97	93.64
GDP, billion USD [a]	29.46	43.70	61.15	85.35	115.93	164.11
GDP growth rate (%)	5.10	9.54	6.79	7.54	6.42	6.21

[a] **based on constant US dollar prices of 2010**

Fig 3.1 shows the total final consumption (TFC) by sector in Vietnam between 1990 and 2016. As shown (Fig.1), residential energy use was dominant in 1990, while in 2016, the industry became the major energy consumer in the country. As a whole, TFC increased nearly 3.8 times during the years 1990-2016, mainly attributable to the significant industrial expansion and rapid economic growth in Vietnam corresponding to this period (Tang et al., 2016). The picture of changing energy consumption denoted that after reformation and industrialization, Vietnam has reformed remarkably in economic structures, political strategies, and living standards. Furthermore, during this period, Vietnam has made great strides in economic development and expanded diplomacy with many countries worldwide, including the United States, China, South Korea, Japan, African countries (Tho, 2003). Participating in major regional playgrounds such as ASEAN in 1995, as well as participating as a member of the WTO (2007), have made positive changes in the past two decades of Vietnam (Perkins and Anh, 2009). However, this was also a period of significant volatility in the world economy such as the 2008 economic crisis. Therefore, 1990-2016 was a critical period for this country.

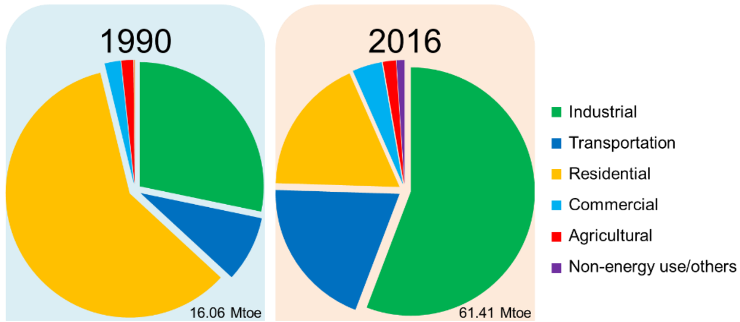

Figure 3.1. Sectoral total final consumption in Vietnam for 1990 and 2016 [source: EREA & DEA (2019)].

However, with the rapid economic development, the level of environmental degradation in the country cannot be avoided. In particular, the increase in emissions is driven by higher energy consumption due to the strong development of Vietnam's economy.

Fig 3.1 shows the emissions by sector, helping us understand the specific activities from which emissions. Since 1990, three prominent sectors have been the fastest-growing sources of greenhouse gas emissions. These comprise electricity and heat procedures (42.7% in total emission in 2016), industry (33.68% in the total emission in 2016), and 19.25% sharing by transport in 2016. Meanwhile, residential, commercial, and agriculture slightly contributed 4.3%, 2.67%, and 0.53% in 2016, respectively.

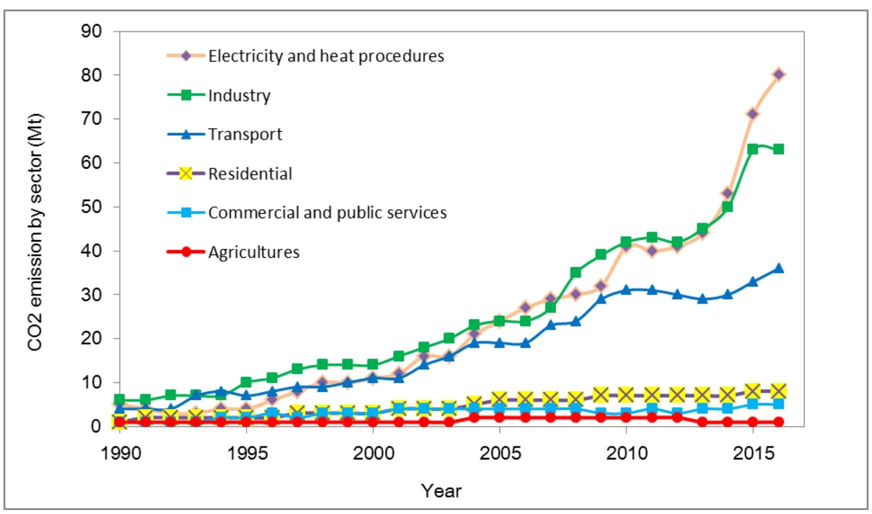

Figure 3.2. CO_2 emissions by sector in Vietnam during 1990-2016

Source: International Energy Agency

In Vietnam, fossil fuels now hold an overwhelming share in net energy supply. Thus, impact reduction through renewable energy resources seems highly favorable in this situation (Al-mulali et al., 2015). Nonetheless, there is scarce research in this area. Previously, there have been some studies on Vietnam that have used different approaches to analyze carbon emissions. For instance, Nguyen et al. (2018) used input-output structural analysis to decompose CO_2 emissions from a production-consumption perspective. However, as input-output tables are usually published after 5 years, the analysis did not cover individual annual transactions. In addition, emission intensity and fuel mix effect variables were also completely ignored. Another study (Thi and Anh, 2012) used structural decomposition of Kaya identity for the period 1986-2008. However, this study also ignored the impact of fuel mix on CO_2 emissions as significant changes in fuel mix have occurred especially during the 1990s and 2000s (Shem et al., 2019). Moreover, most previous studies have also overlooked the changing CO_2 emissions from a macro-policy and low-carbon economic development perspective.

This study investigates the different influencing factors on carbon emissions from 1990-2016 by using Kaya/IPAT identities with LMDI analysis. It explored the first relative time between effect size and its coefficient effect. Furthermore, the research has provided three novelties: Firstly, it overcomes all the limitations such as consideration to price effects, substitution, changing technology, or economies of scale. These disadvantages are always presented in other methods include the input-output model (Bureau et al., 2006). Secondly, the study period witnessed how shocked the Vietnamese economy was by major indoor and outdoor issues in the selection process such as financial crisis, trade, energy strategy, and policy. Thirdly, we track the history of research related to carbon emissions through previous studies, relevant strategies, and policies in the country. To understand the importance and model of the factors that affect CO_2 emissions in Vietnam. It is also important and necessary to indirectly predict future climate change to be a helpful document for government regulations and climate change policymakers. This analysis has implications for Vietnam's long-term equity and shares the burden of global responses to climate change. Furthermore, we aim to address some of the main purposes:

(1) We focus on analyzing the impact of Vietnamese energy consumption. This paper analyzes the mechanism of impact and decomposition of energy-related CO_2 emissions from 1990 to 2016 (the period after the reform and opening later, which is the Vietnamese government's plan to promote

industrialization and modernization). In addition, the rapid development of urbanization and domestic industrial activities promotes the nation's focus on long-term resource-efficient strategies.

(2) To analyze the changes in CO_2 emissions in the 1990-2016 periods by Kaya/IPAT identity with LMDI analysis, as well as identify the main factors driving CO_2 emissions out of the 5 factors (Population, affluence, energy intensity, substitution, and emission intensity) assessed in this study during the study period.

(3) Which variables can be targeted, from a policy perspective, for low-carbon economic growth in Vietnam as well as other emerging economies? The answers to these research questions are expected to bring forward important implications for emission reduction in many industrializing countries, including Vietnam. The focus is to provide a demarcated overview of carbon emissions and derive key policy implications to improve energy efficiency for a low-carbon and sustainable economic development in the context of emerging industrializing economies.

The rest of the paper is organized as follows: section 3.2 details the literature review adopted in this work, including the mathematical notations used. Results are presented in section 3.3, together with policy recommendations, study limitations, and the future scope of this work. Lastly, the main conclusions of this work are provided in section 3.4.

3.2. Literature review

Energy incidents and environmental problems originated in the 1970s when energy prices soared and evolved into an energy crisis. Therefore, researchers have been trying to help policymakers find effective solutions to reduce energy use by using decomposition analysis to isolate changes in energy consumption (Baffes et al., 2015). Many surveys and studies have been successfully indicated the importance of decomposition analysis, which is a facility to identify the driving factors in increasing GHG emissions. For instance, in early 1970-1990, Ang (Ang, 1995) and Zang (Li et al., 2015a) determined that energy consumption and energy intensity are major factors that impact GHG by applying decomposition analysis. Some common analyses are widely used in decomposition analysis, such as LMDI (Ang and Liu, 2001; Jeong and Kim, 2013; Jiang et al., 2019a; Ma and Cai, 2018; Sumabat et al., 2016). Economic growth, industrialization, and energy consumption are closely associated with carbon emissions, and many studies have focused on examining relative drivers of

CO_2 emissions with the help of mathematical tools (Shah et al., 2019). Popular methods such as the IPAT framework (impact on environment equals the product of population, affluence, and technology), and Kaya identity (an extended form of IPAT equation) have been widely applied for carbon emission assessments (Liu and Wang, 2017; Rafaj et al., 2014). In addition, the log mean Divisia index (LMDI) decomposition method has also been employed in combination with Kaya identity to decompose drivers of carbon emissions at different levels of analysis. For instance, several studies used the Kaya identity and LMDI approach to decompose CO_2 emissions at the national level, such as in the United States (Kaivo-oja et al., 2014), China (Li et al., 2015b; Wang et al., 2012; Zhang and Wang, 2014), Turkey (Tunc et al., 2009), and Mexico (Ozawa et al., 2002), etc., and larger regions such as the ASEAN (Chontanawat, 2019) and the G20 countries (Yao et al., 2015). The very same approach has also been adopted at the sectoral level (Wang et al., 2019a), such as in the chemical industries (Lin and Long, 2016), heavy industries (Boqiang and Liu, 2017), manufacturing sectors (Jeong and Kim, 2013), etc. International organizations, including the Intergovernmental Panel on Climate Change (IPCC), have been using Kaya identity-based approach extensively to determine driving forces behind greenhouse gas emissions (IPCC, 2014). Moreover, the existing scholarship in this area has confirmed the robustness of Kaya identity and LMDI framework at different levels of analysis (regional, national, and sectoral) and via incorporating a variety of variables (driving forces) such as energy intensity, economic affluence, energy mix, carbon intensity, population etc. (Mavromatidis et al., 2016). Furthermore, the flexibility of adding new variables through Kaya identity and LMDI approach is also large. For instance, variables such as industrial structure effect (Li et al., 2015b), fuel mix effect (Chontanawat, 2019), activity effect (Karmela et al., 2016), energy transformation effect (Kaivo-oja et al., 2014) etc. have been previously studied. Based on the literature review, it is evident that using a set of variables which affect CO_2 emissions can be beneficial to understand both its major and minor drivers so that targeted emission mitigation measures/strategies can be developed. Some populous methods such as IPCC method (IPCC, 2014), SIRPAT method (Fu et al., 2015; Zhang et al., 2017), variance analysis (Pani and Mukhopadhyay, 2013, 2011). Recently, new knowledge about the relationship between innovation and economic growth on CO_2 emissions has been interested in the field. Meanwhile, Mensah et al using the STIRPAT equation STIRPAT model for the OECD economics indicated that innovation prevented CO_2 emission (Mensah et al., 2018). In addition, one relevant study for BRICS economics was well done to show the impact of three factors (innovation, renewable energy consumption, income) on CO_2 emissions (Naseem et al., 2020). However, Kaya/IPAT analysis can examine various factors, as well as the method adopt for each region. Furthermore, the method basically collects major factors including population, affluence (economic growth), and technology (innovation). Besides, our study provides more driving factors related to energy consumption (the relationship between renewable energy and total primary energy consumption), emission intensity. These factors are comprehensive to draw country problems. In the case of Vietnam, limited comprehensive studies about decomposition CO_2 were carried out, as well as based on the country's history for development and global fluctuations, we chose a period (1990- 2016) is the study time. Based on previously established methodology (Chontanawat, 2019; Li et al., 2015b; Yao et al., 2015; Zhang and Wang, 2014), Kaya identity and LMDI approach was used to analyze and decompose drivers of CO_2 emissions in Vietnam during 1990-2016. The overall research framework is presented in Fig.3. At the first part, many bibliographic records were collected and analyzed (including official reports, national statistics, and global databases). The second section, we approached the method, which used for indexing strategies, as well as scientific technology for analysis. As shown, the extended IPAT equation (Kaya identification) is used as the basis of analysis in which the operating effect is analyzed for five different CO_2 change drivers by the index decomposition method. Part 3.4 analyzed bibliographic data using scientific techniques, and then showed specific results with some discussions. Part 3.5 were drawn conclusions and highlights the results of the carbon emission trend. In addition, it can be a lesson and reference in the mapped network for the field, also suggest areas for future research.

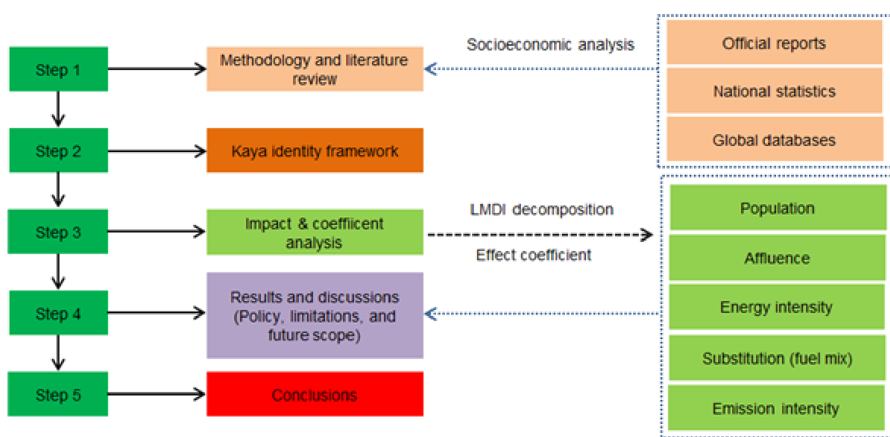

Figure 3.3. Research framework in this study.

3.3. Methodology

3.3.1. Energy-related CO_2 emissions estimation approach

The IPAT framework is widely known as the basic equation concern about the social impact of the environment (I) is associated with population size (P) combined with the way function (f) functions, formed by factors such as affluence (A) and available technology (T) (Ehrlich and Holdren, 1971). Mathematically, this relationship is written as Eq. (1):

$$I = P \times A \times T \qquad (1)$$

Similarly, Kaya identity – a modified/extended form of the IPAT equation – is often used to study carbon emissions related to energy resources (Nakicenovic and Swart, 2000). In this study, we have used the Kaya identity framework to calculate the environmental impact of energy consumption in Vietnam during 1990-2016, as given by Eq (2) to (4). The Kaya identity for analyzing carbon emissions from energy sources is often considered as a concrete form of IPAT (Kaya, 1989). The factors in Eq.(2) represent ratios that are part of the Kaya identity (Mavromatidis et al., 2016). These factors in Kaya identity [Eq.(2)] showcase the relationship between anthropogenic CO_2 emissions and its four major drivers (Ma and Cai, 2018). Moreover, these variables act as knobs; that is, lowering any one of them will reduce net carbon emissions and vice versa (Bunge, 2012).

$$\mathrm{C} = P \times A \times \frac{TPES}{GDP} \times \frac{CO_2}{FFC} \qquad (2)$$

When incorporating the fossil fuel consumption (FFC) per unit of TPES (substitution effect) at time "t" we get,

$$I_t = P_t \times A_t \times \frac{TPES_t}{GDP_t} \times \frac{co_{2t}}{FFC_t} \times \frac{FFC_t}{TPES_t} \qquad (3)$$

Or simply,

$$I_t = P_t \times A_t \times E_t \times C_t \times F_t \qquad (4)$$

In Eq.(1), "I" represents environmental impact in terms of CO_2 emissions measured in million tons (Mt), "P" represents the national population, "A" represents affluence in terms of GDP per capita measured in constant US dollar prices of 2005, and "T" represents technology. In Eq.(2) to (4), "P_t"

and "A_t" are population and affluence at the time "t" respectively, "E_t" represents energy intensity in terms of total primary energy supply (TPES) per unit of GDP measured in Mt per million USD, "F_t" represents fuel mix (substitution effect) in terms of fossil fuel consumption (FFC) per unit of TPES, and "C_t" represents emission intensity in terms of CO_2 emissions per unit of FFC. Though the first four variables are widely tested and are known to possess a high correlation with carbon emissions, a complimentary correlation analysis was also performed to examine the level of correlation between the selected variables and CO_2 emissions (details are given in the Appendix). All the five impact categories in Eq.(4) were used to analyze their relative impact on CO_2 emissions during 1990-2016. The addition of the fifth factor, i.e., fuel mix (substitution effect), was based on a literature review (Chontanawat, 2019; Kaivo-oja et al., 2014) and the rising role of fuel mix substitution in energy-related CO_2 emissions globally (O'Ryan et al., 2020). In the case of Vietnam, the fuel mix (substitution effect) becomes more significant as it has changed from 0.20 in 1990 to 0.45 in 2016 – indicating a significant shift towards fossil fuels in the national energy mix.

3.3.2. Decomposition and effect coefficient analysis

This study used the LMDI decomposition method to identify and analyze the impact of different driving forces on economy-wide CO_2 emissions from the start year "$t = 0$" to the end year "$t = 26$" using Eq.(5). Based on this assumption, we can say that changes in total impact at a given time "$\triangle I_t$" are equal to the multiplicative changes in five factors on the right side of Eq. (5), given as:

$$\triangle I_t = \triangle P_t + \triangle A_t + \triangle E_t + \triangle F_t + \triangle C_t \qquad (5)$$

Where "$\triangle P_t$" represents the population effect, "$\triangle A_t$" represents affluence (income) effect, "$\triangle E_t$" represents the energy intensity effect, "$\triangle F_t$" represents the fuel mix (substitution) effect, and "$\triangle C_t$" represents the emission intensity effect. Each of activity effect parameter was calculated using Eq. (6) to (10), respectively:

$$\Delta P_t = L(I_t, I_{t_0}) \times \ln\left(\frac{P_t}{P_{t_0}}\right) \qquad (6)$$

$$\Delta A_t = L(I_t, I_{t_0}) \times \ln\left(\frac{A_t}{A_{t_0}}\right) \qquad (7)$$

$$\Delta E_t = L(I_t, I_{t_0}) \times \ln\left(\frac{E_t}{E_{t_0}}\right) \tag{8}$$

$$\Delta F_t = L(I_t, I_{t_0}) \times \ln\left(\frac{F_t}{F_{t_0}}\right) \tag{9}$$

$$\Delta C_t = L(I_t, I_{t_0}) \times \ln\left(\frac{C_t}{C_{t_0}}\right) \tag{10}$$

Where

$$L(I_t, I_{t_0}) = \begin{cases} \frac{I_t - I_{t_0}}{\ln(I_t) - \ln(I_{t_0})} & ; \text{If } I_t \neq I_{t_0} \\ I_t & ; \text{If } I_t = I_{t_0} \end{cases} \tag{11}$$

Because of the lack of the LMDI model, which is applied to factor analysis based on existing references, is a mismatch with each impacting factor of the weighting algorithm, a lack of meaning of positive and negative effects, and the defects of the existing algorithm "Contribution rate" (Wu et al., 2016). This method can apply in cases where the total contribution value of each effect is negative even for the special case of 0. Important factors refer to the absolute value ratio of each effect contribution value to the total absolute value of each effect contribution, conversely. The greater the coefficient of significance (the maximum value is 1), the more it affects carbon emissions from the same factor; namely, the effect is clearer. The smaller the coefficient of significance (the minimum value is 0), the less the effect on carbon emissions from the same factor is; specifically, the weaker effect (Jiang et al., 2019b). Following the decomposition approach, we also used coefficient effect analysis to further study the changing impact of drivers of CO_2 emissions. The coefficient effect of each driving force (effect) was calculated using Eq. (12) (Li et al., 2015b).

$$e_P = \frac{\Delta P}{I_{Abs}}\ ;\ e_A = \frac{\Delta A}{I_{Abs}}\ ;\ e_E = \frac{\Delta E}{I_{Abs}}\ ;\ e_F = \frac{\Delta F}{I_{Abs}}\ ;\ e_C = \frac{\Delta C}{I_{Abs}} \tag{12}$$

Where, $I_{Abs} = |\triangle P| + |\triangle A| + |\triangle E| + |\triangle F| + |\triangle C|$

3.3.3. Data collection

Statistically, CO_2 emissions in Vietnam were acquired from the International Energy Agency (IEA) database (IEA, 2017) from 1990 till 2016. Some of the energy statistics were also acquired from national energy reports (EREA & DEA, 2019). Socioeconomic data, including population statistics, GDP values, and GDP growth rates, were acquired from the World Bank database (World Bank, 2019). For the policy analysis, publicly available policy documents and energy reports were accessed and analyzed.

3.4. Results and discussion

This section will discuss the main results of this work and highlight important policy recommendations and the scope of this work.

3.4.1. Kaya identity analysis

To begin with main components (effect categories) in Kaya identity, changes in population, affluence, energy intensity, fuel mix, and carbon intensity during the study period, are given in Fig.4. As given, population and income trends have increased rapidly during 1990-2016 while other factors such as energy intensity have reduced moderately. As per the statistical analysis for the period 1990-2016, the total population grew by 38.6%, while the per capita GDP grew by 301.8% – indicating significant economic prosperity achieved by Vietnam during this period. Interestingly, Vietnam's annual GDP growth rate (averaged for the entire study period) was 6.8% – one of the highest in the world (Thanh et al., 2019). With higher economic growth rates, Vietnam was able to rapidly develop urban and industrial infrastructures while uplifting living standards in the country. With technological advancement and foreign direct investments in the manufacturing and services sectors, energy intensity in the country also improved from 0.61 (toe per 1000 USD) in 1990 to 0.49 (toe per 1000 USD) in 2016 – a significant reduction of 18.6%. As the economy grew, this indicates that lesser energy inputs were required to produce an equivalent unit of GDP.

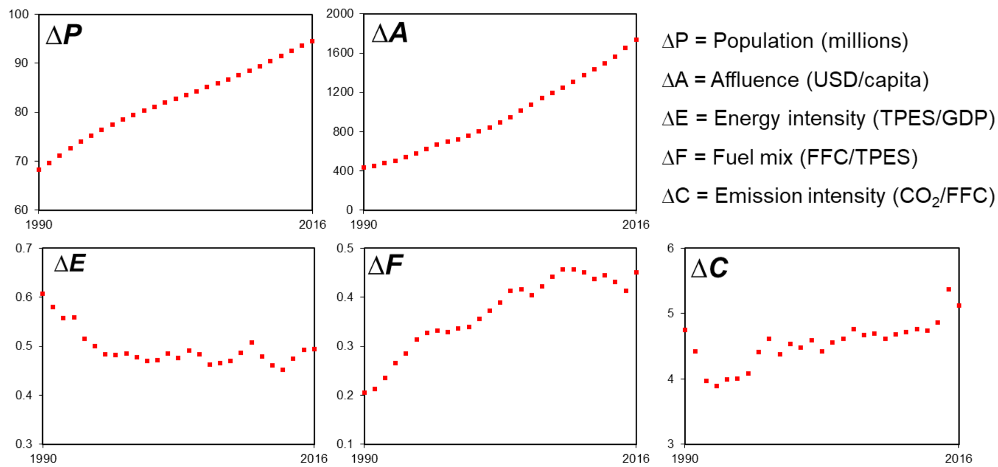

Figure 3.4. Changes in Kaya identity variables during 1990-2016.

At the same time, Vietnam's fuel mix increasingly became more dependent on fossil fuel resources, as illustrated by ΔF values (Fig 3.4). In 1990, fossil fuels had a share of 20.5% in TPES, while that in 2016 reached 45.1% – indicating both higher aggregate consumption and its relative share. The rising intensity of fuel mix has been observed with rising economic growth and industrialization – indicating rapid carbonization of the local economy. Similarly, emission intensity has also risen in Vietnam, as evident from rising energy consumption. From 1990 to 2016, emission intensity increased from 4.75 to 5.12 (Mt CO_2 per ktoe of fossil fuels), indicating higher emissions being released now. Vietnam's emission intensity was also found to be higher than most of the other Asian developing countries (Chontanawat, 2019). Factors affecting this rising emission intensity include: (1) changing industrial structure, (2) higher emission-intensive industries, (3) lack of non-fossil fuel resources such as biomass, wood etc., (4) inefficient use of fossil fuel resources, and (5) lack of high-efficiency energy conversion technologies such as power plants, industrial boilers, steam generators etc. Moreover, in the early 1990s saw a dip in emission intensity mainly attributable to the industrial restructuring efforts in Vietnam, whereas the years 2015-2016 have shown rising emission intensity as growth rates increased sharply in that period.

3.4.2. Decomposition analysis

The decomposition analysis helped uncover the critical drivers of CO_2 emissions in Vietnam from 1990 to 2016. Using shorter time intervals (five and six years), drivers of carbon emissions and their relative contributions are presented in Fig 3.5 (total effect for the entire study period is also given in the last column). As shown, during the first half of the 1990s, CO_2 emissions were driven mainly by fuel mix effect as rising economic growth was pushing for increasing FFC. This was followed by higher affluence which also greatly affected carbon emissions in the country. It is well known that rising household incomes and extravagant lifestyles cause a higher impact on carbon emissions (Cao et al., 2019; Zhang et al., 2020). The role of the population was less pronounced yet important enough to be considered in national-level policies. During the same period, improved energy intensity played a significant role in slowing down CO_2 emissions in Vietnam. This can be partly attributed to the trade openness since the 1990s that stimulated higher exports revenues and provided good economic returns to energy efficiency enhancement programs. However, this was the only period when emission intensity was reduced and prevented additional carbon emissions significantly.

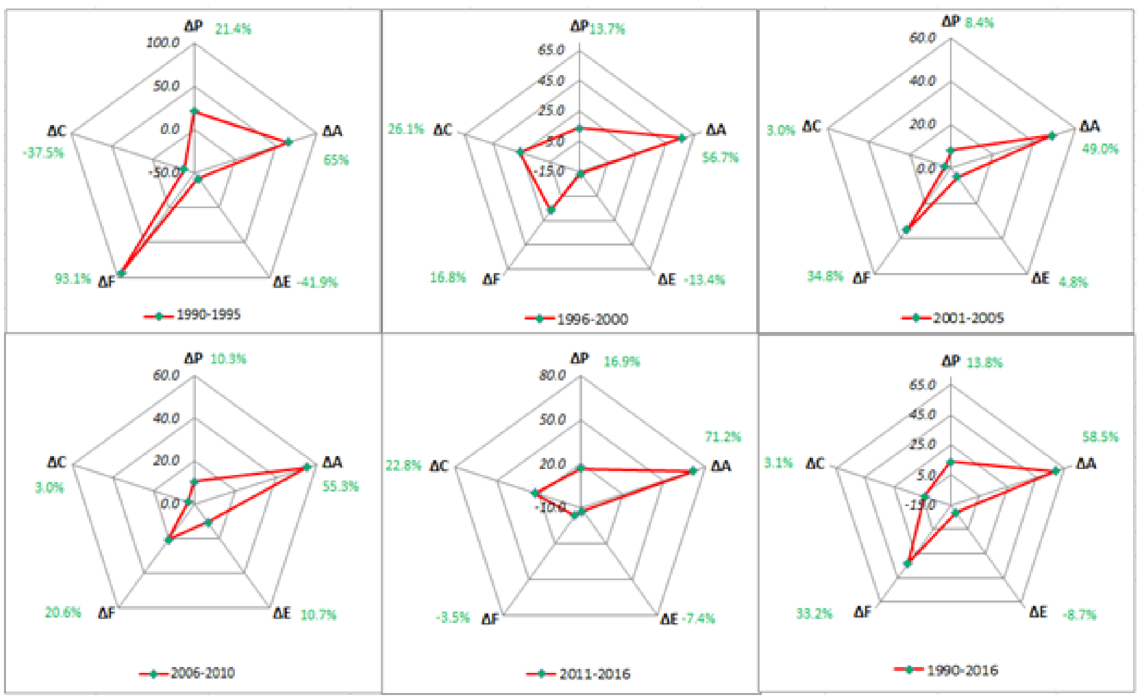

Figure 3.5. Decomposition results for Vietnam based on Kaya identity framework (unit: %) [Note: The first (1990-95) and last (2011-16) interval comprise of 6 years while the rest comprise of 5 years. Negative values indicate decreasing carbon emissions].

During the latter half of the 1990s, changing CO_2 was mainly driven by affluence while energy intensity improvements played a more minor role in mitigating carbon emissions. Similar outcomes have also been previously reported for Vietnam earlier (Thi and Anh, 2012). On the contrary, emission intensity saw a rising influence on CO_2 emissions from this point onwards. During 2001-2005, CO_2 emissions more than doubled from the previous period indicating rising carbonization of national economic development. In addition, all impact categories played a positive role in increasing net environmental impact. From 2006 to 2010 also saw a substantial increase in carbon emissions driven by all factors considered in this study. Thus, the 2001 to 2010 highly influenced increased CO_2 emissions in Vietnam, and no apparent effort on carbon emission mitigation was effective. This is usually the case with most developing countries as they prioritize economic growth over environmental quality, especially during the initial stages of industrialization (Haraguchi et al., 2019; Sadorsky, 2013). However, from 2011 to 2016, energy intensity which shows the energy inefficiency of an economy (measuring by units of energy per GDP), was improved, and the fuel mix effect represents the ratio between fossil fuels on total energy supply, it also improved to a certain degree – resulting in slowing down rising CO_2 emissions. During the entire study period, the major driver of CO_2 emissions was found to be affluence (promoting higher consumption patterns) followed by fuel mix effect (rising fossil fuel shares), population (higher resource demand per capita), and emission intensity (higher CO_2 emissions per unit of FFC). The only opposing driver of CO_2 emissions during 1990-2016 was energy intensity (more economic output per unit of TPES). Thus, based on this result, to promote low-carbon economic growth, variables other than population and affluence need to be focused on from a policy perspective.

3.4.3. Population effect and its coefficient

As shown in Fig.6, the population played a significant role in rising carbon emissions as both grew during 1990-2016. This indicates that future population growth and urban demographic patterns will directly push carbon emissions high. Moreover, the rising population also means higher rates of urbanization coupled with infrastructure, transportation, housing, and energy requirements – all leading to an ever-increasing consumption of energy resources. Results for population effect and its coefficient for CO_2 emissions in Vietnam during 1990-2016 have been shown in Fig 3.6.

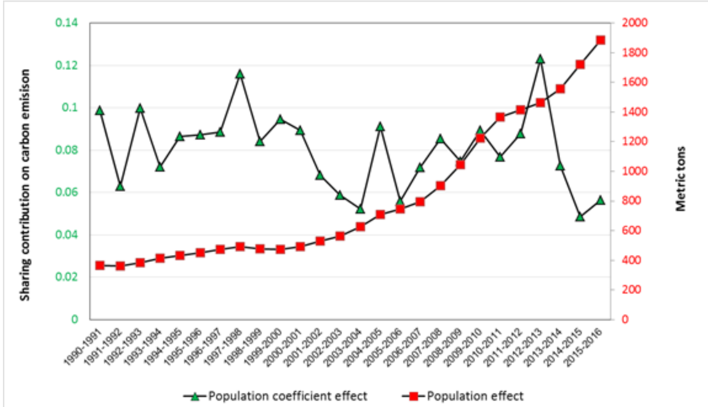

Figure 3.6. Population effect and its coefficient for CO2 emissions

As shown (Fig 3.6), the population effect was relatively stable before the early 2000s after which a rapid increase can be seen. During the same period, decreasing population effect coefficient values indicate that share of the population effect is somehow declining, and factors other than population are driving higher CO_2 emissions in Vietnam. For the entire study period, the population effect coefficient reduced from 0.10 in 1990 to 0.06 in 2016, indicating a significant drop in its overall impact share.

3.4.4 Affluence effect and its coefficient

The affluence effect is closely related to the standards of living and socioeconomic status of people living in a country. As Vietnam has made significant economic progress during the study period, its impact on carbon emissions has also amplified. With the fast growth in per capita GDP levels, higher consumption of finished goods, lavish lifestyles, and increased overall consumption have been witnessed in Vietnam. As given in Fig 3.5, rising affluence was the most vital driver of carbon emissions in the country during 1990-2016. Results for affluence effect and its coefficient for CO_2 emissions in Vietnam during 1990-2016 are presented in Fig 3.7.

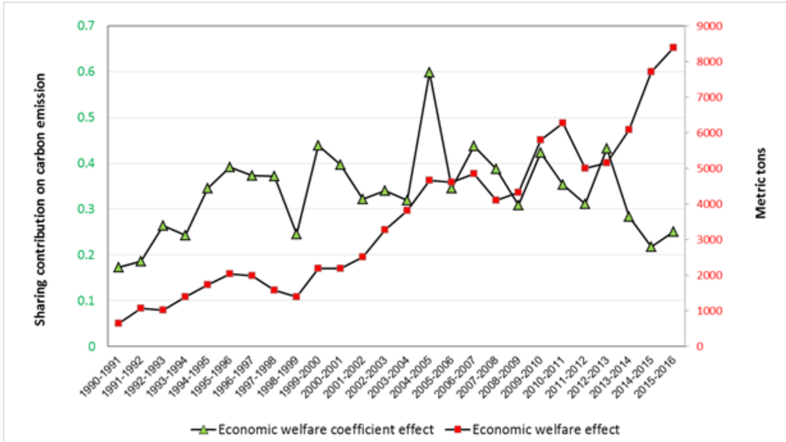

Figure 3.7. Affluence effect and its coefficient for CO2 emissions.

As shown (Fig 3.7), the affluence effect has continuously risen over the last few years. Especially since 1997, after the Asian economic crisis, the affluence effect increased significantly – indicating a higher impact of affluence on CO_2 emissions. However, the affluence effect coefficient has somehow reduced after 2004 – indicating its lower relative impact on net carbon emissions. For the entire study period, the affluence effect coefficient increased from 0.17 in 1990 to 0.25 in 2016, a significant rise in its overall impact share. This highlights that desirable economic prosperity will invite unwanted environmental implications along the way.

3.4.5. Energy intensity effect and its coefficient

In this study, energy intensity was represented by TPES per unit of GDP. This effect variable expresses the energy requirement of an economy with increasing values indicating higher energy price and cost of converting energy into GDP, conversely. Moreover, as energy intensity increases, it leads to industrial output, and this factor is considered as one of the most motivating factors to enhance industrial competitiveness and energy security. It can be the representative results from governmental efforts in reducing carbon emissions with higher energy efficiency and lower energy intensity (M and Miguel, 2020).

As given in Fig 3.5, energy intensity was the only opposing driver of carbon emissions in the country during much of the period, although it positively contributed to CO_2 emissions during 2001-

2010. Results for the energy intensity effect and its coefficient for CO_2 emissions in Vietnam during 1990-2016 are shown in Fig 3.8. Overall, in the whole study time, the energy intensity curve strongly fluctuated, it can explain by some of the impacts of major factors that come from energy prices, energy composition, technological changes (production, transportation, and other consumption sectors), and industrial structure (based on the ratio of the output of small units to larger units, import of components, components, and finished products and other similar elements) and final demand structure (segments different segments of the economy, such as transportation, manufacturing, trade, etc.).

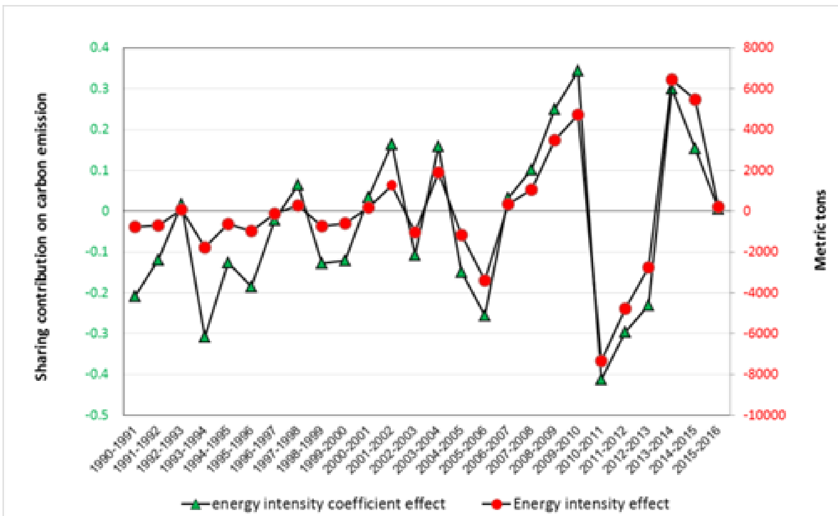

Figure 3.8. Energy intensity effect and its coefficient for CO_2 emissions.

As shown in Fig.8, the energy intensity effect has continuously fluctuated over the last few decades. From 1990-2000, although Vietnam's industry revolution process was strongly influenced by the development, it presented a lower energy intensity compared with the next stages. The major reason could be explained that was lower GDP and concentrated on growing agriculture, forestry, fishery, heavy-industry, and service. Significantly during 2006-2009 and 2010-2013, the energy intensity effect has increased significantly – although many efforts from Vietnamese government by promulgating a few energy-related policies to reduce emissions, as well as improve energy efficiency comprising the National Target Program on Energy Efficient (2006), for renewable energy was promoted by the National Energy Development Strategy (2007). However, it did not bring achievements (Urban et al., 2018) insignificantly.

Moreover, the energy intensity effect coefficient has been coincidental with the energy intensity effect – indicating its fluctuating relative impact on net carbon emissions. For the entire study period, the energy intensity effect coefficient increased from -0.21 in 1990 to 0.01 in 2016, a substantial change in its overall impact share. This shows that rising energy intensity in Vietnam has become a crucial driver for carbon emissions and needs to be adequately addressed. Major factors affecting the rising role of energy intensity in Vietnam, such as old technology and poor energy management (Kanchana and Unesaki, 2014), are further aggravated by the lack of governmental interest in the growth of renewable energy resources.

3.4.6. Fuel mix effect and its coefficient

The fuel mix effect refers to the share of fossil fuels in TPES and is a critical factor in determining the changing impact of fossil fuels and non-fossil resources on carbon emissions. Vietnam has large coal reserves with an estimated energy content (heating value) of around 20-35 MJ/kg (Baruya, 2010; UNDP, 2012). Along with coal, petroleum fuels and natural gas are also important energy resources used in the country. However, the share of fossil fuels has been on the rise during the study period as suggested by the material flow statistics on domestic consumption of fossil fuels which increased from 6.8 Mt in 1990 to 74.7 Mt in 2016 – more than 10-folds increase (UNEP and IRP, 2020). As a result, also presented in Fig.6, the impact of the fuel mix effect has been second strongest to affluence effect on rising CO_2 emissions in Vietnam. Results for the fuel mix effect and its coefficient for CO_2 emissions in Vietnam during 1990-2016 are shown in Fig 3.9.

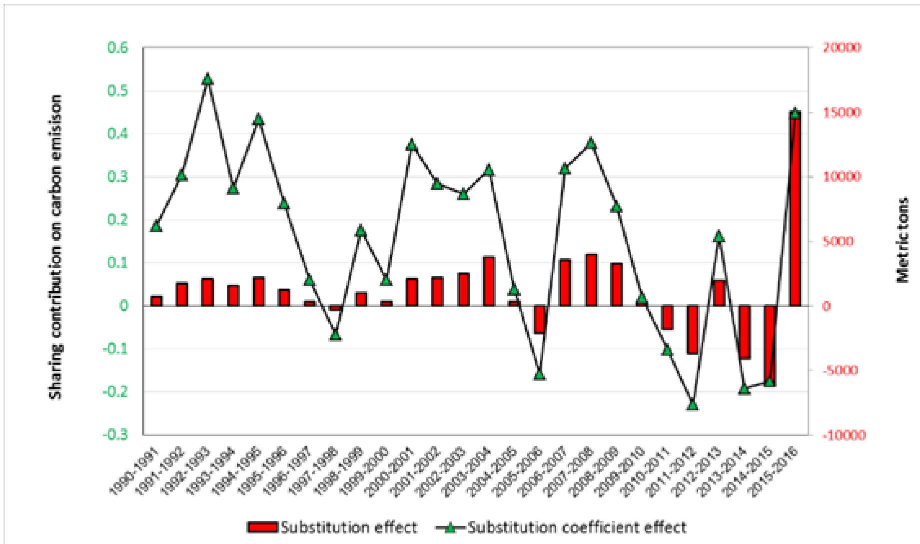

Figure 3.9. Fuel mix effect and its coefficient for CO_2 emissions.

As shown (Fig 3.9), the fuel mix effect has mostly fluctuated during the study period, with a peak appearing in the year 2016. This indicates that the fuel mix has been a uniform driver of carbon emissions in the country, and no structural change has occurred to minimize fuel mix effects. Although there have been periods when the fuel mix effect helped slow down CO2 emissions, its overall impact has been positive. The coefficient effect curve has reached its peak in 1992-1993 with an excess of 0.52. It denotes that fuel mix factor dramatically contributed to emissions at this stage. Because Vietnam officially and favorably opened the border at various northeastern provinces and received FDI and ODA from China to boost trade with attractive investments (Freeman and Thompson, 2014). It led to tremendously raising economic provinces. It was a major reason to consume more and more resources to catch the trade remarkably. On the other hand, it is extremely simulated to build further construction and relevant fields such as services and commercial activities (Van and Sam, 2008).

Also, the fuel mix effect coefficient has followed a similar trajectory as with the fuel mix effect – indicating a strong coupling of the two factors. During 1990-2016, the energy intensity effect coefficient increased from 0.19 to 0.45 – showing more than a doubled impact share. Interestingly, during 2012-2015, the share of contribution carbon emissions sharply dropped. The reason could come from the strong hit of governmental strategies by pushing industrial parks management to transform Eco-industrial parks on scaling up implementation throughout the country (Stucki et al., 2019). However, the trend could not maintain for a while. This highlights that increasing reliance on fossil resources in Vietnam has mainly been responsible for much of the carbon emissions, and its impact share may continue to grow unless adequate policy interventions are taken.

3.4.7. Emission intensity effect and its coefficient

Emission intensity effect refers to the emissions of CO_2 (tons) per unit of fossil fuels (toe) consumed and can talk about the changing economy-wide technological advancement. With the increasing demand for fossil fuels in Vietnam, CO_2 emissions per unit of fossil fuels consumed have increased from 4.75 in 1990 to 5.12 in 2016 – indicating higher emissions corresponding to the previous years. This can be partly attributed to the increased use of coal and petroleum fuels compared to natural gas and other renewable energy resources. Moreover, aging energy infrastructure and mobile emissions sources (transportation sector) also have a negative effect on emission intensity. As given in Fig.5, the impact of emission intensity on CO_2 emissions has been both negative during the early 1990s and positive during the rest of the period indicating its fluctuating nature. Results for emission intensity effect and its coefficient for CO_2 emissions in Vietnam during 1990-2016 are presented in Fig 3.10.

As shown (Fig 3.10), the emission intensity effect has significantly fluctuated during 1990-2016. Emission intensity impact was quite low during 1990-2016 (Fig 3.5), indicating its negligible effect on carbon emissions in Vietnam. This means that current emission intensity levels are neither beneficial nor harmful to affect CO_2 emissions on a large scale. However, attention must be paid tominimizing emission intensity through innovative structural changes. With increasing carbon emissions from fossil fuels, the emission intensity effect coefficient has changed from -0.33 in 1990 to -0.24 in 2016 – indicating a lower impact share from this variable.

3.5. Policy recommendations

Based on the results, some important implications can be drawn from a regional and global perspective. At the regional level, rising carbon emissions and poor air quality issues have pushed for several national-level policies in Vietnam such as the “Decree on Air Pollution Charge in Vietnam,” “National Energy Development Strategy,” “Vietnam National Energy Efficiency Program,” “National Climate Change Strategy,” “National Green Growth Strategy,” and “Law on Energy

Saving and Efficiency." Although quantifying the impacts of these policies goes beyond the scope of this study. However, ambitious emission mitigation targets are yet to be achieved, and sustained action for carbon emission mitigation is critically recommended. From a global perspective, as discussed in section 1.1, Vietnam's per capita GDP grew slower than that of China, but its per capita CO_2 emissions grew almost twice as fast as China – indicating Vietnam's carbon-intensive economic growth during 1990-2016.

Moreover, as opposed to industrialized economies, the carbonization of Vietnam's economy has followed a rapid growth trajectory, and no signs of decarbonization can be predicted with this trajectory insight. Besides, the core of energy industry development in Vietnam is acquired by state-owned corporations. They are a monopoly, thus inhibiting the development of the renewable energy industry. Destroying monopoly economies is the first step in this country. Besides, eliminating the thought of hindering the economic potential of taking strong measures in converting traditional energy into an economy based on renewable energy includes hydroelectricity and wind power, and solar power from the countryside to the city. This will be a green industrial revolution with great benefits and lasting effects. At the same time, it will also help the country to escape major problems of the severe shortage of fossil fuels soon. Secondly, instead of appeals and slogans, Vietnam needs to realize its concrete actions based on remarkable results. It is not wise to choose partners and investment sources from developed countries as a springboard for significant leaps. Thirdly, the focus on training and developing human resources for the green fuel industry has not been paid enough attention. This is reflected in the technological factor after decades of the industrial revolution in the country, which has yet to contribute significantly and the decline in greenhouse gases.

Based on the results of the LMDI analysis and the effect coefficient results, major policy recommendations can be made. From a demographic effect perspective, more efforts are needed to reduce the population's impact on carbon emissions in the country by taking steps such as public awareness of carbon footprints, green consumer purchases, change behaviors about energy saving and car aggregation, etc. Effective affluence plans, early carbon reduction plans that need to be planned include energy and resource-saving technologies, resource mitigation through waste pricing, conversion to renewable energy sources, and promoting an energy-saving culture among the affluent urban population. From the perspective of energy intensity effects, actions such as promoting energy-efficient production, increasing the added value of industries, implementing energy recovery programs, and sharing resources among Sector planning and transition to energy-saving and CO_2-saving economics is critical to low carbon economic development. From a fuel mix effect perspective, strategies include expanding renewable energy sources (such as photovoltaic, wind, bioenergy, etc.), waste to developing energy infrastructure, reducing fossil fuel use (through energy conservation, recovery, and greater efficiency), and gradual transition to energy-free industries can be very beneficial. From a carbon intensity perspective, policies such as promoting industry-level cleaner production technologies, improving inefficient energy infrastructure, increasing physical circulation in industrial ecosystems. Energy recovery of industrial waste in the form of industrial symbioses such as steam and excess heat) is also highly recommended.

3.6. Limitations and future scope

The lack of previous studies on Vietnam with similar approaches made it difficult to compare the outcomes of this research with published literature directly. We used index decomposition analysis due to its wider application from a methodological standpoint. However, the follow-up of this study can be undertaken by testing different decomposition approaches such as the structural decomposition analysis (SDA) and production-theory decomposition analysis (PDA) to assess the robustness of the results (e.g., robustness tests). In addition, other important variables such as the industry structure can also be included in future studies to assess its role in energy-based carbon emissions. The same is not applicable to Vietnam; thus, energy intensity will generally differ among developed and developing countries, and future studies can explore this.

Regarding data availability, sectoral data on energy consumption and carbon emissions is difficult to retrieve, especially in developing countries (lack of data collection, limited data access, low reliability etc.). Thus, alternate approaches such as material flow analysis and/or input-output tables can be explored to overcome this data limitation in the future. Overall, this paper has studied the factors that affect carbon emissions and has the current and future levels of influence on various factors, which are of great significance for low carbon development Vietnam. However, due to the limitations of the research experience and the various conditions, the following aspects need to be improved: firstly, the carbon emission factors need to be further improved. Many factors affect carbon emissions, and need to collect more accurate data for further analysis and discussion. Secondly, to predict the impact of each factor over the next few years, the data selected will remain minimal, and the predicted results may have some limitations. Accordingly, further research can make deeper and more accurate predictions based on index weights over many consecutive years. Furthermore, in future studies, we recommend analyzing the contribution of various influencing factors to other pollution such as SO_2 and NO_x energy growth-related air pollution in Vietnam and the lack of research using methods like those found in this work.

3.7. Discussion

When exploring the factors that influence energy consumption or carbon emissions, the decomposition of several methods has been widely concerned by scholars. Our study results are consistent with previous studies for the country. However, the input-output approach to decompose CO_2 in Vietnam briefly indicated a few parts about population growth and detailed material consumption on contributing CO_2 emissions by the Input-output approach (Nguyen et al., 2018). It lacks insight about technology represented for innovation and the relationship between renewable energy and total energy consumption. On the other hand, the ambiguous analysis of the role of policy in the research period has led to ineffective analysis.

Furthermore, publishing for the input-output tables is not updated every year, and it is one of the weaknesses of applying the method in evaluation. Another relevant study for Asian countries, including Vietnam, was briefly analyzed and superficially evaluated impacts of various factors in a long time study (Sandu et al., 2009). Instead of our study has worked on over two decades with insight of policy, as well as we make recommendations based on the analysis results along with the country's context. It can be a good reference for policymakers to recommend efficient strategies and policies in the upcoming future. Moreover, we have used the regression method (ANOVA) to evaluate the analysis results, which helps increase the reliability of the results. In addition, indicate the correlation between variables included in the study. Specifically, the square estimate of R^2 for regression models is high (R^2 = 0.9858), which is reasonable agreement with the adjusted R^2 of 0.9823 - the difference is less than 0.2. Besides, p-value is less than 0.05 (p-value = 8.766E-18) it is likely that the factors have significant effects on carbon emissions. As a result, our results are trustworthy.

3.8. Conclusion

In the efforts of rapid economic growth in the past decades, Vietnam has also suffered significant losses in the living environment. This is reflected in the results of the LMDI analysis, where economic development contributes more than half (58.5%) to the increase in greenhouse gas emissions, and a minority sharing of population growth contributed to the emission growth. Furthermore, followed by substitution factor was over a third (33.2%). A very small number (3.1%) of emission intensity is shared in rising CO_2. Interestingly, only the intensity energy shares a very small fraction (-8.7%) of its emissions reduction. Based on the results, Vietnam should focus on energy intensity and emission intensity to decline GHG emissions in the upcoming future. To be able to observe positive changes in energy intensity in a short time, Vietnam needs to take a step forward in strong measures to improve the efficiency of changing equipment associated with modern technologies to meet the application of clean energy in production and life. At the same time, to promote the use of renewable energy, it is necessary to increase the cost value of using fossil fuels. Because of the imbalance in the value of energy sources, the consumption balance focuses on excessive fossil fuels. However, this will face many difficulties in changing the inherent structure in production and daily life. Therefore, incentive policies and financial support from the state will be an essential foundation in this reform process.

In addition, looking at the current situation of Vietnam in the structure of the energy sector shows the constraint of energy sector development within state-owned corporations. Therefore, the dissolution or equitization of state-owned corporations will create opportunities for broadening the vision and restructuring of the energy sector. In addition, the country seems to be overloaded and overlapped among many ambitious strategies and policies with unreached targets for the green economy. Especially, a lack of association between government and expert, has led the ambiguous ways, also must be mentioned about their efforts in transforming and implementing renewable energies after over two decades – denoting that these energies still exist like a potential source. Furthermore, the equalization of large government companies is urgently needed, so bureaucracy and corruption are always a major concern in many countries. In the short-term, regulating fossil fuel prices and boosting investment and implementation of renewable energy in many key areas could be a temporary solution for developing countries. However, in the long-term, industrial symbiosis with the implementation of eco-industrial parks and enhanced service development may be a good way to reduce carbon emissions in the upcoming future. On the other hand, instead of becoming the second factory in the world, the country can think about setting up a comprehensive and synchronized system by leading development because Vietnamese tourism and services could be better thanks to its inherent geographical and landscape advantages with cultures.

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Chapter 4

Assessment of eco-efficiency transition in Vietnam by Malmquist data envelopment analysis approach during 1990-2017[3]

Abstract

The relationship between economic development accompanied by environmental friendliness and ecological balance is the top concern of the strategic planners of sustainable development in each country. Vietnam's eco-efficiency during 1990-2017 was investigated based on Tapio decoupling analysis. The outstanding results are as follows: since 2004 onwards, the changes have been recorded in the relationship between affluence and the environment - the ecosystem under the gradual diversity of degrees: expansive decoupling; weak decoupling; expansive coupling, and strong decoupling under Tapio decoupling analysis. At the same time, Malmquist data envelopment analysis indicates that Vietnam's productivity index has been improved and narrowed the gaps with eco-efficiency trend in multi-country. It is a good signal for transforming traditional industrial activities to eco-efficiency under a low-carbon goal. Therefore, the reform of management policy, scientific strategy, and updating of technology system should be considered and implemented synchronously to maintain this change and promote the development in a more positive direction.

Keywords: Vietnam; Eco-efficiency; Sustainable development; Tapio decoupling; Malmquist productivity index.

4.1. Introduction

Recently, developing countries have faced serious environmental issues and ecosystem degradation. Since many researchers have come up with ideas to measure the impacts of development and the environment. Therefore, ecological efficiency has been considered for sustainable development as a core strategy under the known-well "eco-efficiency" (Adb, 2013; Perkins and Anh, 2009). It has been shown in many studies at various fields and levels (Li, 2009; Pai et al., 2018;

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Thieriot and Sawyer, 2015). Its theory aims to create greater affluence (economic growth) under fewer resources and fewer effects on the ecosystem and reduce pollution. Hence, it is an important analytical tool in determining and investigating sustainable development (Gudipudi et al., 2018). In particular, the process of industrialization and urbanization is mainly accompanied by impacts on the environment. Since then, many regulations and emissions taxes have been officially enacted to balance the levers between affluence and environmental quality. In addition, this is also considered an important measure to evaluate the quality of governance (Sanjuan et al., 2011). In 1990, Technical Committee on environmental performance assessment and standardization of environmental management, Sub-Committee of the International Organization for Standardization were formally issued the international standard ISO 14031:1999 "Guidelines for Environmental Management—Environmental Performance Evaluation" and the technical report ISO/TR 14032:1999 "Environmental Management Examples of Environmental Performance Evaluations" as a basic framework for measuring eco-efficiency (Liang et al., 2018). It highlights the importance of eco-efficiency and pays attention to environmental protection. Meanwhile, developed countries pioneering sustainable development research have been working to improve the quality of life and ecosystems. In addition, they are using mathematical modeling approaches to observe and evaluate eco-efficiency performances.

In contrast, most developing countries have not concentrated much on the field, such as Vietnam, the country lacks studies about measuring eco-efficiency and sustainable development at the micro and macro levels. Vietnam is fast-growing country with an annual GDP/capita growth rate of around 11.6% during 1990-2017 (Fig 4.1a). However, it increased total final energy consumption by a 10.68% annual growth rate during the period, while the renewable share in total final energy consumption declined slightly by 2% (Fig 4.1c). On the other hand, economic development also brought the emission growth (CO_2 emission annual growth rate was over 39.5% during 1990-2017; 3.75% for nitrous emission; and 1.43% for methane, respectively) (Fig 4.1c). Since investigating the relationship between economic growth and environmental degradation in Vietnam is necessary. The study was chosen Tapio decoupling analysis and integrated with Malmquist data envelopment analysis (Malmquist DEA). Because Tapio decoupling analysis is flexible with eight categories according to values of economic and environmental degradation values. For Malmquist DEA, it is known as the standard approach to measure the efficiency of decision-making units overtime changes. In addition, it is calculated the productivity growth, which is relative to technological factors.

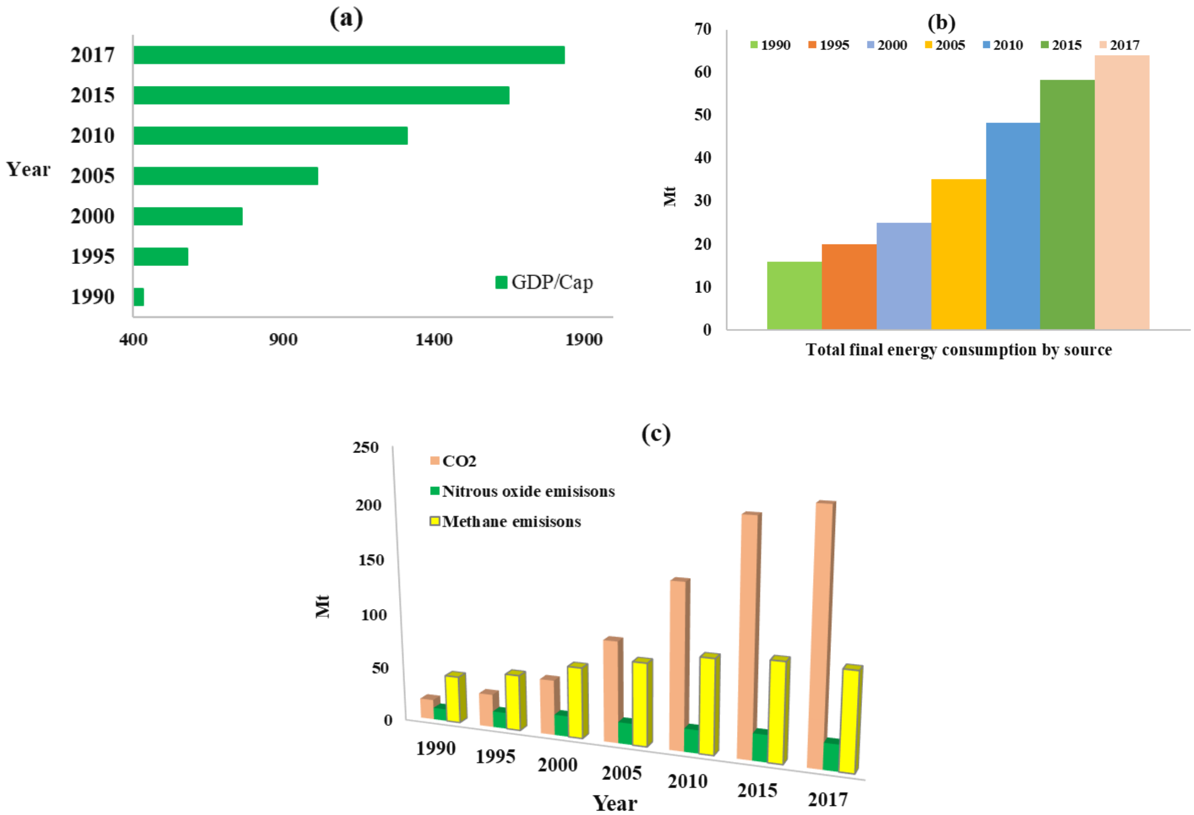


Figure 4.1. (a) Gross domestic product per capita (GDP per capita); (b) Total final energy consumption by source (Mt) and renewable share in total final energy consumption (%); (c) CO_2, nitrous, and methane emissions during 1990-2017 in Vietnam (Mt). {Note: GDP constant price in 2010}

4.2. Data and methodology

4.2.1. Data

The data for Vietnam during 1990-2017 is from the International Energy Agency (IEA) (Baruya, 2010; IEA, 2017) and World Bank Development Indicators (Development et al., 2013; The World Bank, 2018, 2017). Furthermore, the starting and ending points in the study were based on the available data in the country. Particularly, input indicators comprise: population (million), total final energy consumption by source (coal, natural gas, hydro, biofuels-waste, oil, wind, solar, etc in million tons); and renewable share in final energy consumption in percentage. For output indexes include the gross domestic product (GDP) per capita (USD constant price in 2010 per capita); total carbon emission (million tons); nitrous oxide emissions (thousand metric tons of CO_2 equivalent); and methane oxide emissions (thousand metric tons of CO_2 equivalent) during 1990-2017.

4.2.2. Methodology

4.2.2.1. Decoupling analysis

Based on the concept of elasticity, Tapio proposed Tapio decoupling analysis, and it reflects separation among variables and time frame under eight levels: recessive decoupling, recessive coupling, weak negative decoupling, strong negative decoupling, expansive negative decoupling, expansive coupling, weak decoupling, and strong decoupling (Fig 4.2). It was widely used to examine the relationship between economic development and environmental status (CO_2, SO_2 emissions) in China, Russia, Japan, and the United States (Wang et al., 2013). At provincial and city levels were also applied in Beijing and Shanghai (Wang et al., 2019b). Checking the decoupling between CO_2 emissions and transportation factors in Finland (Tapio, 2005). The relationship between urban construction land expansion and economic growth at Cheng-Yu economic zone (WEI, 2020), etc.… In the study, the decoupling method was proposed by Tapio, which was used to examine the link between environmental degradation and affluence (economic growth). In detail, the starting year is represented by subscript 0, and t represents the end of the period study; delta CO_2 (ΔCO_2) denotes the change of its emissions; similarly, delta nitrous and delta methane indicate the change of their emissions. Where n_1; n_2; and n_3 are emission's growth of CO_2, nitrous, and methane, their growth rates are similarly described as equation (1):

$$n_1 = \frac{\Delta CO_2}{CO_2^0} \qquad (1)$$

Similarly, nitrous and methane emissions; $n_2 = \frac{\Delta nitrous}{nitrous^0}$; $n_3 = \frac{\Delta methane}{methane^0}$

Delta GDP (gross domestic production) refers to the change of it. Its growth rate also can be measured by the following equation (2):

$$n_{GDP} = \frac{\Delta GDP}{GDP^0} \qquad (2)$$

The decoupling index (DI) is presented by the ratio of changing emissions and affluence. Precisely, it was calculated by the equation (3):

$$D_1 = \frac{n_1}{n_{GDP}}; \qquad D_2 = \frac{n_2}{n_{GDP}}; \qquad D_3 = \frac{n_3}{n_{GDP}} \qquad (3)$$

Assumption, the environmental degradation in the study, is presented by the total value of three gas emissions when the decoupling index is more precisely shown by:

$$DI = D_1 + D_2 + D_3$$

The specific cases in decoupling analysis are performed under the decoupling metrics (Fig 4.2).

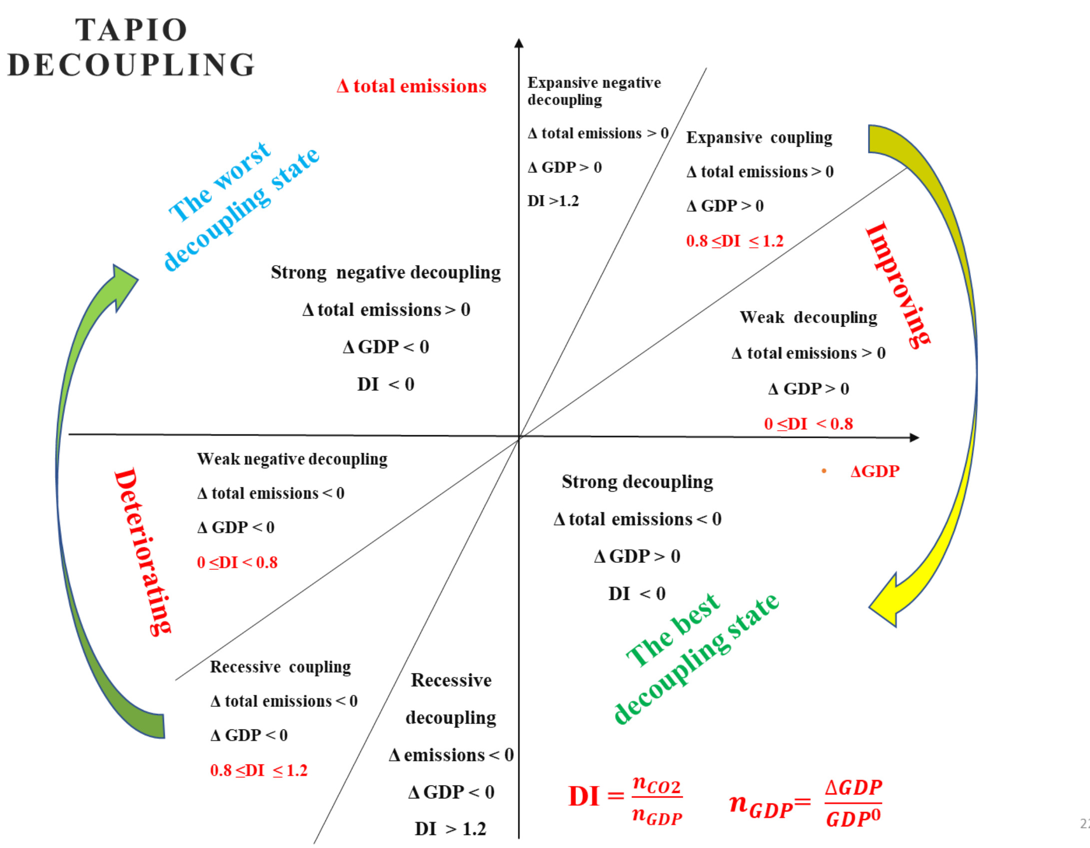


Figure 4.2. Decoupling metrics between affluence (economic growth) and environmental degradation.

4.2.2.2. Malmquist data envelopment analysis

Malmquist DEA, is a unique ability to measure the effectiveness of multiple inputs and outputs of decision-making units without prior weighting the inputs-outputs, as well as it seems to emerge with several advantages other productivity indexes (Candemir et al., 2011). Firstly, it does not impose standard parametric restrictions on the underlying technology (Li et al., 2020). Secondly, no assumptions about profits and prices need to provide in Malmquist DEA (Long et al., 2020). It is helpful for situations about misrepresenting or nonexistent prices. Especially, it is widely used in many fields because it shows the technical performance and its changes. Thus, insight into its results can aid references to sources of productivity variation (Lee et al., 2011; Zhang et al., 2021). Hence, the study aims to apply the method to investigate the eco-efficiency in Vietnam during 1990-2017. The Malmquist productivity index values were measured based on the input-orientated Malmquist DEA under the hypothesis of constant returns to scale.

Particularly, *x* and *y* are respectively represented input and output with *m* inputs and *n* outputs. At time t, input and output can be shown as:

$x^t = (x_1^t, x_2^t, x_3^t, \ \ldots x_m^t)$ x^t denotes the input of period t

$y^t = (y_1^t, y_2^t, y_3^t, \ \ldots x_n^t)$ y^t denotes the output of period t

the study comes up with the following DEA models for measuring four distance function values: $D_0^t(x_0^t, y_0^t)$; $D_0^t(x_0^{t+1}, y_0^{t+1})$; $D_0^{t+1}(x_0^{t+1}, y_0^{t+1})$; $D_0^{t+1}(x_0^t, y_0^t)$. They can be calculated as below (Candemir et al., 2011; Pathak, 2019):

Where, $D_0^t(x_0^t, y_0^t)$ = maximize θ (4)

Such that: $\sum_{j=1}^{s} \alpha_j x_{ij}^t \geq \ \theta x_{i0}^t$ $i = 1, 2, \ldots m$

$\sum_{j=1}^{s} \alpha_j y_{ij}^t \leq \ y_{k0}^t$ $k = 1, 2, \ldots n$

$\theta_j \geq 0,$ $j = 1, 2, \ldots s$

For $D_0^t(x_0^{t+1}, y_0^{t+1})$ = maximize θ (5)

$\sum_{j=1}^{s} \alpha_j x_{ij}^t \geq \ \theta x_{i0}^{t+1}$ $i = 1, 2, \ldots m$

$\sum_{j=1}^{s} \alpha_j y_{ij}^{t} \leq \; y_{k0}^{t+1}$ $\quad k = 1, 2, \dots n$

$\theta_{\mathrm{j}} \geq 0,$ $\quad j = 1, 2, \dots \mathrm{s}$

$$D_0^{t+1}(x_0^{t+1}, y_0^{t+1}) = \text{maximize } \theta \tag{6}$$

$\sum_{j=1}^{s} \alpha_j x_{ij}^{t+1} \geq \; \theta x_{i0}^{t+1}$ $\quad i = 1, 2, \dots m$

$\sum_{j=1}^{s} \alpha_j y_{ij}^{t+1} \leq \; y_{k0}^{t+1}$ $\quad k = 1, 2, \dots n$

$\theta_{\mathrm{j}} \geq 0,$ $\quad j = 1, 2, \dots \mathrm{s}$

The last distance function value: $D_0^{t+1}(x_0^{t}, y_0^{t})$ = maximize θ (7)

$\sum_{j=1}^{s} \alpha_j x_{ij}^{t+1} \geq \; \theta x_{i0}^{t}$ $\quad i = 1, 2, \dots m$

$\sum_{j=1}^{s} \alpha_j y_{ij}^{t+1} \leq \; y_{k0}^{t}$ $\quad k = 1, 2, \dots n$

$\theta_{\mathrm{j}} \geq 0,$ $\quad j = 1, 2, \dots \mathrm{s}$

The distance function values in equations (4) and (6) measure the efficiencies of decision-making units in time *t* and *t*+1. Similarly, equation (5) calculates the efficiency of DMU_0 over the interval time *t*+1 using the production technology of time t. On the other hand, equation (7) measures the effective value of DMU_0 at time t using the production technology at time *t*+1. The Malmquist productivity index (MPI) can be computed as the following equation (8) (Uddin, 2015; Zhou and Ang, 2008):

$$\mathrm{MPI} = \left[\frac{D_0^{t}(x_0^{t+1}, y_0^{t+1}) \times D_0^{t+1}(x_0^{t+1}, y_0^{t+1})}{D_0^{t}(x_0^{t}, y_0^{t}) \times D_0^{t+1}(x_0^{t}, y_0^{t})}\right]^{1/2} \tag{8}$$

$$\mathrm{MPI} = \frac{D_0^{t}(x_0^{t}, y_0^{t})}{D_0^{t+1}(x_0^{t}, y_0^{t})} \times \left[\frac{D_0^{t}(x_0^{t}, y_0^{t}) \times D_0^{t}(x_0^{t+1}, y_0^{t+1})}{D_0^{t+1}(x_0^{t}, y_0^{t}) \times D_0^{t+1}(x_0^{t+1}, y_0^{t+1})}\right]^{1/2}$$

Where, $\frac{D_0^{t}(x_0^{t}, y_0^{t})}{D_0^{t+1}(x_0^{t}, y_0^{t})}$ denotes efficiency change (EFFCH), while $\left[\frac{D_0^{t}(x_0^{t}, y_0^{t}) \times D_0^{t}(x_0^{t+1}, y_0^{t+1})}{D_0^{t+1}(x_0^{t}, y_0^{t}) \times D_0^{t+1}(x_0^{t+1}, y_0^{t+1})}\right]^{1/2}$ shows how to measure technical change (TECHCH) from time *t* to *t*+1.

While, EFFCH = PECH × SECH

Where PECH: Pure efficiency change and SECH: Scale efficiency change, these indicators are shown when EFFCH decomposes (Lee et al., 2011). Since MPI can be expressed by the following equation (8). Moreover, when we utilize the constant returns scale (CRS) and variable returns scale (VRS) in DEA frontiers to calculate the distance function in equation (8). The PECH and SECH can be found out under two equations (9) and (10):

$$\text{SECH} = \left[\frac{D_{VRS}^{t+1}(x^{t+1},y^{t+1})/D_{CRS}^{t+1}(x^{t+1},y^{t+1})}{H_{VRS}^{t+1}(x^{t},y^{t})H_{CRS}^{t+1}(x^{t},y^{t})} \times \frac{D_{VRS}^{t}(x^{t+1},y^{t+1})/D_{CRS}^{t}(x^{t+1},y^{t+1})}{D_{VRS}^{t}(x^{t},y^{t})/D_{CRS}^{t}(x^{t},y^{t})}\right]^{1/2} \quad (9)$$

$$\text{PECH} = \frac{D_{VRS}^{t+1}(x^{t+1},y^{t+1})}{D_{CRS}^{t}(x^{t},y^{t})} \quad (10)$$

4.3. Results

4.3.1. Decoupling result

Fig 4.4 and Table 4.1 show the emission growth and decoupling elasticity results of Vietnam from 1990 to 2017. Overall, economic growth is strongly affected by gas emission growth and decoupling index trends. On the other hand, there is a similar trend between increasing emissions and decoupling index curves. For CO_2 emission growth was significantly reduced during 1990-1991; 2010-2011; 2011-2012; and 2016-2017 (Fig 4.3a), while nitrous gas reduction was dramatically decreased from 2000-2001; 2007-2008; 200-2010; 2010-2011; 2013-2014, and 2016-2017 (Fig 3b). In contrast, methane emission growth only performed one stage with high reduction (1992-1993) (Fig 3c).

Expansive negative decoupling occurred during most of time from 1990-2000; 2001-2004; 2006-2007; 2008-2009; 2012-2013; and 2014-2015. It notes that GDP and emissions increased. However, emissions grow faster than economic growth. The maximum emission growth was reported over 43.4% during 2008-2009, meanwhile, economic growth rose around 4 to 8% (Table 4.1).

At expansive coupling (2005-2006; 2009-2010; and 2011-2012, affluence and emission growth accelerate simultaneously – it is not an ideal state. The economic growth model has shifted from expansion to in-depth development, but changing the economic growth mode can only gradually reduce a small part of CO_2 emissions. Economic growth does not eliminate the increase in energy consumption and CO_2 emissions, and it does not achieve the transition to a segregated state.

Weak decoupling was determined during 2000-2001, 2013-2014, and 2015-2016, which means that economic growth shifts from relying on increased energy–material consumption to improve its efficiency. When the effect of energy consumption on affluence is weaker until it reaches a certain extent, affluence can be decoupled from emissions. It only happens when the country performs robust solutions continuously.

Strong decoupling presents from 2010-2011 and 2016-2017, and these stages show that economic growth increases with more efficient use of energy consumption and positive reflection from reasonable strategies and policies. Energy consumption and emission growth decrease with very small numbers, reaching the ideal state of less energy consumption and more economic growth.

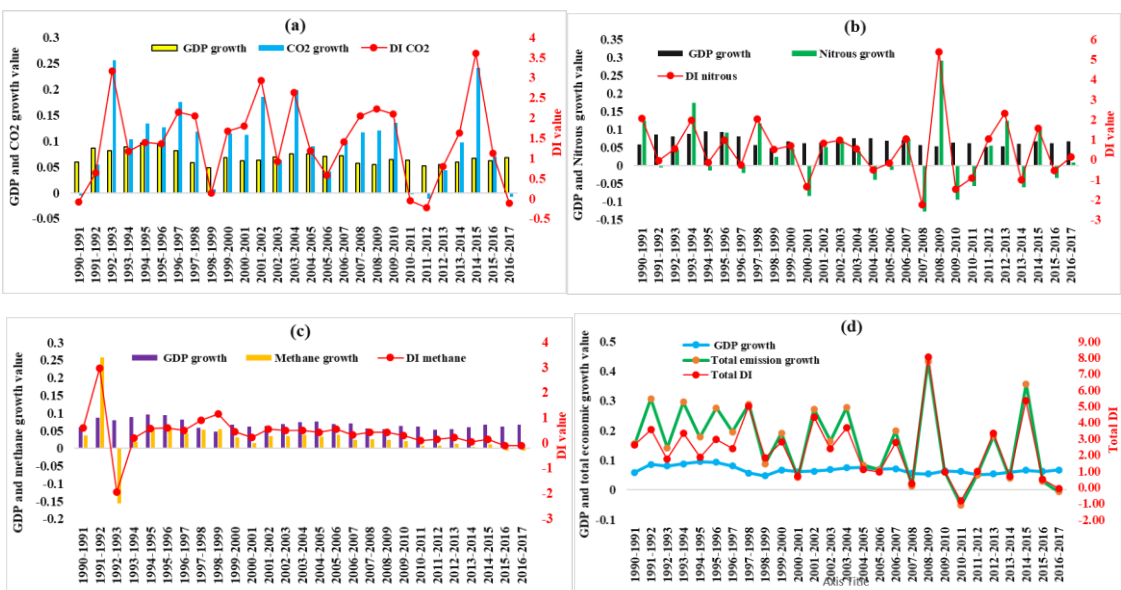


Figure 4.3. Economic, total emission growth in Vietnam during 1990-2017. [*Note: The secondary horizontal presents the decoupling index in each Fig*].

In general, Vietnam has just begun to have a change in awareness about sustainable development, at the same time, the implementation of sustainable development programs has not yet brought about high efficiency. However, this analysis will help this country more closely regulate and manage the implementation and quality monitoring of sustainable development models soon.

Table 4.1. The decoupling states in Vietnam

Year	GDP growth	Total emission growth	Total DI	Adjusted decoupling
1990-1991	0.060	0.155	2.60	Expansive negative decoupling
1991-1992	0.086	0.308	3.56	Expansive negative decoupling
1992-1993	0.081	0.142	1.76	Expansive negative decoupling
1993-1994	0.088	0.296	3.34	Expansive negative decoupling
1994-1995	0.095	0.178	1.86	Expansive negative decoupling
1995-1996	0.093	0.277	2.96	Expansive negative decoupling
1996-1997	0.082	0.196	2.40	Expansive negative decoupling
1997-1998	0.058	0.289	5.01	Expansive negative decoupling
1998-1999	0.048	0.087	1.82	Expansive negative decoupling
1999-2000	0.068	0.192	2.82	Expansive negative decoupling
2000-2001	0.062	0.041	0.67	Weak decoupling
2001-2002	0.063	0.272	4.30	Expansive negative decoupling
2002-2003	0.069	0.165	2.40	Expansive negative decoupling
2003-2004	0.075	0.278	3.68	Expansive negative decoupling
2004-2005	0.075	0.084	1.11	Expansive decoupling
2005-2006	0.070	0.067	0.97	Expansive coupling
2006-2007	0.071	0.199	2.79	Expansive negative decoupling
2007-2008	0.057	0.014	0.25	Weak decoupling

2008-2009	0.054	0.434	8.04	Expansive negative decoupling
2009-2010	0.064	0.061	0.95	Expansive coupling
2010-2011	0.062	-0.051	-0.82	Strong decoupling
2011-2012	0.052	0.051	0.98	Expansive coupling
2012-2013	0.054	0.181	3.34	Expansive negative decoupling
2013-2014	0.060	0.041	0.68	Weak decoupling
2014-2015	0.067	0.357	5.35	Expansive negative decoupling
2015-2016	0.062	0.030	0.48	Weak decoupling
2016-2017	0.068	-0.006	-0.090	Strong decoupling

4.3.2. Eco-efficiency of multi-countries and Vietnam analysis based on Malmquist DEA

This section compares Vietnam and several typical nations (the United States, Singapore, South Korea, and China) in terms of eco-efficiency. These economies were selected under considerations of economic growth and technological advancement. The USA represents mature developed countries, a leading country in economic growth and sustainable development, followed by Singapore and South Korea. They rapidly develop to become high-income nations, suitably utilizing their limited resources. While China likes a symbol for many developing countries, followed its developed growth. Since it was chosen as a typical nation to highlight the eco-efficiency trends in the world.

The general eco-efficiency from multi-country efficiency was shown in Table 4.2 and Fig 4.4. All of the indexes moderately fluctuated in nearly three decades. The annual change of total factor productivity change (TFPCH) is 1.021, and its components (EFFCH and TECHCH) are 1 and 1.022. It denotes that technological factor plays a key role in increasing TFPCH in the whole period (Table 4.2). TECHCH improved dramatically during 1994-1995; 2004-2005; and 2009-2010 from 12 to 25% growth (Fig 4.4). On the other hand, the annual growth of SECH is just 1%, while PECH decreased 0.2%. It indicates that the eco-efficiency scale process is still limited.

Table 4.2. The overall change of each Malmquist Index for multi-country from 1990 to 2017

year	EFFCH	TECHCH	PECH	SECH	TFPCH
1990-1991	1.062	0.97	1.032	1.029	1.03
1991-1992	1.044	0.97	1.008	1.036	1.013
1992-1993	1.002	0.966	1.003	0.999	0.968
1993-1994	1.018	0.997	1.034	0.984	1.015
1994-1995	0.924	1.123	0.977	0.946	1.038
1995-1996	0.991	1.017	1.006	0.986	1.008
1996-1997	0.995	1.011	1.001	0.993	1.006
1997-1998	0.984	1.064	0.855	1.152	1.047
1998-1999	0.985	1.051	1.002	0.983	1.035
1999-2000	1.009	0.982	1.024	0.985	0.991
2000-2001	1.036	0.977	0.978	1.059	1.013
2001-2002	0.995	1.047	1.007	0.987	1.041
2002-2003	0.934	1.101	0.972	0.961	1.029
2003-2004	1.07	0.914	1.028	1.041	0.978
2004-2005	0.869	1.249	0.942	0.923	1.086
2005-2006	1.035	1.006	1.004	1.031	1.042
2006-2007	0.958	1.082	0.993	0.965	1.037
2007-2008	1.041	0.971	1.009	1.032	1.011
2008-2009	1.012	0.987	1.007	1.004	0.999
2009-2010	0.918	1.124	0.992	0.925	1.032
2010-2011	0.938	1.113	1.011	0.927	1.043
2011-2012	1.061	0.967	1.019	1.041	1.027
2012-2013	1.031	0.986	1.023	1.008	1.016
2013-2014	0.976	1.046	0.977	0.999	1.021
2014-2015	1.093	0.922	1.047	1.044	1.008
2015-2016	1	1.021	0.997	1.003	1.021
2016-2017	1.046	0.988	1.025	1.021	1.033
Mean Average	**1**	**1.022**	**0.998**	**1.001**	**1.021**

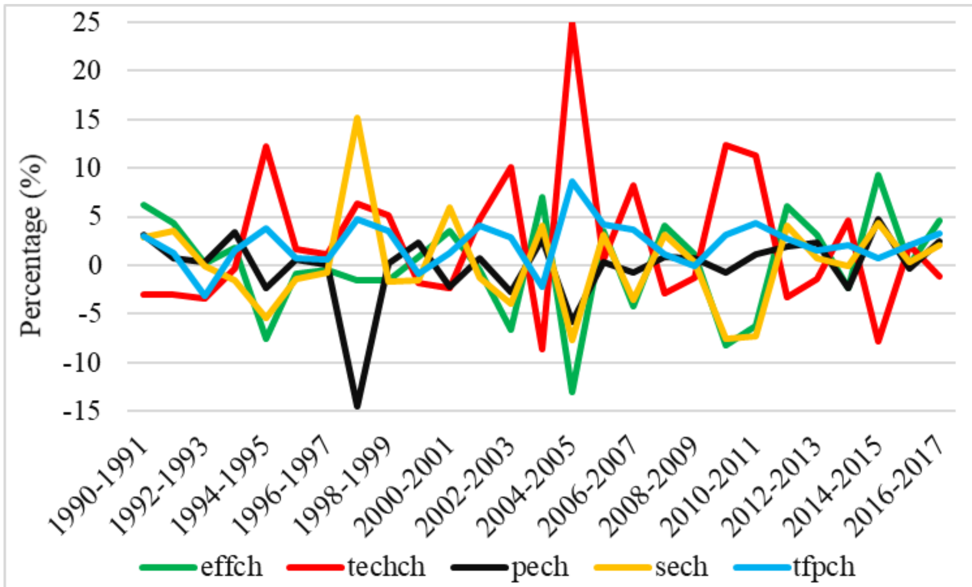
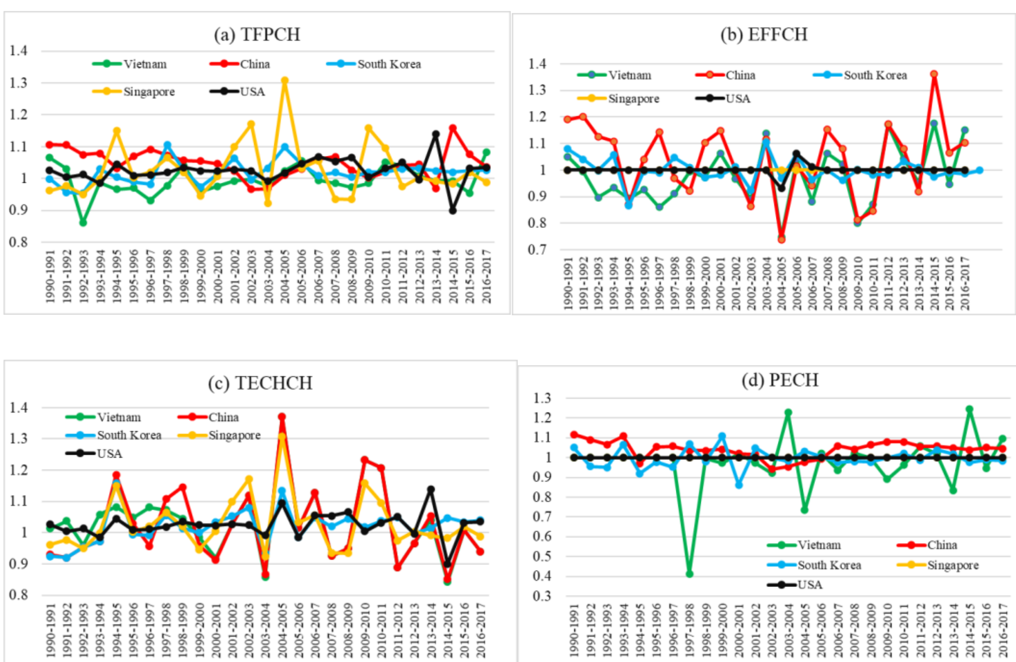


Figure 4.4. The cumulative change rate of TFPECH, TECHCH, EFFCH, PECH, and SECH for the overall trend in multi-country from 1990-2017.

At national scale, the track of TFPCH and its ingredients changes is presented in Fig 5.



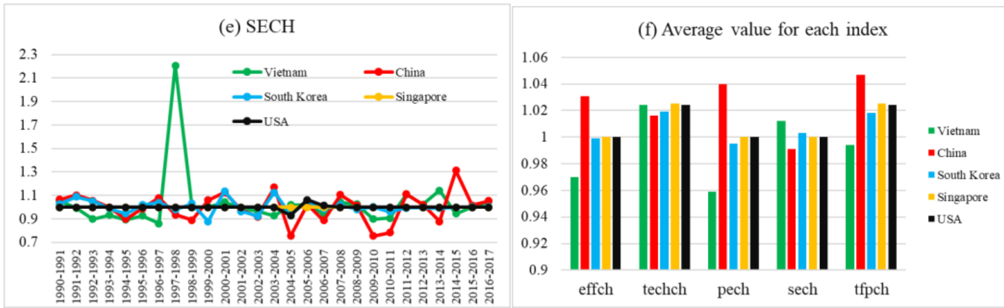


Figure 4.5. Malmquist productivity index for Vietnam, China, Korea, Japan during 1978-2017: (**a**) Total factor productivity change (TFPCH); (**b**) Technology change (TECHCH); (**c**) Efficiency change (EFCH); (**d**) Scale efficiency change (SECH), (**e**) Pure efficiency change (PECH), and (**f**) Average Malmquist index summary for each country.

As per TFPCH result, this indicator enormously changed in Singapore, and its optimal value is 1.308 – being equal 30.8% increase during 2004-2005. Other countries ran with a similar trend. The decline was the lowest 13.9% in Vietnam during 1992-1993 (Fig 4.5a). Compared with subjected countries, average TFPCH in Vietnam declined slightly (0.6%), while comparative countries exhibited improvements 1.8% South Korea; 2.4% in USA; 2.5% for Singapore; and the highest value in China (4.7%) (Fig 4.5f).

EFFCH and TECH indicators are components of TFPCH, they strongly altered in China, South Korea, and Vietnam. In comparison, EFFCH was a table in Singapore and the USA most of the time. It denotes that mature developed countries have been maintained their stable performances (Fig 4.5b and Fig 4.5c). On the other side, developing countries like China and Vietnam, have been made much effort to improve their eco-efficiency and technological advancement. The TECH average value for each nation in Fig 4.5f indicates that all studied countries slightly enhanced innovative solutions. However, EFFCH average value shows that only China performed better than other countries with a 3.1% increase, while Vietnam and South Korea EFFCH dropped slightly, Singapore and USA seem to be stagnant (Fig 4.5f).

Two decomposed components of EFFCH are PECH and SECH. Their changes are shown in Fig 4.5d and Fig 4.5e. Vietnam dramatically enhanced its SECH with 1.2% average growth (Fig 4.5f)- being a leader in its index. During 1997-1998, a 20.9% increase of SECH, while over 40% reduction of PECH was reported in Fig 4.5e and Fig 4.5d. In the following stages, Vietnam's SECH was in line with other studied countries. In contrast, SECH improvement ran with a opposite trend of PECH. This indicator presented a worse exhibition in almost phases. The expansion of eco-efficiency in Vietnam has been centralized, disproportionated to its scale.

Overall, Vietnam closely catches the general eco-efficiency trend in multi-countries. Technological factor could be a long-term solution for eco-efficiency improvement in the economy. Step-by-step improvements in pure scale and efficiency instead of sharp breakthroughs that cause imbalance in a certain period will create a clear and stable trend. Limit solutions to take shortcuts, it is the main cause of imbalance.

4.4. Conclusion

This study examined the interaction between economic growth and environmental status in Vietnam for nearly three decades (1990-2017) by integrating Tapio decoupling analysis. The results show that the ecological efficiency in Vietnam is still in its nascent stage, with the less significant breakthrough. At the same time, the Tapio assessment shows that efforts are not worthy of expectations and sometimes even show instability in the implementation of sustainable development programs. Besides, although the value of the productivity index has slightly higher than 1, it tended to decrease in recent years, showing the lack of seriousness in monitoring and management, and technology improvement is only average. This country needs to make breakthroughs in improving the scale and structure of the economy and the strategy of efficient energy exploitation and use scientifically in the coming time.

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Chapter 5

Assessment of Eco-industrial park (EIP) performance and industrial symbiosis cases in UNIDO EIP project in Vietnam

Abstract

Recently, Vietnam has been accelerated in converting traditional parks into the eco-industrial park (EIP) which is a locomotive strategy for sustainable development. However, lack of performance analysis of EIP results in reports in this nation. Hence, this study aims to examine the effectiveness of applying the EIPs performance analysis from the viewpoint of the integrative mathematical model, such as the full permutation polygon synthetic indicator analysis (FPPSI) to normalize the values of the indices at two levels (enterprise and park level). In detail, the FPPSI analysis for enterprise-level showed that most of the food, beverage and paper companies dominate with outstanding performance under moderate to excellent ratings. In the park level, Ninh Binh and Can Tho stand out with many remarkable successes (5 out of 13 indicators reaching the optimal value "1"). Specifically, these EIPs saved 51% of fuel LGP, 67.1% of coal, 78.16% of wastewater reduction in Ninh Binh compared to the total value for each indicator; while saved 77% of fresh water, more than 66.8% of electricity saving, 77% of COD reduction, and 56% of cost-saving at Can Tho pilot project.In addition, many potential and reasonable opportunities have been revealed and practiced during the first step. Energy recovery, green energy, reusable waste (metals, paper, and woods), utilizing heat-steam, and wastewater treatment in the whole EIP pilots have been centralized and emerged in EIP symbiosis networks. However, as a recommendation, this country needs to promote the participation of companies in the heavy industry sector. On the other hand, maintaining and expanding current successful symbiosis networks, parallelly, all stakeholders and the Vietnamese government should create new innovative symbiosis networks to deal with hazardous wastes and disclose acquire knowledge for all industrial zones in the nation.

Keywords: Eco-industrial parks; industrial symbiosis; Full Permutation Polygon synthetic indicator analysis; Data envelopment analysis; Vietnam.

5.1. Introduction

Environmental degradation and resource insecurity are alarmingly the most prominent global issues (Mancini et al., 2015). Awareness of environmental aspect challenges, such as climate change, pollutions, unstainable development, and resource depletion, have adverse impacts on economic growth, human health, and ecosystems. Hence, creative and innovative solutions always encourage to solve these problems. The correlation between industrialization, urbanization, and ecosystem health should be centralized for green growth and sustainable development. Recently, the eco-industrial park concept seems to fully respond to these targets (Behera et al., 2012). It can address economic growth and sustainable development (Kim, 2017; Yu, 2014). Besides, EIP is widely known as a small-scale circular economy; this program highlights efficient material consumption and saves energy (Thieriot and Sawyer, 2015).

The initial EIP program was successfully implemented in Kalundborg (Denmark), explored in 1990 under the regional industrial symbiosis (Ehrenfeld and Gertler, 1997), which bloomed as a sustainable development status. The top economic countries also early performed this program, such as the USA (Sakr et al., 2011), Canada (Hwang et al., 2016), Japan ("IndigoEco-Japan," n.d.), South Korea (Kim, 2017), China (Yu, 2014), and European countries (Massard et al., 2018). In recent years, the flourishing's program has spread to developing countries through the support and guideline from the United Nations Industrial Development Organization (UNIDO) under the joint global Resource Efficient and Cleaner Production (RECP) program with the United Nations Environment Programme (UNEP) (Massard et al., 2018). Therefore, UNIDO has run the EIP program in Thailand, India, Morocco (Pilouk and Koottatep, 2017), South Africa, etc. (Of et al., n.d.). Especially, an EIP national project has been implemented in Vietnam, funded by the Global Environment Facility (GEF) and State Secretariat for Economic Affairs of Switzerland (SECO) (Stucki et al., 2019).

Mathematical analysis and industrial ecological tools have been widely used to investigate the monitoring and assessment of blooming EIP performances in many countries scientifically (Liu et al., 2015; Zheng et al., 2012). In contrast, immature countries applying EIP programs, such as Vietnam, lack studies in this field. Vietnam EIP's performances only stop at mere analysis in terms of resource, environmental, and saving indicators (Dong, 2016; Massard et al., 2018; Stucki et al., 2019). These studies lack consideration and evaluation based on mathematical analysis tools, such as rendering the results unsystematic and disjointed (Boldyrev et al., 2019; Subramanian et al., 2018). However, choosing an appropriate evaluation method is key task before constructing a comprehensive indicator system.

As mentioned in the International EIP framework by UNIDO (UNIDO, 2017), environmental, social, and economic aspects were set as indicators for EIP performance. This study presented indicators focused on environmental reduction, material saving, and energy saving. Under the aggregate enterprises' system in an industrial park, a comprehensive evaluation method needs to combine all synthetic indicators of companies. According to this condition, a suitable method is the full permutation polygon synthetic indicator analysis (FPPSI).

In addition, FPPSI is independent of weights – making assessment has a scientific objective and reflects reality (Jiang et al., 2018; Xu et al., 2019). Moreover, as a part of the FPPSI method, the standardization of indicators is defined at enterprise and industrial park levels. However, the FPPSI cannot measure the efficiency of decision-making units. Therefore, this study integrated with Data Envelopment Analysis (DEA) to find efficient performance based on each area's multiple inputs and outputs.

Under the author's investigation, the study can be one of the pioneering studies in EIP assessment in Vietnam with comprehensive methods in the investigation and analysis of EIP results. In detail, the paper aims to answer the following research questions:

(1) how to standardize the values of multiple indicators that can be described at the enterprise level and the park level?

(2) Which EIP pilot project is practical? In addition, the author mentions the main relevant policies to better understand the EIPs program in Vietnam and some recommendations for the following steps to implement EIPs.

General information of EIP program in Vietnam

Starting in the 2000s, Vietnam has amazingly grown with a GDP growth rate that ranks among the top globally at 7.9% (Perkins and Anh, 2009). In recent years, this growth still reached a high level of 6.8% (in 2017). At the same time, this country has also become one of the critical links in the import and export network of the region and the world (Konrad Adenauer Stiftung, 2017). Vietnam's economic growth is inevitable due to the large consumption of materials and fuels to serve the construction and development of the country. From a material consumption perspective, all major resource categories were dramatically consumed between 2000 and 2017. Overall, metal ores, fossil fuels, non-metallic minerals, and biomass consumption increased over the period. The most predominant material used in Vietnam was non-metallic minerals, consumed 528%. This material was far higher than metal ores, fossil fuels, and biomass; they were used 442.4%, 332.1%, and 65%, respectively (Fig. 2a). As for energy consumption, industrialization accounted for a large proportion of energy consumption, increasing 348.9%. At the same time, the transport, agriculture/forestry, and service sectors also contributed to the increase in energy consumption between 2000 and 2017 with 262%, 170%, and 132.3%, respectively. For the rest of the sectors, energy consumption did not change significantly. These results indicate that industrialization and modernization of infrastructure and production have rapidly improved in this country (Revilla Diez, 2016).

On the other hand, the great support and investment come from leading traders like South Korea, Japan, Singapore, etc., helping Vietnam promote construction and manufacturing activities. Accumulated in March 2018, South Korea continued to be the leading foreign investor in Vietnam with more than 59 billion USD, followed by Japan (49.84 billion USD), Singapore (43.10 billion USD), and Taiwan (30.94 billion USD). It forecasts that Vietnam's affluence will continuously increase in the coming time (Konrad Adenauer Stiftung, 2017).

In the face of risks to the environment, energy scarcity, and resource depletion, specific actions must be taken by the Vietnamese government. Since August 28, 2014, the Prime Minister approved the Project "Implementing the Eco-Industrial Park Initiative to develop sustainable industrial zones in Vietnam" - decision 1526/QĐ-TTg. It aims to promote technological transformation, hazardous waste reduction, and cleaner production in this nation (Massard et al., 2018). In 2014, the Ministry of Planning and Investment of Vietnam and UNIDO linked and implemented the EIP program in three regions: (1) Ninh Binh province with two areas: Khanh Phu and Gian Khau industrial parks; (2) Da Nang City has the specific project pilot known as Hoa Khanh industrial park; the last area is Can Tho province with two industrial parks: Tra Noc I & II. This program attracted 72 participating businesses in three regions, while 16 enterprises stopped joining and 3 companies refused to continue during the implementation (note: further information can be seen in Fig 5.1).

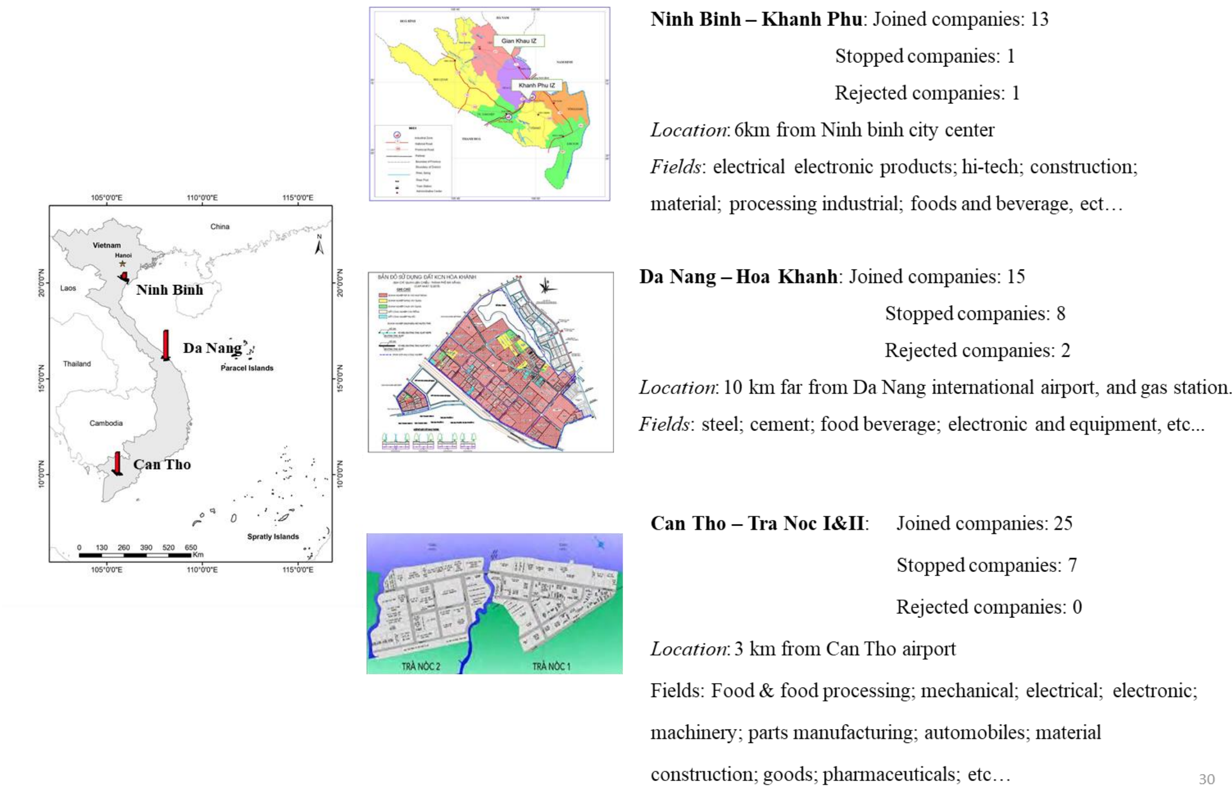


Figure 5.1. General information about EIP in Vietnam

As per industrial sector points, several key industrial sectors, such as food-beverage, fishery, paper, construction materials, textiles, plastics, steel, chemicals, and fertilizers, are centralized. . In detail, predominant sectors are run in the Ninh Binh pilot project, including waste treatment, floating glass, knitwear, aluminum alloy, battery, cement, asphalt emulsion, oil-liquid plastic, plastic bag, ball casting, jewelry, magnets, and fertilizers. The total investment at the preliminary stage is 4,101,465 Euro for this region. This investment was the highest compared with the Da Nang case (2,857,108 Euro), the Can Tho pilot project (2,905,877 Euro), around 1.44 times and 1.41 times higher, respectively. Construction materials, metallic, and equipment manufacturing of paper, steel, ceramic, furniture, fishing rod, cloth, oil-fuel filter, and refrigeration production dominate in Da Nang – Hoa Khanh industrial zone.Meanwhile, Can Tho – Tra Noc I and Tra Noc II emerge with food manufacturing, seafood productions, biological pesticides, beverage, coffee, and milk productions.

Concurrently, Tra Noc I and Tra Noc II mainly produce steel, kraft paper, beverage, glove, leather, fertilizer, and gas manufacturing.

Aggregated industrial activities in an industrial zone bring many potential opportunities to establish industrial symbiosis networks under many by-products and wastes. However, it is a big challenge for specialists and managers to create ideas for making symbiosis businesses.

5.2. Methods and data

5.2.1. Indicator system of EIP

Referencing the performance of EIP, a total of 13 indicators were selected to construct the index system, such as material (in ton), electricity (in kWh), water (in m^3), fuel LGP (in ton), chemicals (in ton), coal (in ton), wood (in ton), saving money (in Euro), and the environmental performance, such as CO_2 emission (in ton), polychlorinated dibenzo (p) dioxins and furan PCDD/F (in μg), COD (in kg), solid waste (in ton), and wastewater (in m^3). Quantitative description of the performance level is concededly classified under four thresholds (Table 5.1).

Table 5.1. Classification of indicator levels

Range of values	Level
> 0.75	Excellent
0.5 – 0.75	Better
0.25 – 0.5	General
< 0.25	Poor

Besides, some assumptions note in this study:

(1) In this study, impacts from expansion of activities, technological advancement, affluence (economic growth), past and ongoing policies and strategies do not consider as driving factors that have no impact on results in the study. Concurrently, the profit hypothesis does not change according to the aforementioned variables.

(2) Environmental reduction and saving material with energy are benefits.

Socio-economic information of Vietnam gathered from the International Energy Agency (IEA) (IEA, 2017), World Bank indicators (The World Bank, 2018, 2017; World Bank, 2019), and several official Vietnamese reports (Bank, n.d.; Dinh, 2013; EREA & DEA, 2019; Jung Eun et al., 2019; Of et al., 2015; Report, 2018). The EIP database was collected under economic, environmental, and social indicators. They are the main aspects to evaluate and assess EIP performances. Detailed results provided through the final report “Eco-Industrial Park Initiative for Sustainable Industrial Zones in Vietnam: Industrial Symbiosis Feasibility Study and Implementation – Version: 16th May 2019” (Valenzuela-Venegas et al., 2016).

5.2.2 A full permutation polygon synthetic indicator method (FPPSI)

The full permutation polygon synthetic indicator (FPPSI) method was used for data standardization and indicator synthesis that rescaled each indicator from -1 to 1 and then altered the traditional additive approach to combine indicators by using a multidimensional approach (Xu et al., 2019). A variety of studies have been widely applied to the FPPSI method to evaluate economic, social, and environmental performances. For example, urbanization in China's Jining city case was assessed over two decades with 52 indicators, including main types of economic growth, ecosystem, infrastructure, environment, social, and welfare. It is known as a highlight to mark the advantages of the FPPSI method (Li et al., 2009). The approach is to understand agricultural standardization in peach orchard ecosystems with green indicators such as atmospheric environment, irrigation water, soil, seedling quality, and effect on production with living conditions (Wan et al., 2016). Similarly, urban governance efficiency in Sri Lanka was investigated by the method (Ranasinghe et al., 2016). Furthermore, 13 restricted indicators out of 33 considered as key environmental sustainability indexes in the urban industry from Chinese cities were analyzed during 2005-2017.

According to Deng’s research in 2020, it shows this method is widely used for many fields in data normalization and index aggregation (Deng, 2020). A synthetic scale from -1 to 1 replaces the conventional scale, adopts a multidimensional approach to evaluate integrated system principles for all indicators (Xu et al., 2019). Its strengthen is its eligibility to evaluate all values above and below, which significantly eliminates the subjective discretion evaluation since the method does not need to adjust the weight coefficients (Xiao, 2017).

A polygon with n-sides represents n-indicators with an upper limit of all indicators as the radius and connecting lines of indicator values. Its forms have an irregular center. The asymmetrical edges of the vertices are the complete permutations of these indicators with (n-1)!/2 arrangement of the irregular polygon n-sides (Xiao, 2017; Xu et al., 2019). The normalization process expresses as a function F(t), it takes a value between [-1, 1] (Umar and Asghar, 2018; Xiao, 2017).

$$F(t) = \frac{a(t+b)}{t+c} \; (a \neq 0; t \geq 0) \qquad (1)$$

F(t) needs to satisfy F(L) = -1; F(T) = 0; and F(U) = 1, in which L is the lower limit, similarly U is an upper limit of the indicator t, respectively, and T is the threshold of the indicator t.

Based on the three conditions above. We figured out the specific set of numbers (a; b; c) are:

$$a = \frac{U-L}{U+L-2T} \text{ ; } b = -T\text{; and } c = \frac{UT+LT-2UL}{U+L-2T}$$

When F(t) can be rewritten by the equation below:

$$F(t) = \frac{(U-L)(t-T)}{(U+L-2T)t+UT+LT-2UL} \text{ with } t \in [L, U] \quad (2)$$

Where, $t \in (L, U)$

When $t \in (T, U)$, $F''(t)>0$

When $t \in (L, T)$, $F''(t)<0$

At the *i*-th indicator is:

$$S_i = \frac{(U_i - L_i)(t_i - T_i)}{(U_i + L_i - 2T_i)t_i + U_i T_i + L_i T_i - 2U_i L_i} \qquad (3)$$

S_i presents the standardized indicator value

U_i denotes the upper value of the existing value

L_i indicates the lower value of the existing value

t_i is the value of the indicator

T_i performs the target value of the indicator

The full polygon, which is described in Eq (4) below:

$$S = \frac{1}{2n(n-1)} = \sum_{i=1}^{n} \sum_{k=1}^{n} [(Si + 1)][(Sk + 1)] \quad i \neq k \quad (4)$$

S is the value of the synthetic indicator.

S_i is minimum value of the standardized value

S_j is maximum value of the standardized value

N is number of indicators.

Where the center point represents by $S_i = -1$; the distance from a center point to the corresponding standardized indicator is known as the radius. An inner polygon between the outer polygon and the center of the polygon represents the threshold values of the dices, where $S_i = 0$ when $t_i = T$.

5.3. Results

5.3.1. The full permutation polygon synthetic indicator for each region

The heatmap presents a total of 13 indicators for each EIP pilot project (Fig. 4), which indicates the EIP performance at each enterprise-level. Overall, electricity, water, CO_2, PCDD/F, COD, wastewater, and saving money are more active and fluctuated than material, LPG, chemical, coal, wood, and solid waste indicators at each pilot. In particular, in Ninh Binh pilot project with 13 companies having officially joint EIP program (Fig.5.2a), we can easily observe that Duong Giang Co.Ltd – Trang An floating glass factory, which has achieved remarkable performances on resource-saving (notably over 3,700,000 kWh electricity/year) and emission reduction (12473 ton CO_2/year; 2511.6 PCDD/F/year). On the other hand, other companies have poorly presented with most of the color scales being lower zero limits. It denotes that the different achievements among these companies were significant.

At the Da Nang pilot project, most paper and textile companies' achievements in saving materials are reported (Fig.5.2b). Among 15 companies, A Chau Architecture and Trading Co.Ltd – Tan Long Paper factories obtained 7 indexes with the maximum value per 13 indicators, following Daiwa Vietnam Co.Ltd and Da Nang Dairy Factories. Meanwhile, Vinamilk company shows an upper limit value for many important indexes (material; water; wood; CO_2; PCDD/F; COD; and wastewater indicators). Nevertheless, saving chemicals and coal reductions seem to obtain outcomes insignificantly. It shows that fossil fuels still play a key role in almost of enterprises in this area. On the other hand, chemical mitigation measures in manufacturing industries have yet to find specific effective solutions, indicating that the characteristics of each industry make it difficult to create linkages between industries to form industrial symbiotic bonds.

At the Can Tho pilot project, although different achievements among 25 studied companies are observed (Fig.5.2c), where normal wastes (wastewater), resources (water supply), and energy (electricity) contribute remarkably to the overall achievement. Some enterprises emerge with outstanding presentations. For instance, food and beverage companies (Saigon-Western Beer JSC-SaiGon beer Can Tho factory; Hanoi-Can Tho seafood JSC; Vietnam dairy products JSC Vinamilk-Can Tho dairy factory; CP Vietnam corporation; and Co Chien Co, Ltd), and some steel – equipment companies (Tay Do steel Co.Ltd) confirmed with high levels (Fig.5.2c).

Overall, fossil fuels and detrimental waste reductions (LGD, chemicals, PCDD/F, hazardous wastes) are also ineffectively achieved in all studied areas. It reveals that efficient and transcendent symbiosis networks are yet to be discovered and that current technologies do not meet innovative solutions in the EIP program.

(a)	Ninh Binh pilot project	a	b	c	d	e	f	g	h	i	j	k	m	n
1	Eni-Florence Vietnam Co., Ltd	-1	0.25	0.13	1	-1	-1	0	-0.28	-0.65	0.05	-1	1	0
2	Duong Giang Co., Ltd - Trang An floating glass factory	1	1	-1	-1	-1	1	0	1	1	-1	1	-1	1
3	Chia Chen Co., Ltd	-1	-0.58	1	-1	1	-1	0	-0.85	-0.92	1	-1	-0.86	-0.73
4	Ninh binh electric Mechanical Co., Ltd	0.82	-0.86	-0.67	-1	-1	-1	0	-0.95	-0.98	-0.65	-1	-1	-0.85
5	Dong duong Magnetic Material Co., Ltd	-1	-0.91	-0.79	-1	-1	-0.94	0	-0.93	-0.92	-0.77	-1	0.18	-0.93
6	Great Global International co., Ltd	-1	-0.45	0.42	-1	-1	-0.26	1	-0.43	0.35	0.33	-1	-0.97	-0.20
7	Cement equipment Co., Ltd	-1	-0.76	-1	-1	-1	-1	0	-0.92	-0.96	-1	-1	-1	-0.91
8	Changxin Vietnam Co., Ltd	-1	-0.28	-1	-1	-1	0.18	0	0.07	-1	-1	-1	-1	0.01
9	Hoang Phat Vissia Group Co., Ltd	-1	-0.20	-1	-1	-1	-1	0	-0.67	-0.83	-1	-1	-1	-0.62
10	HAS Fashion Co., Ltd	-1	-0.94	0.28	-1	-1	-1	0	-0.98	-0.99	0.19	-1	-0.98	-0.96
11	Vietnam K's International Polybags JSC.	-1	-0.70	-1	-1	-1	-1	0	-0.89	-0.97	-1	-1	-1	-0.95
12	Thanh Nam Construction and Commerce Co., Ltd	-1	-0.99	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	-1
13	Bachchambard Co., Ltd	-1	-1	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	-1

(b)	Da Nang pilot project	a	b	c	d	e	f	g	h	i	j	k	m	n
1	A Chau Architecture and Trading Co., Ltd - Tan Long Paper factory	1	1	-0.34	-1	0	0	1	1	1	-0.33	1	-0.40	1
2	Danang Dairy Factory - Vinamilk	-1	0	1	-1	0	0	-1	-0.10	-0.63	1	-1	1	0.39
3	Daiwa Vietnam Co., Ltd	-1	0.52	0.88	1	0	0	-1	0.52	-0.18	0.96	-1	0.96	0.61
4	Nguyen Phuc paper Co., Ltd	0.88	-0.91	-0.98	-1	0	0	0.39	-0.90	0.22	-0.98	-1	-0.98	-0.71
5	DIC Danang Investment & Trading JSC.	0.64	-0.93	-1	-1	0	0	-1	-0.93	-0.98	-1	-1	-1	-0.58
6	NBB Industry holding company	0.06	-0.88	-1	-1	0	0	-1	-0.88	-0.96	-1	-1	-1	-0.03
7	America Vietnam steel Corporation	-1	-0.23	0	-1	0	0	-1	-0.23	-0.71	0.07	-1	0.07	-0.27
8	Trung A Manufracturing and Trading Co., Ltd	-0.89	-0.54	-1	-1	0	0	-1	-0.54	-0.84	-1	-1	-1	-0.65
9	Danang printing & Service JSC	0.97	-0.90	-0.98	-1	0	0	-1	-0.89	-0.98	-0.98	-1	-0.98	-0.91
10	Ba Loc Adhesive and Abrasive Cloth Co., Ltd	-1	-0.63	-0.80	-1	0	0	-1	-0.63	-0.88	-0.75	-1	-0.78	-0.74
11	SEA refrigeration Electrical Engineering (SEAREE)	-1	-0.84	-0.84	-1	0	0	-1	-0.84	-0.96	-0.82	-1	-0.82	-0.87
12	Vinafor Danang JSC	-1	0.20	-0.50	-1	0	0	-1	0.20	-0.45	-0.47	-1	-0.46	-0.06
13	Viet Lang Forest Product Co., Ltd (FDI)	-1	-0.72	-1	-1	0	0	-1	-0.72	-0.92	-1	-1	-1	-0.84
14	19-5 Garment enterprise-Ministry of public security	-1	-0.71	-1	-1	0	0	-1	-0.71	-0.92	-1	-1	-1	-0.83
15	Secoin Danang JSC	-1	-1	-1	-1	0	0	-1	-1	-1	-1	-1	-1	-1

(c)	Can Tho pilot project	a	b	c	d	e	f	g	h	i	j	k	m	n
1	CP Vietnam Corporation	-1	0.60	-0.45	-1	-1	0	1	1	1	-0.18	-1	-1	0.49
2	Vietnam dairy products JSC (VINAMILK) - Can Tho Dairy factory	-1	0.20	0.99	-1	-1	0	-1	0.03	-0.10	0.99	-1	0.99	0.63
3	Hanoi - Cantho Seafood JSC	-1	0.14	1	-1	-1	0	-1	-0.03	-0.15	1	-1	1	0.61
4	Tay Do Steel Co., Ltd	-1	0.73	-0.91	-1	-1	0	-1	0.94	0.31	-0.87	1	-0.91	1
5	Co Chien Co., Ltd	-1	0.48	0.59	-1	-1	0	-1	0.30	0.11	-0.99	-1	0.58	0.42
6	Saigon-Western Beer JSC - Saigon Can Tho Beer factory	-1	1	0.72	-1	-1	0	-1	0.85	0.52	-0.99	-1	0.71	0.82
7	Mekong Fisheries JSC	-1	0.85	-1	-1	-1	0	-1	0.69	0.40	-1	-1	-1	0.49
8	KWONG lung Mekong 2 Co., Ltd	-1	0.47	-0.39	-1	-1	0	-1	0.29	0.11	-0.22	-1	-0.40	0.16
9	Quang Minh SEAfood Co., Ltd	-1	-1	-1	-1	-1	0	-1	0.22	0.05	-0.14	-1	-0.33	0.29
10	Nam Tien JSC	-1	-1	-1	-1	-1	0	-1	-0.70	-0.73	-1	-1	-1	-0.78
11	Nam Hai SEAfood processing Export Co., Ltd	-1	0.46	-0.9	1	-1	0	-1	0.34	0.11	-0.83	-1	-0.88	0.29
12	Thanh The Seafood Co., Ltd	-1	0.08	0.15	-1	-1	0	-1	-0.08	-0.20	-1	-1	0.27	-0.03
13	BIO Vietnam Co., Ltd	-1	-0.89	-0.71	-1	1	0	-1	-0.91	-0.94	-0.61	-1	-0.72	-0.86
14	Mekong river Orchards JSC	-1	-0.96	-0.96	-1	-1	0	-1	-1	-1	-0.94	-1	-0.96	-1
15	Tri-Viet International Co., Ltd	-1	-0.59	-0.78	-1	-1	0	-1	-0.69	-0.70	-0.63	-1	-0.74	-0.73
16	Nam Hung Phat packaging Manufacturing and Trading LLC	-1	-0.92	-0.97	-1	-1	0	-1	-0.96	-0.55	-0.96	-1	-0.97	-0.95
17	Nguyet Trang manufacturing and Trading Co., Ltd	-1	-0.95	-0.82	-1	-1	0	-1	-0.99	-1	-0.75	-1	-0.83	-0.96
18	Can Tho import export fishery limited (CAFISH)	-1	-0.39	-1	-1	-1	0	-1	-0.52	-0.56	-1	-1	-1	-0.63
19	Pataya Vietnam food industries Co., Ltd	-1	-0.69	0.18	-1	-1	0	-1	-0.77	-0.78	0.35	-1	0.17	-0.50
20	Tam Phuong Nam Seafood JSC	-1	-0.43	-0.27	-1	-1	0	-1	-0.55	-0.59	-0.09	-1	-0.28	-0.51
21	Can Tho Mechical electrical machinery JSC - MITAGAS factory	-1	-0.86	-1	-1	-1	0	-1	-0.92	-0.92	-1	-1	-1	-0.94
22	Hung Phuc ONE Member Co., Ltd	1	-0.28	-1	-1	-1	0	-1	-0.41	-0.47	-1	-1	-1	-0.46
23	Huu Sang Co., Ltd	-1	-0.95	-0.97	-1	-1	0	-1	-0.99	-0.99	-0.95	-1	-0.97	-1
24	Can Tho ferilizer & Chemical JSC	-1	-0.22	-0.66	-1	-1	0	-1	-0.36	-0.42	-0.54	-1	-0.67	-0.45
25	Can Tho ferilizer & Chemical JSC - Co Bay Animal Feed factory	-1	-0.83	-0.98	-1	-1	0	-1	-0.89	-0.90	-0.97	-1	-0.98	-0.92

Figure 5.2. Heatmap of EIP indicators. (a) – Ninh Binh pilot project; (b) – Da Nang pilot project; and (c) – Can Tho pilot project (Enterprise level)

Note: The index values are color-coded in the heatmap. Deep green reflects that the observed indicator has the worst performance, and the distance between the standardized indicator and the center point (-1) is significantly narrowed. From light green to yellow, the observed indicator is higher than -1 and closer to zero. Suppose the color comes from orange to red. The radius of this synthetic polygon is widened with a center point. At that time, it indicates that the observed indicator is much higher than zero and close to the boundary curve of the standardized polygon (its radius is the distance between center point -1 to upper limit).

Note: a-material indicator (ton); similarly, b-electricity (kWh); c-water (m^3), d-fuel LGP (ton); e-chemicals (ton); f-coal (ton); g-wood (ton); and n-saving money (Euro) indicators. Environmental benefits are presented by h-CO_2 (ton); i-polychlorinated dibenzo(*p*)dioxins and furan PCDD/F (μg); j-COD (kg); k-solid waste (ton); and m-wastewater (m^3).

5.3.2. Full permutation polygon synthetic indicator for comparison in the three-pilot projects.

Under the total value for each indicator in the specific industrial park, a comparative performance at the park level is shown in Fig.5.3 through FPPSI approach. The compliance for each indicator is presented in Fig.5.4.

Park level	a	b	c	d	e	f	g	h	i	j	k	m	n
Ninh Binh	-1	-1	-1	1	1	1	-1	0.58	1	-1	-1	1	-0.713
Da Nang	1	-0.940	-0.383	-1	-1	-0.012	1	-1	-1	-0.36	1	-0.53	-1
Can Tho	-0.86	1	1	0.56	0.20	-1	-0.27	1	0.0039	1	-0.51	-1	1

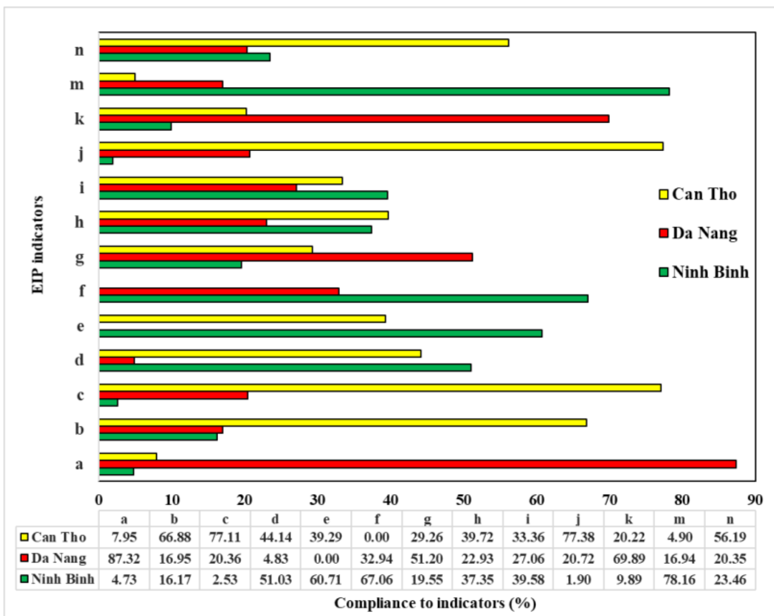
Figure 5.3. A heat map of the full permutation polygon synthetic indicator analysis to compare among the three-pilot project performances (at park level).

Fig.5.3 illustrates the evaluation of each indicator in the three-pilot projects. The value is given on a scale from -1 to 1, and the level indicator is classified in Table 1. Overall, each industrial park has its own achievements.

At Ninh Binh – Khanh Phu and Gian Khau industrial parks: Although the categories of material-saving and pollutant reduction poorly achieved most on material, electricity, water, wood, COD, solid waste, and saving cost indicators, its comprehensive result was excellent compared with the remaining two areas about LPG, chemicals, coal, PCDD/F, and wastewater reduction performances. LPG (51.03% in the total performance), chemicals (over 67.06% in the total chemical saving in all pilot projects), 39.58% for the total PCDD/F achievement, and 78.16% for wastewater indicators are the highlight in this region.

For Da Nang – Hoa Khanh industrial park: two distinct values are easily observed (poor – excellent) (Fig.5.3). The outstanding performance of material saving accounts for 87.32% per the total material saving in the EIP program, followed by significant proportions for wood saving and solid waste reduction; these values are around 51.2% and 69.9% contribution to their total values, respectively (Fig.5.4). In contrast, chemical saving performance did not report any achievement. Other indicators are a third or a minority value.

While Can Tho province – Tra Noc I & Tra Noc II: General to excellent levels presents almost indexes. For instance, 66.88% electricity saving is the highest in the three-pilot projects, while Ninh Binh and Da Nang reported with similar value (around 16%). Saving water supply is also excellently with over 77.1% per its total value. COD performance is predominant with 77.38%. Over half of saving cost accounts. Carbon emission reduction is known as a representative indicator for greenhouse gases. This indicator shares 37.35%, 22.93%, and 39.72% for Ninh Binh, Da Nang, and Can Tho, respectively (Fig.5.4). Besides, other indicators include material, LDG, chemicals, wood, PCDD/F, and solid waste recorded with values higher than the minimum value (-1). Even though some met general and better level (Fig.5.3). It indicates that most participating companies in Can Tho attained a significant contribution to pollution reduction and resource savings.



	a	b	c	d	e	f	g	h	i	j	k	m	n
Can Tho	7.95	66.88	77.11	44.14	39.29	0.00	29.26	39.72	33.36	77.38	20.22	4.90	56.19
Da Nang	87.32	16.95	20.36	4.83	0.00	32.94	51.20	22.93	27.06	20.72	69.89	16.94	20.35
Ninh Binh	4.73	16.17	2.53	51.03	60.71	67.06	19.55	37.35	39.58	1.90	9.89	78.16	23.46

Figure 5.4. Comparison the performance of each industrial park on the total at each indicator.

Note: a-material indicator (ton); similarly, b-electricity (kWh); c-water (m^3), d-fuel LGP (ton); e-chemicals (ton); f-coal (ton); g-wood (ton); and n-saving money (Euro) indicators. Environmental benefits are presented by h-CO_2 (ton); i-polychlorinated dibenzo(*p*)dioxins and furan PCDD/F (µg); j-COD (kg); k-solid waste (ton); and m-wastewater (m^3).

5.4. Potential industrial symbiosis networks in Demonstration EIP

5.4.1. Opportunities of symbiosis networks in Gian Khau industrial zone – Ninh Binh pilot.

Fig 5.5 shows the four opportunities of industrial symbiosis networks in Gian Khau IZ – Ninh Binh area. Waste gasification plant treatment; utilizing heat and steam by-products at the boiler in glass company; mutualization of safety rules and equipment related to welding activities; using of ash waste for cement production. However, the dissertation is only selected a highlight symbiosis network for each pilot to make a balance among all chapters.

Opportunities: Waste gasification plant for domestic waste from Khanh Phu IZ -Ninh Binh and neighboring residential areas.

According to some surveys from ENTEC and IZ management board, the total domestic waste is around 37.3 tons/month, equivalent to 1.24 tons/day. Meanwhile, surrounding areas produce an average waste of 1.2kg/person. In 2017, the population for the neighboring areas was a total of 28,143 (Khanh Phu 5,500 people; Ninh Phuc 10,343; Khanh Hoa 5,758; Khanh An 6,542) 35 tons/day of domestic waste needs to deal with. While the total amount of domestic waste in Ninh Binh province is 982 tons/day, the value is forecasted to increase 45% soon. Hence, the studied symbiosis network to disposal waste gasification plant could bring an excellent lesson for upcoming approach in the whole province and this country. As we know, some popular solid waste treatment technologies can be determined: uncontrolled landfill; controlled landfill; composting; incineration; mechanical biological treatment (MBT); and HT33E gasification for electricity. As per studying for all suggested methods, the efficient option for treating domestic waste is the HT33E gasification technological system. The major treatment system is present in Fig 5.6.

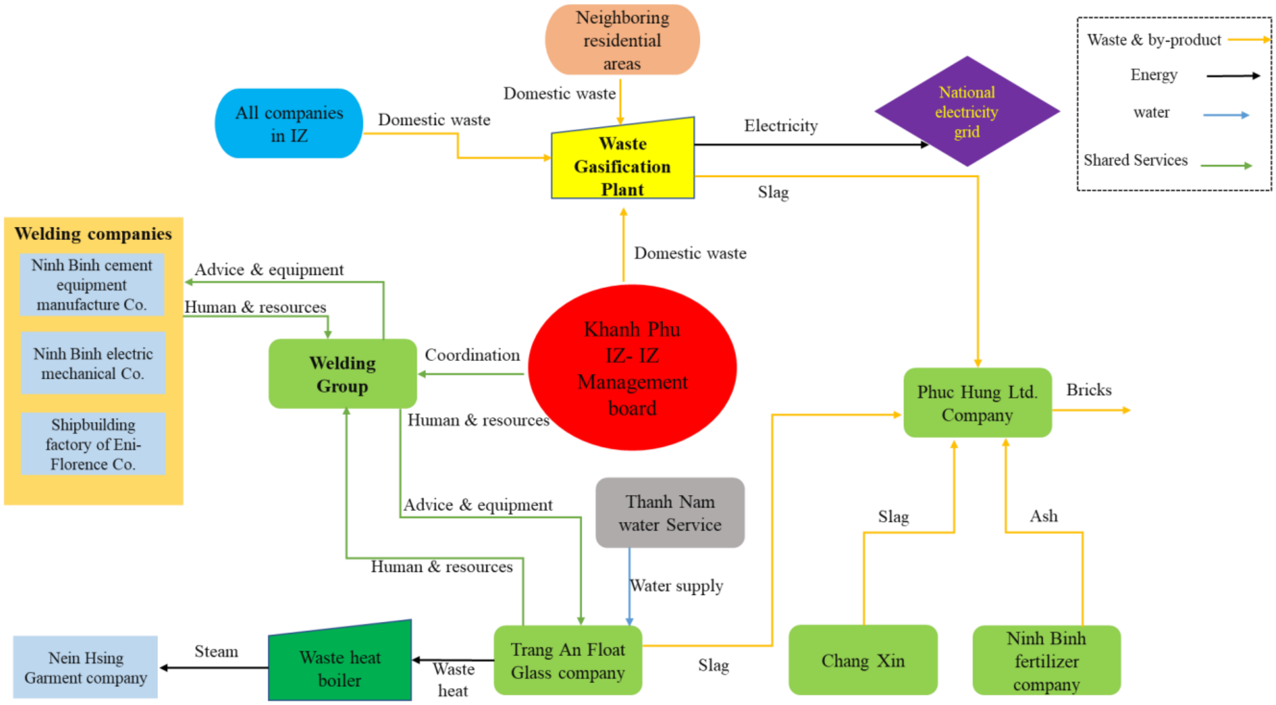


Figure 5.5. Symbiosis opportunities in Khanh Phu IZ

This is a 2-stage gasifier and is preferred over a 1-stage gasifier due to increased stability through the production of liquid dimethyl ether (DME) as opposed to unstable gas production. In detail, the brief introduction of this technology is shown in Fig 5.6.

The organic waste was converted to syngas. This gas kept transforming dimethyl ether (DME) via a two-step process: (1) Methanol in the presence of a catalyst, then subsequently by methanol dehydration in the presence of a different catalyst into DME.

$$CO + 2H_2 \rightarrow CH_3OH$$

$$CH_3OH \rightarrow CH_3OCH_3 \text{ (DME)} + H_2O \text{ or } C_2H_6 + H_2O \,/\, CH_3OCH_3 + H_2$$

The DME production, which goes through the condenser to decrease its temperature and continuously passes through the fine filter prior to reaching the DME tank. At the tank, this temperature is maintained at 25°C and 0.5-7 Bar to ensure the liquefaction of DME. This gas can use to run internal combustion engines (such as diesel engines). In this performance, it could be used as an alternative fuel in a generator set to produce electricity.

The biochar by-product is discarded at every two hours. And then, it is transferred to the pellet biochar production zone to create pellets that are used through combustion to meet the energy needs of industrial or daily life purposes. Biochar and its ingredients do not cause secondary environmental impacts. This process produces two major products: (1) – The electricity produces from DME combustion. (2) – Slag from the gasifier, which can be used in cement; roof shingles; sandblasting, or a filler in road surfacing.

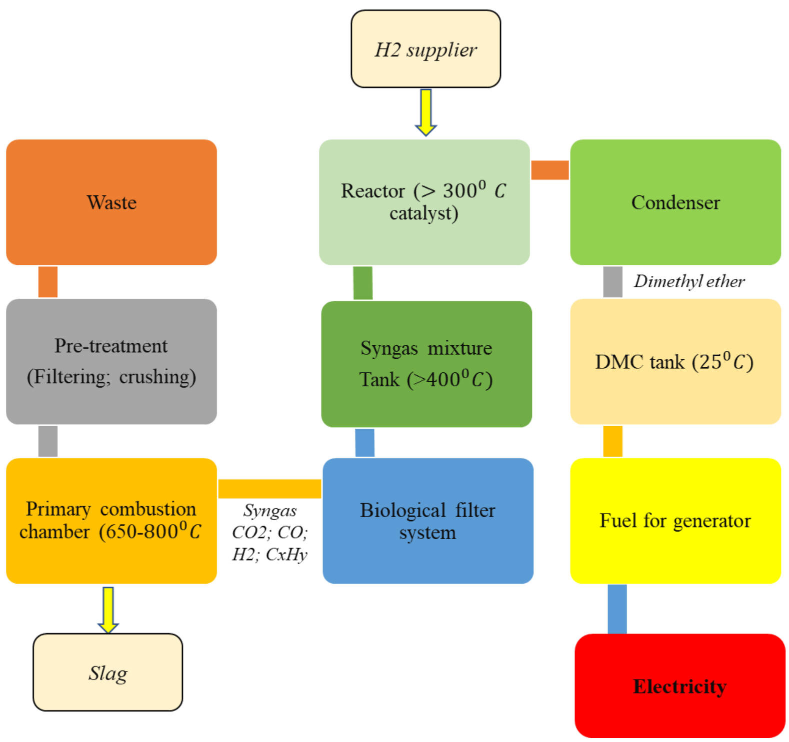


Figure 5.6. HT33E gasification technology – process flow diagram

5.4.2. Opportunities of symbiosis networks in Hoa Khanh industrial zone – Da Nang pilot.

At Da Nang pilot, several potential and opportunities are revealed. Biogas recovery at Heineken company for use as fuel in the boiler of the green energy company, solar energy production on rooftops of Tan Long paper company – A Chau Co.Ltd, green energy company provides qualified boiler operators for Tan Long paper and package factory, using of ash for non-fired bricks and tiles production, collecting and sorting of paper and cardboard waste to be used as input for companies making Kraft paper, and use of waste wood from Viet Lang forest products Ltd company to fuel green energy company boiler, these are symbiosis network opportunities in Da Nang case.

Interestingly, most of these symbiosis networks are centralized on green energy. Hence, one of these green energy performances is chosen to exhibit in this dissertation.

Opportunity: Use of waste wood from Viet Lang Forest products Ltd company to fuel green energy company boiler.

The strategy aims to utilize biomass waste from surrounding communities, milling rice facilities; and scarp dealers, as described in Fig 5.7. Viet Lang company produces the wood waste of 400 m^3 per year with the main inputs (wood and plywood). Meanwhile, wood waste is produced during sawing, drilling, assembling, polishing, and finishing activities. Under the wood waste from Viet Lang company and collecting from nearby areas and milling rice facility, the Green Energy company can save money and make a profit. 400 m^3 or 320 tons (assuming a wood density of 800 kg/ m^3) of waste wood per year, replacing about 3.5% of the annual requirement of woodchips. The fuel consumption of the functioning boilers is 1,000 tons/month of woodchips and 800 tons/month of rice husk. Besides, the steam is about 4000 tons of steam/month-produced by these boilers is supplied to Heineken company.

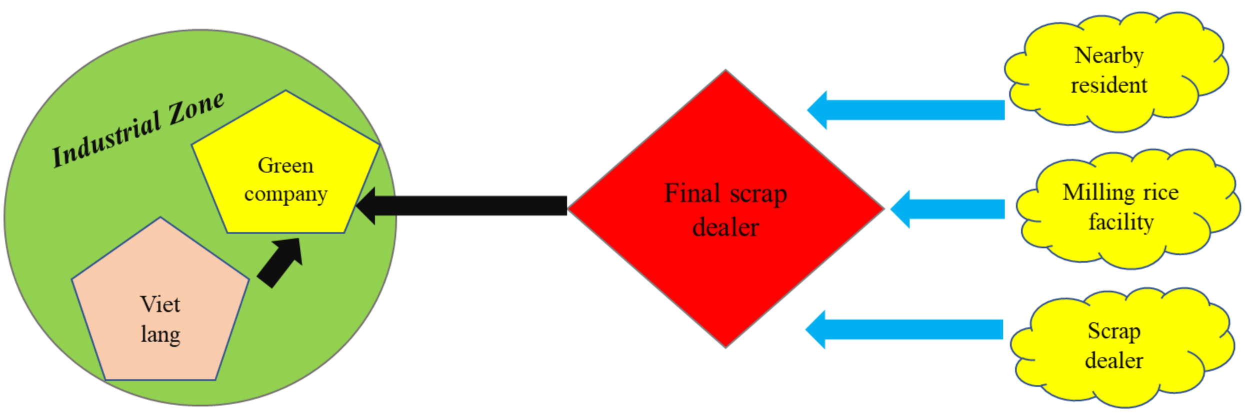


Figure 5.7. Simulation for the collection of waste wood from industrial zone and neighboring areas.

5.4.3. Opportunities of symbiosis networks in Tra Noc I & Tra Noc II industrial zone – Can Tho pilot.

At Can Tho pilot: the variety of industrial symbiosis networks have been performed. All of them are briefly described in Fig 5.8. For instance, utilizing wastewater after treatment of redundant water for the purpose of fire prevention and suppression in Tra Noc II industrial park; segregation of type wastewater before treatment for the purpose of reuse as process water; provide targeted training to improve worker's skills for companies operating in the same sectors; reuse of iron and steel scrap materials from companies in an industrial park by Duc Trien steel company; boiler service company provides qualified boiler operators for companies with large boiler operators in both Tra Noc I &II; and sharing of the cold storage between the seafood companies Nam Hai and Thanh The – Tra Noc I industrial zone; leasing the cold storage of Co Chien seafood company – Tra Noc II industrial zone (Fig 5.8).

While a beneficial performance by recycling wastepaper in this pilot is shown through the opportunity: Collection and sorting and cardboard waste to be used as input for companies making kraft paper. Currently, approximately by the 132 companies located inside Tra Noc industrial park. The wastepaper is generated mainly from the office-use and packaging paper use of all companies. The total value of wastepaper is around 1718 tons per year. It is non-reusable waste and collected by many individual collectors. Throughout the EIP program, the wastepaper has been collected from nearby communities; wastepaper in the own industrial zone; from intermediate scrap dealer; final scrap dealer. All these wastepaper sources provided as input to Nam Hung Phat Kraft company. It saves cost for transportation, storage; human resource costs to collect; as well as is helpful in classified solid waste (reusable wastes: metals; papers; and others). This waste could be used all by this company – reducing 22% of its wastepaper demand (Stucki et al., 2019).

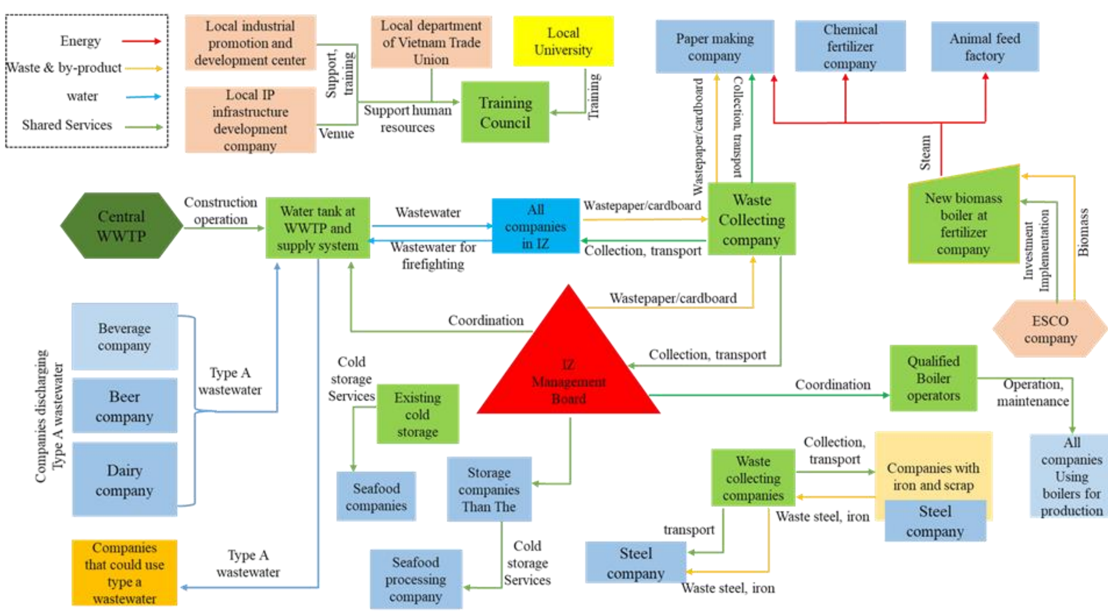


Figure 5.8. Symbiosis opportunities in Tra Noc Iz

5.5. Conclusion

Sustainable development and eco-efficiency goals seem to be caught closer through eco-industrial strategy in this economy. Undoubtedly, many profits, and potential businesses have been formed during the EIP application in Vietnam. Reductions or eliminations of gas emissions, water consumption, wastewater, persistent organic pollutants, solid wastes, chemicals of global concern have been remarkably controlled. Furthermore, this program brought many outstanding and innovative technologies to traditional industrial parks and managers and all stakeholders through workshops/trainings. At the same time, protective and safety methods are provided to workers and workplaces. Especially, many prominent opportunities and great lessons could be approached and extended in many relevant industrial parks in this country and level-multi nations in the world.

However, based on the EIP exhibition, the Vietnamese government, participants, and partners should consider establishing more and more symbiosis networks that can be eligible for reducing hazardous and persistent wastes. On the other side, encouragement and support for other non-EIP program implementations can approach with efficient EIP symbiosis networks under funding from their own government, instead of looking for outer investments or outside support. In addition, upgrading sustainable development and eco-industrial park knowledge might be provided as one of the extra subjects in the educational system. Making encouragement for individuals and operations can provide any feasible ideas in creating symbiosis networks.

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Chapter 6

Conclusion, contribution, future recommendation

Vietnam's national-level efficiency of resource metabolism, environmental issue, eco-efficiency, and the sustainable transition was analyzed, monitored, and optimized through ecological assessment tools. The major objective of this dissertation is to understand national-scale and regional-scale resource and energy consumption from an ecosystem perspective. Also, spread out the ecological scholarship to regions rarely studied. Concurrently, we analyzed policies and upcoming strategies for sustainable development, eco-transition, economic growth in developing countries like Vietnam. Basic and background research questions are as follows:

(1) The changes and fundamental characteristics of resource extraction, consumption, trade in Vietnam at the macro level?

(2) How did the studied country and multi-nation respond to energy consumption and carbonization? Which driving factors do lead the trend, and which is the reasonable way soon?

(3) Do eco-efficiency and industrial symbiosis programs bring and help reach sustainable development and eco-transition?

(4) Any potential and successful symbiosis network that can be performed and extended for entire industrial zones in Vietnam?

(5) How did the previous relevant policies affect on economic growth and environmental degradation? This question was answered under each issue in each chapter.

Under the major questions, the dissertation was designed in "national" and "industrial" ecosystems. Several results are revealed and exhibited below:

6.1. Outcome summary

Starting from the first chapter, some fundamental concepts were refined and considered as a basic background for the dissertation. The missing points of material and energy flow under an ecological perspective have been discussed. It filled out the picture of regional and industrial ecosystems in Vietnam. Tracking this issue in long decades revealed and identified some critical hotspots. Through the research gap, research questions, and analyzed results, the role of the industrial ecosystem leads to sustainable development being concentrated.

To understand the basic characteristics of resource metabolism and assessment of material consumption in regional ecosystems in Vietnam, a conscientious study of physical flow materials was analyzed. It also examined the economic-national wide, following driving policy at the macro-scale. Under the Vietnam case and comparison with multiple typical nations (based on the levels of economic growth and technological advancement), it was highlighted the changes of material extraction, use, and trade in Vietnam and unrealistic materialization in the global trend (Chapter 2). Resource consumption patterns, resource efficiency, and productivity, trade-related issues, as well as drivers and policies affecting resource consumption were analyzed in-depth. The results show that the resource was used inefficiently, with the material intensity index increasing too high (862%), while the resource productivity index significantly decreased (1.8 times from 1978-2017). The balance of imports and exports has been completely changed in recent years. From an environmental perspective, the decline in CO2 intensity has only begun to decline since 2012. Multinational analysis denotes that the technical efficiency gap between Vietnam and comparative countries such as China and South Korea, the efficient technical gap has been widened during the study period. It shows that the level and performance in improving resource shortages and environmental degradation vary widely in each country. As a big step into the future, closely coordinated policies on sustainable resource consumption, carbon reduction, economic growth accompanied by advances in science and technology will help this country overcome the difficulties it is facing. Besides facing the scarcity of materials, Vietnam and the comparative countries have been highly dependent on outside materials through import and export networks.

Furthermore, the impacts from the global trading market, political changes, competitive markets, and innovative technologies, etc. could bring challenges for Vietnam when many primary and mature developed countries like South Korea, Japan, etc. leans on import resources. As per our investigations, all studied countries continuously use intermediate and secondary material and energy with large amounts. Besides, technological factor still plays a key role in rising resource productivity. At the same time, synchronization between agriculture and industrial activities, as well as integrated businesses and correlation sectors, are recommended to lift values of ultimate products as a pathway for the future.

The picture of energy use and carbonization in Vietnam was drawn in Chapter 3. It also addressed the second research question. As per our findings, Vietnam consumed more and more energies – it brought a carbonization increase. Industrialization and modernization are slightly and unstably improving efficient energy and the environment. Dependence on non-renewable energy and narrowly and insufficiently applying renewable energy in entire sectors and fields that causes of rising carbonization in Vietnam. On the other hand, low value of exports with overexploitation resources are advantages – making high material and energy intensity and low profits.

Moreover, the backward technologies and stagnant in applying and changing in internalization production and management apparatus in most developing countries could be the main reason – making developing nations have not yet released their own struggling. Especially, the dynamic of global trade balances, import-export market changes, expansion of regional resource and economic connectivity, big issues in the world could positively and negatively affect developing countries. They easily and significantly suffer from impacts. On the policy analysis, Vietnam has been implemented under the leapfrog approach for a while. In the short-term, it seems to be helpful for this economy to narrow with the economic growth in the world; however, limited in the capable workforce; acquire knowledge; unsynchronous system in applying innovative technologies that made unstable development. Since improvement in human resource with masterful in new technologies and synchronous changes in all fields when leapfrog approach might promote its own meaning.

The third research question was solved in chapter 4. Let us look at the results of eco-efficiency assessment in this country and some other typical countries. Once again, the relationship between economic growth and environmental degradation is reminded in this chapter under the mathematical assessment tool – Taipo and Malmquist - data envelopment analysis. Improving the ecological efficiency of the nation is a meaningful way to realize the synchronous development of society, and environmental policy instruments are a powerful means of improving ecological efficiency in this country. This analysis shows that Vietnam has seen significant changes in eco-efficiency over the last two decades (1990-2017). Compared with typical countries (fasting developing country: China; primary developed: South Korea; mature developed nations: Japan and USA), the pursuit in technology development and scale-up in Vietnam is gradually closing the gap with the compared countries. This effort can be seen through Malmquist indicators. Even though technical efficiency change was a little higher than comparable countries, and scale efficiency change was highest. It notes that Vietnam has centralized on upgrading and improving eco-efficiency performance. However, along with the expansion of scale and equipment, Vietnam needs to pay attention to efficiency because the efficiency index (EFFCH) and TFPCH tend to decrease. That signals the need for early adjustment through careful consideration and consideration of relevant factors (such as capacity of human resources, management, assessment, and monitoring or relevant policies).

To answer the research question four, chapter 5 was performed. A good thing is that the industrial ecosystem transformation in Vietnam has initially achieved remarkable results. In the context of material and energy scarcity, establishments of green energy, recover energy, reusable wastes (wastewater and solid wastes) open the new future for Vietnam and multi-countries. As per economic profits, these creations are helpful in saving costs (avoiding costs for waste disposal, transportation, costs for buying inputs) and increasing product values. Most benefits come from saving materials (total 9364 tons), water supply (1465960 m^3), electricity (57824866 KWh), 91710 tons CO2 emission, etc. It denotes that the EIP program is suitable for dealing with environmental problems in Vietnam. Many opportunities have been performed in a variety of fields. For instance, utilizing wastewater for firefighting, segregation of a type of wastewater for reuse, reuse iron and steel scrap, reuse paper and cardboard, mutualization of the use of boilers, cold storage sharing, biogas recovery, solar energy production, green energy, using ash from non-fired bricks, and provide targeted training to improve worker’s skills. However, under the full permutation polygon synthetic indicator analysis reveals that most food, beverage, slight industrial activities shared significant benefits per total. Meanwhile, heavy industrial activities are less efficient. At the same time, normal waste and materials have been dramatically saved compared with hazardous and persistent wastes. Hence, the EIP program in Vietnam should be active and form new symbiosis networks that can solve harmful wastes.

6.2. Some contributions of the dissertation in the field.

The created aspects of “ecosystems” and their spatial analysis using some mathematical ecological tools were provided in the dissertation. It contributed to management and assessment in industrial ecology. Concepts of regional ecology and industrial ecology with the concrete database. The integration of resource metabolism, economic growth, and regional trade dynamics with extending environmental policies opened the boundary of materialization. In comparison, developing countries like Vietnam have not yet centralized the industrial ecology analysis in industrialization and modernization. Hence, this thesis investigated the physical flow and eco-transition in the low-income nation to find out the potential pathways for the future of dematerialization and decarbonization in this country. Furthermore, evaluation and assessment of eco-efficiency and eco-industrial park transformation in this country show the strength and weaknesses in pursuing sustainable development in this country. Under the analysis of the decision-making unit was highlighted the link between economic growth and environmental degradation in this country. At the same time, some hotspots and efficient strategies with reasonable policies were also confirmed in this dissertation. The comprehensive result could be a key to promoting eco-industrial and sustainable development as a potential way in developing countries. Through the outstanding performance of the EIP program in Chapter 5 that will forecast a blooming of technological and reasonable policies might be announced soon. Towards expectations of urbanization and industrialization under the sustainable development objective will decrease material, energy consumptions with decarbonization reduction soon in Vietnam.

Peer-reviewed articles

1.Ta Thi Huong, Izhar Hussain Shah, Hung-Suck Park, Decarbonization of Vietnam's economy: decomposing the drivers for a low-carbon growth, Environmental Science and Pollution Research (2021) 28:518–529

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1.Ta Thi Huong, Angelo Earvin Sy Choi, Urjinlkham Ryenchindorj, Hung-Suck Park, Critical assessment of the Eco-industrial parks (EIP) program in China and South Korea towards strengthen the EIP program in Vietnam, International Conference on Resource Sustainability 2018, 27-29 June 2018, Beijing, China

2. Gideon Nkam Taka, Ta Thi Huong, Daye Lee, Izhar Hussain Shah, Yujin Park, Urjinlkham Ryenchindorj, Hung-Suck Park, Eco-industrial Parks/Development - A potential strategic tool of circular economy transition in Korea, 2018 Circular Economy for Agri-Food Resource Management, 13-15 June 2018, Seoul, South Korea

3. Ta Thi Huong, Izhar Hussain Shah, Urjinlkham Ryenchindorj, Hung-Suck Park, Resource metabolism in China, South Korea and Vietnam – A pan-regional analysis, 2019 International Society for Industrial Ecology, 7-11 July 2019, Beijing, China