Doctor of Philosophy

Resource Metabolism in Regional and Industrial Ecosystems

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Abstract

Resource metabolism, which refers to the flow, consumption, and transformation of natural material resources into products and wastes, has been rarely studied in the context of regional and industrial ecosystems. Moreover, the existing literature indicates that regional and industrial ecosystems are not distinctive from an industrial ecology perspective and that industrial ecology scholarship is yet to ingress most of the rapidly industrializing economies such as those in South Asia including Pakistan, Bangladesh, and India. These three countries alone represent a 22.6% share in the world population with a meager 3.8% share in the global economy. This is important as developing South Asian countries – a representative regional ecosystem – are implementing rapid economic growth policies at the expense of higher resource intensity. At the same time, Eco-Industrial Parks (EIPs) – a manifestation of industrial ecosystems – are becoming drivers of technologically advanced industrial production in many developed economies around the world. Therefore, bridging the resource efficiency gap between regional and industrial ecosystems requires *an improved understanding of regional and industrial ecosystems and their distinct resource metabolism*. This knowledge becomes crucial as global resource transition is taking place, and industrialized countries are outsourcing resource-intensive production to developing countries. Narrowing this gap could help industrializing economies to design a future transition to low-carbon economic development and higher resource efficiency.

Concerning regional ecosystems, the dissertation applies economy-wide material flow accounting in Chapter 2 and conducts a macro-policy analysis. The results show that with rising per capita income, the three largest South Asian economies (Pakistan, Bangladesh, and India) are witnessing a fast expansion of urban infrastructure, agricultural production, transportation, and small-to-medium scale manufacturing industries. This economic expansion has triggered rapid growth in the consumption of fossil fuels, agricultural chemicals, construction minerals, and industrial materials – most of which are

imported and could have implications for the regional resource supply chain. Moreover, these three countries consume relatively higher materials per unit of economic output (when compared with developed economies) due to their industry structure, narrow range of manufactured goods, and technological backwardness. As a way forward, developing countries could potentially improve resource efficiency through process innovation, sustainable design, sectoral restructuring, and promotion of resource-frugal and high-end production.

The dissertation then applies an efficiency evaluation method, using data envelopment analysis in Chapter 3, to analyze material and carbon efficiency in a typical developing economy i.e. Pakistan. The results illustrate that material intensity has reduced by 39.1% while CO_2 intensity has risen by 21.5% in Pakistan during 1971-2015. Moreover, industrialization in developing countries improves material and carbon efficiency to a certain degree but these improvements are not equally distributed among countries connected through trade. Pakistan, when compared with its top 10 export countries, is found to be relatively more material and CO_2 intensive due to resource-intensive production and low value-added exports. Our results show that the internalization of resource-intensive production has made developing economies relatively inefficient, thus, widening the resource efficiency gap between developing and developed countries. This trend is likely to continue unless resource management policies, environmental best practices such as leapfrog approaches, and technology transfer from developed economies are facilitated through regional cooperation and collective action.

Regarding industrial ecosystems, the dissertation develops an eco-efficiency assessment protocol, using data envelopment method and eco-efficiency indicators in Chapter 4, to analyze urban sustainability transition through Eco-Industrial Development (EID) in Ulsan, South Korea. The results show that improvements within industries (as opposed to industry structure change) could lead to significant eco-efficiency enhancement. Moreover, EID policy implementation offers promising solutions for energy recovery, waste valorization, resource conservation, and value creation. The results also reveal that resource efficiency enhancement at the industrial park level adds to the eco-efficiency improvement at the urban level. According to the results, EID promotion and industrial symbiosis through the Ulsan EIP program improved industrial waste and energy eco-efficiency by 35% and 21%, respectively, during 2000-2015. Resource efficiency in industrial ecosystems is found to improve through industrial symbiosis (e.g. excess energy networking, steam sharing, by-product exchange) and technological improvements (e.g. cleaner production technologies, resource conservation/recycling, and waste valorization).

The dissertation then analyses multiple industry-scale symbiosis projects in Ulsan, in Chapter 5, and studies the waste valorization approach in industrial ecosystems through urban-industrial symbiosis. According to our results, waste valorization is an attractive approach towards value creation from wastes in the form of bio-products (biochemicals, biofuels, and bioenergy) and revenues (avoided costs of waste disposal and selling bio-products). Our findings highlight that integrating industrial ecosystems with urban environmental infrastructures (e.g. municipal wastewater treatment plants and waste incinerators) is an effective strategy for valorizing wastes in industrial ecosystems. Nevertheless, innovative business strategies for urban-industrial symbiosis and governmental support for EID policy are also important. Moreover, by analyzing several large-scale symbiosis projects, we find that urban-industrial symbiosis enhances ecosystem efficiency, improves organic and industrial waste management, creates new business opportunities, and reduces the carbon footprint of a city.

Based on our results, the dissertation potentially contributes to environmental engineering/management and industrial ecology in several ways. First, by analyzing developing economies, the dissertation provides critical insights on materialization and carbonization in the developing world, thus extending the application of industrial ecology to regions rarely studied before. Second, the dissertation defines "regional ecosystems" for the very first time based on systems thinking and industrial ecology literature. Based on this definition, the boundaries of economy-wide

material flow accounting could extend further into environmental policy, regional trade dynamics, and economic development. Third, the dissertation develops an eco-efficiency assessment protocol that could be utilized as a reliable assessment of eco-industrial development and the sustainability transition of industrial ecosystems. Fourth, with the help of several empirical industrial symbiosis projects, the dissertation presents the emergence and application of waste valorization in industrial ecosystems. Based on this, a critical understanding of technical, environmental, and policy considerations in urban-industrial symbiosis could be developed.

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Chapter 1

Introduction

1.1. Overview

Material resources are the fundamental part of industrial and consumer activities, by virtue of which they become essential elements defining industrial ecology. Industrial ecology can be broadly defined as the "study of material and energy flows throughout industrial production and human consumption, environmental impacts arising from these flows, and of the role of economic, regulatory, and socio-political actors on resource flows, consumption, processing, and final disposal (White, 1994). As a result, industrial ecology greatly focusses on resource metabolism within ecosystems and its re-entry into the environment. The overall goal remains to mimic "natural" or "biological" ecosystems as models of industrial activity thereby improving resource efficiency and reducing environmental impact. Resource efficiency can be enhanced using a number of approaches such as material recycling, energy recovery, cleaner production, product innovation, and industrial symbiosis; while it can be quantitatively assessed using a variety of tools such as material flow accounting, life cycle assessment, data envelopment method, and eco-efficiency assessment. Therefore, optimizing resource metabolism at the regional and industrial scales requires an in-depth understanding of the materials involved and their flows in-and-out of the system boundaries. This in turn enables the design and execution of policy scenarios emphasizing environmental and economic sustainability.

This dissertation aims to develop and apply innovative environmental assessment tools to facilitate such a sustainability transition in the regional and industrial ecosystems. The innovative application of various industrial ecology tools is expected to yield efficient resource transformation pathways for sustainable economic and eco-industrial development. The dissertation further aims to contribute to the field of industrial ecology by extending its application to regions and ecosystems rarely studied before. To this end, the focus is kept on developing economies such as those in South Asia. Moreover, to characterize the nexus between resource metabolism and economic growth, the dissertation further compares developing countries with industrialized economies so that “sustainable benchmarks” or “environmental best practices” could be inferred from a policy perspective.

Therefore, the core objective of this dissertation is to enhance our understanding of the distinct resource metabolism in regional and industrial ecosystems and stretch industrial ecology scholarship to regions rarely studied before. To achieve this objective, this dissertation will focus on the materialization and carbonization in developing South Asian economies as a representative “regional ecosystem”, while on the eco-industrial development and urban-industrial symbiosis in Ulsan, South Korea, as a representative “industrial ecosystem”. The research findings at the “regional” and “industrial” ecosystem levels are expected to complement each other in reaching a conclusive and meaningful policy direction for a sustainable economic transition that encompasses environmental considerations to a higher degree.

1.2. Background: Resource metabolism and ecosystems approach

Material resources have become an essential building block for rapid economic growth, industrialization, and urban development. While extremely low resource consumption would not be ideal to support rapid economic growth yet excessive consumption surely leads to severe environmental impacts (Schaffartzik et al., 2019). Moreover, all global material consumption statistics have shown exponential growth in recent decades. In 2015 alone, global material extraction went up to an all-time high of about 12 tons per capita (UNEP, 2019) out of which most ended up being consumed in the developed countries (Steffen and Smith, 2013). This means that low-income developing economies are consuming far less quantity of resources which could affect their survival and quality of life (O’Neill et al., 2018). At the same time, developing countries consume resources inefficiently due to technological limitations and industrial structure. As a result, they are likely to consume more resources to produce an equivalent amount of economic output when compared with developed countries (Shah et al., 2020). Thus, we see a close nexus between the efficiency of resource metabolism and the extent of industrialization.

Industries are known to fuel national economic growth but, at the same time, they also act as a large source of environmental emissions due to extensive resource consumption (Wang et al., 2020). Moreover, the intensity of material and energy consumption is dictated by the industry structure and its technological characteristics. For instance, petroleum and chemical industries could be termed as energy-intensive industries (Hammond, 2000) whereas electronic equipment manufacturing could be termed as less energy-intensive (USEIA, 2016). Apart from energy intensity/consumption, material requirements can greatly vary depending on the type of economic sector. For instance, agriculture requires large quantities of water, land, and chemical resources but produces a relatively low economic output. Comparatively, high-end production of electronic equipment requires relatively fewer materials but produces high economic output. For this reason, we find material use patterns to vary greatly in regional and industrial ecosystems due to their industrialization status and economic structure.

From a systems perspective, combining environmental analysis and decision making for regional and industrial ecosystems lies at the core of industrial ecology (Lifset and Graedel, 2002). More explicitly, systems approach (or systems thinking) in industrial ecology is crucial for understanding how a variety of sub-systems within the main system affect each other temporally and spatially (Arnold and Wade, 2015; Hafner et al., 2020). The systems approach also helps in avoiding conclusions based on narrow analysis, rather it provides an opportunity to extend system boundaries to cater to all potential environmental impacts associated with interconnected sub-systems (Senge et al., 2008). As a result, analyzing resource metabolism in regional and industrial ecosystems could be termed as a powerful manifestation of systems thinking (Lifset and Graedel, 2002).

The term “metabolism” has, however, multiple historical connotations. For example, the term has been previously used in biology (Purves et al., 1992), social sciences (Marx, 1867), and anthropology (Morgan, 1877). In industrial ecology, the term “metabolism” is sometimes used as a metaphor but it has been traditionally portrayed as a core concept characterizing material and energy flows between ecosystems and their natural environment (Fischer-Kowalski, 2002). In this regard, Wolman (1965) was the one to lay the foundations of this concept from an industrial ecology perspective as:

> *“The metabolic requirements of a city can be defined as all the materials and commodities needed to sustain the city's inhabitants at home, at work and at play. Over a period these requirements include even the construction materials needed to build and rebuild the city itself. The metabolic cycle is not completed until the wastes and residues of daily life have been removed and disposed of with a minimum of nuisance and hazard”.*

Certainly, city-level resource metabolism was first to attract scholarly attention, especially in industrial societies. Soon after, Ayres and Kneese (1969) highlighted the potential impacts of an “unbalanced” resource metabolism on the economy. These findings also laid the foundations of “economy-wide material flow analysis”. Along those lines, the concept of “urban metabolism” also emerged and received great attention from urban engineers and environmental managers (Zhang, 2013). Generally, urban metabolism is described as the sum of economic, technical, and social processes occurring in cities causing economic growth, energy generation/consumption, and emission of wastes (Kennedy et al., 2007). Nonetheless, in industrial ecology, the term “industrial metabolism” is often used to depict industrial ecosystems as an ideal biological ecosystem which “feeds” (i.e. consumes) on natural resources, materials, and energy, “digests” (i.e. transforms) them into useful products, and “excretes” (i.e. emits) waste products (Johansson, 2002). Put simply, industrial metabolism follows the basic principles of mass balance approach in tracking material/energy flows throughout their extraction, processing, consumption, and disposal.

With this circumstance, the idea of “resource metabolism” emphasizes material resources as a basic unit of transactions between different ecosystems. Whether a biological ecosystem or an industrial ecosystem, the basic unit of interconnected material exchange could very well be represented by the flow of natural resources in different forms including fossil fuels, biomass, industrial/agricultural minerals, and construction materials. By tracking those flows, the efficiency of their extraction, processing, consumption, and disposal could be better characterized with respect to spatially or temporally defined “ecosystems”.

The concept of “ecosystems” also emerged when Tansley (1935) established it as an analytical unit in biology and plant sciences. In biology, ecosystems are defined as the “organisms and their effective inorganic factors in a habitat”. The concept of “industrial ecosystems” in industrial ecology has emerged from the very need for industrial activity to mimic natural ecosystems (Ayres, 2002). In this sense, natural biological ecosystems are viewed as “efficient” in their resource metabolism and thus serving as an exemplar for efficient cycling of material and energy resources in the industrial production (Lifset and Graedel, 2002). As per the initial typologies presented by Graedel and Allenby (1995), ecosystem definition would vary depending on their reliance on inputs and outputs. Among those inputs, material and energy resources are of primary importance while outputs would include emissions and discharge of wasted resources to the environment. Though there have been different classifications of ecosystems, two important ecosystems based on the flow of resources are presented in Figure 1.1.

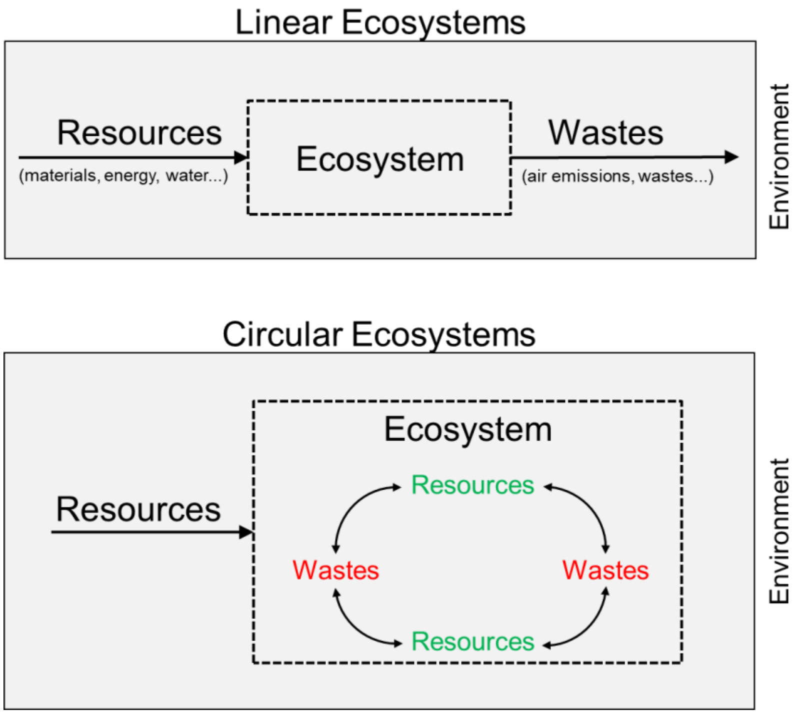

Figure 1.1: Linear versus circular ecosystems.

As illustrated, all input resources are ultimately discarded as waste to the external environment in “linear ecosystems” whereas all input resources are recirculated within the “circular ecosystems” as wastes are seen as potential resources. However, existing scholarship indicates that industrial economies are making progress towards circular ecosystems although ideal circularity may not be technically possible (Lifset and Graedel, 2002).

Another important aspect concerning ecosystems approach is their classification based on spatial boundaries rather than internal characteristics. Some of the regional ecosystem classifications are reported by Host et al. (1996), yet they mostly relate to land classification systems. In this dissertation, we define “regional ecosystems” for the very first time based on systems thinking and industrial ecology literature as:

> *"An ecosystem defined by its geographical boundaries with the flow of resources originating from domestic extraction of resources, followed by their trade (imports/exports), processing, consumption, and waste emissions back into the national environment represented by economy-wide material, carbon, and/or monetary flow statistics."*

Following this definition, regional ecosystems at the macro-scale could be better understood and their relationship with meso-scale industrial ecosystems better characterized. An important aspect of focusing on regional ecosystems is that policy is mostly devised and implemented at the regional ecosystem level, therefore, insights into regional resource metabolism could help strengthen decision making especially at the national level.

1.3. Research objectives and questions

The dissertation was focused on analyzing, tracking, and optimizing resource flows in regional and industrial ecosystems. A variety of environmental assessment tools were developed and/or applied to understand the distinct resource metabolism in terms of energy flows, material processing, waste generation, and production output. The objective was to enhance scholarship on the subject and extend the boundaries of industrial ecology and environmental management to developing countries from a resource sustainability perspective. This dissertation aims to achieve the overall research objective by addressing the following questions:

(1) At the macro-scale, what are the underlying characteristics of resource extraction, consumption, and trade in developing economies?

(2) How a typical developing country could respond to rising materialization and carbonization? What derives its resource metabolism in the long run? And what are the potential pathways for future resource-efficient economic growth?

(3) Can industrial ecosystems help achieve urban sustainability transition through eco-efficient industrial production? And what drives the eco-efficient production and/or consumption within the industrial ecosystems?

(4) Are industrial ecosystems capable of valorizing waste? Is waste valorization even feasible from an economic, technical, and environmental point of view?

1.4. Assessment tools and scope

The quantitative assessment tools used in this dissertation are based on the concepts of environmental engineering and industrial ecology. The methods used will include material flow accounting (MFA), IPAT hypothesis, Log-mean Divisia Index (LMDI) decomposition, Environmental Kuznets Curve (EKC) analysis, macro-policy analysis, Data Envelopment Analysis (DEA), and eco-efficiency assessment. These approaches will be used in a variety of combinations to address our research questions. The results based on the above-described assessment methods will then be used to synthesize key policy recommendations for a transition towards economic and resource sustainability.

The scope of this dissertation is bifurcated into two spatial scales comprising “regional ecosystems” and “industrial ecosystems”. The scope of the “regional ecosystems” research will be limited to developing countries in South Asia, including Pakistan, with a time coverage of about 40 years. Whereas the scope of the “industrial ecosystems” research will be confined to eco-industrial parks in Ulsan, South Korea, with a time coverage of about 15 years.

1.5. Dissertation organization

This dissertation has been written in a modern manuscript style format. Following this chapter, two chapters are dedicated to “regional ecosystems” research and another two dedicated to “industrial ecosystems" research. The last chapter concludes this dissertation. Figure 1.2 shows the dissertation organization based on regional and industrial ecosystems approach followed.

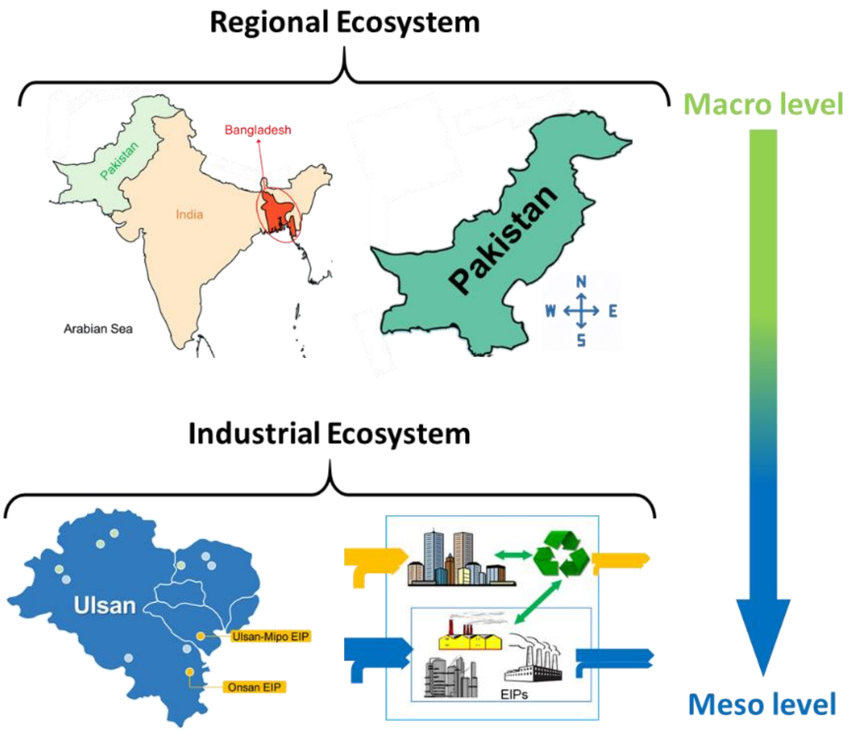

Figure 1.2: Dissertation organization based on an ecosystems approach.

The research on "regional ecosystems", in Chapter 2 and 3, will cover contents such as economy-wide resource use patterns, material use efficiencies, national-level policy developments, driving forces behind several environmental impacts, dematerialization trends, carbonization patterns, regional comparisons, and future sustainability transition scenarios. For this research part, developing South Asian economies have been selected as a representative regional ecosystem. These include the top three economies of South Asia comprising Pakistan, India, and Bangladesh in Chapter 2, after which the dissertation will focus specifically on a typical developing country, Pakistan, in Chapter 3.

The research on “industrial ecosystems”, in Chapter 4 and 5, will cover contents such as eco-efficiency assessment protocol development and application, material and energy efficiencies of industrial production, relative efficiency comparisons among industrial parks/complexes, drivers of industrial waste generation and energy use, eco-industrial policy development and implementation, and integrated waste valorization approaches through urban-industrial symbiosis. For this research part, eco-industrial parks in Ulsan have been selected as a representative industrial ecosystem. The role of eco-industrial development at the urban level will be analyzed in Chapter 4 followed by the study of industry-scale waste valorization projects in Chapter 5.

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Preface to Chapter 2

This chapter will focus on the distinct resource metabolism in regional ecosystems. As we know, transition in global material use has begun over the last few decades. With developed economies outsourcing many of their production elsewhere, low-income developing countries are becoming hubs for economic growth, such as those in the Asian subcontinent, at the cost of rapid industrialization, urbanization, and materialization. Particularly, the three largest economies in South Asia comprising Bangladesh, India, and Pakistan have a huge impact on the global resource supply chain which has never been studied from an industrial ecology viewpoint. These three South Asian economies have a population and GDP share of around 22.6% and 3.8% in the world respectively, as of 2017. In this chapter, we present a regional outlook on the above-mentioned countries by analyzing their resource metabolism from a transitional perspective. The chapter will also analyze policy developments in the region and the impacts of mutual trade on their domestic resource metabolism.

This work is a first-ever attempt to study resource metabolism in Bangladesh, India, and Pakistan, and as a result, an extension of industrial ecology scholarship to such regions. The outcomes are expected to help emerging economies better understand regional material efficiency patterns and the underlying drivers of rapid materialization during the economic growth phase.

Chapter 2

Resource metabolism in regional ecosystems

Abstract

This chapter explores the resource metabolism in three main economies in South Asia (in terms of both scale and growth rate of the economy) namely Bangladesh, India, and Pakistan, with a standard economy-wide material flow accounting approach using the most updated data from 1978-2017. In detail, resource consumption patterns, resource efficiency/productivity, mutual trade dynamics, as well as macro-policies affecting regional resource utilization have been analyzed. Results highlighted that the rapid consumption of imported resources, especially fossil fuels and industrial minerals, has taken place during the last 4 decades. Domestic material consumption per capita has increased by 81%, 93%, and 46% during 1978 to 2017 in the three countries, respectively, due to the living standards enhancement, improved urban infrastructure as well as rapid industrial development. With rapidly growing resource consumption, improvements in resource productivity were still low compared with mature economies like Japan and the United States. Resource productivity was 410.7 USD/t in Bangladesh, 358.7 USD/t in India, and 275.0 USD/t in Pakistan, as of 2017. One critical finding was that resource-intensive production (e.g., primary materials, textile products, agricultural goods etc.) was driving most of the bilateral trade among the three countries, which resulted in lower overall resource productivity. The other critical insight was the increasing regional and global resource competition in the future as indicated by the rising inflow of foreign resources in the subject countries. Finally, the macro-policy analysis highlighted that the impacts of environmental protection and resource conservation policies were quite insignificant. In addition, lower per capita GDP in this region was still a significant impediment for integrated environmental and resource management.

2.1. Introduction

Resource efficiency is a key to realize the Sustainable Development Goals (SDGs), particularly for transitional economies. Clearly and scientifically identifying the status and driving forces behind resource exploration and utilization, in the procedure of rapid economic growth, industrialization, and urbanization, will be critical for developing countries to design innovative and leapfrog pathways towards a resource-efficient future (Chiu et al., 2017; Dong et al., 2017). In this context, leapfrogging refers to non-continuous technological advancement while skipping some phases or steps (Chen and Richard, 2011). The leapfrog concept is highly relevant to developing countries that can learn from the earlier transition of developed countries and avoid the risks associated with research and development as well as experimentation (Gray and Sanzogni, 2004; Tan et al., 2018). Among the popular tools to study a resource-efficient transition, Economy-Wide Material Flow Accounting (EW-MFA) provides a systematic analytical approach and looks into the socio-economic progress together with environmental quality up-gradation (Patrício et al., 2015). Moreover, this method has been widely acknowledged as a tool for assessing and improving resource efficiency and productivity (Huang et al., 2012). It hence offers a sound basis for decision making on resource-efficient and circular economy policies (Bringezu, 2015; Fischer-Kowalski et al., 2011; Raupova et al., 2014; Wiedenhofer et al., 2019).

As far as the application is considered, most EW-MFA studies focus on material resources (abiotic or biotic) which usually exclude sinks, water, ecosystem services, biodiversity etc. Moreover, EW-MFA has been applied in: developed economies like Japan (Krausmann et al., 2011; Moriguchi, 2001) and Australia (Wood et al., 2009); fast-developing countries like China (Wang et al., 2012; Xu and Zhang, 2008) and Philippines (Chiu et al., 2017); regions such as European Union (Calvo et al., 2016; EUROSTAT, 2013, 2007) and Latin America (Russi et al., 2008); industrialized economies such as

China, Australia, and Japan (Schandl and West, 2012) and China, South Korea, and Japan (Dong et al., 2017); and at global levels (Giljum et al., 2014). Results and experiences from these studies and countries are still valuable to provide critical policy insights on sustainable resource management. From the literature review, it is evident that large and low-income developing countries are neglected in this regard and resource use trajectories and country-wide comparisons are absent. Hence, studies on emerging economies are very important to characterize past material transactions and provide policy recommendations for future resources management, particularly in the context of rising regional and global resource supply chain complexity. Under such research challenges, the disparity in economic development phases among different countries is particularly a critical debate linked to local economic conditions, structural characteristics of the industry, technological innovation, and regional resource efficiency (Giljum et al., 2014). Moreover, environmental sustainability relies on the maintenance and improvement of the planet's life supportive capacity through efficient use of natural resources (Moldan et al., 2012) with developing countries at a comparative advantage due to their larger ecological surplus (Sumaila, 2012).

In the developing world, South Asia presents a huge potential for economic and urban development (Sehgal et al., 2017). Given their large populace and resource base, rapid economic growth has been observed during the last two decades (ADB, 2017). However, concerns over resource efficiency and associated environmental implications are scarcely reported in the literature. Bangladesh, India, and Pakistan are the three largest South Asian economies with a population and Gross Domestic Product (GDP) share of around 22.6% and 3.8% in the world respectively, as of 2017. Their socio-economic progress has been marked with a largely underutilized economic, natural, and human resource potential (United Nations, 2017). Although, these countries achieved varying economic development patterns during the last few decades, yet, future economic growth is expected to improve with increasing efforts on security, policy, and economic reforms (ADB, 2017). In summary, the varying economic development and resource use patterns in Bangladesh, India, and Pakistan, with geographical and historical proximity, give rise to several critical questions: (1) how material consumption and economic growth patterns have evolved in the subject countries? (2) what are the driving forces behind changes in material consumption overtime? (3) are the changes in resource intensity and productivity comparable with the rest of the regional economic players? (4) how the trade among the three countries could have affected domestic resource consumption and its efficiency? (5) from a resource productivity perspective, what is there for developing countries to learn from developed economies?

Enlightened by previous works (Chiu et al., 2017; Dong et al., 2017; Schandl and West, 2012), and to address the above-mentioned questions as a first attempt, this study aims to explore the resource metabolism in Bangladesh, India, and Pakistan with EW-MFA approach using up-to-date data from 1978-2017. The aim is to highlight the relative importance of developing South Asian countries in regional and global resource consumption at a time when no previous research exists. Particularly, this study attempts to comprehend how the externalization of resource-intensive sectors by industrialized countries has altered material consumption and efficiency in selected developing economies. Decomposition analysis based on the IPAT equation has also been carried out to explore the driving forces of resource consumption in South Asia to uncover policy insights from a transitional perspective. This study further applied the Environmental Kuznets Curve (EKC) hypotheses to examine the level of dematerialization taking place, if any, followed by a detailed macro-policy analysis to uncover potential pathways towards resource-efficient economic development.

2.2. Materials, methods, and data

This section will elaborate on the chosen methods and the overall research framework along with the sources of data.

2.2.1. Methodological framework

A methodological framework was developed to address the above-stated research questions. The framework comprised of 5 steps and is illustrated in Figure 2.1. Under this research framework, step 1 focused on economy-wide resource metabolism in Bangladesh, India, and Pakistan. In step 2, an analytical structure was established for material flow indicators and efficiency measurements. In this step, a panoramic view was presented, and the existing state of resource metabolism was examined on a macro-scale. Besides, the economic situation was also analyzed along with regional trade among the three countries. In step 3, a database structure was established and applied to subject countries to verify the feasibility of our analytical framework. In step 4, the results of this work were compiled and analyzed based on material flow indicators (described in step 2), and a macro-policy analysis was conducted for the selected countries. In step 5, conclusion and policy implications were drawn based on step 4.

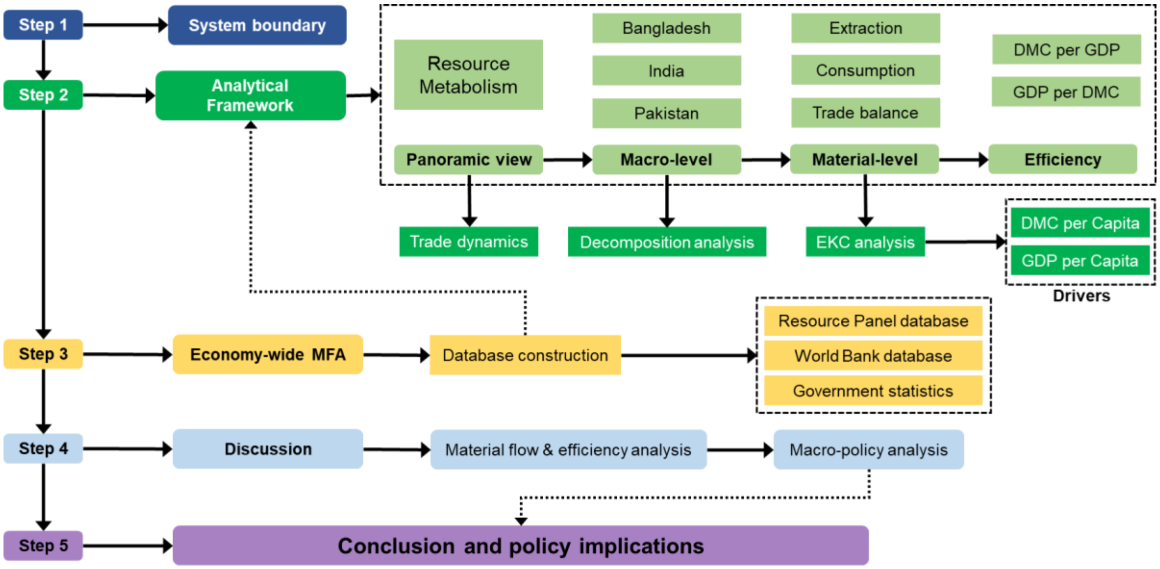

Figure 2.1: Framework for assessing economy-wide resource metabolism.

The three countries were selected based on their importance from both geographic and historical perspectives (Broadberry et al., 2015). Historically, all three of them were part of British India until

1947 when it was partitioned into India and Pakistan, and a later secession of Bangladesh from Pakistan in 1971 – making them regional competitors for natural resources and international trade. Geographically, they are co-located with India sharing borders with both countries – making transboundary trade of primary resources and finished products highly favorable yet socio-politically challenging at the same time. Moreover, no previous economy-wide MFA research has been carried out for the selected countries especially when other Asian countries such as China, Vietnam, Japan, South Korea etc. are emerging as strong competitors for both regional and global material resources. To conduct this analysis, the most recent long-time series data, from 1978 to 2017, has been used as per the established guidelines (EUROSTAT, 2013). As 2017 was the end year, the start year was selected to be 1978 considering past studies which have used datasets of 28 years (Chiu et al., 2017), 29 years (Giljum et al., 2014), 35 years (Schandl and West, 2012), and 38 years (Dong et al., 2017). The selected timeline of 40 years was considered to adequately cover both resource use patterns and policy developments in the region. A four-category demarcation of material flows was done into metal ores, fossil fuels, non-metallic minerals, and biomass which is in line with the standard guidelines. Details of material categorization are given in Table 2.1.

2.2.2. MFA approach and indicators

Based on the research design (Figure 2.1), standard EW-MFA was conducted following the methodological guidelines in EUROSTAT (2013, 2007). As complementation, we referred to some recent studies (Chiu et al., 2017; Fischer-Kowalski et al., 2011; Schandl and West, 2012; Wang et al., 2012) to design and define the main indicators. In summary, three basic indicators were applied, namely, Domestic Material Consumption (DMC), Domestic Extraction (DE), and Physical Trade Balance (PTB). These indicators were also used and analyzed in combination with other socio-economic indicators such as GDP, population, GDP per capita etc. Finally, the EKC was developed based on the selected MFA indicators.

Table 2.1: Categorization used in material flow accounting.

4 categories	13 categories	62 categories
Metal ores	(i) Ferrous ores	Iron ores.
	(ii) Non-ferrous ores	Ores of silver, bauxite, aluminum, gold, chromium, copper, manganese, nickel, lead, platinum, tin, titanium, uranium, zinc, and others.
Fossil fuels	(iii) Coal	Lignite (brown coal), sub-bituminous coal, anthracite, coking coal, other bituminous coal, and peat.
	(iv) Natural gas	Natural gas.
	(v) Oil shale and tar sands	Oil shale and tar sands.
	(vi) Petroleum	Crude oil and natural gas liquids.
Non-metallic minerals	(vii) For construction	Ornamental and building stone, chalk, dolomite, gypsum, structural clays, sand gravel, crushed rock and limestone.
	(viii) For industry/agriculture	Fertilizer minerals, chemical minerals, industrial minerals, salt, specialty clays, industrial sand and gravel, and other non-metallic minerals.
Biomass	(ix) Crops	Rice, wheat, cereal, spice, beverage, pharmaceutical, tobacco, root and tuber, sugar, pulses, nuts, oil bearing, vegetables, fruits, fibers, and other crops.
	(x) Crop residues	Straw, sugar and fodder beet leaves etc.
	(xi) Grazed biomass/fodder	Grazed biomass and fodder crops including biomass harvest from grassland.
	(xii) Wild catch/harvest	Wild fish catch, aquatic plants, and other aquatic animals.
	(xii) Wood	Timber (industrial roundwood), wood fuel and other extraction.

Note: Material flow accounts at the country level are available online in 4, 13, and 62 categories at: www.resourcepanel.org

Among different material flow indicators, “DMC” is an important factor representing territorial consumption of primary materials, while at the same time, taking imports and exports into consideration. The second material flow indicator “DE” refers to the domestic extraction within a territorial boundary and is an important indicator for domestic material availability (Eisenmenger et al., 2016). Mathematically, DMC is calculated as: DMC = DE + imports – exports. The third material flow indicator “PTB” refers to the physical basis of economies and is used to determine the level of self-reliance of a country or a region for different material types (Dittrich and Bringezu, 2010). The PTB indicator is also used to analyze the flow of materials between importing regions (consumers) and exporting regions (suppliers) (Lopez N. et al., 2015). All material flows are expressed in tons (t) or million tons (Mt), where required. Based on DMC, DE, and PTB, intensity and efficiency indicators are designed. The intensity indicator is represented by material consumed (in terms of DMC) per unit of economic value generated (in terms of GDP) and is applied to trace the resource consumption intensity. The second efficiency indicator, which is material productivity, is represented by GDP per DMC based on the so-called concept of “resource productivity” defined as the economic output per unit of resource consumption (Bartelmus, 2002). It is highlighted that this study uses DMC as a proxy for economy-wide material consumption.

2.2.3. Decomposing the drivers of material consumption

Finally, decomposition analysis was used to identify the driving forces of resource utilization in the three countries. The widely used equation in environmental analysis, the IPAT equation, was employed which determines the environmental impacts driven by socio-economic and technological factors (Graedel and Allenby, 2003) and was originally proposed by Ehrlich and Holdren (1971) as given by Equation 2.1:

$$I = P \times A \times T \tag{2.1}$$

Where “I” denote environmental impact, “P” accounts for population, “A” is the economic affluence indicator usually represented by GDP per capita, and “T” is the technological indicator measured in terms of environmental impact per unit of GDP, thus we can re-write the above as Equation 2.2:

$$Environmental\ Impact = Population \times \frac{GDP}{capita} \times \frac{Environmental\ Impact}{unit\ of\ GDP} \tag{2.2}$$

As environmental impacts are influenced by all of the three components in the IPAT equation, this necessitates a need to gain insights into the drivers of environmental impact (Liu and Ang, 2007), thus, leading to the decomposition of IPAT equation. Among the two widely used decomposition methods i.e. Laspeyres and Divisia index, LMDI is often recommended (Liu and Ang, 2007) and was used in our analysis to decompose drivers of “I” in the IPAT equation. The additive factorial decomposition method has been selected due to its ability to report results in absolute quantity of DMC variations whereas multiplicative factorial decomposition is often used when relative contributions are required, however, both produce similar results (Jeong and Kim, 2013). As per our selected method, drivers of change in DMC can be calculated according to Equations 2.3 to 2.6.

$$\Delta I = \Delta DMC = DMC_{t_1} - DMC_{t_0} = \Delta P + \Delta A + \Delta T \tag{2.3}$$

$$\Delta P = \sum \frac{DMC_{t_1} - DMC_{t_0}}{\ln DMC_{t_1} - \ln DMC_{t_0}} \times \ln \frac{P_{t_1}}{P_{t_0}} \tag{2.4}$$

$$\Delta A = \sum \frac{DMC_{t_1} - DMC_{t_0}}{\ln DMC_{t_1} - \ln DMC_{t_0}} \times \ln \frac{A_{t_1}}{A_{t_0}} \tag{2.5}$$

$$\Delta T = \sum \frac{DMC_{t_1} - DMC_{t_0}}{\ln DMC_{t_1} - \ln DMC_{t_0}} \times \ln \frac{T_{t_1}}{T_{t_0}} \tag{2.6}$$

Where ΔDMC is the environmental impact indicator representing changes in DMC from the starting year t_0 (1978) to end year t_1 (2017), ΔP represents population change, ΔA represents the change in economic affluence (in terms of GDP per capita), and ΔT represents the change in technology (in terms of DMC per GDP), respectively.

2.2.4. Data resources

In this research, we used the International Resource Panel (IRP) database (www.resourcepanel.org), launched by the United Nations Environment Program for economy-wide material flow accounts from 1978 to 2017. According to IRP, material flows and consequent resource productivity indicators can be used for monitoring changes in the patterns and rates of resource use with high accuracy and reliability.

Although material flow data until 2017 are available, yet some of the datasets are projected based on values from previous years (IRP, 2018). In detail, data from 1978 to 2012 is real without any projections. For the years 2013-2014, most of the data is real but partially complemented by projected values, while the data for 2015-2017 is mostly based on projections from previous years, due to the reason that original official statistics usually lag for some years in most developing countries (including those selected for this study). However, socioeconomic data such as GDP and population are real data for all the periods. Moreover, the socio-economic statistics are adjusted based on constant 2010 US dollar prices (or otherwise indicated) available at the World Bank's statistical archives (data.worldbank.org). Dollar prices based on exchange values were used in this study instead of Purchasing Power Parity (PPP) as they accurately represent a stable value of economic activity within a country (Schandl and West, 2010). This was done to avoid any overestimation of resource productivity or underestimation of resource intensity that may occur due to inflated nominal GDP values reported by individual countries.

2.3. Overview on Bangladesh, India, and Pakistan

Bangladesh, India, and Pakistan are the three largest South Asian economies, yet their environmental issues are rarely studied from a macro-policy and transitional perspective. The detailed socio-economic status of Bangladesh, India, and Pakistan is summarized in Table 2.2.

Table 2.2: Socio-economic data for Bangladesh, India, and Pakistan.

	Bangladesh	India	Pakistan
Population, million	164.67	1,339.18	197.02
Population rank (world)	8th	2nd	6th
GDP, billion USD [a]	179.99	2,660.37	240.86
GDP rank (world)	43rd	6th	40th
GDP rank (South Asia)	3rd	1st	2nd
Avg. GDP growth rate, 1978-2017	5.04%	6.05%	4.95%
Per capita GDP, USD	1,093	1,987	1,223
Per capita DMC, tons [b]	2.66	5.54	4.45

[a] *GDP figures are based on constant 2010-dollar prices.*

[b] *DMC refers to the domestic material consumption.*

Note: Data corresponds to the year 2017 or otherwise indicated.

Moreover, with vast areas of land covered by these countries – around 3.84 million square kilometers – and an enormous population, the hunt for natural resources is ever-increasing to support the regional development and rapidly evolving economic and urban paradigms. In Bangladesh, significant economic growth has been fueled by its agricultural, textile manufacturing, and shipbuilding/breaking industries especially during the last two decades (Asadullah et al., 2014; Ethirajan, 2012; Reuters, 2013). India, the largest South Asian economy with a huge population, is an aggressively developing country at rapid growth rates where economic liberalization and rising foreign direct investments since the 1990s have helped sectors including information technology and software, services, manufacturing and processing, and agriculture etc. to significantly contribute to the national economic growth (Kathuria et al., 2018; Mazumdar, 2014; WTTC, 2016). Similarly, Pakistan is also making significant economic progress with rapid urbanization occurring during the last two decades mainly attributable to the growing agricultural and light-manufacturing industries, trade openness with the global markets, a surging population, and a strategic partnership with China under the "Belt and Road Initiative". Nevertheless, most of the dominant industrial sectors in Bangladesh, India, and Pakistan could be termed resource, energy, and pollution-intensive carrying low-to-medium economic value, thus, resulting in a large ecological burden (Hu et al., 2019; Sumaila, 2012; Wu et al., 2018).

2.4. Results and discussion

This section will discuss some of the important outcomes of this work. With the help of material flow analysis, key policy implications will also be drawn. The section also discusses the drivers behind material consumption in subject countries.

2.4.1. Domestic extraction and domestic material consumption

As per the results, local resource exploration and extraction have increased, almost uniformly, during the last four decades fueling national economic growth and regional infrastructure development. In this regard, the domestic extraction of resources increased from 109.9 Mt (1978) to 398.9 Mt (2017) in Bangladesh; from 1,914 Mt (1978) to 6,991 Mt (2017) in India; and from 217.7 Mt (1978) to 831.3 Mt (2017) in Pakistan. Table 2.3 presents per capita domestic extraction and material consumption in Bangladesh, India, and Pakistan at five different temporal points. Interestingly, DE per capita during 1978 was highest in Pakistan followed by India and Bangladesh, however, in 1996, India's per capita

DE (3.6 t/capita) surpassed that of Pakistan (3.5 t/capita) while Bangladesh was still at the third place (1.5 t/capita). As of 2017, India's DE per capita was more than double the Bangladesh's per capita DE – indicating large-scale material extraction taking place in the country.

Table 2.3: Per capita material extraction and consumption trends.

DE per capita (t)	1978	1988	1998	2008	2017	% change [a]
Bangladesh	1.43	1.36	1.69	2.10	2.42	69.8
India	2.88	3.16	3.56	4.46	5.22	81.5
Pakistan	2.97	3.42	3.61	4.04	4.22	41.9
DMC per capita (t)						
Bangladesh	1.47	1.44	1.81	2.25	2.66	81.2
India	2.87	3.16	3.62	4.56	5.54	92.8
Pakistan	3.04	3.53	3.74	4.18	4.45	46.2

[a] *Percent (%) change in 2017 relative to the year 1978.*

Among the DE of specific material categories, an increasing share of non-metallic minerals (mainly used in construction) was observed for all countries. One the one hand, the relative share of construction-based aggregate minerals (in total DE) increased from 2.1%, 27.5%, and 10.1% in 1978 to 28.9%, 45.1%, and 24.8% in 2017 for Bangladesh, India, and Pakistan, respectively, indicating rising extraction of these resources to support the national infrastructure development. While on the other hand, the relative share of locally extracted biomass reduced for all countries during the 1978-2017 period, indicating a transition towards fossil fuel-based growth coupled with rising shares of construction-based minerals. In the subject countries, the extraction of fossil fuels has increased noticeably. Fossil fuel extraction increased from 0.6 Mt in 1978 to 20.2 Mt in 2017 for Bangladesh, from 109.5 Mt in 1978 to 797.1 Mt in 2017 for India, and from 5.1 Mt in 1978 to 32.7 Mt in 2017 for

Pakistan. Although, considerable quantities of energy resources are being locally extracted within these countries, however, rising urbanization and industrialization have caused enormous demand for energy resources especially in India which imported an additional 430 Mt of fossil fuels in 2017 (mainly comprising coal and petroleum products) to sustain its economic expansion. This highlights the unavailability of local resources in subject countries and their rising dependence on global resource supply networks.

Coming to DMC trends in the three countries, as given in Table 2.3, overall DMC per capita has been on the rise quite similar to DE results but with varying shares of each material type. Moreover, the DMC growth pattern was almost uniform within each of the economies. During 1978-2017, Bangladesh's DMC increased from 113.1 Mt to 438.3 Mt, India's DMC increased from 1,912 Mt to 7,417 Mt, while that of Pakistan increased from 222.6 Mt to 875.8 Mt – all countries showing a manifold increase. When the per capita DMC in subject countries was compared with other regional countries for 2017, Bangladesh, India, and Pakistan had a lower per capita DMC than that of China (25.4 t/capita), South Korea (15.7 t/capita), Vietnam (14.7 t/capita), Bhutan (10.3 t/capita), Maldives (10.3 t/capita), and Japan (9.0 t/capita) – indicating their developing economic status. However, rapid urban, industrial, infrastructure, and regional socio-economic development are expected to drive per capita DMC up in the coming years.

With regard to specific material categories, DMC patterns nearly coincided with DE patterns for construction-based minerals showing almost a similar growth trend in each of the three countries. As far as DMC of biomass is concerned, in spite of its rising sheer mass, its relative share reduced to 62.3% (from 95.3%) for Bangladesh, to 37.5% (from 63.8%) for India, and to 66.4% (from 85.3%) for Pakistan, during 1978-2017. The reduced share of biomass was compensated partly by fossil fuels and mostly by non-metallic minerals that were used in construction, industrial, and agricultural activities. Moreover, biomass remained a major shareholder in DMC for Bangladesh and Pakistan throughout this period. However, this was not the case with India where construction minerals surpassed biomass consumption, both in sheer mass and relative share after 2010, mainly attributable to the expansion of transport infrastructures, industrial facilities, residential buildings, urban development etc. Also, India's material use has become increasingly dependent on coal and petroleum resources whose relative share in DMC increased from 6.6% in 1978 to 16.0% in 2017. This becomes more important in the wake of global supply fluctuations including, for example, oil export bans on Iran (Dudlák, 2018) which has been a substantial supplier of petroleum fuels to India (World Bank, 2018). On the contrary, Bangladesh and Pakistan have a smaller share of fossil fuels (below 7%) in total DMC and are unlikely to be immediately affected by international trade bans and supply instabilities.

To further analyze the natural material independence of these countries, the ratio of DE over DMC was computed and analyzed. In 1978, DE/DMC was 0.97 in Bangladesh and 0.98 in Pakistan – indicating marginal resource inflow from other countries to meet the local resource demand. While in India, DE/DMC was equal to 1.0 indicating somewhat balanced extraction and consumption status. However, in 2017, the situation has drastically changed as all three countries have a reduced DE/DMC ratio of 0.91 (Bangladesh), 0.94 (India), and 0.95 (Pakistan) – indicating higher domestic consumption and increasing reliance on foreign material inflows. Particularly, India transformed from a resource-neutral country to a resource-deficient country importing higher quantities of natural materials. By 2017, all three countries had become net importers of primary resources.

Factors that may have affected increased resource demand and net resource imports include insufficient local material extraction, higher demand for locally unavailable resources, limited or declining material reserves, incentives on certain material imports, and an increased overall economic and industrial activity. However, for dematerialization to begin, developing countries need to develop locally applicable policies for reducing material consumption with efficient technologies so that resource sustainability is achieved with reduced per capita DMC at all economic levels.

2.4.2. Physical trade balance

The PTB trends for three countries during 1978-2017 are presented in Figure 2.2. Generally, PTB trends provide great insights into the net resource flows to and from an economy with a positive PTB indicating net resource import and vice versa.

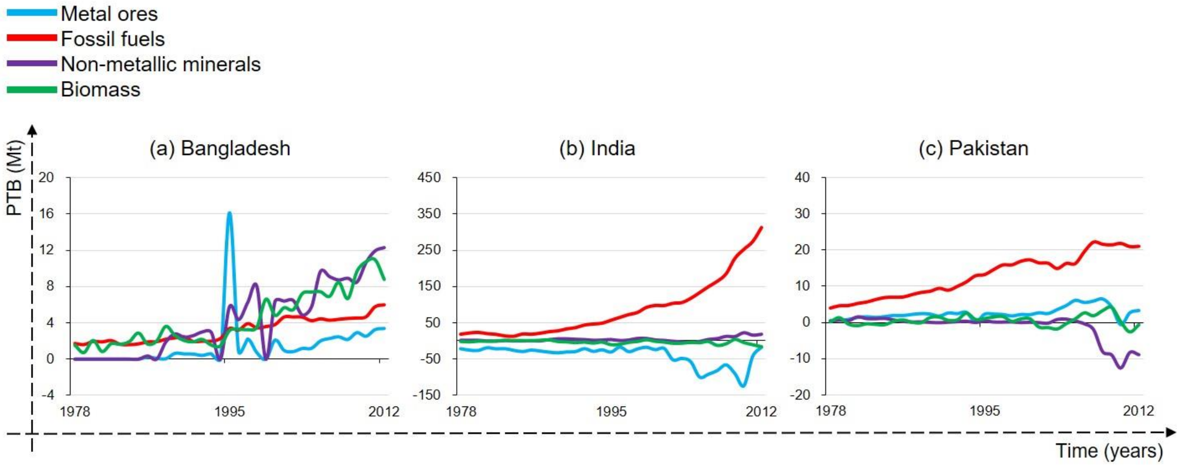

Figure 2.2: Physical trade of materials for the subject countries.

As shown in Figure 2.2 (a) and (c), Bangladesh and Pakistan have traditionally been net importers of resources – though with relatively small aggregate volumes. Back in 1978, Bangladesh’s net resource import was equal to 3.2 Mt with imports only of fossil fuels (1.7 Mt, mainly petroleum and coal) and biomass (1.6 Mt, mainly agricultural crops). In 2017, however, Bangladesh’s net resource import reached 39.3 Mt (~12 times higher than that in 1978) with all imports including non-metallic minerals (14.1 Mt, mainly construction minerals), biomass (13.4 Mt, mainly agricultural crops and wood), fossil fuels (7.8 Mt, mainly petroleum and coal), and metal ores (1.6 Mt, mainly ferrous ores). For Pakistan, net resource import in 1978 was 4.9 Mt with all imports comprising fossil fuels (3.9 Mt, mainly petroleum products), metal ores (0.4 Mt, mainly ferrous ores), non-metallic minerals (0.3 Mt, industrial, agricultural and construction minerals), and biomass (1.6 Mt, mainly wood). Whereas in 2017, Pakistan’s net resource import reached 44.5 Mt (~9 times higher than that in 1978) with imports of fossil fuels (26.2 Mt, mainly petroleum and coal) and non-metallic minerals (21.1 Mt, industrial and agricultural minerals), but with exports of metal ores (1.5 Mt, non-ferrous metals) and biomass (1.3 Mt, mainly wood). Future growth in Pakistan's GDP is expected to exacerbate energy intensity causing higher dependency on imported fossil fuel resources (Rehman et al., 2019), thus, policy measures on energy efficiency and diversification with non-renewable resources could be highly beneficial.

Furthermore, as shown in Figure 2.2 (b), India's PTB profile shows two different phases – before and after the year 1990. During 1989, India's net exported resources amounted to 0.5 Mt comprising imports of fossil fuels (27.5 Mt, mainly petroleum and coal) and non-metallic minerals (6.0 Mt, mainly industrial and agricultural minerals), but with exports of metal ores (32.5 Mt, mainly ferrous ores) and biomass (1.5 Mt, mainly agricultural crops) can be seen. However, in 2017, India's net imported resources (imports minus exports) equaled 426.3 Mt comprising imports of fossil fuels (430.1 Mt, mainly petroleum, coal, and some natural gas) and non-metallic minerals (18.7 Mt), but with exports of biomass (20.9 Mt, mainly crops) and metal ores (1.6 Mt, mainly ferrous ores). Thus, India's transition from a primary resource exporting economy in 1978 to a large resource importing country in 2017 highlights the increased demand for natural resources from developing countries and calls for increased efforts on improving domestic resource efficiency sooner rather than later.

Nevertheless, as of 2017, all three countries had a positive PTB showing increasing dependence especially on non-renewable energy resources and non-metallic minerals used for industrial and agricultural activities – indicating their rising vulnerability to global resource supply and price fluctuations. This situation could further deteriorate in developing countries due to their lack of technological development, low value-addition capability, and internalization of material-intensive sectors. This becomes more important at a time when important regional countries such as China, Japan, and South Korea are also seeking higher resource inflows (Schandl and West, 2012). This means that either domestic extraction has to be greatly expanded or resource trade flows are redirected (Schandl and West, 2010) – all leading to greater competition for regional and global resources.

2.4.3. Material efficiency trends

As a measure of material efficiency, material intensity (DMC per unit of GDP) indicates how efficiently three economies are consuming resources per unit of economic output. As given in Figure 2.3 (a), the material intensity has reduced considerably in all three countries during 1978-2017 with the highest reduction achieved in India (57.4%) followed by Bangladesh (41.7%) and Pakistan (37.9%). The reduced material intensity highlights the fact that increasingly fewer resources are being consumed per unit contribution to the national GDP. Interestingly though, during this period, Pakistan's population grew by 169.2% while that of India increased by 101.2%, thus, indicating an inverse relationship between population growth and material intensity.

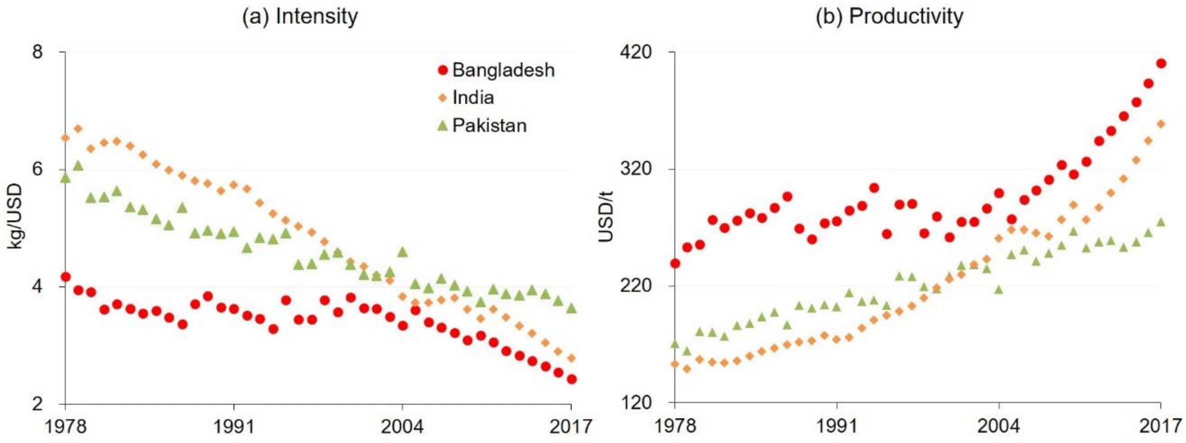

Figure 2.3: Material efficiency trends in Bangladesh, India, and Pakistan.

As of 2017, the material intensity was highest in Pakistan (3.6 kg/USD) followed by India (2.8 kg/USD) and Bangladesh (2.4 kg/USD). Such levels of material intensity were comparable with China (3.5 kg/USD) but were quite low as compared to Vietnam (7.9 kg/USD). On the contrary, subject countries were much more material-intensive as compared to developed countries such as Japan (0.2 kg/USD), United States (0.4 kg/USD), and South Korea (0.6 kg/USD). This endorses the view that material intensity improvements achieved by post-industrial economies have been counter-balanced by material-intensive countries in the developing world – offsetting some of the material efficiency gains made at the global scale (Bithas and Kalimeris, 2018). Nonetheless, developing countries could reduce their material intensities through light-weight design approaches, extended product lives, increased re-use, remanufacturing, and recycling approaches (Stahel and Clift, 2015).

Material or resource productivity, expressed as the economic output produced per unit of DMC, is an important indicator to compute economic contribution per unit of material consumed. Results for material productivity, as shown in Figure 2.3 (b), indicated considerable improvements within the subject countries. As per the results, resource productivity during 1978-2017 improved by about 72%, 135%, and 61% in Bangladesh, India, and Pakistan, respectively, indicating significant improvements made especially by India. Despite such improvements, resource productivity in 2017 was highest in Bangladesh (410.7 USD/t) followed by India (358.7 USD/t) and Pakistan (275.0 USD/t). Comparatively, productivity here was significantly low compared to industrialized economies such as Japan (5,393 USD/t), United States (2,628 USD/t), and South Korea (1,664 USD/t), yet similar or even higher as compared to China (288.7 USD/t) and Vietnam (125.1 USD/t). Interestingly, India and Bangladesh had higher productivity than China, yet, their comparatively lower resource consumption translates into lesser economic output. Nonetheless, as material intensity reduction go hand in hand with productivity improvement, steps such as process innovation, industrial restructuring, design change, and material intensity reduction are particularly important for developing countries to achieve significant resource productivity such as Japan and United States (Lee et al., 2014). One approach to improve resource productivity is to outsource low-value and material-intensive manufacturing and promote resource-frugal (high-tech) industries and services. But on the flip side, higher productivity at one place at the cost of higher material intensity at another adds no value to the system as a whole. Some even argue that mimicking the urban development model of developed countries may lead to “concrete forests” with unsustainable material consumption patterns (Kapoor, 2001; Sheraz, 2014). However, a transition towards a service-oriented economy could be used to promote resource efficiency (Koskela et al., 2013) along with regional resource management strategies that incorporate local economic, social, and environmental considerations.

2.4.4. IPAT equation and its drivers

With the help of the IPAT framework, drivers of change in material use were investigated for Bangladesh, India, and Pakistan. The environmental impact (ΔDMC) was decomposed into population, affluence (GDP/capita), and technology (DMC/GDP), and the overall results are presented in Figure 2.4. In Bangladesh and India, rising DMC was driven partly by population and mainly by economic affluence, however, technological enhancement played a major part in slowing the growth of DMC. Among the drivers of DMC increase, the role of population was relatively less yet very significant as compared to affluence, highlighting large resource consumption due to expanding urban and social lifestyles. In Bangladesh and India, the contribution from technology in reducing DMC was lower than the impact of affluence in increasing DMC, yet it was able to partially offset growth in resource use driven by the other two factors. In Pakistan, rising DMC was driven largely by population followed by affluence, however, technological enhancement played a relatively smaller role to curb ΔDMC. This indicated significant impacts of rapid population growth in Pakistan which has led to higher human consumption of resources without much contribution to the national economy. In fact, population growth rates in Pakistan are among the highest in South Asia (DGIS, 2008) but are rarely addressed due to socio-political reasons. Nonetheless, to minimize impacts of population on ΔDMC in Pakistan, efforts should also be directed towards discouraging extravagant resource use in modern-day lifestyles and controlling rapid population growth rates in the country.

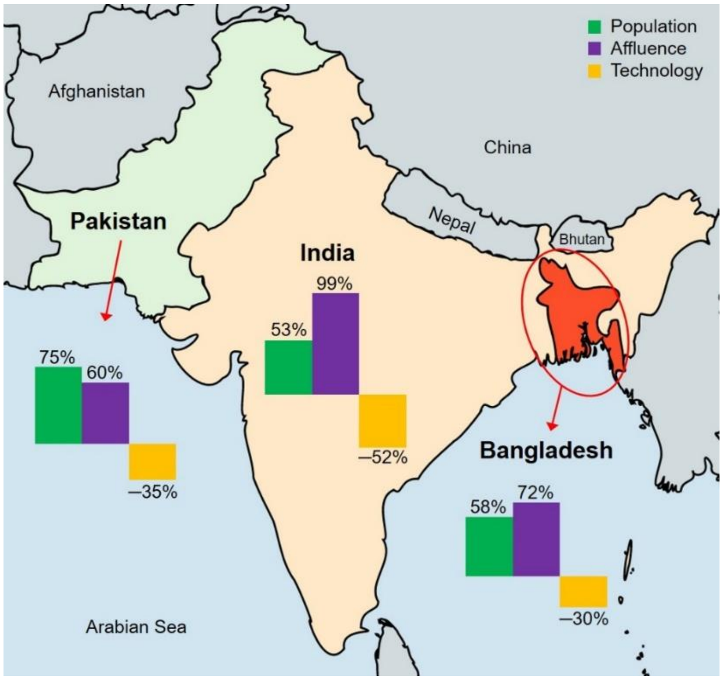

Figure 2.4: Drivers of domestic material consumption in three countries.

The decomposition results for individual 10-year periods are presented in Table 2.4. Interestingly, ΔDMC was significantly higher during 1998-2017 as compared to 1978-1997, which is in accordance with large urban and infrastructure development taking place in the three countries. During the last decade (2008-2017), large material consumption has taken place in Pakistan due to the development of large-scale infrastructure projects and special economic zones under the "Belt and Road Initiative" in partnership with China causing DMC to rise significantly especially for construction and energy resources. In India and Bangladesh, rising exports coupled with rapid urbanization have fueled economic affluence which in turn has caused rising resource consumption.

As of now, all three countries show a large potential for technological innovation that can be strengthened through improved environmental management via eco-industrial development and the promotion of sustainable agriculture.

Table 2.4: Drivers of material consumption during 1978-2017.

Driver (%)	1978–87	1988–97	1998–2007	2008–17
	Bangladesh			
ΔDMC (Mt)	32	84	105	104
Population	109	49	43	37
Affluence	38	47	99	164
Technology	-47	3	-42	-103
	India			
ΔDMC (Mt)	723	1,045	1,780	1,957
Population	71	59	42	37
Affluence	66	100	114	165
Technology	-37	-59	-56	-102
	Pakistan			
ΔDMC (Mt)	135	137	189	192
Population	69	82	66	75
Affluence	68	42	72	66
Technology	-37	-24	-38	-41

2.4.5. Application of EKC hypothesis

Based on the material use and economic indicators, EKC curves were developed and examined. The EKC of Bangladesh, India, and Pakistan are illustrated in Figure 2.5. Comparatively, EKC of China, South Korea, Japan, and the United States are also presented. The vertical axis was used to represent environmental impact (DMC/capita) while the horizontal axis was used to represent economic prosperity (GDP/capita) using the second-order regression curves.

As per the EKC analysis, countries achieving dematerialization did not follow a straight economic path, rather their economic capacity varied at the time of crossing the inversion point. Among the developed countries presented here, Japan was first to reach the inversion point in 1987 with a per capita GDP of around 32,000 USD. United States was next to achieve dematerialization in around 1997 when their per capita GDP surpassed 40,000 USD. This was then followed by South Korea which achieved EKC inversion with a per capita GDP of about 20,000 USD in 2007. Although, these results are based on 2010-dollar prices, however, the EKC inversion point does not appear to be correlated with any income range. This shows that DMC can be decoupled from economic growth at a lower economic stage as seen in the case of South Korea. As with China, it has crossed per capita DMC of Japan and South Korea and is about to reach that of the United States, indicating a potential dematerialization taking place sooner probably at a per capita GDP below 20,000 USD. This highlights the significance of sustainable development policies adopted by China in order to promote cleaner production, eco-friendly industrial development, and resource efficiency – all under the ambit of a circular economic model (Su et al., 2013).

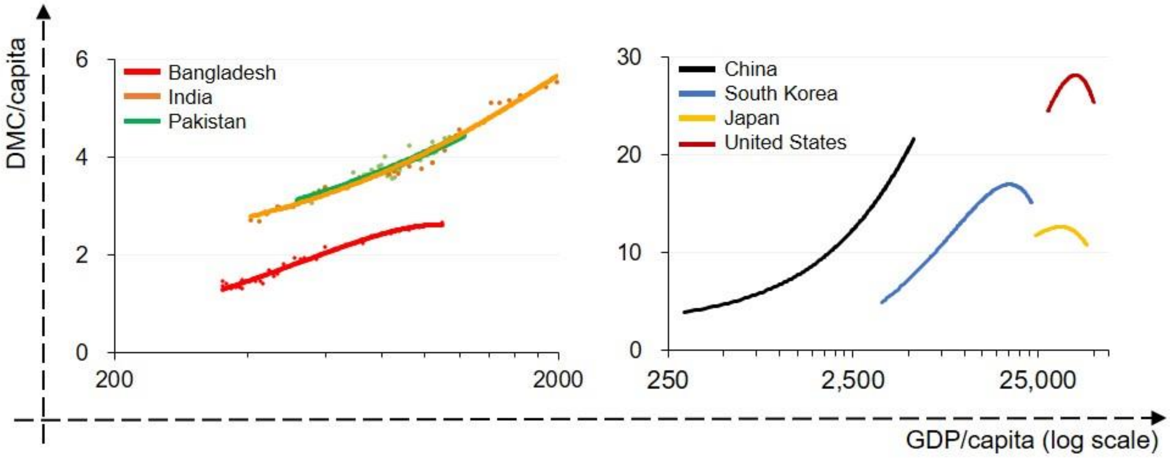

Figure 2.5: Kuznets curves for selected countries.

Nonetheless, Bangladesh, India, and Pakistan are still far behind the EKC inversion point. Moreover, they need not follow the same development path of mature economies. Rather, these countries should focus on applying locally developed innovative technologies and efficient resource management strategies to decouple rising resource consumption from economic growth via transitioning towards material-efficient industrial production.

2.5. Macro-policy analysis

At a macro-level, some of the economic and material indicators, in three dimensions, are presented in Figure 2.6 using second-order polynomial regression curves.

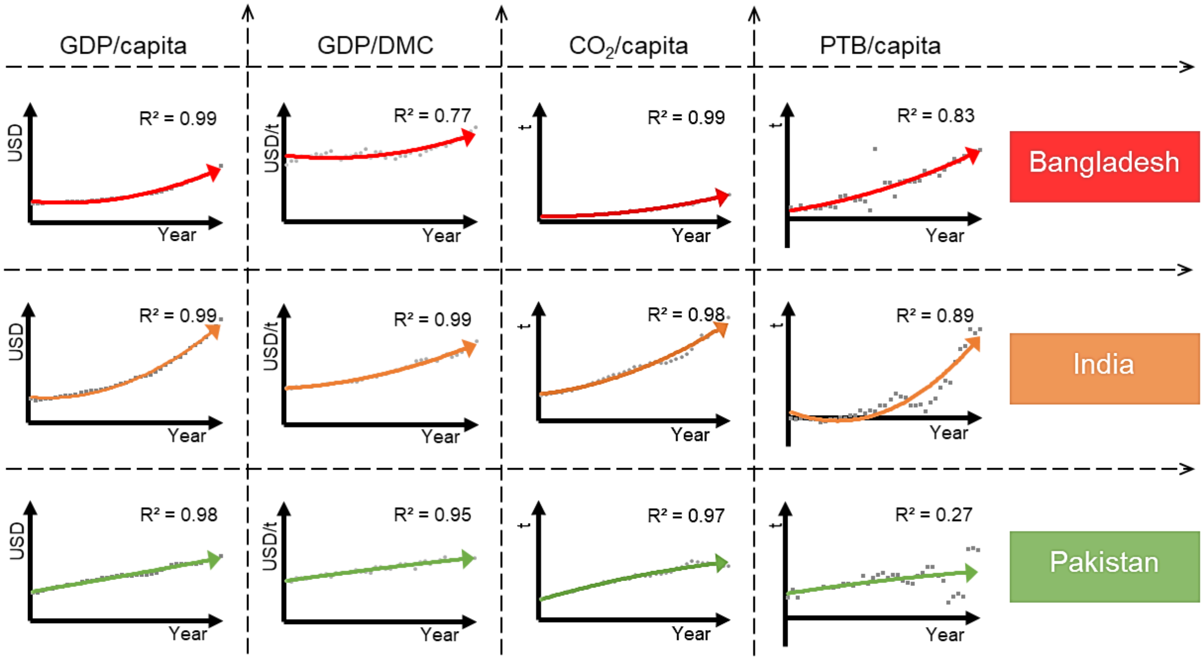

Figure 2.6: Overview of economic, environmental, and material flow indicators.

[*Note: Vertical and horizontal axis bounds are uniform for each indicator*]

Based on Figure 2.6, some of the discernable aspects are discussed below.

(1) All three countries achieved considerable and uniform GDP growth with India making the fastest economic progress.

(2) The GDP/DMC improvements in Bangladesh were relatively less uniform but highest compared to the other two countries. The period after 2000 showed the highest improvements in all three countries.

(3) As a consequence of rising GDP and material consumption, CO_2 emissions have also been on a uniform rise from 1978 to 2014. As shown in Figure 2.6, per capita CO_2 emissions in 2014 were consistently highest in India (1.73 t), followed by Pakistan (0.90 t), and Bangladesh (0.46 t). More interestingly, Pakistan's per capita CO_2 emissions during 2007-2014 actually reduced by 9.5% whereas per capita GDP increased by 6.7%, indicating decarbonization of economy mainly coming from reduced consumption of fossil fuels (applicable to that timeframe only). Reduced per capita CO_2 emissions during this period were driven by a prolonged energy crisis in Pakistan due to generation capacity issues, demand-supply gaps, price hikes, load management etc. The energy crisis in Pakistan was also aggravated by the energy price surge during the 2008-2009 global financial crisis (Bekhet et al., 2016). As a result, domestic consumption of fossil fuels remained stagnant during 2007-2014 while the population continued to grow rapidly – making the per capita CO_2 emissions drop slightly. Policies in Pakistan are now becoming better aligned with climate change issues particularly with increasing public-private partnerships on efficient resources management and the government's resolve to tackle rising environmental pollution (Javid and Sharif, 2016). However, the quantitative impact of CO_2 mitigation policies remains unreported.

(4) Per capita PTB was positive throughout the study period in Bangladesh and Pakistan, however, in India, per capita PTB changed from negative to positive in the year 1990, indicating impacts of trade liberalization on the physical inflow of resources. Based on R^2 values, per capita PTB was the least uniform in all countries mainly due to large year-on fluctuations in supply and demand for imported resources. This means that future economic growth would translate into higher

demand for imported resources in these countries with significant implications for regional resource supply chains and geopolitical volatility.

2.5.1. Overview of the environmental policy development

The changing regional economic dynamics with open trade policies especially since the 1990s have aided rising exports and consequently higher material consumption in the subject countries. As a result, noticeable changes in regional economic affluence began in 2001 when India's per capita GDP (854 USD/capita) surpassed that of Pakistan (847 USD/capita) for the very first time and has been at the top since then. During the same year, per capita DMC of India (3.7 t/capita) also exceeded that of Pakistan (3.6 t/capita) – indicating a correlation between material use and economic affluence among the regional countries. For this very reason, it is important to understand the evolution of environmental governance and material consumption in subject countries against national economic development – before and after the year 2001. Some of the key features of this environmental evolution are illustrated in Figure 2.7.

As shown (Figure 2.7), environmental policy synthesis in Bangladesh, India, and Pakistan mostly began during the late 1970s and continued for the next two decades. Before 2001, subject countries mainly dealt with institutional development and environmental framework planning and execution, compliance, and total quantity control along with trade liberalization with the world markets to boost local industries and export sectors. During the 1980s and early 1990s, local environmental issues came in the limelight, and the role of state institutions in environmental management was strengthened to some extent. Later in the 1990s, enhanced environmental compliance and emission control regulations were developed in all three countries. This period also showed some environmental improvements at the regional levels when some of the major environmental laws were implemented along with multiple resource conservation policies.

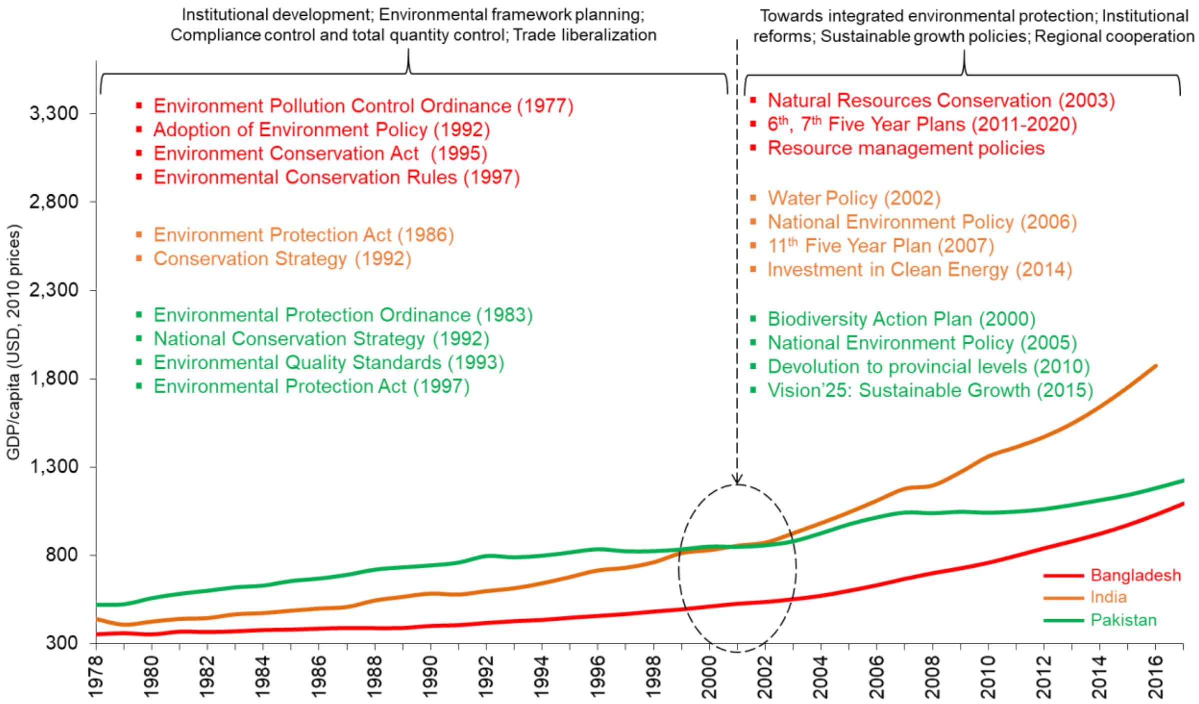

Figure 2.7: Environmental governance versus economic growth.

The time during the 2000s presented rising GDP growth rates, though, performance on resource conservation, energy efficiency, and environmental management was still in early stages. During the late 2000s, rapid economic growth, especially in Bangladesh and India, helped them to strengthen their institutional ability to integrate environmental protection with sustainable development policies. During this time, Bangladesh implemented the seventh five-year plan for accelerating growth and empowering citizens, India began following cleaner production policies, while Pakistan initiated a sustainable development policy (Vision 2030) for the next fifteen years. The integration of environmental policies with economic development was also a result of global developments following the 2030 Agenda for Sustainable Development (United Nations, 2015).

Having said that, environmental compliance is traditionally less prioritized in developing countries as compared to developed countries (Nakicenovic and Swart, 2000). Moreover, as developing countries grow economically, investments in environmental infrastructure and compliance increase gradually – even when environmental laws already exist (Schandl and West, 2010). Thus, with a per capita GDP below 2,000 USD, environmental protection had understandably been fragile in these countries. A traditional practice of "pollute now and clean up later" is also highly relevant to developing countries where later environmental expenditures become significantly large (Chiu and Yong, 2004; Shenoy, 2015). Nevertheless, the socio-economic impacts of national-level policies need to be further explored in the future to optimize environmental resource management.

2.5.2. Mutual trade dynamics

Mutual trade dynamics among Bangladesh, India, and Pakistan were also analyzed to synthesize key policy implications for regional resource supply availability and competition. Figure 2.8 presents the inter-country trade of commodities based on Harmonized System classification level-4 (HS4) for the year 2017 and reported in current dollar prices (World Bank, 2018; USITC, 2019).

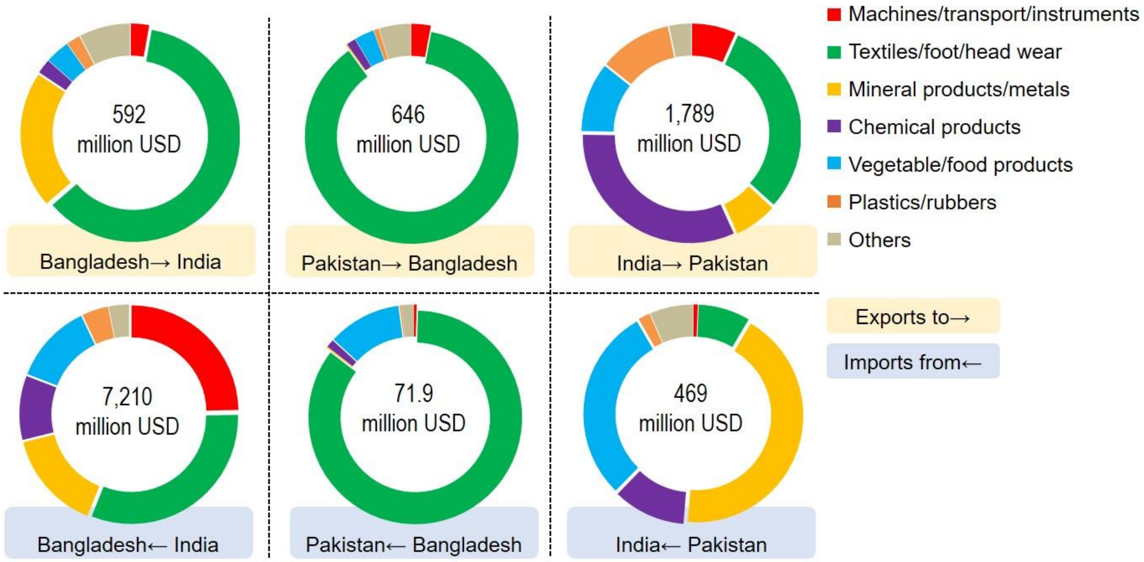

Figure 2.8: Trade dynamics using Harmonized System Classification (HS4).

As shown (Figure 2.8), the traded items mostly belong to material-intensive and low-value sectors such as textiles, agricultural products, minerals, and chemicals – all possessing a higher environmental footprint (Barrett et al., 2018). Therefore, the import dominant trade (in subject countries) with insignificant exports of high-value finished products can be a good area for improving resource efficiency especially when labor availability and their associated costs are comparatively low in this region. With current market dynamics, the trade balance relatively favors India whose exports to the other two countries amounted to 8.7 billion USD while imports from the two countries equaled about 1 billion USD. Understandably, India's large agro-industrial and manufacturing sector can substantially provide trade surplus with its neighboring economies at competitive prices (due to economies of scale). Pakistan and Bangladesh, however, need to make a transition towards energy-efficient and value-added manufacturing industries through which they can produce products of higher economic value but lesser environmental footprint. This can be done through industry restructuring, technological up-gradation in existing industrial areas, phasing-out resource-intensive agricultural products, value-addition in primary and intermediate production industries, and increasing shares of finished products and capital services.

Mutual trade of goods based on their processing stage depicts an interesting picture. India's exports to both Pakistan and Bangladesh comprises about 15% raw materials, 47% intermediate goods, and 38% consumer and capital goods. Bangladesh's exports to India and Pakistan include around 27% raw materials, 28% intermediate goods, and 45% consumer and capital goods. Pakistan's exports to Bangladesh and India consist of nearly 18% raw materials, 68% intermediate goods, and 14% consumer and capital goods. Therefore, with a significant share of primary materials and intermediate goods in exports, the region understandably lacks resource productivity. Since agriculture and industries contribute roughly in the range 40-50% to national GDP in all three countries, self-sufficiency in agricultural chemicals and fertilizers, fossil fuel carriers, and industrial minerals is very crucial from a futuristic policy perspective. Furthermore, as primary and secondary products usually carry low economic value compared to the finished products, a transition towards higher value addition and high-end production can help these countries to sufficiently increase their resource productivity. With regional exporting countries such as China, Japan, and South Korea, competition for future resource supply and entry into new foreign markets for trade, at the time of protectionist policies by some countries, is also very challenging for most of the developing countries including Bangladesh, India, and Pakistan.

2.6. Conclusion and policy implications

This section will highlight the important findings of this study. Based on the results, key policy insights are also provided. The section will conclude by presenting some of the limitations of this work.

2.6.1. Main findings and conclusion

In this chapter, we examined the economy-wide resource metabolism in Bangladesh, India, and Pakistan – the three largest and rapidly growing economies in South Asia. Various material flow and efficiency indicators were analyzed in the context of the regional and global resource supply chains. The domestic drivers of material consumption, environmental policy evolution, and regional trade dynamics were also analyzed. As per the results, per capita GDP levels have risen uniformly with India showing the fastest growth. With rising income levels, the expansion of urban centers, agricultural output, transport infrastructure, industrial facilities, residential buildings etc. have led to a steady increase in DMC especially for construction minerals, fossil fuels, and industrial and agricultural minerals. This rapidly rising DMC has resulted in increasing inflows of foreign resources indicating a potential competition for regional and global resources in the future when important regional economies have already become net importers of primary resources. Material efficiency (in subject countries) was comparable with other developing countries, but significantly lower than developed economies – indicating a higher resource consumption per unit contribution to the national economy coupled with the internalization of energy and material intensive sectors. This was also reflected by higher mutual trade of primary and intermediate products among the three countries mostly comprising textiles, agricultural products, industrial minerals, and processing chemicals. Based on the macro-policy analysis, environmental policy synthesis was found to begin during the 1970s, though, higher GDP growth during the early 2000s provided more opportunities for environmental protection and resource management policies. With considerable legislative progress, current per capita GDP levels were, however, a huge impediment for integrated environmental management.

2.6.2. Policy implications

Based on our findings, we hereby present some of the important policy implications for Bangladesh, India, and Pakistan:

(1) Resource productivity needs to be improved, from a policy perspective, particularly in agricultural and industrial sectors which represent a significant chunk of national economies in all three countries. In the industrial sector, steps including process innovation, the substitution of raw materials, reduced material loss, restructuring, and promotion of resource-frugal and high-end production could have positive impacts. In the agricultural sector, minimizing the use of imported chemicals and fertilizers without compromising the net yield, supporting research on new generation crops, and expanding domestic extraction of agricultural minerals could produce beneficial outputs.

(2) Based on the IPAT analysis, technological improvement was found to offset rising material consumption and reduce the material intensity in all three countries. From 1998-2017, the highest contribution from technological improvement was observed (in slowing the growth in DMC that

was driven mainly by affluence and partly by population). However, technological contribution usually drops with economic growth (Dong et al., 2017), therefore, continued policies on resource conservation and waste reduction must concurrently be implemented.

(3) Lessons from developed countries can also be drawn and incorporated in national-level policies from resource conservation and cleaner production point of view. The application of "circular economy model" in China (Su et al., 2013), "eco-towns" in Japan (Low, 2013) and "eco-industrial development" in South Korea (Park et al., 2018), all provide good examples to developing countries for improving domestic material efficiency. Nonetheless, the rebound effects of industrial and economic development could be avoided using leapfrog approaches (considered during the policy development phase).

(4) As dematerialization in South Korea came at a lower per capita GDP (20,000 USD) compared to Japan and the United States, a similar pattern can also be achieved by other developing countries. Dematerialization in one country at the cost of increased materialization in another country adds no value to the system as a whole, however, small improvements are better than no improvements at all.

2.6.3. Discussion on the limitations of this research

First, data availability in annual transactions [which may neglect manufactured stock materials (Wiedenhofer et al., 2019)] is critical, therefore, data segregation on a lower time resolution could be helpful to incorporate impacts of material stocks. Resource management through the "global trade" point of view could also be a handy research addition in this area.

The other critical issue is the uncertainty generated by the projected data. As some of the available material flow data are projections based on previous years, up-to-date database development is also of utmost importance. For countries with incomplete data, a complementary bottom-up approach (such as a survey of a specific area, individual unit or a sector) for data compilation will be helpful to improve the accuracy of data projection. Application of economic and econometric methods to uncover more information may also offer good data validation and value-added findings. However, uncertainty in macro-level data, even when partially projected, is always a limitation for such type of a study, thus, a necessary investigation of data constraining factors is suggested. Lastly, quantifying the socio-economic impacts of environmental and resource management policies at the national level is also an interesting area and needs to be explored in the future.

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Preface to Chapter 3

Typical developing countries are still struggling to achieve Sustainable Development Goals (SDGs). This chapter focuses specifically on a typical developing country, Pakistan, to examine the extent of materialization and carbonization occurring due to economic development. In this context, materialization refers to the increasing total resource consumption while carbonization refers to the growth in carbon emissions – both closely linked to expanding economic systems. The results are used to see whether Pakistan’s performance with regards to material and carbon intensity has improved or not over a period of 40 years. Also, changes in material and carbon intensities have been compared with those of Pakistan’s major export destinations. This work also delved into national policy development and economic challenges faced by Pakistan that could provide insights for other developing countries. The aim was to identify key areas of improvement, identify best benchmark countries, and assist emerging economies in achieving sustainable growth using industrial ecology concepts and tools.

The outcomes of this work are expected to provide important insights to all other countries with similar socio-economic profiles. The discussions are also expected to help understand major drivers of material use and carbon emissions during early-to-mid developmental stages. The results could be used to develop policies on decoupling economic growth from rising materialization and carbonization.

Chapter 3

Materialization and carbonization in Pakistan

Abstract

With economic growth in many developing countries, not all are making similar progress with regards to material and environmental efficiencies. This study examines material use and CO_2 emission patterns and intensities from 1971 to 2015 in a typical developing country, Pakistan, and investigates national-level and multi-country level efficiency improvements using data envelopment analysis. The results are used to drive key policy insights for a sustainable economic transition with higher resource and carbon efficiencies. Results show that material intensity has reduced by 39.1% while CO_2 intensity has risen by 21.5% in the country. Pakistan, when compared with its top 10 export countries, was relatively more material and CO_2 intensive. National-level efficiency was found to be low in most of the periods due to material/energy intensive agriculture and industries, low value-added exports etc. Insights from the national-level efficiency analysis indicate that surging CO_2 intensities have started to decline since 2010 and the economy has greatly stabilized. The multi-country analysis revealed that the efficiency gap between Pakistan and its developed export countries (such as the United Kingdom and France) has widened during the study period. Insights from the multi-country analysis suggest that the economic growth and industrialization improves material and environmental efficiencies to some extent, yet these improvements are not equally distributed among all countries. As a way forward, integrated policies on sustainable resource consumption, carbon mitigation, and economic growth are necessary for accruing higher benefits from rising global trade and resource connectedness.

3.1. Introduction

Energy and material resources are known to drive economic growth around the world (Ayres 2002; Giljum et al. 2008). At the same time, the rising material consumption is considered to create a proportional environmental burden as well (Mancini et al. 2015). Clearly, a nexus between the scale of resource consumption, economic growth, and environmental pollution exists (Behrens et al. 2007). In addition, rising resource consumption and materialization, in many countries, have made material efficiency a primary policy goal (Cicea et al. 2014). The concept of material efficiency is usually defined as “reduced resource consumption and their associated environmental impacts with sustained economic benefits” (Huysman et al. 2015). Thus, material efficiency calls for responsible consumption of natural resources without compromising the economic aspects (Spuerk et al. 2017) which could be achieved by design improvements and closing the material loops (Choi et al. 2019). Similarly, the idea of environmental efficiency (sometimes also referred to as ecological efficiency) is also gaining interest among researchers and policymakers in the wake of rising CO_2 levels and climate change concerns (Mandal and Madheswaran 2010; Cicea et al. 2014). The national-level response to these challenges is highly influenced by the capacity of individual economies and their scale. This economic capacity can generally be distinguished based on Gross Domestic Product (GDP) of an economy, it’s per capita GDP distribution, and/or its development stage (Kuznets 1995; Ward et al. 2016). Based on contrasting development stages of individual countries, a wide gap between developed and developing countries is visible. For instance, countries such as China are making a rapid transition towards higher affluence while others, such as Pakistan, are moving up the economic ladder rather slowly.

Countries in Asia, including China, India, Pakistan etc., have become “growth hubs” of the world with rising global investment interests (Aneel et al. 2019). However, rising economic growth means higher demand for material and energy inputs (for mass production and consumption), and resulting CO_2

emissions (from energy use, industrial processes etc.). Another effect of rising affluence is the greater consumption of finished products and services within the boundaries of an economic system (as improved living standards tend to increase material consumption) (Zink and Geyer 2017). Therefore, we see a compound effect of economic growth in terms of rising material and energy consumption and higher environmental emissions. Although various strategies have been developed and applied globally to decouple economic growth from environmental impacts, yet the results are not satisfactory (Allwood 2014). To present a larger perspective, Figure 3.1 shows per capita Domestic Material Consumption (DMC), CO_2 emissions, and GDP patterns during 1971-2015 in Pakistan and the top three economies of the world comprising the United States, China, and Japan.

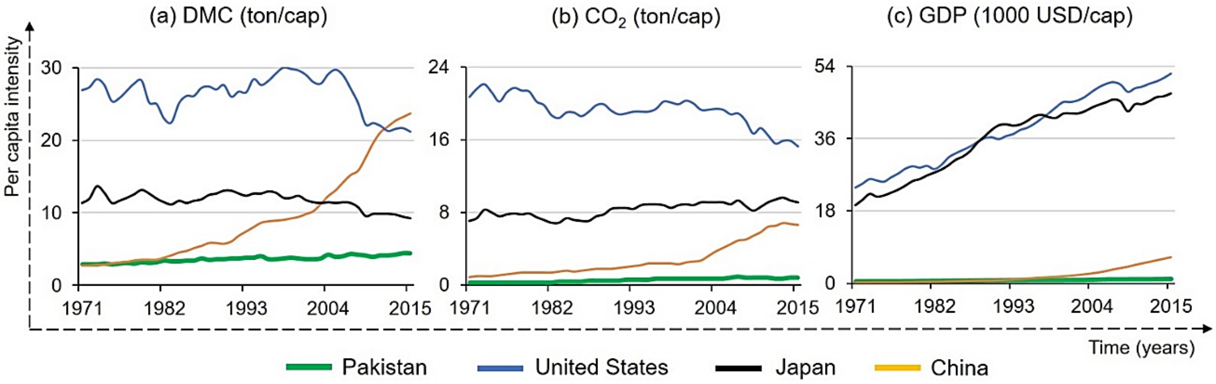

Figure 3.1: Per capita DMC, CO_2, and GDP in Pakistan and the top three world economies.

[*Note: The data pertains to the period 1971-2015 and GDP is in constant dollar prices of 2010*]

Although this comparison might appear unrealistic (large differences in economic affluence, industrial structure, technological status etc.), yet some important patterns can be identified. As shown, the gap in per capita DMC and CO_2 between the developed and developing countries has been narrowing yet the income gap continues to widen. This means that largely populated developing countries, such as Pakistan, are becoming comparatively more material-intensive without achieving higher affluence. At the same time, material use and CO_2 emissions are declining in industrialized economies such as Japan and United States (Figure 3.1) while their economy continues to grow – a typical example of dematerialization and decarbonization taking place in many of the developed countries. However, this apparent decoupling has been attributed to the externalization of resource and emission-intensive sectors to other parts of the world (Schandl and West 2012), most of which are still developing (Baumert et al. 2019). Thus, the notion of dematerialization at one place at the cost of materialization at another appears to be futile, or even damaging, from a systems perspective. In addition, developing countries suffer greatly from the internalization of material- and emission-intensive sectors due to weak environmental institutions/management and the absence of environmental controls (e.g. end-of-pipe technologies). Therefore, this transition in material use and carbon emissions could have crucial implications for developing countries in their pursuit of sustainable economic growth.

To better understand this transitional phenomenon, we have selected a typical developing country, Pakistan, to study material use and CO_2 emission patterns based on long-time series data. The innovative use of Data Envelopment Analysis (DEA) on economy-wide material flows and carbon emissions, as a very first attempt, is made for the period 1971-2015. As per our knowledge and the literature review, no published studies exist on this topic with similar approaches. Another novel contribution of this work is to present a multi-country efficiency comparison of Pakistan with its major export countries. The study also presents, for the first time, a comprehensive overview of Pakistan's economic development, environmental performance, and resource use patterns from a historical and macro-policy viewpoint. Through this work, we aim to address some of the important research questions such as (1) how material consumption and carbon emissions evolve in a typical low-income developing economy? (2) are changes in material and carbon intensities comparable with countries connected through trade/export? (3) does material and carbon efficiencies vary temporally (at the national level, within a country) and spatially (at the regional level, in comparison with other export countries)? and (4) what are the strongest (and weakest) drivers of rising material use and CO_2 emissions based on the available data? Through this study, we intend to address these research questions and derive key policy insights for an integrated approach towards sustainable resources management and economic development.

3.2. Overview on Pakistan

Pakistan is located in South Asia having shared borders with India (east), Iran and Afghanistan (west), and China (north), with a land area encompassing 880,000 square kilometers. With the Arabian Sea (also known as the Indian Ocean) to its south, the geographic location of Pakistan is shown in Figure 3.2.

Figure 3.2: Map showing Pakistan and its neighboring countries.

Pakistan’s nominal GDP ranks 2nd in South Asia and 40th in the world (World Bank 2019). The population of Pakistan, the 6th largest in the world, is about 208 million with an annual growth rate of 2.4% (Hussain et al. 2018). This population growth rate is higher than the average growth rate of 1.7% in all South Asia (DGIS 2008). Moreover, the urban population in Pakistan, as a percentage of the total population, is 36.4% (that in South Asia is 33.5%) indicating higher urbanization in the country.

3.2.1. Economic development

Pakistan's real GDP in 2017 was equal to 240.9 billion USD (constant 2010-dollar prices) translating into a per capita GDP of 1,222.5 USD. The sectoral contribution to national GDP was highest from the services sector (60.2%), followed by industrial (20.9%) and agricultural (18.9%) sectors (Government of Pakistan 2018). The detailed sectoral and sub-sectoral contribution to GDP is provided in Table 3.1.

Table 3.1: Sectoral share in Pakistan's GDP during 2013-2018.

	2013-14	2014-15	2015-16	2016-17	2017-18
	Agriculture (%)				
Crops	8.5	8.17	7.4	7.09	6.96
Livestock	11.7	11.72	11.59	11.33	11.11
Forestry	0.5	0.38	0.42	0.39	0.39
Fishing	20.45	20.67	20.90	20.91	20.91
	Industries (%)				
Mining and quarrying	2.9	2.95	3.0	2.83	2.73
Manufacturing	13.6	13.56	13.44	13.5	13.56
Electricity/gas generation	1.6	1.75	1.83	1.84	1.77
Construction	2.3	2.41	2.62	2.74	2.82
	Services (%)				
Wholesale and retail trade	18.5	18.28	18.31	18.67	18.98
Transport and communication	13.3	13.4	13.44	13.32	13.04
Finance and insurance	3.1	3.16	3.21	3.38	3.39
Housing services/ownership	6.8	6.76	6.72	6.63	6.52
General government services	7.1	7.14	7.49	7.53	7.93
Other private services	9.7	9.88	10.09	10.34	10.38

Note: The statistics are based on Pakistan Bureau of Statistics (Government of Pakistan, 2018).

Industries in Pakistan have seen some growth in recent decades with manufacturing industries having the largest share (mainly comprising textile manufacturing). Textile products in Pakistan, having a large share in exports, are increasingly becoming less competitive as world demand for low value-added products such as textiles is declining (Biller and Sanchez-Triana 2013), thus, making this sector less attractive for investment and growth. In addition, growth in Pakistan's global exports has been slow when compared with other regional countries. As of 2017, Pakistan ranked 68th in global exports (amounting to 19.6 billion USD) which was visibly lower as compared to other regional economies such as China (1st), India (17th), Malaysia (19th), Indonesia (25th), Iran (46th), and Bangladesh (54th) (Simoes and Hidalgo 2011; United Nations 2019).

As far as the GDP growth is concerned, there have been periods of higher economic growth since 1971, however, those periods were rather sporadic and brief. Moreover, much of the recent decades have shown slower GDP growth in Pakistan compared to other regional economies. Several reasons have been attributed to a slow economic growth such as low foreign direct investments (Zubair 2009), import-friendly regimes and informal sectors (i.e. undocumented economic activities) (Sherani 2019), weakening of institutional governance (Husain 2019), terrorism and militancy (Malik and Zaman 2013; Shahbaz 2013), undemocratic interventions (Siddiqa 2017), defense spending and debt servicing (Gizewski and Thomas 1996), and recurring balance of payment crisis (Tariq 2019).

More recently, however, Pakistan has embarked upon a renewed economic partnership with China (since 2016) known as China-Pakistan Economic Corridor (CPEC) program under the "Belt and Road Initiative". With projects budgeted above 60 billion USD, this initiative is boasted to strengthen Pakistan's macro-economic performance in the long run through infrastructure development and trade connectivity.

3.2.2. Resource consumption patterns

As seen in most developing countries, resource consumption has increased with economic growth in Pakistan. Based on the economy-wide material flow statistics (UNEP 2019), the consumption of material resources has surged nearly four-folds in Pakistan during 1971-2015. Figure 3.3 shows the DMC by material type during 1971 and 2015 whereas detailed DMC data is provided in Table 3.2.

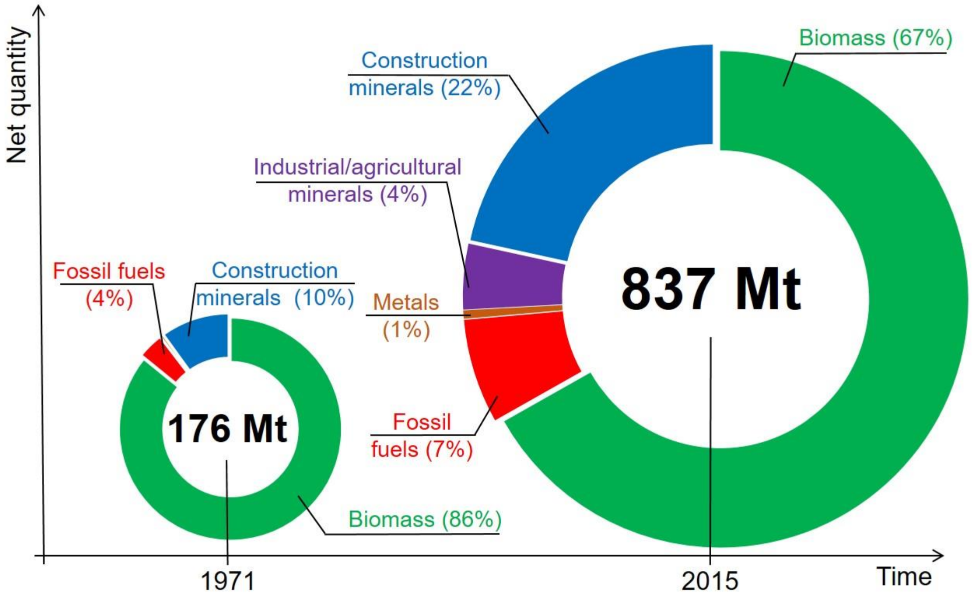

Figure 3.3: Resource use by material type during 1971 and 2015.

[*Note: The donut size is proportional to the value of DMC; materials with shares less than 1% are not shown*]

As of 2015, biomass (defined by its high volume and low energy density) still remains the largest physically consumed resource in the country. This has been a typical phenomenon observed in most of the developing Asian countries (Schandl et al. 2009). However, increasing shares of construction minerals (a low value and high volume) and fossil fuels (high value and high energy density) have also been witnessed. The rising use of energy resources has both advantages and disadvantages for Pakistan's economy. The agricultural and industrial growth can be supported by increased energy supply but with insufficient domestic extraction of local energy resources, importing those resources puts enormous economic pressure on the country.

Table 3.2: Total and per capita domestic material consumption.

Year	Biomass	Fossil fuels	Metals	Agro-industry minerals	Construction minerals	DMC/capita
1971	150.82	6.58	0.03	0.76	17.50	2.94
1975	162.28	8.36	0.01	0.71	21.02	2.88
1980	201.01	10.87	0.75	1.18	26.03	3.07
1985	244.83	15.85	1.85	1.71	46.76	3.37
1990	308.45	23.21	1.68	3.02	55.26	3.64
1995	390.98	30.57	3.07	3.82	64.20	4.01
2000	398.25	37.23	2.15	1.97	74.80	3.71
2005	439.74	46.11	9.62	4.18	107.95	3.95
2010	476.71	51.31	4.34	3.43	128.19	3.89
2015	559.53	56.83	4.59	35.68	180.75	4.42

Note: Domestic material consumption data is acquired from UNEP (2019) and expressed in Million tons (Mt); while DMC per capita is based on total DMC values and population statistics for the corresponding period and expressed in tons/capita.

When domestic extraction (or availability) of certain material resources is inadequate to meet DMC demand, resources can be imported from other countries. Pakistan has traditionally been a resource importing country particularly for coal, petroleum, ferrous ores, and industrial and agricultural minerals. With rising imports, the national exchequer faces huge pressure which sometimes results in a balance of payment crisis. In 2017 alone, 26.2 million tons of fossil fuels and another 33.5 million tons of industrial and agricultural minerals were imported amounting to 10.1 billion and 8.8 billion USD, respectively. During the same year, Pakistan's net imports amounted to 43.9 billion USD while net exports amounted to 19.6 billion USD, thus, indicating a large trade deficit Pakistan faces.

3.2.3. Environmental challenges and management

Rapid urbanization, population growth, industrial expansion, and agricultural development are known to affect environmental quality especially in the early economic development phase (Apergis and Ozturk 2015; Dasgupta et al. 2002). Pakistan is no exception to this phenomenon where environmental costs associated with air, water, and soil pollution have reached alarming levels (Khwaja 2012; Shah and Zeeshan 2016). Sector-wise, agricultural activities contribute to the contamination of soil and water resources due to the immense use of fertilizers and pesticides (ADB 2008) whereas household and commercial solid wastes remain largely untreated and/or are poorly disposed of (Zahid et al. 2018). Higher rates of deforestation in the country, with already a low forest cover of 2.5%, are also known to aggravate environmental dilapidation (Ahmed et al. 2015). But most importantly, the impacts of inefficient energy systems (Abas et al. 2017), poor resource utilization (Sherani 2019), and material/energy-intensive industries (Khan et al. 2009) have greatly exacerbated environmental contamination in Pakistan. Rising global carbon emissions have made Pakistan highly vulnerable to climate change impacts (Shah et al. 2019). As per the long-term climate risk index, Pakistan ranked 8th among the countries most affected by climate change from 1998 to 2017 (Eckstein et al. 2018). This makes material and carbon efficiency analysis in Pakistan, a typical developing country, highly crucial from carbon mitigation and resource management standpoint.

From an environmental management perspective, early efforts on environmental regulation and management were largely absent since the green "agricultural revolution" began during the 1960s. During the 1980s, however, rising environmental awareness partly translated into institutional development and regulatory framework. The first-ever effort in this regard was the promulgation of "Environmental Protection Ordinance" in 1983. Following this ordinance, practical actions were still inadequate owing to social resistance, lack of political will, and institutional and economic limitations. After nearly a decade, industrialization and trade liberalization brought environmental consciousness back into policymaking thus paving the way for the "National Conservation Strategy" in 1992. During this time (the early 1990s), environmental compliance and emission control became mainstream as export-oriented industries started to thrive. Later in 1997, the landmark "Pakistan Environmental Protection Act" was enacted which institutionalized environmental management in the country (both at the national and regional levels). During the next decade, significant growth in per capita income and trade liberalization, particularly since 2002, was accompanied by the "National Environment Policy" of 2005 which systematically promoted cleaner production and environmental efficiency especially in the industrial sector (ADB 2008). These efforts were complemented by banning leaded gasoline, reducing the sulfur content of petroleum fuels, promoting natural gas in transportation, establishing cleaner production centers across the country, tightening environmental quality standards, implementing environment impact assessments for large projects etc. More recently, "Pakistan Vision 2025" was announced in 2014 which acknowledged environmental sustainability as an important pillar of future economic growth (Planning Commission 2014).

3.3. Materials, methods, and data

This section presents the overall methodology used to analyze the efficient use of material resources and CO_2 emissions. Figure 3.4 illustrates the system boundaries and different economy-wide flows relevant to this study.

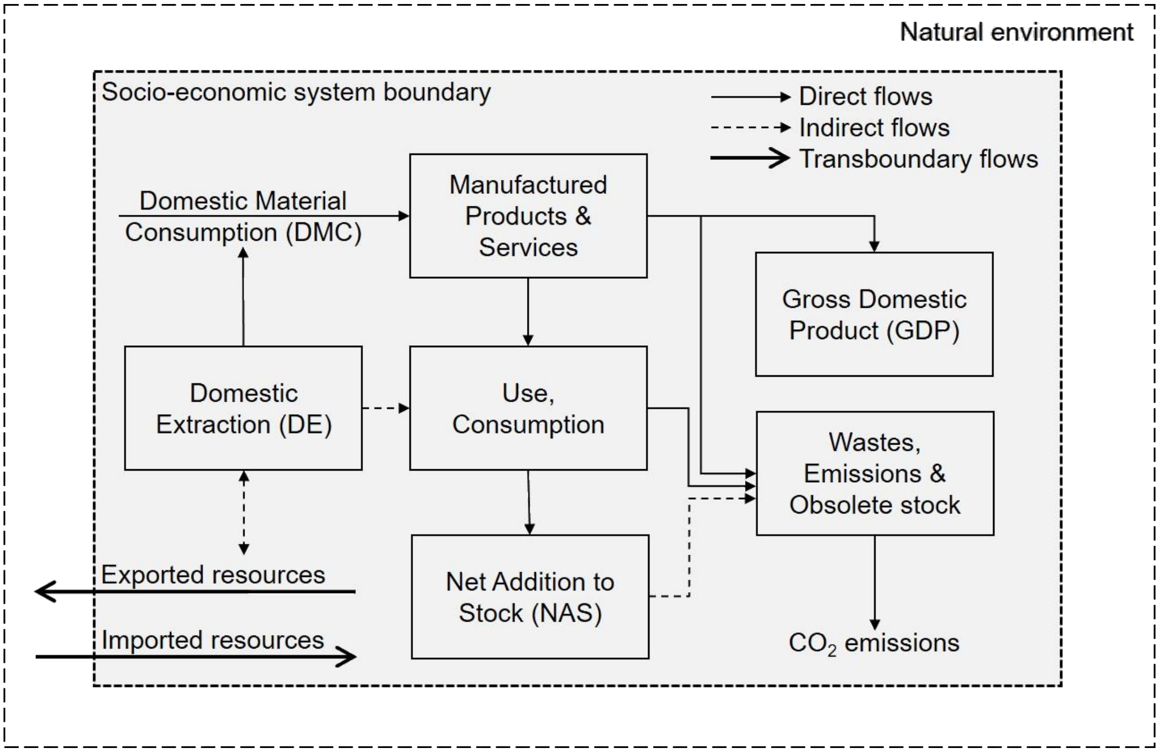

Figure 3.4: Flow of resources within a regional socio-economic system.

3.3.1. Intensity analysis

As a first step, material and carbon intensity was determined using publicly accessible long-time series data. As shown in Figure 3.4, the entire socio-economic system was considered responsible for converting material resources into products, waste emissions, and economic output. In this regard, the material intensity was represented by DMC per unit of national GDP while carbon intensity was represented by CO_2 emissions per unit of national GDP. The DMC indicator was selected as it is a good representation of the amount of resources taking part in the economic function of a country (Chiu et al. 2017; Wang et al. 2012); while CO_2 emissions are known to be closely linked with economic growth (Muhammad 2019; Wang et al. 2019); and GDP is a widely used macro-economic performance indicator (Wursthorn et al. 2011). Data from 1971 to 2015 was used and Pakistan's major export countries were also included to analyze multi-country intensity improvements. Among Pakistan's top 10 export countries in 2015, complete data for Afghanistan and the United Arab Emirates was not available, thus, Saudi Arabia and India (the 11th and 12th partner, respectively) were included in the analysis.

As a complementary analysis, eco-efficiency was also evaluated. The concept of eco-efficiency relies on the economic and environmental dimensions of a product or service and is calculated by dividing economic output by environmental impact. For eco-efficiency analysis in this study, economic output was represented by gross value-added (derived as the sum of the value-added in the agriculture, industry, and services sectors) (World Bank 2020), while the environmental impact was represented by Direct Material Input (DMI). The DMI indicator is an input material flow indicator used to quantify materials of economic value used in production and consumption activities (excluding hidden/unused flows such as mining overburden, soil excavation during construction, and unused biomass from harvest) (EUROSTAT 2001). With the help of this eco-efficiency comparison, country-wide disparities could be identified, and eco-efficient economies could be used as "best practice benchmarks" by other economies.

3.3.2. Data envelopment analysis

Data envelopment analysis is a data-oriented mathematical programming method used to evaluate efficient production functions of "comparable entities" (i.e. entities operating under the same or worse conditions) (Charnes et al. 1978). The definition of these "comparable entities" is flexible, however, they are commonly referred to as Decision Making Units (DMUs) which transform inputs into outputs (Cooper et al. 2011). The DEA method was originally developed for comparative efficiency assessments such as examining the efficiencies of policies within which managers operate (Boussofiane et al. 1991). Since the initial development, DEA has gained wider acceptance due to several benefits such as (1) no prior weights required for assigning relative importance to any input or output (i.e. they can be expressed in arbitrary units) (Sanjuan et al. 2011), and (2) no information needed on the functional relationship between inputs and outputs owing to its non-parametric nature (Halkos et al. 2016). These advantages are possible because the DEA method is based on efficient production surfaces rather than central tendencies (Cooper et al. 2011). For these reasons, DEA has been widely applied to analyze the performance of numerous entities such as airports (Ennen and Batool 2018), schools (Charnes et al. 1981), products (Sanjuan et al. 2011; Laso et al. 2018), industrial parks (Liu et al. 2015; Guan et al. 2019), national policies (Lee and Mogi 2018), cities (Sanjuan et al. 2011; Moutinho et al. 2018), countries (Camarero et al. 2013), and regions (Halkos et al. 2016).

In a traditional DEA, inputs (such as energy, materials, and capital) and outputs (such as GDP, value-added, and waste emissions) can be used to construct an efficiency frontier (Lee and Mogi 2018; Liu et al. 2015; Yu et al. 2018). All points lying on the efficiency frontier are considered "technically efficient" while those lying away from the frontier are relatively inefficient (Fan et al. 2017; Ennen and Batool 2018). In this context, "technical efficiency" is defined as the ability to produce the highest possible output from the available set of inputs (Farrell 1957). In the DEA literature, the incorporation of undesired outputs, such as waste streams and air emissions, has been given great importance (Färe et al. 1989). Among different methods to include undesired outputs in DEA efficiency evaluation (Tyteca 1996; Scheel 2001), this study treats undesired outputs as inputs that are to be minimized (Mardani et al. 2017). Ideally, any resource used (or product produced) by a DMU should be included as a DEA input (or output) (Boussofiane et al. 1991), however, the selection of inputs and/or outputs is greatly dictated by data availability (Masternak-Janus and Rybaczewska-Błażejowska 2017). In this study, the DEA application 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 economy-wide material flow accounts are also available (UNEP 2019); while 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 DMUs) in order to guarantee the method's discriminatory power. This means that the number of inputs and outputs needs to be small compared to the number of DMUs so that DEA can discriminate effectively among the considered DMUs. In this study, the number of inputs and outputs was considered adequate (it was 2 and 1, respectively) given that the sample size was not large enough [e.g. 10 DMUs in the national-level efficiency analysis (i.e. number of 5-year periods) and 11 in the multi-country level efficiency analysis (i.e. 10 major trade partners plus Pakistan)].

As part of the DEA methodology, we analyzed (1) national-level efficiency at 5-year intervals and (2) multi-country level efficiency in 1971 and 2015. Both levels of analysis compared different entities (explained in the following sections). Equation 3.1 was utilized to calculate both national-level and country-level efficiencies using the input-oriented "Charnes, Cooper, and Rhodes (CCR)" model which is based on Constant Returns to Scale (CRS) assumption.

$$\begin{aligned} &\min \eta, \text{ subject to} \\ &[\eta \times x_0] - [X \times \lambda] - s^{-} = 0 \\ &[Y \times \lambda] - s^{+} = y_0 \qquad (3.1) \\ &\lambda \geq 0,\ s^{-} \geq 0,\ s^{+} \geq 0 \end{aligned}$$

where η is the efficiency score (a value of 1 indicates a point on the frontier and hence highest technical efficiency); x_o and y_o represent the input and output vectors, respectively; X and Y are the input and output matrices, respectively; λ is a weight vector (N×1); and s^{-} and s^{+} represent the input and output slack variable vectors (if any), respectively.

The use of the CRS assumption ensures that the "best practice" benchmarking units are only based on the inputs explicitly considered in the DEA model (Xing et al. 2020). Furthermore, we used an input-orientated DEA model where inefficiency can be decreased (or efficiency increased) through proportional reduction of inputs by means of projection onto the frontier (Cooper et al. 2011). The input-oriented CCR model is highly capable to measure efficiencies at the regional level (Masternak-Janus and Rybaczewska-Błażejowska 2017). Lastly, based on the literature review, production efficiency based on the DEA approach could be termed as "eco-efficiency" (Kuosmanen and Kortelainen 2005), however, the term "efficiency" has been widely used in the standard DEA literature (Boussofiane et al. 1991; Zhou et al. 2016). Therefore, we will use the term "efficiency" when referring to DEA results.

3.3.3. National-level efficiency

The efficiency of material use and CO_2 emissions at the national-level was determined for Pakistan's socio-economic system by using input data at 5-year intervals from 1971 till 2015. Using window-type DEA analysis, a DMU at each of the selected time period can be treated as a different "time labeled" DMU (Charnes and Cooper 1984). This means that the performance of a DMU at a given time can be contrasted with its own performance during other periods based on the time-series data (Cooper et al. 2011). Through this DEA approach, efficiency frontier can be plotted based on a moving average analog, and policy introspection can be carried out more specifically (Yang and Chang 2009). This analysis was also important for comparing Pakistan's actual performance relative to its capacity.

For national-level efficiency, DEA inputs included economy-wide DMC and CO_2 emissions represented by "x_1" and "x_2" respectively. Both inputs were selected to analyze their relationship with economic growth and to examine inefficient periods with respect to material use and carbon emissions. The DEA output was represented by GDP in constant dollar prices denoted by "y". The DEA based efficiencies, calculated by Equation 3.1, were then plotted against an optimum efficiency frontier using material intensity (x_1/y) as the y-axis and CO_2 intensity (x_2/y) as the x-axis.

Details of input and output parameters used in the DEA model are given in Table 3.3.

Table 3.3: Input and output parameters for the efficiency analysis.

Indicator	Description
DMC	Consumption of resources, treated as inputs, comprising: (i) fossil fuels (FF) including coal, natural gas, oil shale and tar sands, and petroleum; (ii) biomass (BM) including crops, crop residues, grazed biomass and fodder crops, wild catch and harvest, and wood; (iii) metals (MT) including ferrous and non-ferrous ores; (iv) minerals for industrial and agricultural use (MN_{i-g}); and (v) minerals for construction use (MN_{con}) given, $$DMC_t = \sum_{i=1}^{5} BM + \sum_{i=1}^{4} FF + \sum_{i=1}^{2} MT + MN_{i-g} + MN_{con}$$ Where DMC_t represents material consumption during a particular year and i represents number of specific material types within each category.
CO_2	Annual emissions of carbon dioxide. Treated as an undesired output during a given year.
GDP	Economy-wide output in terms of national GDP (reported in constant 2010 US dollar prices). Treated as a desired output.

3.3.4. Multi-country efficiency

As part of the multi-country analysis, efficiency was calculated using Equation 3.1 by selecting Pakistan and its major export partners at two temporal points i.e. 1971 and 2015. The two selected years were considered sufficient to analyze long-term variations in efficiency among all the selected countries and understand evolving efficiency patterns. The spatial comparison was also important in providing insights into Pakistan's performance in relation to its trade partners. In should be noted here that direct strategies for improving efficiency cannot be realized with the help of this multi-country DEA application. Rather, this multi-country analysis will assist in identifying "best practice" benchmark countries from which other inefficient countries could derive policy insights and seek guidance (Kuosmanen and Kortelainen 2005). This means that the relatively efficient countries could provide examples of good operating practice to inefficient countries since both have been examined using the same set of inputs and outputs (Boussofiane et al. 1991). For this analysis, DEA inputs included DMC and CO_2 emissions of individual countries represented by "x_1" and "x_2" respectively while the output was represented by GDP as denoted by "y". Based on the DEA results, actual efficiency values were plotted against an optimum efficiency frontier. The results were then used to examine spatially occurring efficiency patterns to draw important policy insights.

3.3.5. Decomposition analysis

As a final step, economy-wide DMC and CO_2 emissions in Pakistan were decomposed into their driving forces using the IPAT equation. The components of the IPAT equation were decomposed using Logarithmic Mean Divisia Index (LMDI) method. The LMDI method is a widely used decomposition method due to its strong theoretical basis, adaptability, and ease of interpretation (Ang and Liu 2007). Using the LMDI method, influencers of material use and carbon emissions were determined based on Equation 3.2:

$$\Delta I = \sum \frac{\mathrm{P}_t - \mathrm{P}_0}{\ln \mathrm{P}_t - \ln \mathrm{P}_0} \times \ln \frac{\mathrm{P}_t}{\mathrm{P}_0} \tag{3.2}$$

Where ΔI represent the change in environmental impact (i.e. DMC or CO_2), P_t represents the IPAT parameter for the end year (2015) and P_0 represents the IPAT parameter for the start year (1971). Drivers of material use (IPAT parameters) included (i) population, (ii) affluence (GDP per capita), (iii) material intensity (DMC/GDP), and fossil fuel (FF) resource intensity (FF/DMC). Similarly, drivers of carbon emissions included (i) population, (ii) affluence, (iii) energy intensity (TPES/GDP), and carbon intensity (CO_2/TPES) where TPES stands for "Total Primary Energy Supply". The analysis was applied to the period 1971-2015.

3.3.6. Data sources

Multiple data sources were used to collect data. Environmental data such as CO_2 emissions (from fossil fuel combustion) were gathered from International Energy Agency (IEA) database (IEA 2019), while socio-economic data were acquired from the World Bank's statistical database (World Bank 2019). The constant dollar prices of 2010 (or otherwise mentioned) were used to avoid the impacts of inflation and monetary devaluation of the local currencies. Resource consumption statistics, based on the EUROSTAT methodology, were gathered from the International Resource Panel's database (UNEP 2019; EUROSTAT 2001). The study period was selected keeping in view the availability of reliable data.

3.4. Results and discussion

This section will discuss our main findings. The focus remains on analyzing economic sustainability in Pakistan and the underlying materialization and carbonization patterns (temporally and spatially).

3.4.1. Material and carbon intensity

In contrast to rising absolute and per capita DMC, the material intensity has uniformly reduced in Pakistan from 6.4 kg/USD in 1971 to 3.9 kg/USD in 2015, as shown in Figure 3.5 (a). However, Pakistan's material intensity in 2015 was still relatively higher compared to its export countries as given in Table 3.4. This shows that Pakistan remains highly material-intensive as a whole and lacks comparative productivity, irrespective of its development status. Pakistan's relatively high material intensity can be attributed to factors such as poor agricultural efficiency (Ahmed and Gautam 2013), material-intensive manufacturing sectors (World Bank 2013), inefficient energy system (Aziz and Saqib 2013), and lack of export dynamism and value addition (Reis et al. 2013). All these factors lead to a narrow range of manufactured goods which usually carry low-to-medium economic value (e.g. textile and food products). Moreover, the growth of high-value and export-oriented industries has been rather slow in the country. Unfortunately, recent development plans including CPEC projects (largely focusing on energy and infrastructure development) have also overlooked industrial development and resource productivity in Pakistan (Rafiq 2017).

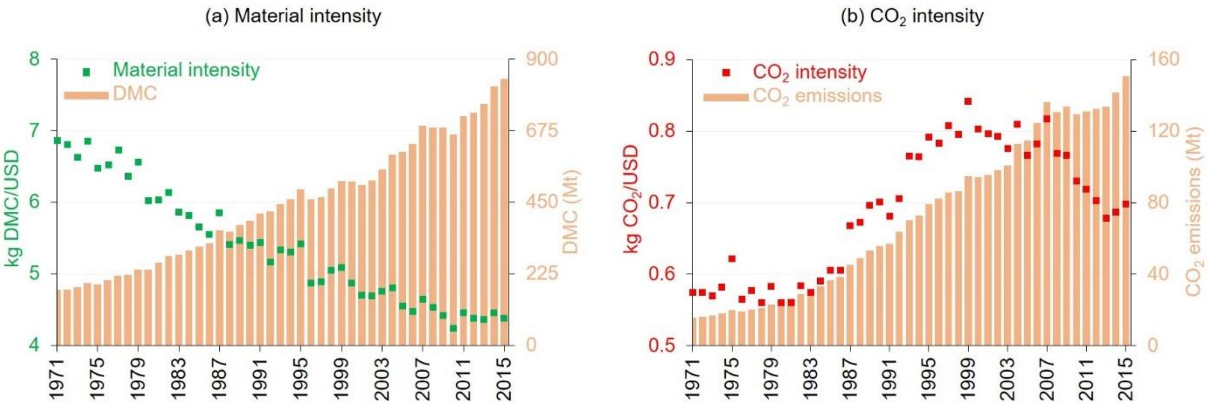

Figure 3.5: Intensity of material use and CO_2 emissions in Pakistan.

Carbon intensity, as opposed to material intensity, has increased in Pakistan as illustrated in Figure 3.5 (b). However, a rise in carbon intensity has not been uniform as it peaked in 1999 after which significant improvements were observed. From a comparative perspective (illustrated in Table 3.4), Pakistan’s carbon intensity was higher in 2015 than in most of its exporting regions (except China, India, and Saudi Arabia). As most of the developed countries have improved their carbon intensities, developing countries are seen at the higher intensity end.

Three important factors could have influenced this widening gap between the developed and developing countries such as (1) significant gaps in technological advancement, (2) industrial structure and the share of high-value industries, and (3) internalization of energy- and emission-intensive primary and secondary production by developing countries leading to a comparative disadvantage. These factors, in combination with weak environmental governance, have made developing economies relatively more intensive in terms of material use and carbon emissions.

Table 3.4: Material and carbon intensities in Pakistan and its top 10 export destinations.

Destination	Share (%) [a]	Material intensity (kg/USD)		CO_2 intensity (kg/USD)		Eco-efficiency [b]	
		1971	2015	1971	2015	1971	2015
Pakistan	-	6.4	3.9	0.57	0.70	140	237
United States	15.0	1.1	0.41	0.87	0.29	921	2,150
China	9.3	11.4	3.65	3.90	1.02	-	-
Germany	6.2	0.94	0.33	0.62	0.20	911	2,294
United Kingdom	5.6	0.78	0.20	0.60	0.14	1,106	3,714
Spain	3.5	0.63	0.39	0.25	0.17	1,408	1,944
France	3.1	0.68	0.28	0.39	0.11	1203	2712
Bangladesh	2.7	3.70	2.65	0.12	0.45	269	362
Italy	2.5	0.63	0.32	0.30	0.16	1316	2500
Saudi Arabia	2.1	0.18	1.12	0.08	0.78	-	565
India	1.7	6.93	3.0	0.81	0.88	131	295

[a] *Share in Pakistan's total exports for the year 2015.*

[b] *Eco-efficiency measured as value-added (USD) per domestic material input (kg); complete data for China and Saudi Arabia was not available.*

As per the eco-efficiency indicator results (Table 3.4), by 2015, United Kingdom was the most eco-efficient economy followed by France, Italy, Germany, United States, and Spain; whereas Pakistan was the least eco-efficient country as compared to all other countries (data for China and Saudi Arabia was not available). During the 1971-2015 period, significant eco-efficiency improvement was achieved by United Kingdom (236%) which was almost double than that achieved by United States (133%), France (125%), and India (125%). Pakistan's eco-efficiency enhancement during the study period was about 70% which was higher than that by Bangladesh (34%) and Spain (34%) but lower than all other countries. Based on the results, we may conclude that industrialized economies have achieved rapid eco-efficiency improvements during 1971-2015. Whereas, developing countries have witnessed speedy industrialization but with relatively slower eco-efficiency improvements.

3.4.2. National-level efficiency based on DEA

The national-level efficiency values could be used to examine periods of relatively inefficient economic performance while the economic system (i.e. Pakistan) remains unchanged at a given temporal point. Also, with a fixed system, variations in the DEA efficiency can be linked to the socio-economic developments in that specific period. Based on the DEA results, the optimum efficiency frontier for Pakistan was constructed and is presented in Figure 3.6 (a).

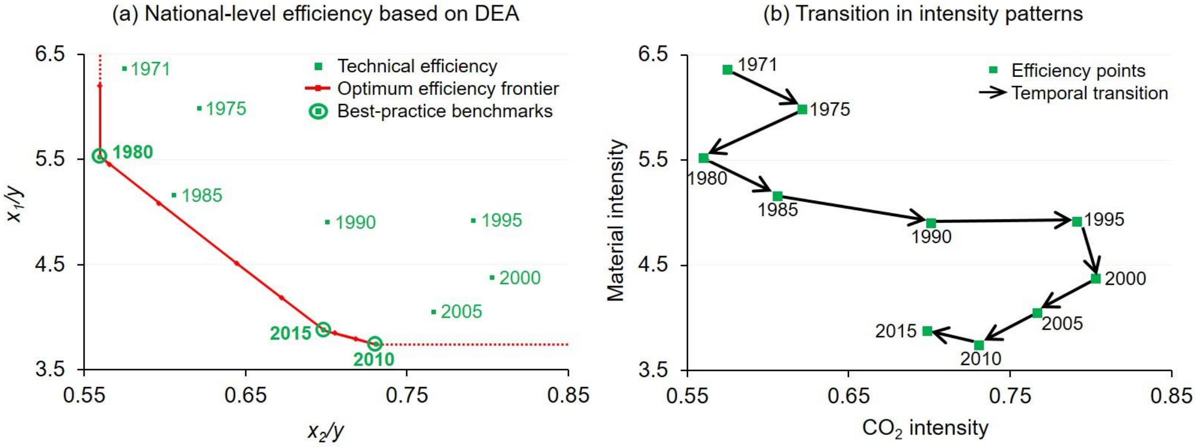

Figure 3.6: System-level efficiency results for Pakistan.

[*Note:* x_1 *refers to material use (kg),* x_2 *refers to* CO_2 *emissions (kg), and y refers to GDP (USD)*]

As shown, out of the 10 temporal points selected, only three points i.e. 1980, 2010, and 2015 were found technically efficient while the rest being relatively inefficient (meaning excessive material use and/or CO_2 emissions were taking place in those periods). This shows some serious limitations of Pakistan's economic system which has been underperforming in most of the periods than ideally required. Moreover, a clear trend can be seen towards rising CO_2-based economic growth where CO_2

intensity (x_2/y) has increased during the past 45 years. In this regard, the gap between optimum efficiency frontier and actual efficiency values particularly widened from 1985 to 2005 indicating Pakistan's unsatisfactory performance with relatively higher CO_2 emissions.

The transition in intensity patterns, as shown in Figure 3.6 (b), highlights the dynamic interplay between material and CO_2 intensity in relation to Pakistan's technical efficiency. On the one hand, the material intensity has improved significantly throughout the study period [though there was a period of stagnation (1985-1995)]. On the other hand, Pakistan's carbon intensity has surged particularly after the 1980s. This can be traced back to the initial stages of the industrialization process and the growth of large-scale agriculture in the country that began in the 1980s and caused CO_2 intensity to grow at unprecedented rates. With high CO_2 intensity, technical efficiency had greatly reduced during the period 1990-2000. Factors such as slowed economic growth (average annual GDP growth rate was about 4% during 1990-2000) (World Bank 2013), regional economic dynamics (Asian financial crisis in 1997), economic sanctions following the nuclear tests in 1998 (Zubair 2009), and geopolitical instability (frequent regime changes during the 1990s, and a military coup in 1999) (Asia Society 2019) had also affected economic and industrial growth in Pakistan. Moreover, industries in Pakistan tend to focus on resource-intensive production, and as a result, they lack technological innovation which is common in competitive high-end industries. Thus, the lack of technological advancement by industrial sectors has greatly contributed in slowing down Pakistan's economic expansion. This is reflected by low industrial value-added in Pakistan, which was equal to 17.9% (% of GDP) in 2017, as compared to China (40.5%), Indonesia (39.4%), Malaysia (38.8%), Iran (34.9%), Bangladesh (27.8), India (26.5) etc. (World Bank 2019). These figures signify Pakistan's weak performance with respect to industrial productivity and value-added from a regional perspective. Slow economic growth and low industrial productivity, when seen in conjunction with institutional constraints and lack of technology development/transfer, have stalled efforts on carbon intensity improvements in Pakistan.

The period from 2000 to 2005, with good GDP and export growth, was found to bring significant carbon intensity improvements. A few years later, after the energy crisis in Pakistan during 2008-2012 (demand-supply gap, price hikes, load management etc.), GDP growth rates began to improve particularly during the 2011-2015 period. This was complemented by the rapid growth of telecommunications and information services sectors in the country during 2005-2015 (Imtiaz et al. 2015) which indicates a transition towards a service-based economy. As of 2015, the CO_2 intensity was back at the 1990s levels and further improvements are also possible given that sustainable economic growth policies are implemented. Nonetheless, analysis of the future intensity transition will be highly meaningful as CPEC related projects have begun in Pakistan and their impact on Pakistan's material or carbon intensity profile is still unknown.

3.4.3. Multi-country efficiency based on DEA

This section compares Pakistan and its major export partners with regards to the efficiency of material consumption and CO_2 emissions. The results for the multi-country efficiency analysis are presented in Table 3.5. As given, during 1971, most of the countries were performing inefficiently when compared with the best performer, i.e. Saudi Arabia (though its economic size was quite small). Pakistan's efficiency was behind most of the countries yet just ahead of China and India. However, things have changed drastically since then. As of 2015, the United Kingdom and France were the most technically efficient economies followed by Italy, Germany, and Spain. This can be attributed to the dematerialization and decarbonization efforts in the European Union (Kemp-Benedict 2018; Ziolkowska and Ziolkowski 2015). At the same time, China remained the least efficient economy relative to the best performers. China, being the world's factory and large exporter of intermediate and finished goods, has relatively higher material, energy, and emission intensities (Guo et al. 2018). But with tremendous growth in the economy during this period, China has performed exceptionally well to reduce its material and carbon intensities (partially offsetting some of the environmental impacts).

Table 3.5: Multi-country efficiency results.

Country	1971				2015			
	GDP	DMC	CO_2	η	GDP	DMC	CO_2	η
Pakistan	27.6	175.7	15.9	0.142	215.9	837.4	150.8	0.150
United States	4,937	5,579	4,289	0.163	16,710	6,804	4,920	0.497
China	200.0	2,279	780.2	0.021	8,908	32,540	9,103	0.103
Germany	1,582	1,486	978.1	0.197	3,719	1,212	729.7	0.685
United Kingdom	1,033	808.5	621.1	0.236	2,720	549.8	393.5	**1.000**
Spain	479.2	300.1	119.1	0.328	1,421	553.4	247.1	0.669
France	1,100	742.8	423.4	0.273	2,781	788.1	292.2	**1.000**
Bangladesh	25.0	92.4	2.9	0.706	156.6	415.0	70.9	0.232
Italy	967.4	610.0	289.4	0.293	2,062	652.0	329.7	0.775
Saudi Arabia	155.7	28.7	12.7	**1.000**	678.7	759.0	531.6	0.183
India	223.5	1,548	181.1	0.101	2,295	6,998	2,026	0.119

Note: GDP is in billion constant 2010 USD prices, DMC and CO_2 are in Mt. Values in bold show the highest technical efficiency.

Two important insights can be drawn from results in Table 3.5: (1) countries having lower technical efficiency, such as Pakistan, are likely to consume more material resources and produce higher CO_2 emissions for an equivalent amount of contribution to the national GDP; and (2) the efficiency gap between developing and developed countries has greatly widened during the last 45 years. Based on these results, we see that industrialization has brought considerable improvements in material and environmental efficiencies in most cases, yet these improvements are not equally distributed among all countries. For instance, countries such as China, Spain, and Italy have achieved higher efficiency improvements during 1971-2015, while countries such as Pakistan and Bangladesh have become more inefficient in relative terms. There could be several factors affecting this phenomenon. One important aspect has been the unsustainable industrial and urban growth policies in some developing countries which made material and CO_2 intensity to be very high. Another factor is the global industrial transition where industrialized economies are increasingly investing in material and environmental efficiency (Park et al. 2008), whereas low-income economies have overlooked this important aspect – the case mostly relatable with Pakistan. Moreover, technological spillover and innovation have been largely limited to advanced economies, thus, resulting in a rather slow technology transfer to emerging economies. In any case, the efficiency paradigm seems highly dynamic and future analysis into this area would lead to more revelations.

From a policy viewpoint, some implications can be drawn from the DEA efficiency results. First, for a systematic transition towards high material and carbon efficiency, resource management policies, and environmental best practices from developed economies can be greatly utilized. Second, innovative leapfrog policies may also be developed to reach targeted efficiency improvements faster than those achieved by developed economies. In this context, leapfrog refers to the advantage developing countries have by switching from old to new technological systems (Grubler 1998). Third, an important step is to plan a transition to decouple economic growth from the extensive use of non-renewable energy resources to increase resource productivity and reduce carbon intensity. Fourth, technological development and transfer should be facilitated at the governmental level to approach the dematerialization and decarbonization phase as soon as possible. Lastly, from a systems perspective, as individual efficiency improvements are yet to impede rising material consumption and environmental emissions globally (Zink and Geyer 2017), we recommend integrated and mutually inclusive mechanisms to mitigate the impact of materialization and carbonization. This could be achieved by international and regional cooperation initiatives and collective action.

In Pakistan, much of the policy and regulatory efforts concerning material and carbon efficiency have brought modest improvements as shown in Table 3.5. Having said that, factors such as weak institutions, fragmented policy implementation levels (national, provincial, and urban), and slow and intermittent economic growth need to be addressed exclusively. Even when environmental regulations are in place, low economic affluence appears to be the most important barrier against effective environmental management – a phenomenon well established globally (Schandl and West 2010). This means that developing countries such as Pakistan will initially be less motivated to invest in environmental enforcement, but as the economy progresses, environmental compliance could be strengthened. This is particularly reflected by the "pollute now and clean up later" approach in most developing economies (Shenoy 2015; Chiu and Yong 2004) even if environmental consequences become significantly expensive later. This phenomenon is quite similar to what environmental Kuznets curve theorizes (Kuznets 1995) and appears greatly applicable to Pakistan.

3.4.4. Drivers of material use and CO_2 emissions

As a final step, DMC and CO_2 emissions in Pakistan during 1971-2015 were decomposed into their driving forces using the IPAT framework and the results are illustrated in Figure 3.7. As shown, the rising population was the strongest driver of both DMC and CO_2 emissions. Affluence was the second strongest driver after population. As per the literature review, in most cases, rising per capita income drives most of the increase in resource consumption (Shah et al. 2020) and CO_2 emissions (Jung et al. 2012) and the population is not the major driving force. However, Pakistan's higher population growth rates during 1971-2015 have led to a rapidly rising populace. This has resulted in higher resource consumption, but a relatively lower contribution to economic growth. The existing situation, however, could be improved by taking steps such as economic restructuring, socio-economic interventions on population control (socio-politically challenging), and resource conservation practices (e.g. public awareness on energy saving and product recycling).

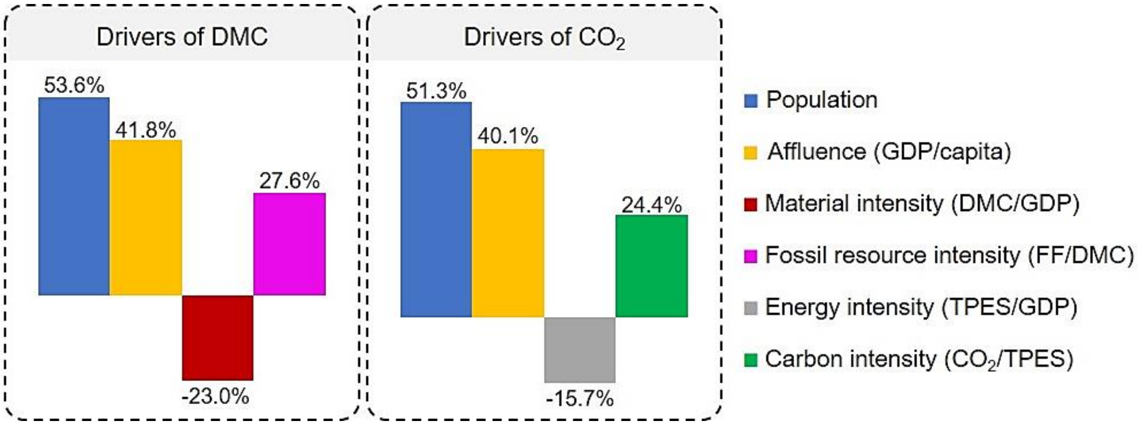

Figure 3.7: Drivers of material use and CO_2 emissions in Pakistan.

Coming to other drivers of DMC, the intensity of fossil fuel resources also caused a rise in DMC though its impact was nearly half than that of the population. Material intensity, among all driving forces, was the only negative driver of DMC and has considerably slowed down the rise in material use. This shows that with technological and sectoral advancement, material intensity improvements could reduce growth in DMC to a great extent. However, there could be some rebound effects of improved material intensity such as increased economic activity, and additional consumption due to reduced market prices. Thus, policy efforts on material efficiency must be chalked out carefully by considering all potential rebound impacts.

Among the drivers of CO_2 emissions, increased carbon intensity has also contributed to rising CO_2 emissions to some extent. This goes in line with the rising share of fossil fuels in DMC. Contrary to carbon intensity, energy intensity improvements were responsible for slowing down CO_2 emissions in the country. This becomes more important when Pakistan’s economy heavily relies on energy-intensive agriculture and low value-added manufacturing, and when technological advancements have not been at par with its regional peers and export partners. To speed-up energy efficiency improvements, Pakistan’s economic and structural reorganization is required where technological improvements are coupled with efforts on climbing up the value-addition ladder. A transition away from the emission-intensive economy will require steps to boost new industries and value-added manufacturing, green agriculture, and energy conservation and recovery programs. Moreover, rigorous policies are needed to plan a transition from an existing linear economic model to more material circularity with optimum utilization of energy within available resources.

3.5. Conclusion and policy implications

This work analyzed economy-wide material use and CO_2 emissions in Pakistan using long-time series data. Based on the results, this section will highlight some of the significant policy insights, research limitations, and future recommendations.

3.5.1. Policy implications

Presently, Pakistan has witnessed a relative decoupling of material consumption and CO_2 emissions from economic growth. When compared with its major export partners, both material and carbon intensities in Pakistan were quite high due to low agricultural and industrial efficiency which means more material use and CO_2 emissions for an equivalent GDP contribution. The multi-country analysis revealed that the gap between developing and developed countries has widened during 1971-2015 making developing economies relatively intensive in terms of DMC and CO_2 emissions. This widening gap can be reduced by actively seeking technology development and transferring from developed countries and by incorporating best-practices of resource and energy management from industrialized economies. Besides, not all developing economies have achieved proportionate efficiency improvements during the study period. Also, population and affluence were found to be the major drivers of rising DMC and CO_2 emissions in Pakistan while material (DMC/GDP) and energy (TPES/GDP) intensities, respectively, played a role in slowing their growth. Steps such as economic restructuring, green agriculture, industrial value-added, energy efficiency, resource recovery/recycling etc. were identified to mitigate imminent growth in material use and carbon emissions, although future research will determine the extent to which individual strategies could be successful.

From a regional perspective, Pakistan has been an under-performer when compared with its regional and exporting peers. Also, higher dependence on inefficient agriculture and low-value industries has resulted in relatively higher material and CO_2 intensities. Apart from developed countries, also many developing countries have transitioned towards high-value production with increasing global exports. However, as per the multi-country analysis, Pakistan has been left far behind in this area aggravated further by a huge trade deficit (attributed to rising imports of energy resources and finished goods) and low industrial productivity (material-intensive production, low value-added exports, high raw material costs, the rising cost of doing business, and energy inefficiency). Therefore, policies such as higher value-added production in agriculture and industries, resource efficiency promotion through reduced material throughput in manufacturing, material recovery and waste reduction in secondary processing industries, and emission mitigation from large energy and industrial infrastructures were identified as potential pathways for sustainable economic growth with higher material and environmental efficiency. Moreover, sustained action against growth-inhibiting factors presented in this article is crucial to ensure sustainable economic development based on a long-term policy framework.

3.5.2. Research limitations and future recommendations

There were some limitations to this study as well. To begin with, considering DMC and CO_2 emissions as the only drivers of economic development can exaggerate impacts while ignoring other factors such as macro-economic policies, geopolitical stability, and resource availability and its extraction. Secondly, we have only considered DMC and CO_2 as inputs for economic output which might have affected results in favor of economies in the developed world. This is because the externalization of resource and emission-intensive sectors has taken place in developed economies (Schandl and West 2012), thus, developing countries are likely to consume more materials and emit higher CO_2 for the same amount of economic output. Moreover, a set of different inputs and outputs may lead to a different set of efficiency results, thus, results should be interpreted with adequate caution. Thirdly, in the multi-country DEA analysis, comparing developing and developed countries can be tantamount to "comparing apples and oranges" leading to an inherent bias (favoring industrialized economies as they import large quantities of finished goods that are manufactured in developing countries). This is the reason why a comparative efficiency analysis among a group of countries lying in a similar income bracket and/or with similar industrial structure could be very insightful as follow-up research. The interplay of national-level policies, material use, and carbon emissions can also be quantitatively analyzed in the future. Impacts of domestic crises, such as the energy crisis in Pakistan during the late 2000s, were not examined in this study and remains an interesting area for future research. The DEA analysis can be complemented by analyzing the dynamic evolution of DMC, CO_2, and other indicators in future studies. In addition, macro-level socio-economic indicators (employment, education, mortality, industrial output etc.), environmental indicators (freshwater use, wastewater generation, greenhouse gas emissions etc.), material flow indicators [Net Additions To Stock (NAS), Total Material Requirement (TMR) etc.], and material circularity indicators can also be explored with the use of DEA approach.

3.5.3. Conclusion

Pakistan's national-level efficiency was optimum in 1980, 2010, and 2015 while relatively inefficient during all other periods with a clear trend towards decreasing material and CO_2 intensity. Multi-country efficiency analysis revealed that Pakistan remains a technically inefficient economy when compared with its major export partners though slight improvement has been achieved during 1971-2015. At a time when DMC and CO_2 emissions have increased, declining material and carbon intensities portray a promising picture. From a transitional perspective, these results establish the view that economic growth, global trade, regional resource connectivity, and industrialization improves the efficiency of material use and carbon emissions in a typical low-income developing country. Nonetheless, equitable efficiency enhancement in the developing world may seem challenging yet the historical patterns over the last few decades are appearing to move in the right direction – albeit slowly.

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Preface to Chapter 4

There is a widespread consensus that industrial ecosystems, mostly located in or around urban centers, have become the engines of economic growth in many countries throughout the world. Industrial ecosystems could mimic biological ecosystems to a certain degree by using each other’s waste and/or by-products for a greater cumulative benefit. The sharing of waste resources, as a result, enables them to enhance the ecosystem efficiency and minimize the use of virgin resources while maintaining the required levels of production output. This chapter will analyze how eco-efficiency improvements at the industrial park level could coincide with those at the regional level. The emphasis will be kept on waste generation (a proxy for virgin material consumption) and energy use (a critical resource for industrial activity) at the industrial ecosystem level. The chapter will also develop and apply an eco-efficiency assessment protocol that tracks changes in industrial level efficiency over time. The chapter will also identify and discuss regional policy developments and their nexus with industrial eco-efficiency during a period of fifteen years.

The work is expected to bring forward important aspects of industrial productivity based on waste and energy eco-efficiency enhancement. The results are also expected to provide detailed insights into Ulsan’s sustainable urban transition through eco-industrial development.

Chapter 4

Sustainability transition of industrial ecosystems

Abstract

The ecologically efficient transformation of natural resources into economic output by industrial ecosystems is a critical pathway to achieve urban and industrial sustainability. Eco-efficiency assessment is an effective tool to uncover both the status and trends of such a transformation. In this chapter, an eco-efficiency assessment protocol was developed, using data envelopment analysis and eco-efficiency indicators, to analyze the urban sustainability transition of Ulsan through eco-industrial development (EID). In the design for analysis, eco-efficiency change – both at the industrial park and regional levels – was investigated to analyze whether eco-efficiency improvements at the park level coincide with those at the regional level. Our main findings were highlighted as: At the urban level, from 2000 to 2015, eco-efficiency of industrial waste generation and energy use has improved by 35.0% and 21.4%, respectively, driven by a significant reduction in waste and energy intensities attributable to technological improvements (EID promotion and urban-industrial symbiosis). At the industrial park/complex level, two national eco-industrial parks (EIPs) in Ulsan showed the highest eco-efficiency (pure technical efficiency was 1.0) in analytical years, compared with nine regional industrial complexes. At both levels of analysis, EIPs stood out as eco-efficient and their contribution to urban sustainability transition was overwhelming. Moreover, EIP implementation and urban-industrial symbiosis were identified as the major drivers of regional EID policy in Ulsan. Based on the results, EID was highlighted as a preventative and regenerative approach to improve eco-efficiency at the regional and industrial park level, enlightening other regional and local initiatives towards urban sustainability.

4.1. Introduction

To enhance the economic output per unit of natural resources consumed, together with mitigating associated negative environmental impacts, it is critical to promote sustainable industrial development in the context of industrial ecosystems (Figge et al., 2017; Leme et al., 2018). The concept of eco-efficiency is among the popular sustainability tools used to understand improvements in industrial ecological efficiency (Bai et al., 2018; Simon et al., 2017; Wu et al., 2018). According to the World Business Council for Sustainable Development (WBCSD), reduced ecological impacts and lower resource intensity at a competitive price of goods and services leads to eco-efficient systems – measured in terms of their eco-efficiency (Simon et al., 2017; Verfaillie and Bidwell, 2000). From an urban metabolism viewpoint, material/energy flows in the urban socio-economic processes, including industrial production, can very well be described and analyzed (Guan et al., 2019b, 2019a). Industrial energy input flows provide power and steam for the conversion of raw materials into usable products (Caiado et al., 2017; Kluczek and Olszewski, 2017) and have a significant impact on the regional economy (e.g. jobs, infrastructure, and prosperity) and its environment (e.g. industrial wastes and emissions) (Han et al., 2018; Pappas et al., 2018; Zhang and Xu, 2017).

Industrial energy eco-efficiency, an innovative approach, can lead to increased production output with reduced energy consumption (Martínez and Silveira, 2013). This is important since industries worldwide continue to be the single largest energy consumer (about 37% share in total final consumption in 2015) (IEA, 2017). Similar to energy flows within the industrial ecosystems, quantities of industrial waste have also been rising globally thanks to the rapidly rising production and consumerism, though the emphasis on waste reduction and treatment has increased in recent years (Guan et al., 2019a). With usually delayed impacts, industrial waste presents a greater risk to the environment, thus, requiring improved ways of waste reduction and recovery (Cetrulo et al., 2018). The waste from industries alone can serve as an indicator for efficient transformation of raw materials into more and better products – with less waste indicating higher resource utilization and vice versa (Simon et al., 2017). Industrial waste eco-efficiency can be in the form of treatment after generation or in the form of waste prevention and recycling – sometimes referred to as eco-effectiveness (Simon et al., 2017). Either way, the aim remains to reduce industrial waste generation while ensuring optimum production output.

Eco-Industrial Development (EID) – employing Eco-Industrial Park (EIP) and industrial symbiosis as typical practices – offers an innovative, preventative, and regenerative pathway to address the increasing environmental pressures, impacts, and costs of industrial activity (Dong et al., 2016). In addition, EID also explores innovative technologies for increased resource efficiency and recovery in industrial ecosystems (Tseng et al., 2018). In this way, industrial parks, or even individual companies, enhance their eco-efficiency that adds to their positive perception (customer relations), creates new business opportunities and benefits, as well as increases their cumulative environmental gains. To the best of our knowledge, to date, no research has been conducted to report such evidence in terms of matching eco-efficiency at both the urban and individual park level. This becomes highly pertinent when urban sustainability can be enhanced through EID promotion, especially in the developing world.

Coming to the regional context, South Korea's industrial sector – a huge economic contributor, major energy consumer, and the largest GHG emitter – has been actively looking for ways to improve its environmental performance and production efficiency. To strengthen industrial development under the "Green Growth" strategy, South Korea's central government initiated a 15-year EIP program in 2005 to incorporate best practices of cleaner production and industrial symbiosis for waste recovery and valorization, energy savings, GHG mitigation, production growth, and job creation in then "regional industrial complexes (IC)" now referred to as EIPs (Park and Behera, 2014). Implementation and promotion of the EIP program achieved significant economic and environmental benefits (Behera et al., 2012; Park et al., 2016, 2018), yet their impacts on eco-efficiency enhancement at the urban and industrial park levels remain unreported. With this circumstance, this chapter developed an eco-efficiency assessment protocol to analyze the sustainability transition of eco-industrial development in Ulsan, South Korea during 2000-2015. The research was designed to answer the following questions: (1) is there a link between industrial energy use, waste generation, and production efficiency? (2) do eco-efficiency improvements occur at multiple levels of an industrial ecosystem? and (3) what are the major drivers behind changes in industrial eco-efficiency?

4.2. Eco-industrial development and urban-industrial symbiosis

In nature, EID is a systematical optimization approach that aims to optimize material flows within an industrial park/complex and minimize waste and/or by-products. Whereas industrial symbiosis and eco-industrial parks are the prevailing practices for EID promotion around the globe. Illustrated as Figure 4.1, the concept of industrial symbiosis refers to the synergistic collaboration among disparate entities to enhance their competitive advantage through the physical sharing of resources (materials, by-products, and infrastructures) which is aided by their geographical proximity (Chertow, 2000). Urban-industrial symbiosis is an extended version of industrial symbiosis and refers to the sharing of resources within urban and industrial areas having some geographic proximity (Dong et al., 2017; Sun et al., 2017). By exchanging or redirecting wastes, energy, and/or by-products in a mutually beneficial way, the efficiency of urban metabolism could be improved (Sun et al., 2020; Van Berkel et al., 2009). Compared to a business as usual condition shown in Figure 4.1 (a), the resource inputs and waste outputs are expected to reduce through urban-industrial symbiosis shown in Figure 4.1 (b), hence increasing the environmental efficiency of the region.

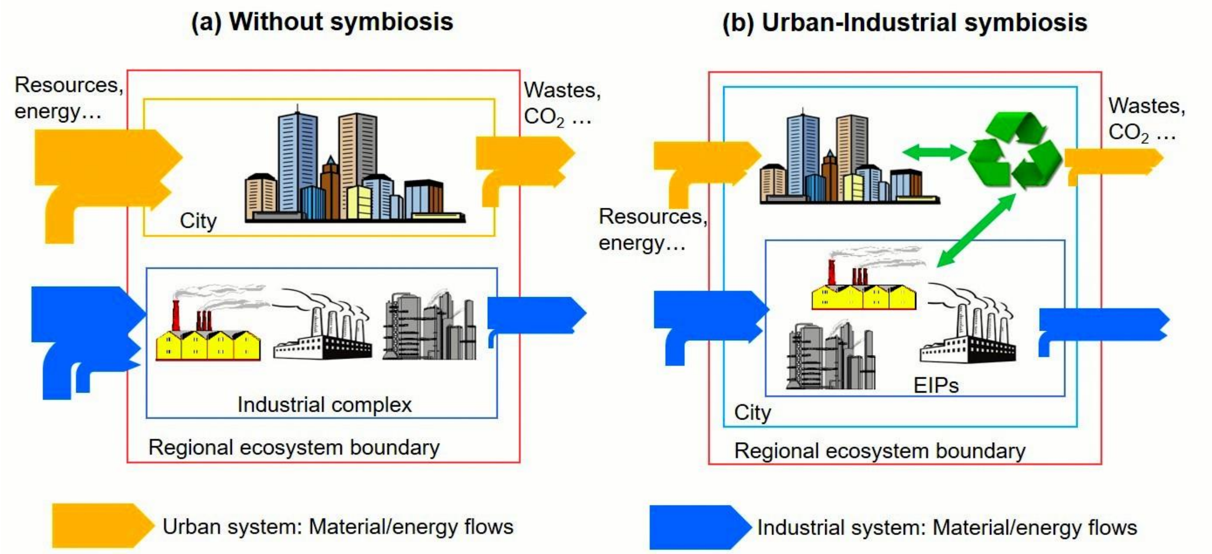

Figure 4.1: Material and energy flow in industrial ecosystems.

Ulsan metropolis has promoted EID for decades and has been a pivotal part of the South Korean national EIP program since 2005. Being a world-famous industrial city, Ulsan's sustainability transition through EIP and industrial symbiosis development can offer key insights to other emerging economies as well. Ulsan, also referred to as the growth engine of South Korea's economy, is located in the southeast and has been the most significant heavy industrial region for more than 40 years (Kim et al., 2017). Ulsan is among the seven metropolitan cities in South Korea having a total land area of 1,061 km^2 and a population of about 1.2 million (corresponding to a 2% share in national population) (Ulsan Metropolitan City, 2019). In addition, due to proximity with the coast, Ulsan is considered as the gateway to domestic and overseas markets with major industries comprising petrochemicals, non-ferrous production, automobile manufacturing, and heavy industries (ship and vessel production). Thanks to its large industrial base, Ulsan's per capita GDP (65.52 million KRW) was almost twice that of the national average, as of 2018 (KOSIS, 2018). Figure 4.2 shows the map of Ulsan and the geolocation of industrial areas within the city.

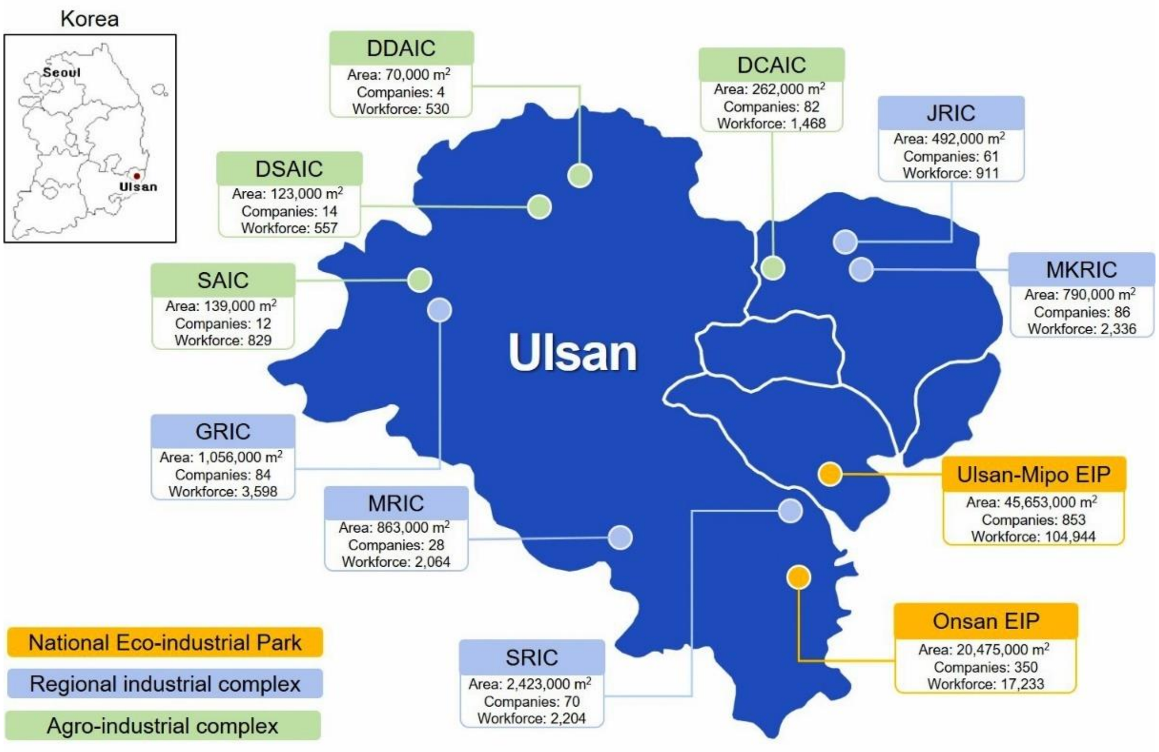

Figure 4.2: Map of Ulsan with designated industrial areas.

[*Note: Abbreviations used are as follows: Ulsan Mipo National EIP (Ulsan-Mipo EIP); Onsan National EIP (Onsan EIP); Shin Regional Industrial Complex (SRIC); Gilcheon Regional Industrial Complex (GRIC); Modulehwa Regional Industrial Complex (MRIC); Maegok Regional Industrial Complex (MKRIC); Jungsan Regional Industrial Complex (JRIC); Songbuk Agriculture and Industry Complex (SAIC); Duseo Agriculture and Industry Complex (DSAIC); Dudong Agriculture and Industry Complex (DDAIC); Dalchan Agriculture and Industry Complex (DCAIC)*]

Nevertheless, economic growth and urban development have put enormous pressure on natural resources and the environment. With rising environmental concerns, Ulsan was designated as a “demonstration site” in 2005 under South Korea’s national EIP program. To this end, a regional EIP center was established in Ulsan to systematically design and steer symbiotic exchange networks under the “research and development into business” framework (Park and Behera, 2014). Although industrial symbiotic exchange networks existed before 2005, yet they were mostly undocumented. Officially, the industrial base here consists of two EIPs and nine regional ICs. The two EIPs, Ulsan-Mipo and Onsan EIPs, represent major industrial activity in Ulsan and were part of the Ulsan EIP project as demonstration sites. Under this EIP initiative, several industrial symbiosis projects on waste valorization, energy recovery, steam networking, CO_2 sharing, resource exchange etc. were developed (through feasibility studies) and later commercialized with significant outcomes as reported elsewhere (Behera et al., 2012; Park and Behera, 2014; Park and Won, 2008; Park et al., 2016, 2018). Furthermore, urban-industrial symbiosis has also emerged in Ulsan extending the boundaries of EIP to the entire Ulsan region. For instance, waste incinerators are supplying steam to a paper mill. Similarly, municipal waste incinerators are supplying steam to an acid manufacturing company. These urban-industrial symbiosis projects have also helped attain improved levels of regional eco-efficiency.

Before the implementation of the national EIP program, no distinction was made between EIPs and ICs in Ulsan although major export-oriented industries existed in Ulsan-Mipo and Onsan EIPs. Based on Ulsan's industrial output data, as of 2015, both EIPs were responsible for 98.5% industrial output, had a workforce of 122,177 (out of 136,674 persons), and housed 1,203 companies (out of 1,644) including several large companies such as Hyundai automobiles, Hyundai heavy industries, SK energy, S-oil etc. (KOSIS, 2018; Ulsan Metropolitan City, 2019). Apart from the two designated EIPs, the rest of the ICs represent either small to medium scale manufacturing (e.g. JRIC, MRLC), agro-industrial production (e.g. SAIC, DSAIC, DDAIC, DCAIC) or those manufacturing complexes developed since 2010 (e.g. SRIC, GRIC, MRIC). As described, the industrial production output is mainly represented by the two EIPs thus making their impact on Ulsan's EID transition more profound and its assessment highly insightful.

4.3. Methods and data

For this study, regional level urban sustainability was assessed using a modified eco-efficiency approach. In addition, a decomposition analysis was performed to identify key drivers of environmental impact based on the IPAT framework. For eco-efficiency evaluation at the industrial park/complex level, data envelopment analysis (DEA) was used. The aim was to focus on Ulsan's EID transition and analyze whether eco-efficiency improvements at the park level coincide with those at the regional level. Since the scope of this study was limited to Ulsan, all 11 industrial parks/complexes in this region were considered.

The overall research methodology is presented in Figure 4.3. The research framework comprised of four steps: step 1 focused on research questions and methods; step 2 focused on the analytical structure; step 3 focused on results and its analysis; and step 4 presented a macro-policy perspective based on the results.

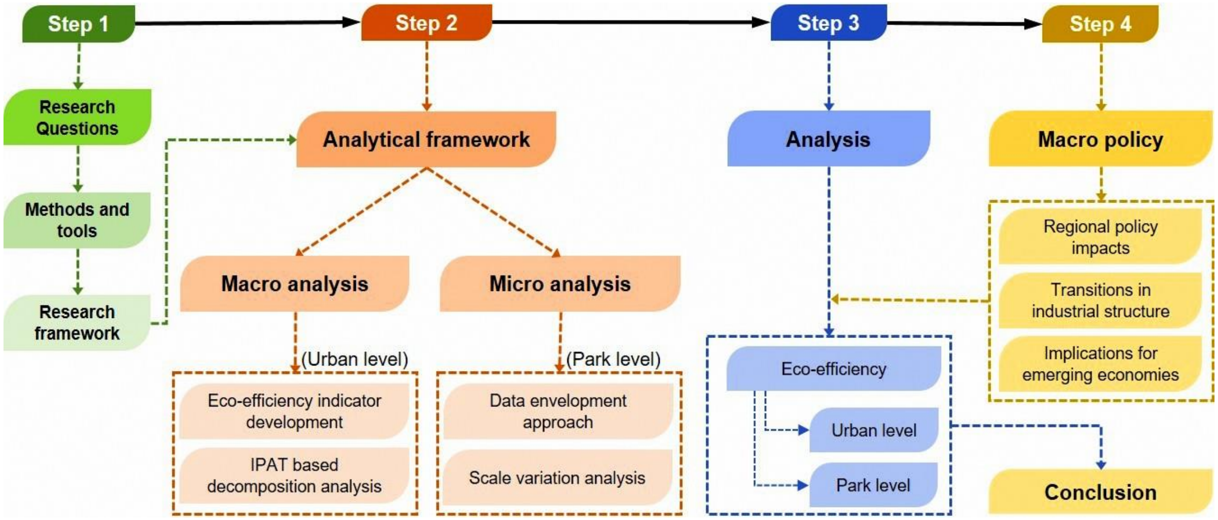

Figure 4.3: Research framework for the eco-efficiency analysis.

4.3.1. Eco-efficiency at the regional level and its drivers

Eco-efficiency is a mature concept used to analyze the ecological and economic efficiency improvement in systems such as products, industrial parks, or even cities (Bohne et al., 2008; Kicherer et al., 2007). Based on the established eco-efficiency framework (WBCSD, 2000), we defined industrial eco-efficiency at time "t" by Equation 4.1 which emphasizes the trade-offs between environmental and economic aspects of industrial development while giving equal emphasis to both (Kuosmanen and Kortelainen, 2005):

$$EE_t = \left(\frac{P_t\,E_0 - P_0\,E_t}{P_t\,E_0}\right) \times 100 \tag{4.1}$$

Where EE_t is the percent eco-efficiency improvement at time t relative to the base year (t=0); E_0 and E_t are the environmental indicators for the base year and at time t, respectively; and P_t denotes production output at time t and P_0 represents production for the base year. Since the base year eco-efficiency is the reference point, it is given a value of 0% and any growth in EE_t corresponds to improved eco-efficiency or vice versa. Although the base year can be set equal to any year for which the data is available, however, the year 2000 was selected as the base year for this analysis. In Equation 4.1, the economic aspect was represented by gross industrial production output, as it better reflects economic activity in contrast to net sales, shipments, exports etc. (Ho et al., 2018). And according to WBCSD (2000), environmental aspects can be represented by industrial waste and energy consumption. Moreover, changes in waste eco-efficiency can also be a proxy for material savings (Guan et al., 2019a; Halme et al., 2007). Therefore, both industrial waste generation and energy use become very important in assessing industrial eco-efficiency at the regional and industrial park/complex levels.

Furthermore, a decomposition analysis following the additive log-mean divisia index (LMDI) method was also carried out to characterize driving factors behind environmental pressures associated with industrial production (e.g. industrial waste generation and energy consumption). By using the IPAT framework, the environmental impact indicator can generally be expressed as Equation 4.2 shown below:

$$I = P \times A \times T \tag{4.2}$$

Where "I" stands for environmental impact, "P" accounts for population, "A" accounts for affluence, and "T" accounts for technology. To quantitatively measure the contributions of these drivers, LMDI method (Liu and Ang, 2007) was used to decompose the changes in environmental impact ΔI during t_0 (the start year) to t_e (the end year), expressed by Equation 4.3 to 4.8:

$$\Delta I = I_{t_e} - I_{t_0} = \Delta P_{pop} + \Delta A_{aff} + \Delta T_{prod} + \Delta T_{int} + \Delta T_{str} \tag{4.3}$$

The components of change in Equation 4.3 can be calculated as:

$$\Delta P_{pop} = \sum \frac{\mathrm{I}_{t_e} - \mathrm{I}_{t_0}}{\ln \mathrm{I}_{t_e} - \ln \mathrm{I}_{t_0}} \times \ln \frac{P_{t_e}}{P_{t_0}} \tag{4.4}$$

$$\Delta A_{aff} = \sum \frac{\mathrm{I}_{t_e} - \mathrm{I}_{t_0}}{\ln \mathrm{I}_{t_e} - \ln \mathrm{I}_{t_0}} \times \ln \frac{A_{t_e}}{A_{t_0}} \tag{4.5}$$

$$\Delta T_{prod} = \sum \frac{\mathrm{I}_{t_e} - \mathrm{I}_{t_0}}{\ln \mathrm{I}_{t_e} - \ln \mathrm{I}_{t_0}} \times \ln \frac{TP_{t_e}}{T_{t_0}} \tag{4.6}$$

$$\Delta T_{int} = \sum \frac{\mathrm{I}_{t_e} - \mathrm{I}_{t_0}}{\ln \mathrm{I}_{t_e} - \ln \mathrm{I}_{t_0}} \times \ln \frac{TI_{t_e}}{TI_{t_0}} \tag{4.7}$$

$$\Delta T_{str} = \sum \frac{\mathrm{I}_{t_e} - \mathrm{I}_{t_0}}{\ln \mathrm{I}_{t_e} - \ln \mathrm{I}_{t_0}} \times \ln \frac{TS_{t_e}}{TS_{t_0}} \tag{4.8}$$

Drivers of environmental impact included regional socio-economic indicators such as (1) population effect and (2) affluence effect (per capita regional GDP), while technological indicators included (1) production effect, (2) intensity effect (i.e. waste/energy per unit production) and (3) industry structure effect (Jung et al., 2012). The regional socio-economic drivers were expected to highlight the indirect contribution of rising population and economic affluence towards industrial eco-efficiency. Similarly, technological drivers were expected to highlight whether regional-level eco-efficiency improvements have emerged from improvements within sectors (e.g. waste recovery, energy efficiency, industrial symbiosis etc.) or as a result of industrial restructuring (e.g. transition to high-tech and high-value sectors). Industry structure was represented by the output value of heavy industries in total industrial production, as previously reported (Liu et al., 2018a, 2018b; Zhang et al., 2017). Due to data limitations, the analysis was limited to the period 2007-2015, however, the results are expected to provide insights into regional eco-efficiency improvements during the entire study period.

4.3.2. Eco-efficiency at the industrial park/complex level

The eco-efficiency analysis at the individual industrial park/complex level was based on the data envelopment approach. In this study, 2005, 2010, and 2015 were selected as representative years and individual industrial parks/complexes were represented as decision making units (DMUs) responsible for transforming inputs into outputs. Table 4.1 presents multiple indicators selected as part of the DEA methodology.

The DEA inputs and outputs were selected based on data availability (across all EIPs and ICs for given periods) and past studies (Fan et al., 2017; Song et al., 2016; Zhang et al., 2017). In this study, both CCR (Charnes-Cooper-Rhodes) model (representing the eco-efficiency level of a DMU proportionally with existing and future development scales) and BCC (Banker-Charnes-Cooper) model (representing how the eco-efficiency of a DMU will change if its scale is altered) were used.

The DEA methodology can be applied to several entities or firms, termed as a DMU, to assess their eco-efficiency by identifying a performance index (Chang, 2011). A DEA model estimates an efficiency frontier considering both inputs (e.g. energy, natural resources, capital, labor, and land) and outputs (e.g. production output, value-added, and waste emissions) and looks for points on the frontier that minimizes inputs and maximizes outputs (Fan et al., 2017). All DMUs which lie on the efficiency frontier are considered eco-efficient while the ones not lying on the frontier are given an eco-efficiency score depending on their radial distance from the efficiency frontier. This method was initially based on the assumption of constant returns to scale (CRS) and was termed as CCR model (Charnes et al., 1978), however, later modifications helped the incorporation of variable returns to scale (VRS) into the DEA which was termed as BCC model (Banker et al., 1984).

Table 4.1: Inputs and outputs used in the DEA model.

Flow	Indicator	Notation	Description
Input	Land resources	x_1	Land area occupied by operating firms within the industrial area reported annually in 1000 m^2.
	Human resources	x_2	Industrial workforce comprising all employees and labor within the industrial park/complex.
	Energy resources	x_3	Total industrial energy consumption reported annually in 1000 tons of oil equivalent (toe).
Output	Gross Output	y_1	Industrial production output adjusted through consumer price index values (2015=100) reported annually in billion KRW.

Some details on the development and application of the DEA approach are already presented in Chapter 3 of the dissertation. However, brief explanations of the two variations of DEA (CCR and BCC) are provided below:

Constant returns to scale: Efficiency based on CCR model is termed as overall efficiency (OE) or technical efficiency (TE) which can represent the eco-efficiency level of a DMU proportionally with existing and future development scales. Equation 4.9 shows the CCR based eco-efficiency using the CRS assumption.

$$\begin{aligned} &\min \theta_c, \text{ subject to} \\ &\theta_c x_o - X\lambda - s^- = 0, \\ &\quad Y\lambda - s^+ = y_o \\ &\lambda \geq 0,\ s^- \geq 0,\ s^+ \geq 0 \end{aligned} \tag{4.9}$$

Where θ_c is DMU efficiency based on constant returns to scale assumption (a value of 1 indicates a point on the frontier and hence a technically efficient DMU); x_o and y_o represent the input and output vectors of a DMU, respectively; X and Y are the input and output matrices, respectively; λ is a weight vector (N×1); and s^- and s^+ represent the input and output slack variable vectors, respectively.

Variable returns to scale: The BCC model, on the other hand, provides eco-efficiency results using the assumption of variable returns to scale. A DMU's eco-efficiency based on VRS can either be increasing, decreasing, or constant in nature (Banker et al., 1984) and is applicable to DMUs not operating optimally. Equation 4.10 shows the BCC based eco-efficiency using the VRS assumption.

$$\begin{aligned} &\min \theta_v, \text{ subject to} \\ &\theta_v x_o - X\lambda - s^- = 0, \\ Y\lambda - s^+ = y_o \quad &\text{whereby: } e\lambda = 1 \\ &\lambda \geq 0,\ s^- \geq 0,\ s^+ \geq 0 \end{aligned} \tag{4.10}$$

Where θ_v is DMU efficiency based on the assumption of variable returns to scale, and e is an N×1 vector of ones (unit vector). Eco-efficiency based on the BCC model can also be decomposed into pure technical efficiency (PTE) and scale efficiency (SE). Mathematically, SE is equal to OE/PTE. Pure technical efficiency represents existing eco-efficiency while SE represents how the eco-efficiency of a DMU will change if its scale is altered. All eco-efficiency results are reported as values lying between 0 and 1.

4.3.3. Data collection

Data for two national EIPs and nine regional ICs was obtained from Ulsan metropolitan city database (Ulsan Metropolitan City, 2019) and Korea Industrial Complex Corporation (KICOX, 2019) where available. Industrial energy consumption statistics were acquired from energy statistical yearbooks by the Korea Energy Economics Institute (KEEI, 2017). Some of the data was also acquired from EIP project reports. Gross production output for each year was adjusted according to the consumer price index (CPI) of Ulsan (2015=100) based on deflator rates published by the Korea Economic Statistics System (ECOS, 2019). Data was gathered for 16 years i.e. from 2000 to 2015.

4.4. Results and Discussion

In this section, the main findings of the research will be discussed based on the previously explained framework.

4.4.1. Eco-efficiency at the regional level

Results illustrating improvements in eco-efficiency for industrial waste generation and energy consumption during 2000-2015 are presented in Figure 4.4. As shown, the eco-efficiency in Ulsan has improved for both industrial waste and energy over the study period. By the end of 2005, eco-efficiency had improved by 19.1% and 17.4% for waste generation and energy use, respectively, relative to 2000. During this time, the Ulsan EIP project began by focusing on energy recovery and waste reduction. By the end of 2010, industrial eco-efficiency improved by 32.8% and 38.0% for waste generation and energy use, respectively. By this time, more than 13 industrial symbiosis projects and multiple cleaner production and resource efficiency programs were in the implementation phase – all contributing to the improved macro-level eco-efficiency. As of 2015, industrial eco-efficiency stood at 35.0% and 21.4% for waste generation and energy use, respectively, relative to the year 2000. By 2015, two EIPs in Ulsan represented about 98.5% share in gross industrial output (KOSIS, 2018) and about 34 symbiotic exchange projects were in operation. This implies that improvements in regional eco-efficiency were closely linked with EID promotion and industrial symbiosis in Ulsan.

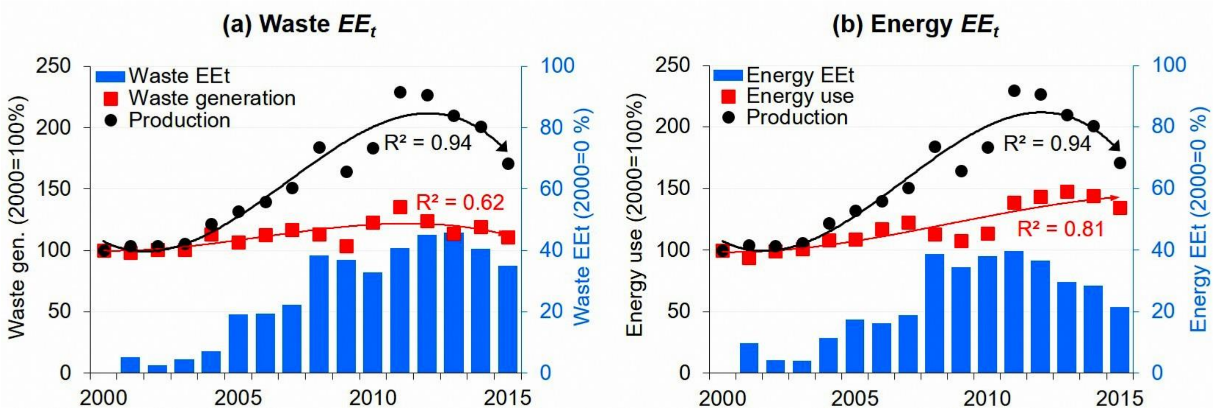

Figure 4.4: Eco-efficiency of industrial waste generation and energy use.

Figure 4.4 (a) and (b) show the respective eco-efficiency trends and annual industrial waste generation and energy consumption statistics (actual values and their 3rd order regression curves). As given in Figure 4.4 (a), industrial production has considerably increased since 2005 whereas waste generation has not increased proportionally indicating relative decoupling of waste from production output. Similarly, in Figure 4.4 (b), relative decoupling of energy consumption and industrial production has occurred especially after 2005. However, as shown in Figure 4.4 (b), when industrial production began to decline after 2011, energy EE_t also started to reduce – less being produced with similar energy inputs. For waste EE_t, reduction in production output was lower as compared to that of waste generation until 2013 – causing waste EE_t to drop only after 2013. As the eco-efficiency concept evolves around both economic and environmental parameters, changes in any of the two factors can influence efforts on eco-efficiency enhancement and, thus, needs to be considered when making decisions based on eco-efficiency assessments.

4.4.2. Decomposition analysis

Decomposition results using region and industry-specific drivers of environmental impact are shown in Figure 4.5. As shown, regional socio-economic drivers (population and affluence) played a positive role in increasing industrial waste generation and energy use – due to increased consumption and industrial expansion. This, however, shows a mutually win-win relation between economic prosperity at the regional level and industrial eco-efficiency enhancements within that urban ecosystem.

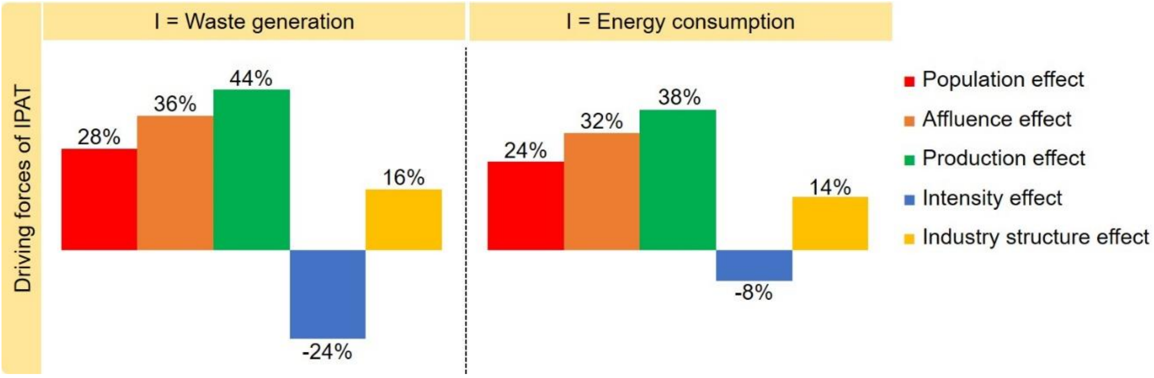

Figure 4.5: Drivers of industrial waste generation and energy use in Ulsan.

Among other drivers, the production effect was the strongest driver for both industrial waste generation and energy use – indicating its indirect influence on eco-efficiency as well. Although growing industrial production generally means increased waste generation and higher energy consumption, however, economies of scale can help improve industrial eco-efficiency at the regional level. As per the results, the industry structure effect also positively pushed waste generation and energy use in Ulsan, nonetheless, its impact was lowest amongst the other positive drivers. This could be attributed to the relatively stable industrial structure in Ulsan, though the share of heavy industries has increased slightly. This highlights the fact that industrial restructuring in Ulsan was not a major driver of regional level eco-efficiency improvements.

As per the decomposition analysis, the intensity effect was found to be the only negative driver of industrial waste generation and energy consumption in Ulsan. This indicates that intensity improvements within industrial sectors (e.g. cleaner production, resource conservation, and industrial symbiosis) were the only driving force behind regional eco-efficiency enhancement. For instance, industrial waste intensity reduced from 3.1 tons/billion KRW (in 2007) to 2.9 tons/billion KRW (in 2015) – a decrease of 6.3% during 2007-2015 (51.2% reduction during 2000-2015). Similarly, industrial energy intensity also reduced from 121.8 toe/billion KRW (in 2007) to 118.6 toe/billion KRW (in 2015) – a decrease of 2.6% during 2007-2015 (15% reduction during 2000-2015). This intensity reduction can be attributed to the Ulsan EIP program through which a variety of projects related to waste valorization, energy recovery, heat extraction, steam networking etc. were implemented – making EIP projects extremely beneficial in offsetting higher energy demands and waste generation from increasing industrial production. Moreover, during 2007-2015, industrial production output had increased by 12.7%, thus, showing an absolute decoupling between industrial production and energy and waste intensities.

4.4.3. Transitions in industrial structure

As discussed in section 2.4.2, changes in industrial structure did not greatly influence eco-efficiency improvements in Ulsan, however, a temporal perspective on recent transitions in industrial structure is crucial. As of 2015, petroleum and chemical industries – both of which are known to be energy-intensive (Hammond, 2000; Worrell, 2018) – had a combined share of 46.7% in total manufacturing output, followed by a 22.1% share of vehicle manufacturing. However, the growth of various high-tech industrial sub-sectors (e.g. semiconductors/chips, smartphones, gadgets, electronics, computers, and accessories) was also observed during the 2007-2015 period. Even though high-tech industries are considered non energy-intensive (Dyer et al., 2008; USEIA, 2016), yet their relative share in total industrial output is still insignificant – making their eco-efficiency contribution almost negligible. As industrial waste generation and energy use data were not available at the sub-sectoral levels, further analysis could not be made.

4.4.4. Regional policy development

In Ulsan, the improvement of industrial complexes had begun on a company-to-company basis by the mid-1990s (Park and Won, 2008). During the early 2000s, industrial production was prioritized through revamping old supply chains and utility systems that used to generate large amounts of by-products and waste materials with no value creation. In 2005, the Ulsan EIP program was launched to improve industrial eco-efficiency and develop new symbiotic resource exchange networks. Figure 4.6 presents the temporal EID policy implementation in Ulsan and changes in industrial eco-efficiency.

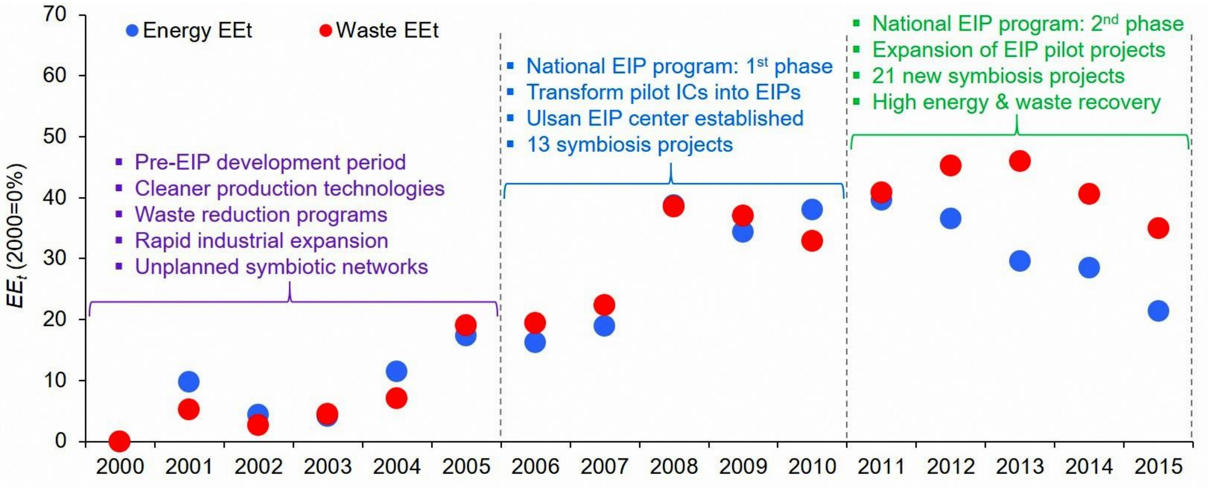

Figure 4.6: EID policy implementation and changes in regional eco-efficiency.

As presented, the first phase of the Ulsan EIP program (2006-2010) focused on transforming two of the existing national ICs into EIPs. However, this is not a quantitative correlation analysis between governmental policies and regional eco-efficiency as it goes beyond the scope of this study. Rather, this section presents a discussion on the changing trends between policy and eco-efficiency at the regional level. The Ulsan EIP center provided guidance and networking for stakeholders and helped industries to identify and implement industrial symbiosis systematically and effectively. During this phase, 13 industrial symbiosis projects were commercialized involving 41 companies – half of which were waste energy exchange while the rest were by-product exchange. During the next phase of the Ulsan EIP program (2011-2015), expansion of pilot projects was implemented, and previously developed symbiosis networks were expanded, where possible. As per the data, 21 new industrial symbiosis projects were implemented including energy networking, wastewater reuse, and by-product exchange – all involving 123 EIP tenants. During 2006-2015, energy recovery/sharing projects alone generated 643.6 billion KRW of economic benefits, GHG reduction of 487 kt CO_2 eq., and energy savings of 136 ktoe each year (Kim et al., 2018). The reduced growth in energy use was attributable to the increase in energy efficiency, energy recovery, and most importantly to the development and execution of industrial symbiosis projects among large energy-consumers and urban environmental infrastructures (e.g. municipal waste incinerators).

As illustrated in Figure 4.6, macro-scale eco-efficiency has been steadily improving since 2000, though a slight decline since 2012-2013 onwards is observed largely due to reduced overall industrial production output. The economic situation after 2013 has been termed as a period of slow growth for South Korea in general, and for Ulsan in particular, as export shipments were lowest in 2015 since the year 2010 and were linked to a slowing Chinese economic growth, falling prices for commodities in Asian markets, and reduced exports (especially to China, United States, and Europe). Though there was a decline in year-on eco-efficiency in the last 2-3 years, nonetheless, the overall improvement relative to the baseline remains significant. Other factors for the declining production of manufacturing industries included uncertain overseas markets, growing protectionism by major trade partners, cheaper Chinese rivals, economies of scale effect, and other external shocks causing Ulsan's export growth to slow down to 5.3% in 2018 from 15.8% in 2017.

As there exists a direct nexus between eco-efficiency and industrial production output (Equation 4.1), technological innovation should be complemented by scale expansion to achieve higher eco-efficiency targets – a task apparently very challenging during times of economic slowdown. However, to address slowing industrial growth in South Korea and boost the local economy, a policy of "innovative growth" has recently been introduced to increase investment in energy-efficient industries such as fuel cells, self-driving cars, smart factories, drones, artificial intelligence, internet of the things, and big data. Moreover, Ulsan was designated, among other cities, as an "industrial crisis zone" with support of around 890 billion KRW in 2018 to upkeep affected stakeholders and promote new industries. However, in the absence of up to date sectoral production data, further analysis could not be made.

4.4.5. Eco-efficiency at the industrial park/complex level

As per the results under constant returns to scale assumption, as of 2015, only the two EIPs in Ulsan had a TE equal to 1.0 indicating their optimum performance (compared to all other DMUs) in transforming material and human resources into economic output [DCAIC had a medium level eco-efficiency {i.e. TE <1.0 but ≥0.40} while eight of the remaining ICs had a low eco-efficiency {i.e. TE <0.40}]. This was applicable to both the current and future scales. Factors such as the presence of high-value production, heavy industries, and the emergence of hi-tech sectors have contributed to the higher economic output from both EIPs. Moreover, the development of waste valorization and symbiotic exchange networks have helped attain higher resource efficiency in both EIPs. Influencers of high eco-efficiency in both EIPs include EID promotion under the Ulsan EIP program, technological improvement, cleaner production technologies, proximity for symbiosis networking, and resource efficiency projects. Although both EIPs require large amounts of natural and human resources, yet the optimum efficiency of both EIPs makes them highly influential on sustainable urban transition in Ulsan. During 2010, DSAIC was also among the technically efficient DMUs when many of the ICs were performing at a reasonable TE compared to both EIPs, however, the IC's eco-efficiency has reduced greatly by the end of 2015 – indicating significant progress made by two regional EIPs towards higher eco-efficiency. In other words, rapid eco-efficiency improvement by the two EIPs have rendered all other ICs relatively more and more inefficient.

As per the results under VRS assumption, as of 2015, two EIPs and one IC (DDAIC) were found with optimum PTE while the rest showing either medium eco-efficiency (JRIC, SAIC, DSAIC, and DCAIC with PTE <1.0 but ≥0.40) or low eco-efficiency (SRIC, GRIC, MRIC, and MKRIC with PTE <0.40). This shows that existing resource transformation in DMUs with PTE <1.0 is not efficient under the current scales, however, their eco-efficiency could be improved with scale expansion as indicated by their increasing returns to scale characteristics. In summary, based on both CCR and BBC models, we can say that:

(1) Both EIPs were found to possess the highest eco-efficiency under both CCR and BCC models.

(2) Both EIPs have become more and more efficient as compared to ICs during 2005, 2010, and 2015 respectively. Or conversely, ICs have not improved their eco-efficiency at the rate EIPs have improved during this period. This can be attributed to the EID implementation in both EIPs under the auspices of the Ulsan EIP program; and

(3) All ICs showed "increasing returns to scale" indicating their relatively inefficient performance under existing scales (i.e. large inputs but lower outputs compared to EIPs). However, this lower eco-efficiency, applicable to their current scales, could improve in the case of scale expansion.

4.5. Research limitations

There were some study limitations that should be mentioned. First, although the South Korean EIP program was implemented in different regions, this study focused only on Ulsan city. It will be important to analyze whether eco-efficiency patterns in the rest of the regions across South Korea are comparable or not. Second, data limitations such as the unavailability of sectoral and industrial park level data for a complete-time series were also encountered. Besides, data unavailability of crucial factors for industrial production, such as water resource consumption, could have a high influence on DEA outcomes and should be considered when interpreting the results. Finally, there were some limitations to the DEA method itself. The DEA results are known to be affected by sample size (Liu et al., 2015) and the number of inputs and outputs considered. In this study, however, both parameters were adequate having no negative impact on the discriminatory power of the DEA model. Another limitation of the DEA method was that it did not consider the structural differences between EIPs and ICs (e.g. large land and human resources required for agro-industrial complexes yet lower economic output; more energy consumed by EIPs and high economic output). Also, lack of environmental emissions data (e.g. wastewater, industrial waste, CO_2, CH_4, N_2O etc.) for each EIP and IC might have favored EIPs (being the largest material and energy consumer). Some of the DEA limitations could be tackled through its integration with regional input-output tables and physical resource flow statistics.

4.6. Policy implications

Based on our results, several policy-level implications can be drawn especially for sustainable industrial development and urban transition in emerging economies:

(1) Based on the decomposition analysis, improvements within industries (as opposed to industry structure change) could be an important tool for regional eco-efficiency improvement. Urban-industrial symbiosis, as described in Ulsan’s case, also offers practical solutions for waste treatment, energy recovery, and value creation in many industrializing economies. From Ulsan’s experience, reliance on direct government funding and/or institutional support needs to be minimized by developing innovative business strategies for long-term industrial symbiosis projects.

(2) The scale of production (i.e. returns to scale) also presents a critical parameter for expansion, or even otherwise, of industrial production. As with Ulsan, the industrial energy consumption and waste generation did not proportionally increase with an increasing industrial output which greatly helped in higher eco-efficiency enhancement. Therefore, similar assessments could be used as a tool to devise strategies for scale expansion of industrial parks/complexes.

(3) Limited access to data, such as the sectoral energy consumption and waste generation, can greatly inhibit deep insights into the industry-level influencers of eco-efficiency. Therefore, the collection and availability of such data are highly recommended for localized eco-efficiency assessments. The database construction and access in developing countries can be considered as the first step towards EID policy design and development.

(4) Eco-industrial development and industrial symbiosis can be challenging at the beginning requiring innovative implementation approaches. In addition, stakeholder consultation is also crucial so that all the environmental, economic, and social factors are incorporated into decision making. Based on Ulsan's EIP experience, the government's financial and institutional support coupled with facilitation and coordination by regional experts can indeed be a success factor for innovative EID policies in developing countries. This is critical in the case of developing countries as governmental support for environmental management could potentially spark ecological innovation (Frondel et al., 2007; Ren et al., 2018).

(5) Governmental support through the regional EIP center was a prominent feature of Ulsan's EID transition though it was different, for example, from that of China's circular economy transition (Geng et al., 2009; Zhang et al., 2010), Japan's eco-town development (Van Berkel et al., 2009), and Kalundborg-Denmark's industrial symbiosis realization (Chertow, 2004). The government funding in South Korea was mainly used for conducting project feasibility, end to end matching,

and cost-benefit analysis with the rest of investments generated by the participating firms. In addition, the Ulsan EIP center provided continued assistance at both the process and the project levels for industrial symbiosis implementation. From these global EID experiences, a combination of different approaches could be used by emerging economies such that local socio-economic and environmental factors are adequately incorporated.

4.7. Conclusion

Eco-industrial development is recognized as an innovative, preventative, and regenerative approach towards industrial and urban sustainability. By applying a modified eco-efficiency assessment protocol, our results verified that industrial park and urban level eco-efficiencies have improved significantly during the fifteen-year EID practice in Ulsan with two national EIPs making the highest contribution. Symbiotic resource exchange networks within EIPs and those within the urban-industrial context have greatly helped Ulsan's sustainability transition. However, the rest of the industrial complexes (relatively low eco-efficiency and economic contribution) were found to possess eco-efficiency improvement through scale expansion. As future work, integration of regional input-output tables with the DEA approach could be explored for analyzing sectoral impacts on eco-efficiency. Moreover, regional input-output tables can be used such that "exports of manufactured and processed products" can be distinguished from local demand/consumption within the region.

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Preface to Chapter 5

In industrial ecology, wastes are often considered as potential resources. In this context, the practice of creating value from waste resources is usually termed as "waste valorization". Moreover, cities are continuously looking for ways to valorize wastes through both industrial and urban-industrial symbiosis. This chapter will examine the extent of waste valorization in Ulsan, popularly known as the industrial capital of South Korea, and the role of eco-industrial parks in facilitating symbiotic waste exchange networks. As part of this chapter, several waste valorization projects will be analyzed in detail. The objective of this chapter is to provide technical, environmental, and economic aspects of multiple industry-scale waste valorization projects and their implementation strategies. The chapter will also provide regional developments on waste valorization in the context of developing Asian countries.

The chapter is expected to outline crucial aspects of urban-industrial symbiosis and discuss efficient resource metabolism through waste valorization in industrial ecosystems. The results are also expected to offer an innovative biorefinery approach for waste valorization from an industrial ecology perspective.

Chapter 5

Waste valorization in industrial ecosystems

Abstract

This chapter discusses the waste valorization opportunities and strategies through urban-industrial symbiosis in the context of industrial ecosystems. The chapter also presents an overview of the Ulsan's waste valorization approach and its experience for efficient industrial and urban metabolism. Based on the study, it was found that significant progress has been made towards material efficiency, resource recovery, and air emission mitigation through the waste valorization approach in Ulsan. The practice of creating value from wastes, whether industrial or municipal, kills two birds with one stone i.e. (1) waste reduction and avoidance of environmental impacts from waste treatment/disposal, and (2) reduced consumption of virgin resources through direct replacement. For the implementation of waste valorization projects, the incorporation of "research into business" was found to drive considerable private investments. Multiple success stories such as industrial symbiosis after landfill gas recovery, conversion of food waste and sewage sludge to biogas, and symbiosis between municipal environmental infrastructures and industrial parks have been demonstrated. The findings highlight the importance of innovative approaches towards waste valorization in industrial ecosystems.

5.1. Introduction

Contrary to the traditional perception of waste as an economic and environmental burden, waste valorization has become a key alternative for enhanced resource recovery. Waste valorization usually involves the recovery of valuable resources and bioproducts that can be used as a feedstock in energy generation, and manufacturing and process industries (Ferronato et al., 2019; Poinern and Fawcett, 2019). Industry-scale extraction of bioenergy and other co-products such as biochemicals, biofuels, and bio-commodities from organic waste is a promising technique towards higher levels of waste valorization (Mohan et al., 2016a). Waste valorization, considered second to waste reduction or avoidance, involves the valorization of waste residues through the co-production of materials and energy. Waste valorization is mostly applied to combustible organic waste which possesses limited recycling opportunity, lower value of recovered materials, the potential for waste contamination, or is preferred when avoidance of land disposal of waste residues is required (Mata et al., 2018).

A waste biorefinery can be termed as a bioprocess used to extract bio-based materials and energy from renewable waste resources through sustainable biotechnology and, thus, can be termed as the integration of remediation and material recovery (Dahiya et al., 2018; Mohan et al., 2016a). According to the International Energy Agency (IEA), biorefining is the sustainable processing of biomass into a range of bio-based products including chemicals, materials, fuels, power, and heat (IEA, 2018). Among the several available technologies used in biorefineries such as anaerobic digestion, fermentation, and incineration, the use of any technology or a combination of technologies depends on the type of feedstock, its availability, characteristics, and market demand (Mata et al., 2018; Nizami et al., 2017). Moreover, the ability of biorefineries to process diverse organic feedstocks from agriculture, forests, municipalities, and industries (Mohan et al., 2016b; Naik et al., 2010) makes biorefineries a cost-effective technological intervention for waste management and energy recovery (especially in the form of biodiesel, ethanol, methane, hydrogen, heat etc.). Among other technologies, the transition from petroleum refinery to waste biorefinery (Kamm and Kamm, 2004) is considered as an efficient pathway to achieve resource sustainability and carbon neutrality – both at the same time (Nguyen et al., 2010).

The most widely cited case with documented success is of Kalundborg city in Denmark (Chertow and Park, 2015). In Kalundborg, a variety of resource exchange networks have existed since the 1970s and have evolved into a complex and adaptive industrial ecosystem. Among the various symbiotic exchange networks, Inbicon Biomass Refinery (or Inbicon biorefinery) was inaugurated in 2009 as a demonstration biomass refinery in Kalundborg. Inbicon biorefinery has the capacity to produce 5.4 million liters of bioethanol annually from 30 kilotons of wheat straw along with the co-generation of lignin pellets (13 kilotons) and C5-molasses (11 kilotons) (ETIP, 2019). The bio-products from this biorefinery are used in a variety of ways including ethanol used in transport (fuel replacement), lignin used in power and heat generation (coal replacement), and molasses used in food production and chemical production (chemical replacement). Thus, bioenergy has been able to substitute fossil fuels and other chemicals using the concept of integrated biorefineries. In fact, biorefineries could very well meet all their internal energy demands and export the rest of the bio-products for commercial purposes – steps leading to the substitution of fossil fuels and mitigation of environmental impacts (Martin and Eklund, 2011). For developing countries, based on the Kalundborg experience, a transition from fossil-based energy consumption to bio-based energy use can partly contribute to CO_2 emission mitigation and improved resource efficiency. This becomes more relevant when high shares of biodegradable waste remain untapped or untreated in most developing countries (Kawai and Tasaki, 2016; World Bank, 2019). Nevertheless, despite low-income levels in developing economies, progress towards biorefinery implementation may come sooner given their rising environmental deterioration and higher climate vulnerability (Choudhary et al., 2019; Sarkodie and Strezov, 2019). However, this transition could only materialize once sustained policies and actions are implemented with the use of the best available technologies and business models.

5.1.1. Waste valorization: South Korea's experience

Biorefineries, mainly classified depending on the type of feedstock source, can be used to process both industrial and municipal wastes (Kamm and Kamm, 2004). Both wastes are highly relevant to waste management practices in South Korea. With rapid urban and industrial development, increasing waste generation coupled with limited land space has put South Korea in pursuit of sustainable waste valorization technologies. Under the national government, the Ministry of Environment and the Ministry of Trade, Industry, and Energy (MOTIE) have been continuously looking for ways to valorize waste generated in the country. This includes implementation of multiple policies and laws such as "waste deposit-refund system (1991)", "Act on promotion of saving and recycling of resources (1992)", "volume-based waste fee system (1995)", "extended producer responsibility (2003)", "Act on food waste separation (2005)", "Act on the promotion of the conversion into environment-friendly industrial structure (2006)", and "low-carbon green growth vision (2008)". Since 2010, a transition towards high-value, material-frugal, and technology-based manufacturing has risen significantly and the share of service sectors is also on the rise (Sonnenschein and Mundaca, 2016). Changes in industrial structure have been promoted through the governmental support under "low-carbon green growth strategy (2009)" and the "five-year plan for green growth (2013)" (Jung et al., 2012; Sasikala et al., 2019). More recently, particularly since 2017, alternate energy policies are being actively pursued to reduce fossil fuel consumption and switch to cleaner energy resources including bioenergy (Park and Kim, 2019). Overall, all these efforts at the national level have resulted in a reduced municipal waste generation [0.40 tons/capita/year in 1995 compared to 0.36 tons/capita/year in 2009 (Seo, 2014)] despite population and economic growth, and have promoted waste valorization, material reuse, material conservation, and energy efficiency/recovery in the country.

Having said that, industrial sectors in South Korea are generally energy-intensive and are responsible for consuming most of the energy resources (Park and Kim, 2019). As of 2017, the final energy consumed by the industrial sector amounted to about 144 million tons of oil equivalent (Mtoe) which represents a share of about 62% in total energy consumption in the country (KEEI, 2017). Similarly, as of 2016, GHG emissions from the industrial sector (including processing and manufacturing but excluding energy production industry) amounted to about 236 million tons CO_2 equivalent, representing a share of about 34% in national GHG emissions (GGIRC, 2016). This is an understated figure as most of the secondary energy ends up being consumed by the industrial sector in the form of electricity, heat, and steam. Nonetheless, this situation has pushed successive governments to act upon rising climate consequences from large-scale energy consumption by domestic industries. Efforts have been, therefore, extensively carried out to mitigate fossil fuel consumption and reduce consequent GHG emissions (Sasikala et al., 2019). From a policy perspective, measures for energy efficiency and GHG mitigation have been promoted at both the national and sectoral levels through green growth initiatives and eco-industrial development strategies. At the sectoral level, industries have been encouraged to employ smart grid storage systems (Lee, 2015), develop offshore wind farms (MOTIE, 2010), use low-carbon power and renewable resources, and invest in energy research and development projects (Lee and Mogi, 2018) to improve energy efficiency at an individual firm or industrial park level. Similarly, national-level strategies on eco-industrial development are also complementing regional efforts on waste valorization and sustainable growth.

5.1.2. Eco-industrial parks

From a temporal perspective, following the Rio Earth Summit in 1992, the South Korean government was harnessing ideas to restructure local industries and businesses with cleaner production practices to uplift their economic, environmental, and social performance (Park et al., 2008). Active governmental involvement towards resource efficiency enhancement paved the way for the 15-year national Eco-Industrial Park (EIP) program which was initiated in 2005. The South Korean EIP program was initiated by the Korea National Cleaner Production Center (KNCPC) in collaboration with MOTIE under the title "Eco-industrial Park: Construction for establishing infrastructure of cleaner production in Korea".

In this context, an EIP is a community of firms and businesses pursuing enhanced environmental, economic, and social performance through mutual collaboration to conserve natural resources and energy, increase productivity, improve industrial efficiency, promote worker health and public image, and harvest economic benefits from the use and sale of waste materials and/or by-products (Côté and

Hall, 1995; Lowe, 1997). An EIP may consist of a group of firms and companies that seek higher economic benefits and improved environmental performance by mutual collaboration and resource connectivity, thus, making collective benefits larger than the sum of individual benefits each firm would accrue if they were improving individually (USEPA, 1996). Industries and governments usually employ industrial ecology practices, such as industrial symbiosis, for reduced overall carbon footprint of industrial ecosystems. The carbon footprint of an EIP can be a measure of the total CO_2 emissions (Wiedmann and Minx, 2007) or the sum of all GHG emissions (Johnson, 2008) directly associated with the functioning of an EIP – although incorporating indirect emissions are subject to interpretation. With this definition in mind, EIP development, whether planned or unplanned, creates innovative pathways for higher resource efficiency at the intra-firm, inter-firm, and regional levels. With higher resource efficiency, the use of virgin raw materials is reduced, and waste resources are optimized within the industrial ecosystem which then mimics the principles of a natural ecosystem to some extent. Figure 5.1 presents the basic concept of EIPs as an industrial ecosystem based on their resource metabolism and waste (by-product) optimization.

According to the concept illustrated in Figure 5.1, only the resources flowing inside (from outside) and wastes flowing outside (from inside) are considered when the environmental impacts of EIPs are to be quantified. The external resources (R_E) are received by firms inside an EIP along with internal resources (R_i) in the form of exchanged wastes and/or by-products. As shown in Figure 5.1, total resource consumption is equal to the sum of R_E^1, R_E^2, and R_E^3 whereas total waste discharge from the EIP is equal to the sum of W_E^1, W_E^2, and W_E^3. Under this ecosystem, the total waste from the EIP is reduced by a quantity equal to the amount of materials exchanged inside. Therefore, both the consumption of external resources and the generation of external wastes is reduced proportionally to the level of internal resources exchanged between the firms.

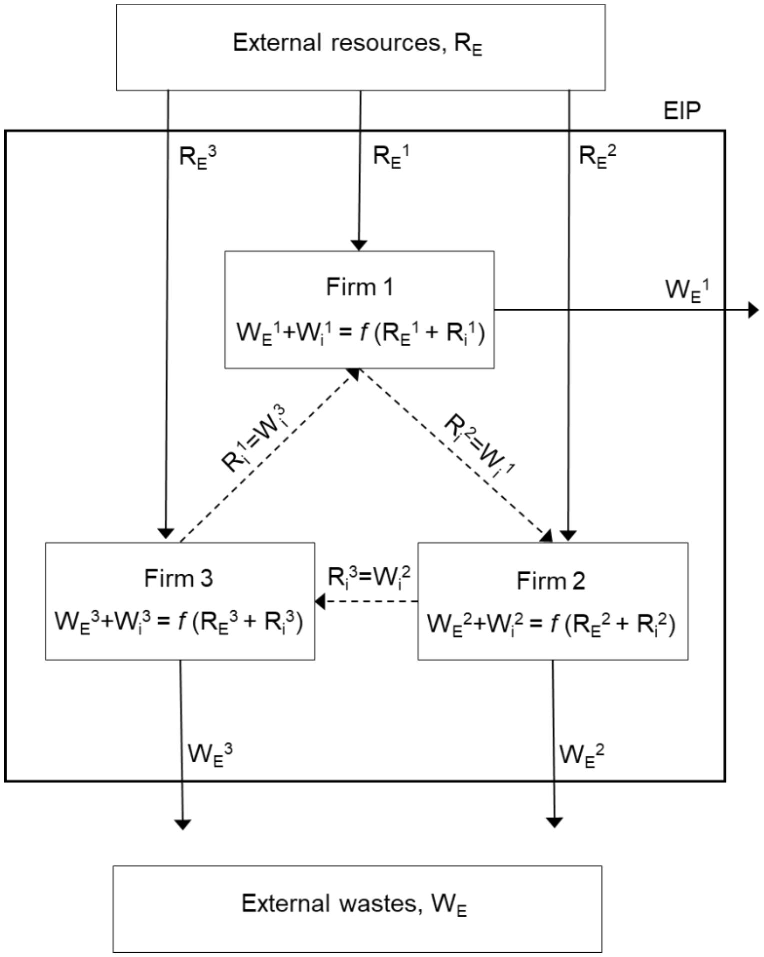

Figure 5.1: Concept of internal versus external resource consumption in EIPs.

[*Note: In this diagram, "R_E" are external resources; "W_E" are external wastes; and "W_i" and "R_i" are internal wastes and resources, respectively*]

As EIPs generate both environmental and economic benefits, all participating firms taking part in resource sharing networks increase their market competitiveness and public image through locally developed business models. Following this approach under the South Korean EIP program, several waste valorization projects through the regional EIPs have successfully materialized producing significant benefits (Yedla and Park, 2017). Table 5.1 presents a summary of the economic and environmental benefits of the South Korean EIP program.

Table 5.1: Economic and environmental benefits from the South Korean EIP program.

Region (projects)	Economic benefits [a]			Environmental benefits [b]			
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Kyeonggi (22)	125	14.2	17.4	86,216	887,085	11,192	56,724
Ulsan (34)	212	80.0	63.0	40,042	79,388	279,761	665,712
Busan (17)	11.3	7.2	10.5	22,961	2,890	22,946	95,669
Chonbuk (25)	36.1	6.0	32.6	150,236	-	-	204,139
Chonnam (42)	93.9	30.6	87.8	791,784	10,980	-	530,173
Kyeongbuk (40)	210.4	47.0	85.8	436,016	36,571,514	55,053	351,834
Daegu (24)	10.1	7.2	40.2	68,220	600	50	35,176
Choongbuk (19)	44.9	5.1	25.6	40,007	36,860	20,521	73,462
Choongnam (6)	15	0.1	11.1	636	-	-	42,337
DaeJeon (1)	0.6	0.2	1.5	322	-	-	-
Incheon (3)	1.5	-	1.3	10	-	1,200	2,869
Total (233)	**760.8**	**197.6**	**376.8**	**1,636,450**	**37,589,317**	**390,723**	**2,058,095**

[a] *Economic benefits are reported in billion KRW, as of 2016, as (i) Investment for projects, (ii) Cost reduction, and (iii) Revenue generated;*

[b] *Environmental benefits are reported, as of 2016, as (iv) waste and by-products reduction/exchange in tons, (v) water saved in cubic meters, (vi) energy savings in tons of oil equivalent, and (vii) CO_2 reduction in tons.*

Note: 1 USD = 1,194 KRW (as of July 06, 2020)

5.1.3. Waste valorization under Ulsan EIP

In Ulsan, the transition of industrial complexes into EIPs has been a continuous phenomenon that has been systematically accelerated by national-level policies on eco-industrial development. The city of Ulsan is one of the nation’s seven metropolitan cities and has been South Korea’s most significant heavy industrial region for more than 40 years. The industrial base includes two majors EIPs comprising petrochemical, chemical, non-ferrous, automobile, and shipbuilding industries with multiple by-product and energy symbiosis networks (Kim et al., 2018; Nguyen et al., 2018; Park et al., 2018). Under the national EIP program, an EIP center was institutionalized in Ulsan to systemically engineer and cultivate the symbiotic exchange of waste materials and process by-products to achieve resource optimization and energy recovery for increased waste valorization. These efforts were motivated by rising concerns about industrial energy consumption and its potential environmental impacts. In 2016 alone, total energy consumption in Ulsan was equal to 27.13 Mtoe from which 89% (24.17 Mtoe) was attributed to the industrial sectors. The overwhelming demand for energy resources had put immense pressure on the government to promote resource and energy recovery programs since the year the 2000. The transition from conventional landfilling of wastes during the 1990s to energy/resource recovery during 2000s was, therefore, a major achievement that is partly attributable to spontaneous energy efficiency activities within the industrial sector. However, the waste valorization approach, under the Ulsan EIP program, systematically helped in partially mitigating the rising energy demand from industries and thereby reducing GHG emissions to a great extent.

From a transitional perspective, during the 1990s, the organic wastes generated within the city were traditionally sent to sanitary landfills with no value creation or energy recovery, although, efforts on waste reduction were in place. This approach transformed, during the early 2000s, into resource recovery mostly in terms of landfill gas extraction and use. This practice further evolved when multiple technologies including recycling, landfill gas collection, anaerobic digestion, and incineration were combined and successful waste valorization began.

As Ulsan has an energy-intensive industrial base, most of the focus has been on providing energy from clean and alternative resources, of which, bioenergy is carbon-neutral – if not carbon-negative (Bui et al., 2018). Therefore, most of the biorefineries in Ulsan focus on providing low-carbon bioenergy to EIPs in terms of biogas and steam (generated from biogas) that mitigates the overall carbon footprint of EIPs. The EIPs themselves showcase the successful sharing of waste resources, energy products, infrastructure, and communication networks to the mutual benefit of participating companies. This symbiotic approach has greatly reduced Ulsan's heavy dependence on fossil fuels, improved its sustainability status, enhanced industrial market competitiveness, and provided significant economic, environmental, and social benefits. In the proceeding sections, successful cases of waste valorization using landfill gas reclamation and steam production from municipal waste are presented. This will be followed by biogas production from food waste and municipal wastewater treatment sludge and its utilization by a chemical processing company through industrial symbiosis. Lastly, the case of strengthening the biorefinery of a paper mill business through steam and CO_2 networking between a zinc smelter and a bioenergy center is discussed. These case studies will provide insights on how the biorefinery concept can be adapted into the real field in the context of industrial ecosystems. The case studies are followed by a summary of the triple bottom line benefits from Ulsan EIP along with a discussion on progress made by other Asian countries.

5.2. Successful waste valorization projects

The waste recovery and resource sharing projects successfully executed in Ulsan provide critical insights into the factors and strategies involved in upscaling the waste valorization infrastructures and biorefineries.

5.2.1. Landfill gas reclamation and industrial symbiosis

Ulsan metropolitan city implemented a Landfill Gas (LFG) reclamation project with a cost of 55 billion KRW at Seongam landfill. The LFG reclamation project was initiated due to several reasons such as large generation rates of organic wastes, scarcity of landfill sites, need for landfill stabilization, increasing energy costs and energy demand from local industries, and most importantly the motivation for resource recovery. After the retrofit installation of LFG collection equipment, the LFG supply began in 2002 at a rate of 100~230 m^3/ton of landfilled waste with a reported calorific value of 4,707 Kcal/m^3. Before the waste valorization project began, the extraction of LFG was smooth due to landfill maturity and an effective collection pipe network consisting of 49 extraction wells. The gas collection network at the landfill site, having a capacity of 4.45 km^2, was able to collect and then discharge LFG through the gas flare system without any heat/energy recovery. Some of the municipal waste in Ulsan city was also sent to a nearby waste incinerator that was used to produce steam for electricity production. Figure 5.2 shows the schematic diagram of the landfill gas reclamation project before and after the industrial symbiosis present at Ulsan Seongam landfill.

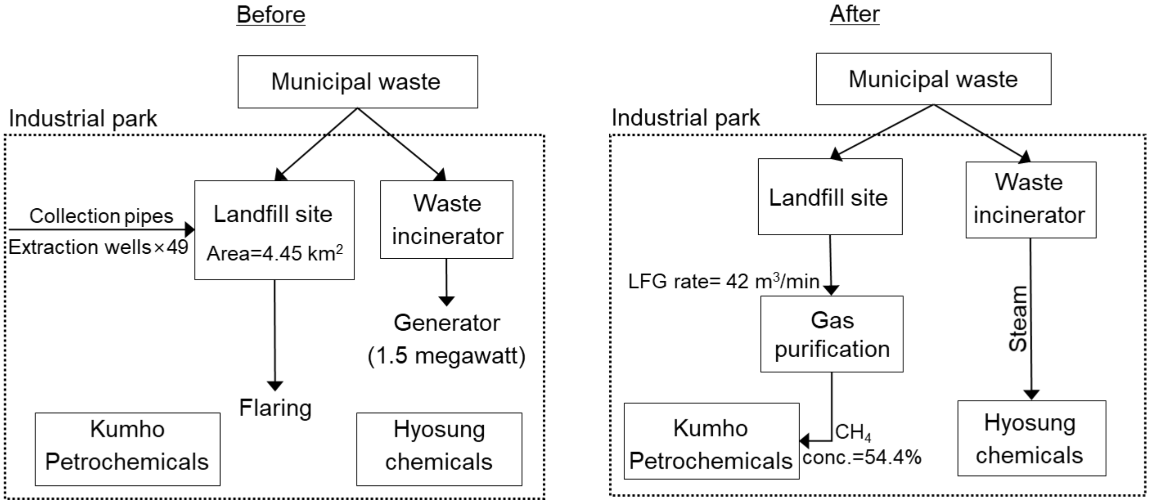

Figure 5.2: Schematic diagram of industrial symbiosis after landfill gas reclamation.

[*Note: The diagram shows Ulsan Seongam landfill site, before and after industrial symbiosis*]

As both facilities (landfill site and waste incinerators) were located within the industrial park area, their proximity to industrial units was turned into a business opportunity for waste valorization. Through the symbiosis project, LFG from the landfill site was diverted to Kumho Petrochemicals, while waste incinerators shared steam with Hyosung Chemicals. This symbiotic exchange project created 6 additional jobs as well to support the operation and maintenance of the energy sharing infrastructure.

With the help of a gas purification facility, LFG with a methane concentration of 54.4% was supplied to Kumho Petrochemicals. The methane concentration in LFG, however, varied between 55-58% throughout the year depending on several parameters such as the composition of feedstock and other environmental conditions.

Under this project, the designed LFG supply of 42 m^3/min (average 30~33 m^3/min) was able to generate total revenue of 13.3 billion KRW during 2003~2016 with an average annual income of 1.77 billion KRW. The LFG supply to the petrochemical company helped them to reduce fossil fuel consumption and their corresponding GHG emissions. In addition, steam networking between waste incinerators and nearby Hyosung Chemicals was also developed, thus, helping the chemical company to reduce their boiler operating costs, fuel consumption, and greenhouse gas emissions.

5.2.2. Biogas sharing network with a chemical plant

A biogas sharing network was developed at the Yongyeon integrated municipal wastewater treatment plant with an investment of 197 billion KRW comprising primary, secondary, and advanced treatment facilities at a wastewater capacity of 250,000 m^3/day. The plant was initially constructed for conventional primary and secondary treatment but was later equipped with advanced bioreactor processes. To develop biogas network with a nearby chemical plant, sludge digesters (7000 $m^3 \times 2$) were renovated by Scandinavian Biogas Fuel (SBF) (with a cost of about 21 billion KRW) to treat 180 tons per day of food waste (which generates a 3 billion KRW revenue per year). The municipal wastewater treatment plant was located within the industrial park and received sewage wastewater from the municipalities and industries. Before the implementation of symbiotic biogas exchange, the primary function of this facility was wastewater treatment and biogas disposal (open flaring) with no heat/energy recovery. However, with the advent of energy sharing industrial symbiosis, biogas was collected and sold to a nearby chemical processing company. This symbiotic biogas sharing project also resulted in the creation of 10 new jobs. Figure 5.3 shows the bioenergy utilization before and after the industrial symbiosis project at the Yongyeon integrated wastewater treatment plant.

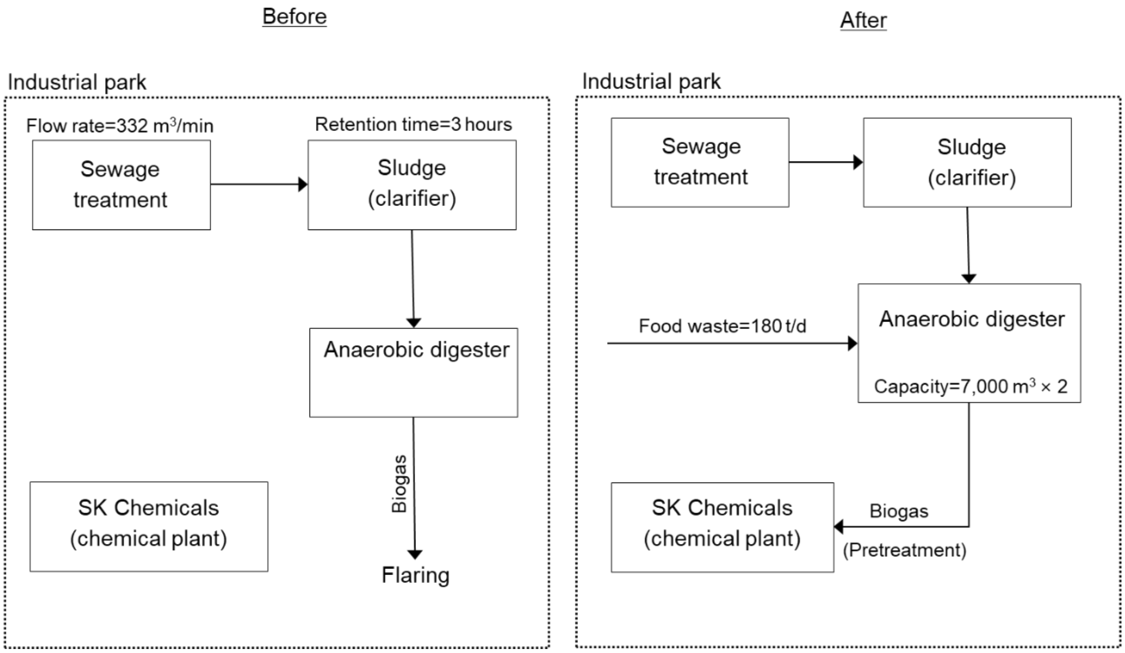

Figure 5.3: Schematic diagram of biogas symbiosis project.

[*Note: The diagram shows Yongyeon integrated wastewater treatment plant site, before and after industrial symbiosis*]

The bioreactor at Yongyeon comprised of anaerobic processes which provided an opportunity to produce biogas through the anaerobic digestion of organic waste. Prior to this biogas networking, the biogas produced by the digester was sent to the gas storage tank where it was temporarily stored before being sent to the gas flare system (open combustion). The biogas sharing network helped the biogas to be used as a bioenergy resource by a nearby chemical processing plant i.e. SK Chemicals. Since the biogas was being sent to the chemical processing unit, the pretreatment of biogas was done before its distribution. Thus, the whole situation, from biogas flaring to its use as a resource, benefitted both participating companies. Although the installed wastewater treatment capacity was significantly larger (i.e. 250,000 m^3/day), yet the average throughput in 2017 was about 217,111 m^3/day. This indicates that the facility could be used to treat the remaining 32,889 m^3/day of wastewater and increase biogas production in the future.

Moreover, as given in Figure 5.3, after the establishment of the biogas sharing network, sludge from the sewage treatment plant was sent to the anaerobic digester along with food waste for more biogas production. This was done to increase the biogas production from the anaerobic digesters and utilize food wastes for resource recovery. For this symbiosis, the digester capacity was also enhanced by adopting ultrasonic technology from “Scandinavia Biogas” to meet a total per day treatment capacity of more than 600 tons of sludge and 180 tons of food waste. With the help of this symbiotic project, successful waste valorization was achieved in which organic wastes were processed to produce biomethane to be used by the chemical company. This biomethane sharing project reduced boiler operation costs and fossil fuel use at SK Chemicals reducing their GHG emissions in the process.

5.2.3. Biorefinery strengthening and bioenergy networking

This case pertains to the integration of a bioenergy facility with a paper mill and a zinc smelter – all co-located within the Ulsan EIP. The evolution of such a biorefinery networking provides valuable insights for readers and will be explained in two parts. The first part explains the actual paper mill competitive strengthening through steam and CO_2 networking, while the second part describes the development of a bioenergy center that focused on bioenergy production from organic wastes.

Paper mill strengthening through steam and CO_2 networking

Steam and CO_2 sharing network, among two different entities, is also an interesting case of waste valorization in which successful integration of biorefinery and EIP took place. The project involved a receiver company i.e. Hankook Paper (classified as a stakeholder of the biorefinery business) which received steam and CO_2 from the zinc smelter (Korea Zinc) located at 3.8 kilometers from each other. The investments by Korea Zinc and Hankook Paper were 16.87 billion KRW and 4.16 billion KRW, respectively, mainly for infrastructure and pipeline development. The entire project development and planning were supervised by the Ulsan EIP center. Figure 5.4 shows the schematic diagram of the steam and CO_2 networking before and after the industrial symbiosis project between Hankook Paper and Korea Zinc.

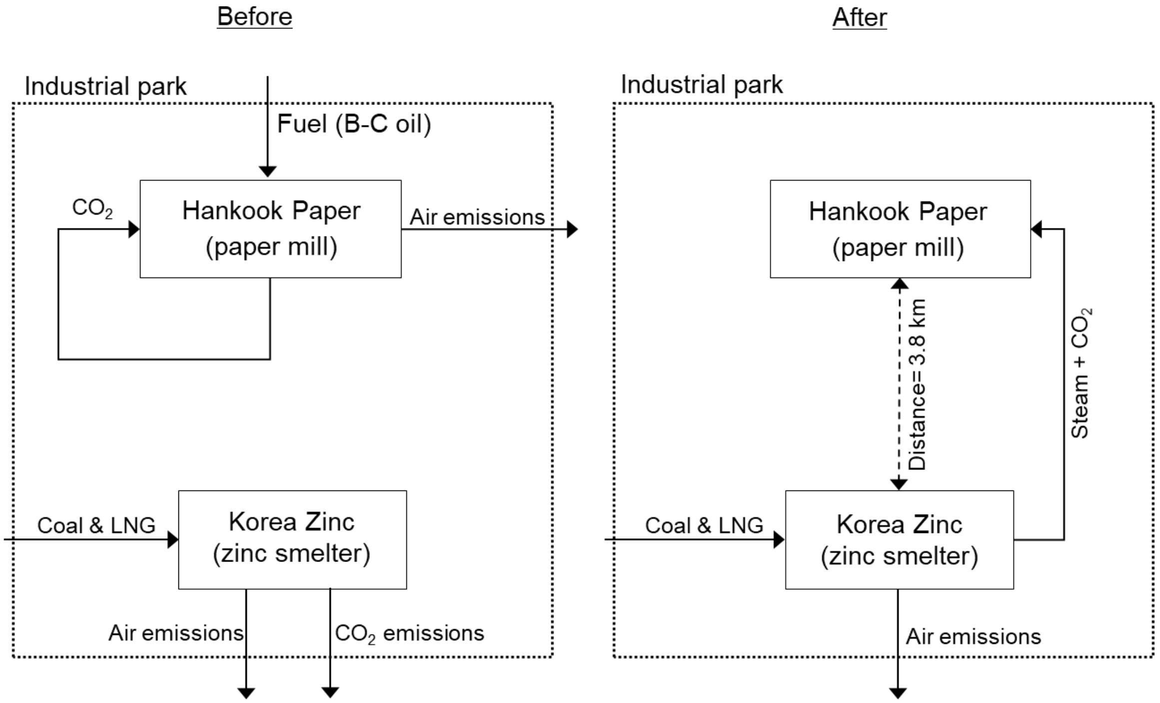

Figure 5.4: Industrial symbiosis between a paper mill and zinc smelter.

[*Note: The diagram shows resource flows, before and after industrial symbiosis*]

Before the industrial symbiosis between the two companies took place, Korea Zinc and Hankook Paper did not explore any resource-sharing opportunities as both were working independently at the industrial park level. That approach transformed when industrial symbiosis networking was conceived and implemented. Hankook Paper previously operated internal boilers to produce both steam and CO_2

gas (for conversion into calcium carbonate to be used as a filler material). Korea Zinc used to emit large quantities of CO_2 as waste flue gas before the implementation of a symbiosis project. However, after the successful implementation of the symbiosis project between the two companies in 2011, steam (690,638 tons per day) and CO_2 flue gas (77.72 million Nm^3) were supplied by Korea Zinc company to Hankook Paper. This multi-faceted symbiosis helped Hankook Paper to shut down its existing boilers that were being operated on Bunker-C oil. This helped in fuel cost and GHG emission reductions for Hankook Paper whereas Korea Zinc was able to earn revenues through the sale of steam and CO_2 (previously discarded wastes). Through this resource exchange networking, the annual profits for Korea Zinc and Hankook Paper were 4.19 billion KRW and 2.42 billion KRW, respectively. The project also helped in a net reduction of GHG emissions by 60,522 tons of CO_2 equivalent.

Ulsan BioEnergy Center

Under the policy to promote renewable bioenergy production from organic wastes and to prepare concrete business plans for the environmental-friendly treatment of food waste and livestock manure, "Ulsan BioEnergy Center" was established with a cost of 23 billion KRW in 2014. The Ministry of Environment provided 70% of the funding while the rest was managed by Ulsan's city government. At the beginning of the project, biogas was generated at a rate of 9,000 Nm^3/day, out of which, 5,850 Nm^3/day of biomethane was produced after the refining process. The bioenergy center generated 16.5 tons/day of impurities and 8.8 tons/day of digestion sludge. Figure 5.5 shows the schematic diagram of the Ulsan bioenergy center.

The designed treatment capacity of the bioenergy center was 150 tons/day of waste comprising of both food waste (100 tons) and livestock manure (50 tons). The treatment process was based on the anaerobic digestion method in which the generated biogas was used for steam production and later shared through industrial symbiosis. The bioenergy center had facilities for anaerobic digestion, biogas production, sludge treatment, odor prevention, and wastewater treatment. Anaerobic digestion process comprised of feed-in and pretreatment, and acid and methane fermentation. The biogas production at the bioenergy center was used to produce steam on site which was then supplied to Hankook Paper. Steam produced at this facility generated a profit of 700 million KRW per year and created 10 additional jobs. For the year 2016, the bioenergy facility revenues through steam supply and waste disposal fees amounted to 2.49 billion KRW. Since improvements in design have been taken up recently, revenue generation is expected to increase in the coming years.

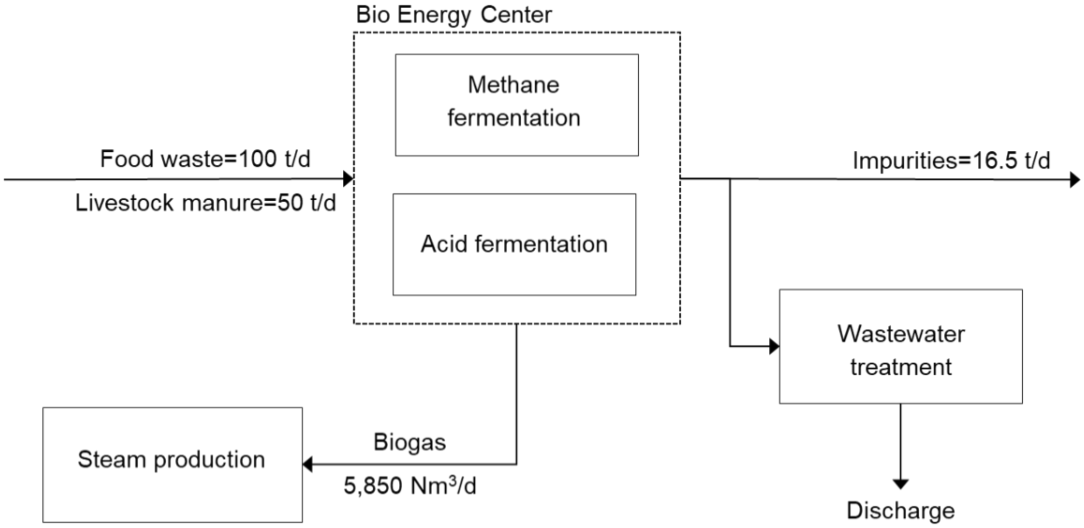

Figure 5.5: Schematic diagram of Ulsan BioEnergy Center.

The symbiotic network is further elaborated in Figure 5.6 which presents the steam and CO_2 networking before and after industrial symbiosis project involving all three participants i.e. Ulsan bioenergy center, Hankook Paper, and Korea Zinc. Prior to the three-party symbiosis project, food and animal waste in Ulsan city were disposed of using conventional methods mainly landfilling and ocean dumping. Such a practice required higher resources for waste disposal with no energy recovery or material recycling. Further, Ulsan bioenergy center became operational during 2014 which provided an opportunity to link its steam production with nearby industries. Therefore, this idea further evolved when the bioenergy center was established within the industrial park, thus, increasing its proximity to the two participating industries. After the successful implementation of this symbiotic network, the Ulsan bioenergy center treated organic waste to produce steam from biogas which was then sold to Hankook Paper (Hankook Paper was already receiving steam and CO_2 from Korea Zinc at this time).

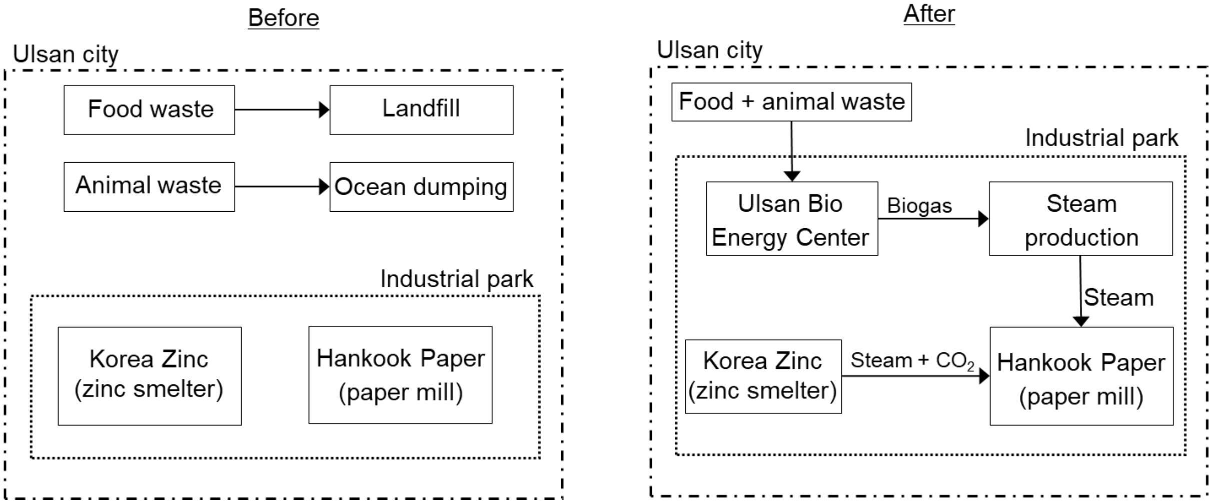

Figure 5.6: Three-party steam and CO_2 networking project.

This waste valorization approach through industrial symbiosis greatly helped the participating firms to reduce their operational costs and pollutant emissions. This case study also illustrates the importance of waste networking which can bring forward significant waste valorization opportunities even when industries are located at a considerable distance from each other. This case also highlights how waste valorization can help reduce GHG emissions from industries and urban environmental infrastructures especially at a time when global consensus over climate change mitigation is very strong.

5.3. Ulsan EIP program and waste valorization

Economic, environmental, and social benefits – the three pillars of sustainable development – were also significant in the context of waste valorization in industrial ecosystems. Ulsan was also able to contribute to the national economy by reducing energy and resource intensity of local industries. The successful commercialization of multiple projects also motivated other industries to implement industrial symbiosis for waste valorization. In total, Ulsan EIP resulted in 77 project proposals from 294 firms (for which feasibility was conducted). From those proposals, 34 projects materialized and were implemented among 123 participating firms.

The economic benefits calculated as the sum of cost savings (reduced resource procurement, operations, and waste management; and replaced virgin material with by-products) and revenues (selling off excess energy or by-products) were highly significant during 2005-2016. By the end of 2016, government investments totaled to 16.64 billion KRW for project research and development, including EIP center operations. From this government research fund, a new income of 73.11 billion KRW per year was generated through the selling of by-products and recovery of materials/energy. An additional income of 87.84 billion KRW per year was generated from energy and material savings. Moreover, total private investment for the construction of industrial symbiosis networking facilities amounted to 276.46 billion KRW. The EIP project also resulted in the creation of 195 new jobs, thus, adding social value to the EIP program.

The environmental benefits evaluated in terms of direct reductions in waste, energy consumption, and CO_2 emissions are presented in Table 5.2.

Table 5.2: Environmental benefits achieved under the Ulsan EIP program.

EIP phase	Waste reduction (t)	Energy saving (toe)	CO_2 reduction (t)
Stage 1 (2005~2009)	31,719	51,767	118,377
Stage 2 (2010~2014)	6,826	144,335	369,249
Stage 3 (2015~2019) [a]	1,497	83,659	178,086
Total	**40,042**	**279,761**	**665,712**

[a] *South Korean EIP program was ended in 2016 instead of the planned year (2019).*

Note: The data presented pertains to the period 2005-2016.

As shown in Table 5.2, a significant amount of energy was saved which resulted in the reduction of CO_2 emissions and other air pollutants such as SOx and NOx. Also, a total of 79,388 m^3 of wastewater generation was avoided, and large quantities of by-products and wastes were either avoided or reused. A large share of environmental benefits was attributed to energy symbiosis networks under the Ulsan EIP program (Kim et al., 2018). Multiple energy sharing networks were developed among several firms where high-grade heat and waste steam were shared between different participating firms. The symbiotic networks for energy exchange directly reduced the combustion of fossil fuels including major fuels, such as B-C oil and other petroleum products, and indirectly caused GHG emission reductions. For details on several industrial symbiosis projects in Ulsan, we refer to the published literature (Behera et al., 2012; Kim et al., 2018). Consequently, these outcomes positively helped industrial parks to improve their public image and enhance their relations with the neighboring/local communities. Industries along with local companies and regional government also disseminated outcomes of the Ulsan EIP program through televised reports and social media campaigns under Corporate Social Responsibility (CSR) initiatives. Environmental benefits were portrayed as the ethical responsibility of industries, thus partially alleviating concerns from environmental groups.

Although the national EIP program was initially planned to complete in 2019, however, the program ended in the year 2016 by the government of South Korea mainly due to government policy shifts. The South Korean government considered that the national EIP program had sufficiently achieved its original objectives and the development of industrial symbiosis could be voluntarily continued in regional EIPs.

5.4. Progress on waste valorization in developing Asian countries

Waste valorization, especially in the developing world, could be the first step towards up-scaling biomass and organic waste management at a time when agriculture, municipalities, and industries lack adequate waste management technologies. Moreover, waste management and co-generation of bioenergy through biorefinery development have become increasingly pertinent to developing countries as most of them face severe environmental challenges (Nizami et al., 2017). This argument is strengthened when energy demand is growing nearly three times faster in developing countries as compared to industrialized countries (Keho, 2016). Therefore, biorefinery development could provide additional opportunities for both waste valorization and carbon-neutral bioenergy production in the developing world.

From an ecosystem's perspective, developing Asian countries have a huge potential to garner benefits from sustainable waste management, bioenergy production, GHG mitigation via fossil fuel substitution, and co-generation of bio-based chemicals for industrial and agricultural purposes. However, progress on biorefinery development in most of the Asian countries is rather unsatisfactory. According to the World Economic Forum (WEF), the policies on biorefineries and biofuels are inconsistently implemented in most Asian countries except China which has invested largely in biomass-derived energy (WEF, 2010). In China, starch crops have been used to produce bioethanol at five ethanol-based biorefineries with an estimated production of 1.7 million tons in 2009, however, food security concerns have forced these biorefineries to substitute grain-based biomass feedstock with municipal and agro-industrial wastes. India, the second-largest country by population in the world, is also promoting policies on bio-products and biofuels for the last two decades (Saravanan et al., 2018). Recent efforts have been focused on large-scale bioenergy production from both energy crops and waste resources (Naqvi and Yan, 2015) with increasing efforts on the valorization of agricultural wastes (Banerjee et al., 2018; Rao et al., 2008). Similarly, Pakistan – an agricultural dominant economy – has a huge potential for bioenergy production from agricultural biowastes and governmental support for research and development has been increasing recently (Khan and el Dessouky, 2009). Although waste valorization through biorefineries is yet to be seen at large-scales in Pakistan, yet biogas production from organic waste at community levels and bioethanol production from a few sugar mills is taking place (Shah et al., 2018). This is in line with the wider integration of sugar mills with biorefineries where co-generation of ethanol, organic fertilizers, and bioenergy is attracting more interest (Nguyen et al., 2010). In Bangladesh – a densely populated Asian country – energy recovery from organic waste is gaining more attention including biogas co-generation and landfill gas reclamation (Hossain et al., 2014). Huge potential for biorefinery development is available particularly for agricultural wastes (Jahan et al., 2013) which also provides economic integration of farming communities through waste valorization (Jahan et al., 2016).

In the rest of the Asian countries, the biorefinery approach is also gaining pace as a viable strategy for organic waste management. Examples include biorefinery in Thailand using molasses for bioenergy and biofertilizer with integrated sugar mills (Gheewala et al., 2011; Silalertruksa et al., 2015) along with the regional-scale implementation of biorefinery approach using organic wastes in Nepal, Vietnam, Cambodia, and Laos where biogas is extracted as an energy resource and bioslurry is co-produced as an organic fertilizer and fish feed (Sawatdeenarunat et al., 2016). Therefore, a transition away from first-generation biorefineries (which mainly use raw biomass and energy crops) is taking place with the rising implementation of integrated biorefineries (which mainly use organic by-products and wastes) for waste valorization, especially in the developing Asian countries. Nonetheless, with the absence of large-scale commercial biorefineries, systematic integration of biorefineries with municipalities and industries is still in the early research and development stage and is likely to mature in the coming decades.

5.5. Conclusion and future perspectives

Due to the advent of symbiotic networks and the successful commercialization of several industrial symbiosis projects in Ulsan, waste valorization has become an important tool to achieve urban sustainability and eco-living. This chapter discussed the emergence of industrial symbiosis as a waste valorization approach in Ulsan. Some of the successful waste valorization projects were also discussed. The chapter highlighted that the integration of biorefineries with industrial symbiosis networks provides an exciting opportunity to tackle organic waste disposal issues and, in the process, recover bio-based products including bioenergy. A biorefinery – like a petroleum refinery – maximizes revenues through the co-production of bio-products including chemicals and energy. Yet, issues such as inconsistent supply of feedstocks, land use competition with food crops, lack of governmental support, and technological limitations may hinder the expansion of biorefineries. Nonetheless, this practical manifestation of industrial ecology has made a considerable contribution to reduce Ulsan's carbon footprint.

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Chapter 6

Conclusion

This dissertation was aimed at analyzing, tracking, and optimizing resource flows in regional and industrial ecosystems using a variety of environmental assessment tools. The major research objective was to understand the distinct resource metabolism at the macro- and meso-scales from an ecosystem perspective and extend industrial ecology scholarship to regions rarely studied before. In the process, we also synthesized several policy directions for a sustainable economic and eco-industrial transition especially for developing economies. Fundamental research questions were as follows:

(1) At the macro-scale, what are the underlying characteristics of resource extraction, consumption, and trade in developing economies?

(2) How a typical developing country could respond to rising materialization and carbonization? What derives its resource metabolism in the long run? And what are the potential pathways for future resource-efficient economic growth?

(3) Can industrial ecosystems help achieve urban sustainability transition through eco-efficient industrial production? And what drives the eco-efficient production and/or consumption within the industrial ecosystems?

(4) Are industrial ecosystems capable of valorizing waste? Is waste valorization even feasible from an economic, technical, and environmental point of view?

As can be seen, the dissertation was designed in such a way that “regional” and “industrial” ecosystems received equal emphasis. Thus, based on these four research questions, our main findings are presented below.

6.1. Summary of main study outcomes

This dissertation began by introducing basic concepts pertinent to the research theme using existing scholarship and evidence from the industrial ecology literature (Chapter 1). After a thorough discussion, it became evident that material and energy flows are rarely examined from an ecosystem’s perspective. Moreover, regional and industrial ecosystems are undistinctive from an environmental and industrial ecology purview. Following this research gap, crucial hot spots were identified, and fundamental research questions were synthesized. Based on synthesized research questions, the role of regional and industrial ecosystems towards sustainable economic and industrial development was highlighted.

To address the first research question related to the *resource metabolism in regional ecosystems*, a thorough analysis of the economy-wide material flows is of great importance. This is so because regional ecosystems, at the macro-level, drive policies directly influencing outcomes at the meso-scale industrial ecosystems. By focusing on the economic growth occurring in the developing world, the three largest economies in South Asia were identified as ideal laboratories to analyze regional resource metabolism (Chapter 2). To this end, resource use patterns and economic development trajectories were studied in Pakistan, India, and Bangladesh. These three countries represent a 22.6% share in the global population but with a mere 3.8% share in the global economy as of 2017. Our findings showed that with rising income levels, the expansion of urban infrastructure, agricultural production, transportation, and small-to-medium scale manufacturing industries have led to a rapid increase in the consumption of construction minerals, fossil fuels, agricultural minerals, and industrial minerals/chemicals. With the scarcity of domestic resources to fulfill all their needs, these countries have become dependent on the import of foreign resources. Moreover, given the geopolitical volatility, strong competition for regional and global resources could create new challenges especially at a time when developed Asian economies such as Japan, South Korea etc. have already become dependent on imported primary resources. As per our findings, major economies in South Asia remain relatively material- and energy-intensive with a large share of primary/secondary goods in their mutual trade. Resource productivity improvements in the agricultural and industrial sectors through technological development and export of value-added finished goods were recommended as a way forward.

To address the second research question related to *materialization and carbonization in Pakistan*, it is even more interesting to examine how typical developing countries, such as those in South Asia, respond to rising materialization and carbonization. It is also pertinent to analyze the drivers of materialization and carbonization in the long run and look for ways to improve such material transactions in the future. To perform such an analysis, Pakistan was selected as a case study to examine the evolving patterns of material consumption, CO_2 emissions, and economic growth (Chapter 3). After analyzing the dynamic interplay between the policy, economy, and environment, we found that industrialization improves material and environmental efficiency only to a certain degree and that these improvements are not equally distributed among all countries connected through trade. Pakistan, when compared with its top 10 export countries, was relatively more material and CO_2 intensive due to material- and energy-intensive agriculture and industries, low value-added exports etc. Moreover, with the internalization of resource-intensive production, developing economies have become technically inefficient when compared with most developed economies. From a transitional perspective, the results from this analysis established that economic growth, global trade, regional resource connectivity, and industrialization help improve resource metabolism in low-income developing countries, but all countries do not improve equally. Rather, we found that some countries (e.g. China, Spain, and Italy) have achieved faster efficiency improvements during 1971-2015, while some (e.g. Pakistan and

Bangladesh) have become more inefficient in relative terms. As a way forward, resource management policies and environmental best practices (leapfrog approaches) from developed economies could produce good results.

After analyzing regional ecosystems, the focus of this dissertation then moved to the third research question regarding the *sustainability transition of industrial ecosystems*, for which analyzing resource metabolism in an industrial ecosystem is of utmost significance. Thus, Ulsan's eco-industrial transition was studied and the role of eco-industrial parks in urban sustainability was evaluated (Chapter 4). This way, changes in eco-efficiency at the industrial park level were studied against eco-industrial development policies implemented at the urban scale. This analysis helped us to verify whether improvements at the industrial-ecosystem level coincide with those at the urban scale. It was found that the eco-efficiency of industrial waste generation and energy use at the urban scale improved by 35.0% and 21.4%, respectively, and that eco-industrial parks played a critical role in enabling such a sustainable urban transition. Factors enhancing the efficiency of industrial ecosystems included technological improvements (e.g. cleaner production technologies, resource conservation/recycling, and waste valorization) and industrial symbiosis (e.g. waste recovery, steam sharing, by-product exchange). Regional policy on eco-industrial development was found to be driving most of the outcomes by following a combination of both top-down and bottom-up approaches. Our results showed that eco-industrial parks have become highly eco-efficient with an overwhelming contribution to Ulsan's urban sustainability transition. Moreover, eco-industrial development was highlighted as a preventative and regenerative approach to improve eco-efficiency at the regional and industrial park level, enlightening other regional and local initiatives towards urban sustainability.

Next, the attention moved specifically to address the fourth research question related to *waste valorization in industrial ecosystems*. To find answers, the implementation of waste valorization projects through urban-industrial symbiosis in Ulsan was analyzed (Chapter 5). The emerging concept of biorefinery, which is quite similar to a petroleum refinery, was also discussed in the context of industrial ecosystems and was found to be an attractive approach towards value creation from wastes in the form of bio-products (biochemicals, biofuels, and bioenergy) and revenues (avoided costs of waste disposal and selling bio-products). Our findings highlighted that integrating industrial ecosystems with urban environmental infrastructures could provide a great opportunity to link waste biorefineries with existing industrial symbiosis networks. To evaluate the real-world application of this concept, multiple industry-scale symbiosis projects were analyzed such as landfill gas recovery from the retrofitted landfills, conversion of food waste and sewage sludge to biogas, and symbiosis between a paper mill and zinc smelter. We found that urban-industrial symbiosis enhances ecosystem efficiency and provides an excellent opportunity to manage organic wastes in an integrated manner. From an industrial ecology perspective, waste valorization through urban-industrial symbiosis could also lead to a reduced carbon footprint of a city to a large extent.

6.2. Potential contributions to the field

The dissertation provides innovative aspects of "ecosystems" and their spatial analysis using a variety of industrial ecology concepts and environmental assessment tools. The dissertation potentially contributes in several ways to environmental engineering/management and industrial ecology.

First, the dissertation provides a detailed definition of a "regional ecosystem" in line with the standard industrial ecology literature in Chapter 1. Based on this definition, the boundaries of economy-wide material flow analysis could extend further into environmental policy, regional trade dynamics, and economic development. Second, low-income developing countries are yet to ingress industrial ecology literature due to their primitive industrialization stage, however, this dissertation analyzes the distinct resource metabolism in developing South Asian countries and synthesizes potential pathways for future dematerialization and decarbonization in Chapter 2 and 3.

Third, the dissertation develops and applies an eco-efficiency assessment protocol in Chapter 4. The eco-efficiency approach could be termed as a reliable assessment of eco-industrial development and the sustainability transition of industrial ecosystems. The methodological framework considered both the economic and environmental aspects of decision making. The outcomes could be used to promote eco-industrial development as a potential pathway for sustainable resources management. Fourth, with the help of several empirical industrial symbiosis projects discussed in Chapter 5, critical understanding of their technical, environmental, and policy dimensions is expected to advance. These research outcomes are also expected to promote urban-industrial symbiosis which offers resource recovery and waste mitigation beyond the spatial boundaries of industrial ecosystems.

6.3. Study limitations and future recommendations

There is always room for improvement. First, the resource metabolism of "regional ecosystems" was largely based on developing South Asian countries and on publicly available statistics that have been gathered using specific methodologies. It is recommended to use alternative methodologies such as sub-regional material flow accounts, physical input-output tables, and life cycle approaches to account for any discrepancies in the available data in the future, and include more developing countries in the analysis. Second, limitations such as the unavailability of resource consumption data (e.g. raw material use, waste recycling, energy use) and environmental emission data (e.g. wastewater, waste, CO_2, CH_4, N_2O), especially at the sectoral and sub-sectoral levels, need to be addressed in the future. It is recommended to use alternative approaches to complement global databases with national and provincial level data to fill the missing links.

Third, the resource metabolism of "industrial ecosystems" was based on the data from eco-industrial parks in Ulsan. Therefore, it is recommended to apply similar approaches to other eco-industrial parks or regions for more insights. Fourth, the empirical cases of industrial symbiosis presented in the dissertation were only from Ulsan, thus, it is recommended to incorporate more case studies from different regions around the world to derive representative conclusions.

6.4. Closing remarks and policy implications

The dissertation was structured around the idea that to understand resource metabolism in regional and industrial ecosystems, the underlying resource flows are properly characterized, tracked, and analyzed. Moreover, as the term “ecosystem” is quite broad, we defined it according to its regional and industrial dimensions using the industrial ecology literature. Based on the dissertation, several policy implications could be drawn.

Regarding regional ecosystems, improvements in resource productivity are essential in most of the material- and energy-intensive sectors in developing countries. These improvements could be possible through process modernization, the substitution of raw materials, reduced material loss, sectoral restructuring, and promotion of resource-frugal and high-end production in the industrial sectors whereas through encouraging automation in farming, new generation of fertilizers without compromising the net yield, and expanding domestic extraction of agricultural minerals. In the end, it is necessary to emphasize that developing countries are lagging far behind the industrialized countries with regards to efficient regional resource metabolism. As illustrated in the dissertation, the gap between the two has been widening and is likely to continue unless technology development and its transfer from developed countries is promoted. This could also be complemented by incorporating best practices of resource and energy management from industrialized economies with the help of regional cooperation and collective action.

Concerning industrial ecosystems, improvements within industries (as opposed to industry structure change) are an extremely important tool for industrial eco-efficiency enhancement. In particular, the urban-industrial symbiosis offers promising solutions for waste valorization, energy recovery, resource conservation, and value creation by integrating industrial ecosystems with urban environmental facilities. Nevertheless, innovative business strategies to implement urban-industrial symbiosis must be chalked out very diligently.

6.5. Scholarly contributions based on this dissertation

This dissertation was designed as a "manuscript-based work" and consisted of a collection of research contributions made by the author. All scholarly contributions, based on this dissertation, are presented below.

Peer-reviewed articles and book chapters:

(1) **Shah, I. H.**, Dong, L., Park, H. S., 2020. Characterization of resource consumption and efficiency trends in Bangladesh, India, and Pakistan: Economy-wide biotic and abiotic material flow accounting from 1978 to 2017. Journal of Cleaner Production 250, 119–136.

(2) **Shah, I. H.**, Park, H. S, 2020. Chronological change of resource metabolism and decarbonization patterns in Pakistan: Perspectives from a typical developing country. Journal of Industrial Ecology (accepted, in press).

(3) **Shah, I. H.**, Dong, L., Park, H. S., 2020. Tracking urban sustainability transition: An eco-efficiency analysis on eco-industrial development in Ulsan, Korea. Journal of Cleaner Production 262, 121286.

(4) **Shah, I. H.**, Behera, S. H., Rene, E. R., Park, H. S., 2020. Integration of biorefineries for waste valorization in Ulsan Eco-Industrial Park, Korea. In: Waste Biorefinery: Integrating Biorefineries for Waste Valorization. Elsevier B.V., pp. 659–678.

International oral presentations:

(1) Integration of biorefineries for waste valorization in Ulsan eco-industrial park, Korea. 10th International Conference on Industrial Ecology (Beijing, China).

(2) Applying the Korean EIP program for sustainability and natural resource management: Industrial synergies under China-Pakistan Economic Corridor (CPEC). 5th International Conference on Energy, Environment, and Sustainable Development (Karachi, Pakistan).

International poster presentations:

(1) Eco-industrial park – An eco-innovation tool of circular economy transition in Korea. International Conference on Circular Economy for Agri-Food Resource Management (Seoul, Korea).

(2) Enhancing the eco-efficiency of industrial waste generation through Eco-Industrial Park (EIP) development. 6th Asia-Pacific Conference of the International Society for Industrial Ecology (Qingdao, China).

(3) Eco-efficiency indicators for energy consumption in the industrial sector: The case of industrial activity in Ulsan, Korea. 6th Asia-Pacific Conference of the International Society for Industrial Ecology (Qingdao, China).

― The End ―