NOT ALL EMISSIONS ARE CREATED EQUAL: A MULTIDIMENSIONAL APPROACH TO EXAMINING HUMAN DRIVERS OF CLIMATE CHANGE

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ABSTRACT

Global climate change is among the greatest crises facing humanity in the 21st century. Mitigating the impacts of climate change requires a substantial reduction in global greenhouse gas emissions by 2030. Despite the urgency, climate actions are lacking in many nations. A rich body of cross-national research on human drivers of emissions is devoted to identifying effective leverage points for emission abatement, which primarily focuses on aggregate emission measures such as production-based accounts and consumption-based accounts. However, a nation's carbon-emitting activities are not monolithic, but can instead be classified into distinct components based on important characteristics such as the supply chain stage to which they belong. These emission components likely have heterogeneous relationships with certain anthropogenic drivers or mitigation measures. Yet, analyses using aggregate emission measures are unable to detect such heterogeneity or inform the unique strategy that might be required to effectively mitigate each emission component. I address this gap using the three empirical chapters of this dissertation. In the first empirical chapter, I propose an analytical framework of Multidimensional Emissions Profile (MEP), which situates nations' contributions to global greenhouse gas emissions into four distinct components: (1) emissions generated by domestic-oriented supply chain activities; (2) emissions embodied in imports; (3) emissions embodied in exports; and (4) direct emissions of end user activities. I then apply the MEP framework to analyze the relationships between national affluence and the four emission components for 34 high-income nations. I find that as these nations grow wealthier, affluence is increasingly decoupled from direct emissions of end user activities but remains positively associated with the other three emission components in various ways. The findings suggest that emission-suppressing mechanisms associated with growing affluence are effective in mitigating direct end user emissions—typically the smallest component—but not the other three emission components. Therefore, high-income nations should prioritize mitigating emissions generated by supply chain activities outside the end use stage. The second empirical chapter is an examination of how renewable energy deployment is related to these emission components in high-income nations. I find that renewable energy deployment mitigates emissions by domestic-oriented supply chain activities, and with increasing effectiveness over time; yet it remains ineffective in curbing the other three emission components, indicating the existence of structural barriers that prevent the decarbonization effect of renewables from spilling over to these three emission components. These barriers must be overcome in order to achieve the full decarbonization potential of renewable energy deployment. In the third empirical chapter, I investigate the time-varying relationships between domestic income inequality and the four emission components, in order to unpack the multiple pathways linking income inequality to emissions. The results suggest that the relationships change over time, vary across emission components, and differ between measures of income inequality, which indicate variations in the causal pathways, both over time and across emission

components. The findings from all three empirical chapters support the validity of the MEP framework. The relationships between greenhouse gas emissions and national affluence, renewable energy deployment, and domestic income inequality are multidimensional: these anthropogenic forces curb some emission components but spur others. Climate policies targeting these anthropogenic forces should optimize their decarbonization benefits while neutralizing the mechanisms through which they drive growth in emissions.

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1.0 CHAPTER 1: INTRODUCTION

Global climate change causes a multitude of disastrous impacts on societies and ecosystems (IPCC 2021). Mitigating these impacts requires substantial reduction in global greenhouse gases (GHGs) emissions by 2030 (IPCC 2018; UNFCCC 2021). However, by the time of the Glasgow Climate Conference (COP26) in 2021, nations' contributions, pledges and commitments to reduce emissions, even if fully achieved, still fall short of the global target, leaving much to be desired for national actions on climate change mitigation (Bansard et al. 2021; UNEP 2021).

Driven by the urgent need for climate change mitigation, a rich body of social science research on anthropogenic drivers of GHG emissions is devoted to identifying effective leverage points for emission abatement at national level (Blanco et al. 2014; Jorgenson et al. 2019; Rosa and Dietz 2012). This body of research is largely rooted in the IPAT/STIRPAT framework or the similarly specified Kaya identity, both identifying population (P), affluence (A), and technology (T) as three main drivers of human impacts on the environment (Dietz 2017; Dietz and Rosa 1994; Kaya 1990; York, Rosa, and Dietz 2003). More specifically, the STIRPAT model is widely used by cross-national empirical studies to identify human drivers of emissions, estimate their effects, test hypotheses, and inform policy efforts. Empirically identified drivers include—but are not limited to—affluence (Aslanidis and Iranzo 2009; Jorgenson and Clark 2012; Thombs 2018), population size and structure (Dietz and Rosa 1997; Jorgenson and Clark 2010; York 2007), urbanization (Jorgenson, Auerbach, and Clark 2014; Marcotullio et al. 2014), trade (Huang 2018; Jorgenson 2012; Liddle 2018; Prell and Feng 2016), and militarization (Jorgenson and Clark 2009; Jorgenson, Clark, and Givens 2012; Jorgenson, Clark, and Kentor 2010). Research also identifies renewable energy deployment as an instrumental measure for climate mitigation (IPCC 2011; Sovacool 2016; Sovacool and Geels 2016; York 2012), and finds that domestic income inequality is an important factor to consider at the intersection of social justice and climate mitigation (Grunewald et al. 2017; Jorgenson et al. 2016; Jorgenson, Schor, and Huang 2017). However, for these human drivers and mitigation measures, there are debates on the magnitude and direction of their effects on emissions, and on the variations in effects over time and across geopolitical or macroeconomic contexts (see Dietz 2017; Jorgenson et al. 2019).

The cross-national research on drivers and mitigation has primarily focused on how anthropogenic forces affect the total emissions of a nation, or related quotient measures that adjust for either the size of population or economy. Earlier research relies on production-based accounts (PBA) of emissions, also that attributes emissions to nations based on where they are emitted (UNFCCC 1997). Emission measures based on this approach do not account for the emissions embodied in a nation's imports, which are generated in other nations. The omission is significant because in the past 25 years, around a quarter of global GHG emissions are embodied in international trade; many high-income nations, in particular, have been net importers of embodied emissions through trading with lower-income nations (Davis, Peters, and Caldeira 2011; Peters et al. 2011; Peters, Davis, and Andrew 2012; Wood et al. 2020). In light of the limitations of PBA, consumption-based accounting (CBA) was proposed, which accounts for all emissions driven by a nation's consumption demand (Davis and Caldeira 2010; Peters and Hertwich 2008). It is an important methodological and substantive advancement. Researchers argue that switching from PBA to CBA as the basis for mitigation policymaking can improve both the effectiveness and justice of climate mitigation policies (Steininger et al. 2014). An increasing number of cross-national drivers studies have used CBA measures either by themselves or in conjunction with PBA measures (Cohen et al. 2018; Huang and Jorgenson 2018; Knight and Schor 2014; Liddle 2018).

Both PBA and CBA are instrumental to understanding how the totality of a nation's GHG emissions are affected by human drivers and mitigation measures. However, analyses using these aggregate emission measures tend to overlook the more nuanced multidimensionality in a nation's contributions to global emissions. A nation's GHG-emitting activities are not monolithic, but can instead be classified into distinct categories based on important characteristics such as the stage of supply chain in which the activities occur, the type of fossil fuels consumed, or the economic sector in which the activities take place. Correspondingly, a nation's GHG emissions are constituted by multiple structural components, each with distinct implications for emissions abatement. Does an anthropogenic force, either a driver or a mitigation measure, equally affect these emission components? Or are the effects of this force instead heterogeneously distributed across these components? What are the implications of the potential heterogeneity for climate mitigation?

Across the three empirical chapters in this dissertation, I seek to address these questions and fill major gaps in the literature. I propose a new analytical framework for the systematic analysis of multiple structural components of nations' emissions. Using this framework, I investigate how these emission components are related to national affluence, renewable energy deployment, and domestic income inequality.

In Chapter 2, I lay out the proposal for an analytical framework of *Multidimensional Emissions Profile* (MEP), which situates nations' contributions to global GHG emissions into four distinct components: (1) emissions generated by domestic-oriented supply chain activities (DOSCA); (2) emissions embodied in imports; (3) emissions embodied in exports; and (4) direct emissions of end user activities. This chapter begins with a review of the cross-national comparative literature on human drivers of climate change. Then, I discuss the rationales behind conceptualizing nations' contributions to global GHG emissions as multidimensional, focusing on the distinctions among emission components in terms of their implications for climate mitigation and climate justice. Next, I describe the proposal of the MEP framework, which, to the best of my knowledge, is the first analytical framework for a systematic analysis of these four emission components, with particular attention to the heterogeneity among emission components in their relationships with human drivers and mitigation measures. I calculate the data on these four emission components using the environmentally-extended multi-regional input-output (EE-MRIO) method (Miller and Blair 2009), and the EE-MRIO tables from the latest version of Exiobase 3 (Stadler et al. 2018, 2021).

In the second half of Chapter 2, I apply the MEP framework to empirically analyze the affluence/emissions nexus. The motivation is two-fold. First, the analyses are used as a proof-of-concept for the MEP framework. The heterogeneity across the four emission components in how they are related to affluence, if found, will support the notion of multidimensionality in nations' contributions to global GHG emissions and in the affluence/emissions relationship. Second, I situate the analyses within the rich body of prior research on the affluence/emissions relationship and seek to demonstrate how the MEP framework contributes to the research literature and policymaking (Burke, Shahiduzzaman, and Stern 2015; Jorgenson and Clark 2012; Liddle 2015; Lohwasser, Schaffer, and Brieden 2020; Wang, Assenova, and Hertwich 2021).

The affluence/emissions relationship plays an important role in informing the broad direction of mitigation policies, and particularly whether some alternative forms of economic development are required to limit global warming to below 1.5°C while improving national affluence. Some studies argue that increases in affluence are associated with increasing societal scale of resource consumption, and hence inevitably lead to more emissions (Dietz 2017; Jorgenson et al. 2019; Rosa and Dietz 2012; Schnaiberg 1980). Others argue that political, technological, and cultural changes such as state environmental regulations, renewable energy deployment, energy efficiency improvement, and environmental social movements, can alter the societal composition of consumption enough to counteract the upward pressure on emissions induced by an increased scale of consumption (Grossman and Krueger 1995; Mol 2000; Mol, Spaargaren, and Sonnenfeld 2014; Rosa and Dietz 2012). Cross-national empirical studies on the affluence/emissions nexus primarily focus on aggregate emission measures such as PBA and CBA.

Different from prior research, I investigate how national affluence is associated with multiple components of nations' emissions in potentially heterogeneous ways, by using the MEP framework. I seek to identify (1) which emission components grow the most along with economic growth, and hence must be prioritized in national mitigation plans; and (2) which emission components, if any, have been decoupled with affluence, and therefore should be further examined to understand whether and how the mechanisms behind the decoupling can be adapted for other emission components.

I analyze a balanced panel dataset encompassing the data for 34 high-income nations from 1995 to 2015. The sample is selected in part based on the availability of the EE-MRIO data used to calculate the four emission components. Results of panel regression analyses with two-way fixed effects indicate that as high-income nations grow even wealthier, affluence is increasingly decoupled from direct emissions of end user activities but remains positively associated with the other three emission components in various ways. In addition to demonstrating the validity of the MEP framework, the results also suggest that after affluence reaches a threshold, emission-suppressing mechanisms associated with growing affluence are effective in mitigating direct end user emissions—typically the smallest component for each nation—but not the other three emission components. Therefore, high-income nations should prioritize mitigating GHG emissions generated by supply chain activities outside the end use stage.

While Chapter 2 addresses a major driver of emissions, in Chapter 3 I focus on an important measure of climate change mitigation, renewable energy deployment, and how it is related to nations' multiple emission components. The urgency of climate mitigation underscores the importance of optimizing the decarbonization effect of renewable energy deployment (IPCC 2011). To this end, a large body of research has examined how renewable energy deployment affects nations' CO_2 emissions, yielding mixed findings. A number of studies find that increasing renewable energy consumption in a nation can reduce its CO_2 emissions (Bilgili, Koçak, and Bulut 2016; Shafiei and Salim 2014; Shahnazi and Dehghan Shabani 2021; Sovacool et al. 2020; Wang et al. 2021). Other studies question whether renewable energy, as it has been deployed, can lead to the rapid and substantial emission abatement that is necessary to meet the global mitigation target (Davidson 2019; Hill, Tajibaeva, and Polasky 2016; York 2012). These studies together underscore that renewable energy transition and its effectiveness as an emission abatement measure are shaped by various political-economic, social, and technological factors (Jorgenson et al. 2019; Sequeira and Santos 2018; Smil 2016; Sovacool 2016; Sovacool and Geels 2016).

Most cross-national research to date on the renewable energy-carbon emissions nexus examines aggregate national emission outcomes and especially PBA. However, prior research has not systematically examined the decarbonization effect of renewable energy deployment on multiple components of nations' CO_2 emissions corresponding to different types of fossil fuel consumption activities. Renewables' impacts on these emission components may differ in magnitude, in direction, and in how the impacts change over time. For example, if renewable energy deployment is found to suppress the PBA of nations' emissions, it does not necessarily mean that the same decarbonization effect is achieved for all emission components. In other words, unless proven otherwise, the renewable energy-carbon emissions nexus is likely a multidimensional process consisting of distinct relationships between renewables and each of these emission components.

To address the gap in the literature, I use the MEP framework to systematically analyze the potentially heterogeneous relationships between nations' renewable energy deployment and their multiple emission components. Compared across these emission components, which are more effectively mitigated by renewable energy deployment? Which components are less effectively mitigated? For each emission component, how has the decarbonization effect of renewable energy changed over time?

I first conduct a baseline analysis of renewables' relationship with nations' PBA, and how the relationship changes over time. Then I analyze renewables' relationships with the emissions by domestic-oriented supply chain activities (DOSCA), emissions embodied in exports, and direct end user emissions, as well as how these relationships change over time. These 3 emission components together constitute PBA. The focus on PBA and its components is consistent with the literature's main focus. The 4th emission component, emissions embodied in imports, is excluded from the main analysis due to a lack of theoretical ground to assume that a nation's domestic energy policies can directly influence the emissions embodied in imports, which are generated in foreign nations. Given the conceptual focus on energy, fuel, and decarbonization, I analyze CO_2 emissions rather than all types of GHG emissions.

Using seemingly unrelated regression modeling with two-way fixed effects on a panel dataset of 34 high-income nations from 1995 to 2015, I find that renewable energy deployment only mitigates emissions by domestic-oriented supply chain activities (DOSCA), and with increasing effectiveness over time; yet it remains ineffective in curbing the other three emission components. Using DOSCA emissions as the benchmark, I discuss potential structural barriers that prevent the decarbonization effect of renewables from spilling over to the other emission components. These barriers must be overcome in order to achieve the full decarbonization potential of renewable energy deployment.

In Chapter 4, I turn to domestic income inequality and examine how it is related to nations' four emission components that constitute the MEP. Rising income inequality has become a prominent issue during the COVID19 pandemic (Deaton 2021; Ferreira 2021), while reducing global CO_2 emissions remains an urgent task (UNFCCC 2021). Can policies seeking to address income inequality also synergistically generate the co-benefits of CO_2 emissions abatement? A growing body of research investigates the relationship between domestic income inequality and CO_2 emissions, and identifies three major theoretical pathways that link domestic income inequality to CO_2 emissions.

The first pathway focuses on power and political economy. When the social groups that benefit from environmental degradation are more powerful than those who suffer, the societal level of environmental degradation tends to increase (Boyce 1994, 2003, 2007). Higher income inequality means greater power differential between the wealthy and the poor, allowing the wealthy to undermine democracy and prioritize their economic interests in perpetuating the fossil fuel-based development over the society's need for climate change mitigation (Cushing et al. 2015; Downey 2015). Therefore, the political economy pathway suggests that greater income inequality may increase the societal level of CO_2 emissions. The second pathway focuses on how greater income inequality can induce a "Veblen effect" where middle- and lower-class groups are pressured by heightened status competition to spend more in order to keep up with the lifestyle standard set by the upper class (Schor 1998; Veblen 1934). The increased competitive consumption can lead to increased CO_2 emissions. In general, the Veblen effect pathway argues that higher income inequality is associated with increased CO_2 emissions. The third pathway focuses on the marginal propensity to emit. Ravallion, Heil, and Jalan (2000) find that greater domestic income inequality is associated with lower emissions, which they attribute to the decline in the marginal propensity to emit that accompanies an increase in household income, an argument supported by other studies (Heil and Selden 1999; Holtz-Eakin and Selden 1995; Jakob et al. 2014; Seriño and Klasen 2015). Following this pathway, reduction in income inequality by redistributing income from the wealthy to the poor is expected to increase the societal level of CO_2 emissions.

Existing cross-national research examines the inequality-emissions nexus and the causal pathways mainly by analyzing how income inequality affects aggregate emission measures such as PBA (Grunewald et al. 2017), and CBA of CO_2 emissions (Jorgenson et al. 2016). However, the literature has not systematically examined how income inequality may heterogeneously affect various structural components of nations' CO_2 emissions that are generated by different categories of human activities. How might the effect of income inequality differ in magnitude or even in direction across emission components? Are the pathways linking income inequality to emissions different across emission components? I address these questions by applying the MEP framework to investigate how nations' four emission components may be heterogeneously related to domestic income inequality, and how the relationships change over time.

I argue that the three aforementioned theoretical pathways concern different types of carbon-emitting activities, and correspondingly, different emission components in the MEP framework. The political economy pathway primarily focuses on the production realm, while the Veblen effect pathway and the marginal propensity to emit pathway are more closely related to the consumption realm. From a nation's standpoint, emissions embodied in its exports belong to its production realm. Conversely, emissions embodied in a nation's imports belong to its consumption realm, same as direct end user emissions. DOSCA emissions of a nation pertain to both its production and consumption. Therefore, the political economy pathway may have more relevance to emissions embodied in exports and DOSCA emissions, while the Veblen effect pathway and the marginal propensity to emit pathway are more pertinent to direct end user emissions, emissions embodied in imports, and DOSCA emissions.

I estimate seemingly unrelated regression models with fixed effects on a panel dataset of 34 high-income nations from 2004 to 2015. In the analysis, I operationalize income inequality in two different ways: the Gini coefficient and the income share held by the top 10% of population. It is possible that all three causal pathways can shape the two inequality measures' relationships with emissions, albeit not in an equal manner. Gini's relationships with emissions are likely more sensitive to the dynamics of the marginal propensity to emit, while the relationships between emissions and income share of the top 10% may be more sensitive to the political economy and Veblen effects (Jorgenson et al. 2017).

I find that the relationships between income inequality and nations' CO_2 emissions change over time, vary across emission components, and differ between measures of income inequality. Most notably, the income share of the top 10% is positively associated with emissions embodied in exports after 2010, and is negatively associated with end user emissions from 2004 to 2006, and from 2009 to 2011. The results indicate variations in the causal pathways, both over time and across emission components. Income inequality affects emissions embodied in exports primarily via the political economy pathway, and especially so after the Great Recession. The marginal propensity to emit pathway, at times, appears to outweigh the Veblen effect pathway as the main mechanism through which income inequality affects direct end user emissions.

In Chapter 5, the final chapter, I summarize the key findings from Chapters 2, 3, and 4, and discuss their implications for climate change mitigation, development, and social justice and equality. I also lay out the limitations of the analyses in these chapters. Taken as a whole, this dissertation underscores the multidimensionality in how nations contribute to global carbon emissions, and in how emissions are related to anthropogenic forces. The multidimensionality informs theories and policies regarding human drivers of emissions and mitigation measures. Additionally, the dissertation research demonstrates the utility of the MEP analytical framework for the research and policy considerations on climate change mitigation. I conclude by discussing how the MEP framework informs directions for future research on human dimensions of climate change.

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2.0 CHAPTER 2: NOT ALL EMISSIONS ARE CREATED EQUAL: MULTIDIMENSIONALITY IN NATIONS' GREENHOUSE GAS EMISSIONS AND THE AFFLUENCE/EMISSIONS NEXUS

2.1 ABSTRACT

Human drivers of greenhouse gas emissions do not homogeneously affect all structural components of nations' emissions. This study proposes an analytical framework of *Multidimensional Emissions Profile*, which situates nations' contributions to global greenhouse gas emissions into four distinct components: (1) emissions generated by domestic-oriented supply chain activities; (2) emissions embodied in imports; (3) emissions embodied in exports; and (4) direct emissions of end user activities. Using this framework, input-output data, and panel regression analysis, I analyze the heterogeneity in relationships between national affluence and the four emissions components for 34 high-income nations. As these nations grow wealthier, affluence is increasingly decoupled from direct emissions of end user activities but remains positively associated with the other three emission components in various ways. The findings suggest that after affluence reaches a threshold, emission-suppressing mechanisms associated with growing affluence are efficacious in mitigating direct end user emissions—typically the smallest component for each nation—but not the other three emission components. Therefore, high-income nations should prioritize mitigating emissions generated by supply chain activities outside the end use stage. I conclude by suggesting directions for climate

change drivers and mitigation research that use the multidimensional emissions profile framework.

2.2 INTRODUCTION

Global climate change causes a multitude of disastrous impacts on ecosystems and human society (IPCC 2021). The Paris Agreement (UNFCCC 2015) and the Glasgow Climate Pact (UNFCCC 2021) recognize that these impacts can be significantly mitigated by limiting global warming to less than 1.5°C above pre-industrial levels, which in turn requires substantial reduction in global greenhouse gases (GHG) emissions by 2030 (IPCC 2018). However, by the time of COP-26, analysts have found that the nationally determined contributions (NDCs), pledges, and commitments to reduce emissions, even if they are fully materialized, will fall short of achieving the below 1.5°C target, leaving much to be desired for national actions on emissions abatement (Bansard et al. 2021; UNEP 2021). Driven by the urgent need for climate change mitigation, a rich and sophisticated body of research on anthropogenic drivers of GHG emissions is devoted to identifying effective leverage points for emission abatement at national level (Blanco et al. 2014; Jorgenson et al. 2019; Rosa and Dietz 2012). National affluence and the closely related economic development are identified as a major driver of emissions (Burke, Shahiduzzaman, and Stern 2015; Jorgenson and Clark 2012; Liddle 2015; Lohwasser, Schaffer, and Brieden 2020; Wang, Assenova, and Hertwich 2021), making the affluence/emissions nexus one of the focal points of climate mitigation research and policy considerations.

The cross-national drivers research has primarily focused on how anthropogenic drivers like national affluence affect the total emission accounts of a nation, or related quotient measures that adjust for either the size of population or economy. Two of the most widely used national emissions accounts are production-based (a.k.a. territorial) emissions account that includes all emissions generated in a nation's territory (UNFCCC 1997), and consumption-based emissions account that includes all emissions driven by a nation's final demand regardless of where in the world the emissions are generated (Davis and Caldeira 2010; Peters and Hertwich 2006, 2008). Research has identified social forces that substantially affect nations' emissions as captured by these aggregate measures, and has been instrumental in guiding national and international climate policies (e.g., Cohen et al. 2018; Knight and Schor 2014; Liddle 2018; Steininger et al. 2014). However, a nation contributes to global GHG emissions in multiple interconnected yet distinct ways, such as through emissions generated by domestic production activities, involvement in international trade, and domestic consumer activities. Does a driver like national affluence equally affect these emission components? Or are the effects of this driver instead heterogeneously distributed across these components? What are the implications of such potential heterogeneity for climate mitigation?

In this study I aim to answer these questions. I first propose an analytical framework named *multidimensional emissions profile* (MEP), which situates nations' contributions to global GHG emissions into 4 distinct but interconnected components: (1) emissions generated by domestic-oriented supply chain activities; (2) emissions embodied in imports; (3) emissions embodied in exports; and (4) direct emissions of end user activities. I then operationalize the 4 emission components using an environmentally-extended multiregional input-output (EE-MRIO) approach, and apply the MEP framework and panel regression modeling to analyze the affluence/emissions nexus for a group of 34 high-income nations for the period of 1995 to 2015. I investigate how national affluence is associated with each of the 4 emission components in potentially heterogeneous ways.

I begin with a review of the cross-national comparative literature on human drivers of climate change. Then, I discuss the rationales behind conceptualizing nations' contributions to global GHG emissions as multidimensional, which is followed by the proposal of the MEP framework. Next, I apply the MEP framework to analyze the relationships between national affluence and each of the four emission components that constitute the MEP framework. I conclude by noting how the analyses advance the policy-oriented research on the affluence/emissions nexus and how other directions of climate drivers and mitigation research can benefit from the MEP framework.

2.3 HUMAN DRIVERS OF NATIONS' GHG EMISSIONS

The long-standing research on human drivers of environmental degradation is rooted in the IPAT framework or the similarly specified Kaya identity, both identifying population (P), affluence (A), and technology (T) as three main drivers of human impacts on the environment (Dietz and Rosa 1994; Kaya 1990). The STIRPAT model, or stochastic impacts by regression on population, affluence, and technology, was later developed to overcome the IPAT model's assumption of proportionality, allowing differences in the three drivers' estimated influences on the impacts (Dietz 2017; York, Rosa, and Dietz 2003). The STIRPAT model also explicitly conceptualizes the technology factor as a combination of many factors, such as culture, that are not captured by population and affluence.

A rich body of cross-national empirical literature has applied the STIRPAT approach to identify human drivers of emissions, estimate their elasticity, test hypotheses, and inform policy efforts. Empirically identified drivers include—but are not limited to—affluence (Aslanidis and Iranzo 2009; Jorgenson and Clark 2012; Thombs 2018), population size and structure (Dietz and Rosa 1997; Jorgenson and Clark 2010; York 2007), urbanization (Jorgenson, Auerbach, and Clark 2014; Marcotullio et al. 2014), and trade (Huang 2018; Jorgenson 2012; Liddle 2018; Prell and Feng 2016), with debates on the magnitude of elasticity, and on the variations in elasticity over time and across geopolitical or macroeconomic contexts (see Dietz 2017; Jorgenson et al. 2019).

Earlier cross-national empirical work relies on production-based or territorial emission account that attributes emissions to nations based on where they are emitted (UNFCCC 1997). Emission measures based on this approach do not account for the emissions embodied in a nation's imports, which are generated in other nations. The omission is significant because for the past 25 years, around a quarter of global GHG emissions are embodied in international trade; many high-income nations, in particular, have been net importers of embodied emissions through trading with lower-income nations (Davis, Peters, and Caldeira 2011; Peters et al. 2011; Peters, Davis, and Andrew 2012; Wood et al. 2020). In light of the limitations of production-based accounting, consumption-based accounting was proposed, which accounts for all emissions driven by a nation's consumption demand (Davis and Caldeira 2010; Peters and Hertwich 2008). It is an important methodological advancement. Researchers argue that switching from production-based accounting to consumption-based accounting as the basis for mitigation policymaking can improve both the effectiveness and justice of climate mitigation policies (Steininger et al. 2014). An increasing number of cross-national drivers studies have used consumption-based emission measures either by themselves or in conjunction with production-based measures (Cohen et al. 2018; Huang and Jorgenson 2018; Knight and Schor 2014; Liddle 2018).

Both production-based and consumption-based emission accounts are instrumental to understanding how the magnitude of a nation's GHG emissions are affected by human drivers. However, drivers research using aggregate emission measures tends to overlook the more nuanced multidimensionality in a nation's contributions to global emissions, and particularly how multiple components of a nation's emissions, each having distinct implications for climate mitigation and justice, may be related to human drivers in differentiated ways.

2.4 MULTIDIMENSIONALITY IN NATIONS' CONTRIBUTIONS TO GLOBAL GHG EMISSIONS

I use the term *multidimensionality* to refer to the characteristic of a nation's contributions to global emissions as being constituted by multiple distinct but interconnected components. Greenhouse gases are emitted by a multitude of human activities, including fossil fuel combustion in various scenarios, cement production, waste treatment, and livestock activities. These activities can be classified according to a number of schemes, including based on the type of GHG emitted, the type of chemical, biochemical, and biological activities that generate the GHG, the economic sector where such activities belong to, and the geographical location where the GHG is emitted. Therefore, a nation's GHG emitting activities, and by extension, its GHG emissions, are multidimensional. Of particular interest to this study is the classification of GHG emitting activities based on whether the emissions are generated directly by end user activities or the rest of supply chain activities (ROSCA), and whether the emissions are embodied in imports, exports, or in domestic supply chain activities serving domestic end users.

2.4.1 Emissions from End User Activities and the Rest of Supply Chains

Emissions directly generated by end user activities and by ROSCA are distinct points of intervention for climate mitigation. Some notable end user activities that directly generate GHG emissions including driving personal vehicles, and using fossil fuel-based household space and water heaters and power generators. In contrast, the rest of supply chain activities that directly emit GHG include fuel combustion that occurs outside the end use stage, a wide range of non-combustion industrial and agricultural activities, and waste treatment.

At the household or individual level, different intervention strategies are required for behaviors that directly generate emissions than for behaviors that do not generate emissions directly but are implicated in the emissions generated elsewhere in the supply chains of the associated goods and services. This is in part due to consumers being unaware of the embodied fossil fuel consumption or emissions in goods and services, a barrier that needs to be overcome before consumer behaviors regarding to the embodied emissions can be effectively tapped for emission abatement (Abrahamse et al. 2007; Cohen and Vandenbergh 2012; Stern et al. 2016). In contrast, this barrier is less relevant for the emissions that are directly generated by consumer behaviors such as driving. Prior research on household emissions at subnational level has found driving forces such as income have differentiated effects on direct household emissions versus ROSCA emissions driven by household consumption (e.g., Yuan, Rodrigues, and Behrens 2019).

At an organizational level, mitigating direct emissions of end user activities is related to business organizations' roles as providers of consumer goods and services: the offering of products with the technical potential to lower direct end user emissions (such as the offering of electric vehicles or vehicles with high fuel efficiency), and marketing campaigns to promote such products in order to increase behavioral plasticity of adopting these products and using them in ways that realize the emission abatement potential (Blumstein and Taylor 2013). In contrast, mitigating ROSCA emissions requires targeting business organizations' role as emitters of greenhouse gases, in conjunction with their roles as providers of products (Stern et al. 2016). Notably, mitigating ROSCA emissions requires business organizations to reduce the emissions from multiple stages of their business operations, such as reducing energy used in workplace and production facilities (for example, Japan's Cool Biz campaign, see Sampei and Aoyagi-Usui 2009; Shinn 2011), and reducing emissions from transportation of goods and personnel, all of which are counted toward the ROSCA emissions of their products. Moreover, business organizations that are consumers and suppliers of immediate goods and services can also influence the emissions generated by other business at the upstream or downstream of supply chains, as evident in case studies on housing and construction (Biggart and

Lutzenhiser 2007; Janda and Parag 2013; Parag and Janda 2014). As suppliers of consumer goods, businesses can offer products, such as high-efficiency appliances, that help lower consumers' electricity consumption and ultimately lower the emissions from power generation (Blumstein and Taylor 2013; Brown and Kim 2015).[1] Given the differences between ROSCA emissions and direct end user emissions, it can be questionable to assume that a emission driver affects the two emission components equally. Analyzing them separately allows researchers to unpack how they might be heterogeneously affected by a certain emission driver or mitigation measure.

2.4.2 Emissions Embodied in Imports, Exports, and Domestic-Oriented Supply Chain Activities

ROSCA emissions can be further decomposed based on whether the emissions are embodied in imports, exports, or are generated by domestic supply chain activities serving domestic end users. Due to globalization and the proliferation of international trade, the end use stage and the rest of supply chain activities of many goods and services have been increasingly separated across national borders. In 2015, the GHG emissions embodied in all international trade amount to 11,333 megatons CO_2-equivalents, which account for nearly a quarter of global emissions (calculated based on the data from Stadler et al. 2018, 2021; see also Wood et al. 2018). The emissions embodied in a nation's imports are generated by supply chain activities outside of its jurisdiction. The

[1] As a reminder, GHG emissions associated with household electricity consumption count toward ROSCA emissions as opposed to directly end user emissions because this part of emissions is not generated directly by end users but rather by power plants, with the exception of electricity from fossil fuel-based household power generators.

importing nation's government can only exert indirect influence over these supply chain activities, via means such as carbon border adjustment, tariffs, and other regulations over imports, which differs from the more direct regulatory power it has over domestic supply chain activities. Conversely, domestic supply chain activities serving foreign end users, which generate emissions embodied in a nation's exports, are subject to the indirect influence of foreign state regulations. These differences in regulatory dynamics could mean differentiated mitigation strategies are required for a nation to reduce the emissions embodied in its imports, the emissions embodied in its exports, and the emissions generated by its domestic-oriented supply chain activities (DOSCA).

Furthermore, the three groups of supply chain activities have different implications for international climate justice. Consumption-based accounting (CBA) is argued to better account for international climate justice than production-based accounting (PBA) in that CBA accounts for the carbon leakage via trade, especially the leakage from wealthier consuming/importing nations to poorer producing/exporting nations (Peng, Zhang, and Sun 2016; Peters and Hertwich 2006; Steininger et al. 2014, 2016). Based on CBA, the emissions embodied in imports can be viewed as a form of emission displacement from the end user nations that import and consume the products to the producer nations where the emissions are generated. On the flip side, the emissions embodied in exports can be viewed as undertaking the emissions displaced from other nations. Moreover, a growing body of literature on emission accounting and climate policies is devoted to quantifiably dividing the cause of emissions embodied in international trade and the corresponding share of mitigation responsibility among end user nations and producer nations (e.g., Dietzenbacher, Cazcarro, and Arto 2020; Lenzen et al. 2007; Lenzen and Murray 2010; Marques et al. 2012). The majority of these schemes of division entail redistributing the emissions embodied in a nation's trade to nations along supply chains, and the redistribution procedure is symmetrical for emissions embodied in imports and in exports. The redistribution is said to enhance the justice in allocating the mitigation responsibility among nations. Unlike emissions embodied in trade, emissions generated by DOSCA do not involve transnational displacement of emissions via trade and are generally not subject to the redistribution. In sum, given that emissions embodied in imports, emissions embodied in exports, and DOSCA emissions have distinct implications for climate mitigation and international climate justice, the analysis of nations' emissions and their relationship with human drivers of climate change can benefit from further decomposing ROSCA emissions into these three emission components.

2.5 MULTIDIMENSIONAL EMISSIONS PROFILE: AN ANALYTICAL FRAMEWORK

I propose an analytical framework named *multidimensional emissions profile* (MEP), which situates nations' contributions to global climate change into the four aforementioned emission components: (1) emissions generated by domestic-oriented supply chain activities (DOSCA); (2) emissions embodied in imports; (3) emissions embodied in exports; and (4) direct emissions of end user activities.[2] Components (1) to

[2] For emission components (1) to (3), I adopt the definitions based on the multi-regional input-output (MRIO) method as opposed to the emissions embodied in bilateral trade (EEBT) method. The two methods differ in the allocation of the emissions generated by the internationally-traded intermediate goods. The

(3) are parts of ROSCA emissions; component (4) are emissions directly generated by end user activities such as driving personal vehicles and household heating that burns fossil fuels on site. Although the MEP framework separates the 4 emission components, it aims to analyze them systematically in order to account for the interconnections among the emission components that are parts of complex feedback loops among components of human-environmental interaction systems (Liu et al. 2007; Ostrom 2010). For example, climate policies targeting DOSCA emissions in nation *A* may inadvertently increase the emissions embodied in its imports due to carbon leakage: climate policies cause certain carbon-intensive industries to relocate from nation *A* to other nations without such policies, and the products of these industries are shipped back to nation *A* for final consumption (King and van den Bergh 2021; Peters 2010). Figure 2.1 presents a conceptual diagram of the four emission components and their relationships with production-based emissions account and consumption-based emissions account, in a simplified 2-nation model that excludes re-imports and re-exports.[3]

A major advantage of the MEP framework for the drivers research is that it enables analyses on how anthropogenic forces affect each component of emissions in potentially differentiated ways, creating avenues for more nuanced hypothesis testing, policy analysis, and theory building. By unpacking these heterogeneous relationships, the MEP reveals how the impacts of the driver may be unevenly distributed among GHG-emitting activities in the end use stage as well as other stages of supply chains both

EEBT method allocates this part of emissions to the nations that consume the intermediate goods, regardless of where the final goods (produced from said intermediate goods) are consumed. The MRIO method allocates this part of emissions to the nation where the final goods are consumed. See Peters et al (2011) for a detailed description of the two methods.

[3] This figure is inspired by Fig. 1 in Steininger et al (2014) that illustrates the three-way separation of emissions embodied in imports, emissions embodied in exports, and the remaining domestic emissions.

within and beyond a nation's territory. Doing so also helps identify effective leverage points for climate mitigation, which is a major objective of the drivers research.

Another advantage is the inclusion of emissions embodied in imports and in exports, both of which are important ways through which a nation contributes to global GHG emissions. Emission accounting methods such as PBA and CBA only account for either emissions in imports or exports but not both, in order to avoid double counting.[4] In contrast, the MEP is *not* an accounting method. It is primarily concerned with capturing how a nation contributes to global emissions in multiple distinct and interconnected ways, including both imports and exports, and how anthropogenic drivers affect each of these ways. As such, drivers research using the MEP can provide a more complete understanding how driving forces (and mitigation policies targeting these forces) affect nations' contributions to global emissions. To circumvent the double-counting issue, the MEP does not conceptualize the sum of all 4 emission components as a nation's total emissions account or as the emissions that this nation is solely responsible for. The MEP also differs from the literature on net emissions transfer via trade, which generally focuses on the degree to which nations are net importers or net exporters of carbon emissions—quantified based on the differential between the embodied emissions in nations' imports and exports (Jakob and Marschinski 2013; Peters et al. 2011; Prell and Sun 2015; Wood et al. 2020). In comparison, the MEP explicitly conceptualizes imports

[4] Kander et al (2015) list 3 desired properties for an ideal national emissions account: sensitivity, monotonicity, and additivity, which can be seen as a subset of the 6 properties formulated by Rodrigues et al (2006) that also include scale invariance, economic causality, and symmetry (see also Domingos, Zafrilla, and Lopez 2016). The full inclusion of emissions embodied in both imports and exports in a nation's emissions account violates the criterion of additivity and potentially other criteria (Lenzen et al. 2007).

and exports as two coexisting ways through which a nation contributes to global emissions.

2.6 APPLY THE MEP FRAMEWORK TO THE AFFLUENCE/EMISSIONS NEXUS

I apply the MEP framework to analyze how national affluence is associated with nations' four emission components. The motivation is two-fold. First, the analyses are used as a proof-of-concept for the MEP framework. The heterogeneity across the four emission components in how they are related to affluence, if found, will support the notion of multidimensionality in nations' contributions to global GHG emissions and in the affluence/emissions relationship.

Second, I situate the analyses within the rich body of literature on the affluence/emissions relationship—which has been a major point of contention in the broader drivers literature and climate mitigation policymaking—and seek to demonstrate how the MEP framework contributes to the research literature and policymaking. The affluence/emissions relationship plays an important role in informing the broad direction of mitigation policies, and particularly whether some alternative forms of economic development are required to limit global warming to below 1.5°C while improving national affluence. Some studies argue that increases in affluence are associated with increasing societal scale of resource consumption, and hence inevitably lead to more emissions (Dietz 2017; Jorgenson et al. 2019; Rosa and Dietz 2012; Schnaiberg 1980). Others argue that political, technological, and cultural changes associated with an elevated affluence level, such as state environmental regulations, renewable energy deployment, energy efficiency improvement, and environmental social movements, can alter the societal composition of consumption enough to counteract the upward pressure on emissions induced by an increased scale of consumption (Grossman and Krueger 1995; Mol 2000; Mol, Spaargaren, and Sonnenfeld 2014; Rosa and Dietz 2012).

The majority of cross-national empirical studies find positive relationships between affluence and total or per capita GHG emission (Dietz and Rosa 1997; Dong et al. 2018; Jorgenson and Clark 2012; Khan et al. 2021; Liddle 2015; Lohwasser et al. 2020; Thombs 2018; Thombs and Huang 2019; Wang et al. 2021), while a smaller number of studies find the relationships to be negative for high-income nations (Dogan and Aslan 2017; Schmalensee, Stoker, and Judson 1998). Prior studies also investigate how the relationships change along with changes in national affluence by estimating the quadratic relationships between affluence and emissions; some find the quadratic term of affluence to be positively associated with emissions (Musolesi, Mazzanti, and Zoboli 2010; Pablo-Romero and Sánchez-Braza 2017), others find negative associations (Franzen and Mader 2016; Jebli and Kahia 2020). Taken as a whole, the literature generally finds the affluence/emissions relationships vary across nations at different levels of affluence, but disagrees on the magnitude and the direction of the relationships.

Among the four emission components that constitute nations' MEP, some components may be positively associated with national affluence while others may remain stable or even decrease along with growing affluence. To the best of my knowledge, prior research has not systematically examined the heterogeneity in the affluence/emissions relationships across the four emission components, in part because most prior studies rely on production-based and/or consumption-based emission measures. The MEP framework allows for a systematic examination of affluence's associations with the four emission components, which in turn allows researchers and policymakers to identify (1) which emission components grow the most along with economic growth, and hence must be prioritized in national mitigation plans; and (2) which emission components, if any, have been decoupled with affluence, and therefore should be further examined to understand whether and how the mechanisms behind the decoupling can be adapted for other emission components. Therefore, the MEP framework helps identify leverage points for climate mitigation.

2.7 DATA AND METHODS

2.7.1 Dependent Variables

I use panel regression techniques to examine the relationships between nations' affluence and their four components of GHG emissions. The four dependent variables are (1) emissions generated by domestic-oriented supply chain activities (DOSCA); (2) emissions embodied in imports; (3) emissions embodied in exports; and (4) direct emissions of end user activities, all measured in megaton CO_2 equivalents. These emission variables are calculated using the environmentally-extended multi-regional input-output (EE-MRIO) method (Miller and Blair 2009), and the EE-MRIO tables from the latest version of Exiobase 3 (Stadler et al. 2018, 2021). Technical details of data compilation and calculation are provided in the Appendix 2.13.1.

2.7.2 Independent Variables

The main independent variable of interest is national affluence operationalized as gross domestic product (GDP) per capita measured in constant 2010 U.S. dollars. To examine whether the association between affluence and emissions vary across different levels of affluence, I include the squared term of GDP per capita after grand mean-centering.

Additional independent variables are total population, urban population as a percent of total population, manufacturing value added as a percent of GDP, services value added as a percent of GDP, and age dependency ratio (i.e., the population of people younger than 15 or older than 64 as a percent of the population of those between 15 and 64 years old). These variables are commonly used in research on the anthropogenic driving forces of climate change (Jorgenson et al. 2019; Rosa and Dietz 2012). Prior research also includes trade openness, operationalized as the sum of imports and exports as a percent of GDP. Given that the dependent variables distinguish the emissions embodied in each nation's imports and exports, I decide to include imports (% GDP) and exports (% GDP) as separate independent variables. Data on all independent variables are acquired from the World Bank's (2022) World Development Indicators Database (https://databank.worldbank.org/source/world-development-indicators).

2.7.3 Sample

The sample for the analyses is consisted of data on 34 high-income nations.[5] These nations are selected from a total of 43 nations that have data available for all dependent variables and the main independent variables, including 34 high-income nations and 9 non-high-income nations based on World Bank's country classification.[6] I decide to only include the high-income nations in the sample. This is because prior research finds that the relationships between national affluence and GHG emissions differ substantially across nations at different affluence levels, and that if there would be nations where growth in affluence is decoupled from growth in emissions, they would most likely be high-income nations (e.g., Jebli and Kahia 2020; Jorgenson and Clark 2012; Schmalensee et al. 1998; Thombs 2018). Analyzing a sample of high-income nations brings the conceptual focus onto the potential decoupling, which is necessary if nations are to maintain growth in affluence while mitigating climate change. While the sample only contains high-income nations, the emission measures of the sampled nations do account for their trades with the rest of the world. For example, the United States' imports from China are accounted for when calculating the emissions embodied in the imports of the United States, even though China as a nation is not in the sample.

The overall sample is a balanced panel dataset consisted of 714 annual observations from the 34 high-income nations in the 21-year period of 1995 to 2015. The

[5] Sampled nations include Australia, Austria, Belgium, Canada, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Italy, Japan, Lithuania, Luxembourg, South Korea, Latvia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Sweden, United States.

[6] https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

sample includes 9 out of 10 biggest emitters of among high-income nations in terms of total production-based CO_2 emissions from fossil fuel combustion in 2015.[7] The sample size is reduced to 710 observations in models that include manufacturing value added or services value added because the United States and Canada have missing data on these two variables for years 1995 and 1996. Descriptive statistics of all dependent and independent variables in their original metrics are reported in Appendix Table A2.1.

2.7.4 Regression Modeling Techniques

I estimate fixed effects regression models with both time-specific and nation-specific intercepts using Stata 17 software. Time-specific intercepts are estimated by including a series of year-specific dummy variables, while nation-specific intercepts are estimated by the within estimator *xtreg, fe* in Stata. The inclusion of two-way fixed effects accounts for unobserved heterogeneity that is unique to each year and affects all nations equally, as well as the unobserved heterogeneity that is unique to each nation and invariant across the whole period of analysis. I estimate country-clustered robust standard errors in order to correct for autocorrelation and heteroskedasticity. All non-binary variables are transformed with natural logarithm, and hence the regression coefficients are elasticity coefficients that represent the percentage change in the dependent variable associated with a 1% increase in the independent variables, net of the effects of other independent variables.[8] The general model is specified as follows:

[7] Based on data by Andrew and Peters (2021).

[8] The minimal value of direct emissions of end user activities is 0.142, below 1 and relatively close to 0. Therefore, I add a constant of 1 to each observation of this variable before transforming it with natural logarithm.

$$y_{it} = \beta x_{it} + u_i + w_t + e_{it}$$

where subscripts i and t represent nation and year respectively; and y_{it} is the outcome variable for nation i at year t; β is the vector of regression coefficients that correspond to the vector of time-varying predictor variables x_{it}; u_i is the nation-specific intercept for nation i; $w_t$is the year-specific intercept for year t; e_{it} is the unique residual for nation i at year t.

I also estimate a set of seemingly unrelated regression (SUR) equations for the 4 dependent variables using the *sureg* suite in Stata, which allows the error terms of the 4 equations to be correlated. Nation and year fixed-effects are estimated by including nation and year dummy variables. Stata command *suregr* is used to estimate nation-clustered robust standard errors (Kolev 2021). SUR model allows for statistical tests on whether the coefficients for affluence differ across the 4 emission components.

2.8 RESULTS AND DISCUSSIONS

2.8.1 Changes in the Four Emission Components over Time

Figure 2.2 presents changes in the 4 emissions components from 1995 to 2015 as a percent of their corresponding levels in 1995, for each of the 34 sampled nations. In every nation, the changes vary in magnitude, direction, or in both aspects, across the 4 emission components during this period, which may indicate that certain human drivers of emissions and/or policies targeting at these drivers have affected the 4 emission components in differentiated manners. This finding supports the notion of multidimensionality in nations' contributions to global GHG emissions. Comparing across nations, the emissions generated by DOSCA increase from 1995 to 2015 in 6 high-income nations and decrease in 28 nations; the emissions embodied in imports increase in 29 nations and decrease in 5; the emissions embodied in exports increase in all nations but the United Kingdom and Romania; direct emissions of end user activities increase in 12 nations and decrease in the remaining 22 nations.

2.8.2 Affluence and the Four Emissions Components

The regression analyses examine the heterogeneity in relationships between affluence and each of the 4 emission components that constitute nations' Multidimensional Emissions Profile. Table 2.1 reports the fixed-effects regression models of all 4 emission components. Model 1, 4, 7, and 10 are the baseline models for each of the emission components and only include GDP per capita and total population. Models 2, 5, 7, and 11 additionally include the squared term of mean-centered GDP per capita. Models 3, 6, 9, and 12 are the most fully saturated models for each of the emission components, and include all other independent variables: exports (%GDP), imports (%GDP), manufacturing (%GDP), service (%GDP), urban population (%population), and age dependency ratio. Country-clustered robust standard errors are reported in parentheses. Elasticity coefficients are flagged for statistical significance in the table. The threshold of $p<.1$ is not considered statistically significant in the analyses, and is only marked in the tables to show changes in coefficients' level of statistical significance across models.

DOSCA emissions is the dependent variable of Models 1 to 3. The coefficient for the linear term of GDP per capita is positive and statistically significant in Model 1. When the squared term of GDP per capita is included as in Model 2 and additional model reported in Appendix Table A2.2, neither the squared term nor the linear term is statistically significant. Therefore, the squared term of GDP per capita is excluded from the most saturated Model 3 for the sake of parsimony. In Model 3, the coefficient for the linear term of GDP per capita is 0.417 (95% CI = 0.053 to 0.782) and statistically significant. Figure 2.3(a) illustrates that this elasticity coefficient remains stable across 9 decile points of GDP per capita in the sample. The results indicate a positive and inelastic (less than proportional) relationship between high-income nations' affluence and their DOSCA emissions, which remains stable as these nations become wealthier.

Models 4 through 6 in Table 2.1 focus on GHG emissions embodied in imports. All 3 models consistently suggest that the coefficients for the linear term of GDP per capita are positive and statistically significant, ranging from 1.243 to 1.375, whereas Model 5 and additional model in Table A2.2 in the appendices indicate that the squared term of GDP per capita is not significantly associated with emissions embodied in imports. Figure 2.3(b) is based on Model 6 and shows that the relationship between GDP per capita and emissions embodied in imports is positive and remain stable at 1.375 (95%CI = 0.859 to 1.892) across the 9 decile points of GDP per capita in the sample. The results indicate a positive and elastic (more than proportional) relationship between high-income nations' affluence and the GHG emissions embodied in their imports, which stays the same as these nations become wealthier. This positive relationship holds when imports (as % GDP) is controlled for, suggesting that the relationship is primarily attributed to mechanisms other than the increased imports as a share of the economy that often accompanies growth in national affluence among high-income nations.

Models 7 through 9 are for GHG emissions embodied in exports. The coefficient for the linear term of GDP per capita is positive and statistically nonsignificant in Models 7 and 8, but becomes significant in Model 9 with all other independent variables included, where it takes the value of 0.728 (95CI= 0.161 to 1.295). The coefficient for the squared term of GDP per capita is positive and significant in Models 8 and 9, ranging from 0.257 to 0.260. Figure 2.3(c) is based on Model 9 and shows that when GDP per capita is $10,148, which is the 1st decile in the sample, its elasticity coefficient is 0.196 (95%CI is -0.263 to 0.656, overlapped with 0). As GDP per capita increases, the association becomes positive and increases in magnitude. When GDP per capita is $19,591, the 3rd decile in the sample, its elasticity coefficient increases to 0.539 (95%CI = 0.054 to 1.025). When GDP per capita reaches $58,682, the 9th decile, its elasticity coefficient further increases to 1.111 (95%CI = 0.382 to 1.840). The results indicate that high-income nations' affluence is not associated with emissions embodied in exports when affluence level is at the lower end of the spectrum for high-income nations. However, as these nations grow wealthier, the association between affluence and emissions embodied in exports become positive and increasingly intensified. The intensifying relationship remains even when exports (% GDP) is controlled for as in Model 9, suggesting that the intensification between affluence and emissions embodied in exports is at least partly due to mechanisms other than the impacts of increased affluence on the relative size of export sectors.

Lastly, direct GHG emissions of end user activities are the dependent variable of Models 10 to 12. Across all 3 models, the coefficient for the linear term of GDP per capita is nonsignificant. The coefficient for the squared term of GDP per capita is negative and borderline nonsignificant in Model 11 (p=0.060) but becomes statistically significant in Model 12, with a value of -0.265 (95%CI= -0.502 to -0.027). Figure 2.3(d) is based on Model 12 and illustrates that as GDP per capita increases, the point estimates of the association between GDP per capita and direct end user emissions trend downward from positive to negative. When GDP per capita is $10,148, its elasticity coefficient is 0.603 (95%CI = 0.136 to 1.070); when GDP per capita is $19,591, its elasticity coefficient decreases to 0.255 (95%CI = -0.144 to 0.653); when GDP per capita reaches $58,682, its elasticity coefficient becomes -0.326 (95%CI = -1.006 to 0.354). The 95% confidence intervals overlap with zero across the 3rd through the 9th decile points of GDP per capita, meaning that the elasticity coefficient of GDP per capita could effectively be zero within this distribution of GDP per capita but might become negative and significantly different from zero as GDP per capita grows beyond $58,682. The results suggest that increases in affluence in high-income nations are positively and inelastically associated with their direct end user emissions when the affluence level is relatively low in high-income nations' standard. The magnitude of the positive association becomes smaller as nations become more affluent. When the affluence level reaches a threshold at around $19,000 per capita, further growth in affluence is no longer associated with increases in direct end user emissions, which indicates an absolute decoupling.

I re-estimate models 3, 6, 9, and 12 using seemingly unrelated regression (SUR) with two-way fixed effects and country-clustered robust standard errors, which are reported in Table 2.2. The results of SUR models are consistent with the results of fixed effects models in Table 2.1. A chi-squared test suggests that the coefficients of affluence are different for DOSCA emissions and for emission embodied in imports (χ^2= 7.64, p-value = 0.0057).

Next, I juxtapose the observed relationships between national affluence and the 4 emission components, in order to explicitly examine their heterogeneity. Figure 2.3 as a whole shows that when GDP per capita is at $10,148, a 1% increase in GDP per capita is associated with 0.332% increase in DOSCA emissions, 1.375% increase in emissions embodied in imports, and 0.603% increase in direct end user emissions, but is not significantly associated with changes in emission embodied in exports. When GDP per capita reaches $58,682, a 1% increase in GDP per capita is associated with an increase in DOSCA emissions, emissions embodied in imports, and emissions embodied in exports by 0.332%, 1.375%, and 1.111%, respectively, but is not significantly associated with changes in direct end user emissions.

Figure 2.4 presents the average predicted values and 95% confidence intervals of the 4 emission components across 9 decile points of GDP per capita in the sample, and are based on Models 3, 6, 9, and 12 in Table 2.1. The 4 subplots together portray the average predicted changes in the multidimensional emissions profile for the 34 sampled high-income nations as their GDP per capita grows from $10,148 to $58,682: DOSCA emissions grows at a steady pace along with GDP per capita, resulting in an increase by 44 Mt across this range of GDP per capita; emissions embodied in imports also grows steadily but at a faster pace, and sees an overall growth by 145 Mt—by far the greatest among of the 4 emission components; emissions embodied in exports grows by 38 Mt overall and picks up its growth rate as GDP per capita increases; the point estimates of direct end user emissions loosely resemble an inverse-U shape, which amounts to a slight overall increase by 4 Mt across this range of GDP per capita. Taken as a whole, the results suggest that the relationships between each of the 4 GHG emission components and affluence of high-income nations are different in magnitude, direction, and in how the relationships vary at different levels of affluence.

The observed heterogeneity supports the notion of multidimensionality in nations' contributions to global GHG emissions, and hence highlights the validity and utility of the MEP framework. Specific to the affluence/emissions nexus, the heterogeneity suggests that the mechanisms of how affluence impacts GHG emissions may be different across the 4 emission components. Prior research has identified both emission-boosting mechanisms and emission-suppressive mechanisms through which growth in national affluence affects GHG emissions (e.g., Jorgenson et al. 2019; Rosa and Dietz 2012): growing affluence can elevate the scale of consumption that in turn increases emissions; growing affluence may also induce changes that facilitate emission abatement such as state environmental regulation, environmental social movement, and the development of renewable energy and efficiency-improving technology. For direct end user emissions, it appears that the impacts of emission-suppressing mechanisms outweigh the impacts of emission-boosting mechanisms after affluence reaches a threshold, leading to the observed decoupling. For DOSCA emissions, its inelastic positive relationship with affluence shows the effects of emission-suppressing mechanisms, in that a percent increase in affluence only brings an increase in DOSCA emissions by less than half a percent. Despite that, the positive relationship remains stable as affluence grows, indicating that emission-boosting mechanisms of growing affluence outweigh emission-suppressing mechanisms by a consistent degree as high-income nations become wealthier, and that the increased affluence does not further strengthen emission-suppressing mechanisms relative to emission-boosting mechanisms for DOSCA emissions.

For emissions embodied in imports, the positive and elastic relationship underscores the sheer magnitude of emission-boosting mechanisms. In comparison, the emission-suppressing mechanisms of growing affluence appear to have little impact on emissions embodied in imports, which may be because environmental regulations, social movements, and other emission-suppressing mechanisms within importing nations have, at best, indirect influence over this emission component that occur overseas. For emissions embodied in exports, the findings show evidence for strong and intensifying emission-boosting mechanisms of growing affluence, while emission-suppressing mechanisms are weak and attenuating as nations become wealthier. Overall, the findings indicate that the emission-suppressing mechanisms of growing affluence have been more successful in curbing direct end user emissions but largely remain inadequate in mitigating the other three emission components, all three of which are generated by supply chain activities other than end use.

Increases in national affluence are associated with changes in not only the magnitude of nations' emissions but also in the composition of a nation's multidimensional contributions to global GHG emissions. Figure 2.5 presents the predicted emission outcomes at 3 affluence levels in a stacked bar chart, based on Models 3, 6, 9, and 12 in Table 2.1. These predicted values can be interpreted as the

Multidimensional Emissions Profile of a hypothetical average high-income nation, and the predicted changes in the MEP as this nation becomes increasingly more affluent. As the GDP per capita of this nation increases from $10,148 to $58,682, the share of its DOSCA emissions relative to the sum of all 4 components decreases from 46% to 26%, while the share of emissions embodied in imports is more than tripled, increasing from 16% to 50%.[9] The share of emissions embodied in exports stays relatively stable, ranging from 16% to 20%. The share of direct end user emissions decreases from 18% to only 6%.

The findings indicate that high-income nations' affluence level shapes how GHG emissions are distributed across end use stage and other supply chain stages, and between supply chain activities within and beyond national borders. As high-income nations become even wealthier, and net of the effects of covariates, direct end user emissions become by far the smallest component out of the four in both magnitude and relative share, while the sum of the other three emission components—all generated by supply chain activities other than end use—rises steeply in magnitude and share. This is partly due to the aforementioned finding that direct end user emissions are the only component decoupled from growth in national affluence, and that the emission-suppressing mechanisms of growing affluence have been inefficacious in curbing the other three emission components. Among these components, emissions embodied in imports grow substantially both in magnitude and as a share of their contributions to global GHG emissions, while DOSCA emissions grow modestly in magnitude and decrease in share.

[9] As a reminder, the MEP does not conceptualize the sum of the 4 emission components as a nation's total emissions account or as the emissions that this nation is solely responsible for. Here, the sum is used to calculate the relative share of each emission component and to quantify the composition of a nation's multidimensional contributions to global emissions.

This may suggest that growth in affluence intensifies the environmental load displacement of GHG emissions via the global production and trade networks, through which the high-income nations increasingly take advantage of the polluting productions outsourced to other nations to fulfill their domestic final demand (Huang 2018; Jorgenson 2012; Kanemoto et al. 2014). This is a form of transnational NIMBYism (not-in-my-back-yard), and is tied to the structural inequality of the global economy in which high-income nations occupy the advantageous position that grants them disproportionate access to the natural resources and sink capacity for waste in other nations, and especially in poorer nations in the Global South (Givens, Huang, and Jorgenson 2019; Jorgenson 2016).

2.9 CONCLUSION AND OUTLOOK

This study proposes an analytical framework of *Multidimensional Emissions Profile* (MEP) that situates national contributions to global GHG emissions into four components with distinct implications for climate mitigation and climate justice: (1) emissions generated by domestic-oriented supply chain activities (DOSCA); (2) emissions embodied in imports; (3) emissions embodied in exports; and (4) direct emissions of end user activities. To the best of my knowledge, the MEP is the first analytical framework for systematic analysis of these 4 emission components, focusing particularly on the heterogeneity among the multiple emission components in their relationships with human drivers of emissions. I apply the MEP framework to empirically analyze the affluence/emissions nexus for high-income nations. The results support the validity of the MEP framework and demonstrate its contributions to the policy-oriented research on human drivers of emissions.

The results suggest that the emission-suppressing mechanisms that are theorized to accompany growing affluence appear to have been more effective in curbing direct end user emissions but largely remain inadequate in mitigating the other three emission components: DOSCA emissions, emissions embodied in imports, and emissions embodied in exports—all three of which are generated by supply chain activities outside the end use stage. This is problematic because these three emission components together account for the absolute majority of high-income nations' contributions to global emissions. Emissions embodied in imports, in particular, increasingly become the largest emission component as high-income nations grow wealthier. If high-income nations aim to reduce GHG emissions while maintaining growth in affluence, it is necessary for them to achieve absolute decoupling between affluence and these three emission components, especially emissions embodied in imports. However, absolute decoupling is only observed for direct end user emissions, the fourth and the smallest emission component.

This study highlights an important and promising direction for climate mitigation research and policy considerations: how can the absolute decoupling between direct end user emissions and national affluence be replicated for the three emission components generated by supply chain activities outside the end use stage? What are the specific emission-suppressing mechanisms accompanying growing affluence that contribute to the absolute decoupling between affluence and direct end user emissions? Whether and how can these mechanisms be adapted to mitigate the other three emission components? Meanwhile, this study underscores the importance for high-income nations to shift their climate mitigation policy agenda from focusing on direct end user emissions to emissions generated by both domestic and foreign supply chain activities outside the end use stage. This shift would require targeting not only consumers but also multiple entities along supply chains such as producers, distributors, and wholesalers (World Economic Forum 2021). This shift can be facilitated by existent and emerging policy instruments such as product carbon footprint labelling (Taufique et al. 2022), supply chain contracting carbon requirements (Peterson and Whitaker 2022; Zu, Chen, and Fan 2018), and border carbon adjustment (Marcu, Mehling, and Cosbey 2020; Steininger et al. 2014).

This study also finds that the structural composition of a nation's contributions to global GHG emissions can potentially shape the relationships between national affluence and total emissions (measured either in production-based or consumption-based accounts). For example, the affluence/emissions relationships differ across DOSCA emissions, emissions embodied in exports, and direct end user emissions. The sum of these three components are nations' production-based emissions. Therefore, the estimated relationship between national affluence and production-based emissions can differ across nations whose production-based emissions have different structural compositions in terms of the relative size of DOSCA emissions, emissions embodied in exports, and direct end user emissions. Prior research identifies a number of human drivers, including affluence itself, that affect the relationship between national affluence and total emission measures (Jorgenson et al. 2019; Rosa and Dietz 2012). To what extents do these forces shape the affluence/emissions relationships by changing the structural composition of nations' emissions? What are the implications for climate mitigation and climate justice? The MEP framework can contribute to this line of future research.

While this study uses the MEP framework to analyze the affluence/emissions nexus for high-income nations, the MEP can also be applied to examine other drivers than affluence, and for middle- and low-income nations. Moreover, the MEP framework can be used to assess how a certain mitigation measure affects the 4 emission components in potentially heterogeneous ways. Doing so reveals how the impacts of the mitigation measure may be unevenly distributed among GHG-emitting activities in the end use stage as well as other stages of supply chains both within and beyond a nation's territory. Which emission components can be most efficaciously curbed by said mitigation measure? Whether the mitigation measure inadvertently causes some emission components to increase, as in the case of carbon leakage? How does the mitigation measure shift the distribution of a nation's emissions among the 4 components? The MEP framework can help answer these questions, and contribute to policy-oriented research on climate change mitigation.

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2.11 TABLES

Table 2.1 Unstandardized coefficients for the regression of nations' 4 emission components, 1995–2015 on GDP per capita and selected covariates: two-way fixed effects regression model estimates with country-clustered robust standard errors for 34 high-income countries.

	DOSCA Emissions			Emissions in Imports			Emissions in Exports			Direct End User Emissions		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
GDP Per Capita	0.332*	0.278	0.417*	1.266***	1.243**	1.375***	0.139	0.565#	0.728*	0.284#	-0.0718	0.0625
	(0.160)	(0.187)	(0.186)	(0.180)	(0.362)	(0.263)	(0.220)	(0.315)	(0.279)	(0.165)	(0.212)	(0.230)
GDP Per Capita Squared		-0.0327			-0.0139			0.257*	0.260**		-0.215#	-0.265*
		(0.107)			(0.191)			(0.120)	(0.0928)		(0.110)	(0.117)
Total Population	1.659**	1.759*	1.361**	1.473#	1.516	1.435*	-0.106	-0.893	-0.311	0.122	0.780#	1.285*
	(0.510)	(0.734)	(0.397)	(0.820)	(1.026)	(0.622)	(0.582)	(0.528)	(0.575)	(0.416)	(0.390)	(0.560)
Imports as % GDP			0.0690			0.615**			-0.282			-0.160
			(0.158)			(0.204)			(0.176)			(0.139)
Exports as % GDP			-0.360*			-0.181			0.871***			-0.0577
			(0.149)			(0.283)			(0.152)			(0.133)
Manufacturing as % GDP			-0.0729			-0.305			-0.386#			0.178
			(0.145)			(0.287)			(0.193)			(0.136)
Service as % GDP			-0.681*			0.319			0.428			0.0535
			(0.327)			(0.479)			(0.393)			(0.395)
Urban Pop. as % Pop.			-0.265			0.116			0.0136			0.393
			(0.658)			(0.708)			(1.155)			(0.666)
Age Dependency Ratio			0.402			0.333			0.373			0.514
			(0.477)			(0.596)			(0.404)			(0.462)
Constant	-25.84**	-24.05*	-18.32#	-32.85*	-20.56	-37.08*	3.463	17.51*	3.928	-1.797	-9.442	-21.14*
	(9.344)	(11.80)	(9.579)	(14.62)	(16.52)	(13.67)	(10.45)	(8.496)	(10.81)	(6.957)	(6.261)	(9.662)
N	714	714	710	714	714	710	714	714	710	714	714	710
# of nation	34	34	34	34	34	34	34	34	34	34	34	34
N per nations, min.	21	21	19	21	21	19	21	21	19	21	21	19
N per nation, avg.	21	21	20.88	21	21	20.88	21	21	20.88	21	21	20.88
N per nation, max.	21	21	21	21	21	21	21	21	21	21	21	21

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
# p<0.1 * p<.05 ** p<.01 *** p<.001 (two tailed).

Table 2.2 Unstandardized coefficients for the seemingly unrelated regression of nations' 4 emission components, 1995–2015 on GDP per capita and all covariates: two-way fixed effects regression model estimates with country-clustered robust standard errors for 34 high-income countries.

	Seemingly Unrelated Regression			
	DOSCA Emissions Model 13	**Emissions in Imports Model 14**	**Emissions in Exports Model 15**	**Direct End User Emissions Model 16**
GDP Per Capita	0.417*	1.375***	0.756**	0.0683
	(0.180)	(0.254)	(0.258)	(0.219)
GDP Per Capita Squared			0.283***	-0.260*
			(0.0800)	(0.109)
Total Population	1.361***	1.435*	-0.397	1.267*
	(0.383)	(0.601)	(0.543)	(0.531)
Imports as % GDP	0.0690	0.615**	-0.283#	-0.160
	(0.153)	(0.197)	(0.170)	(0.134)
Exports as % GDP	-0.360*	-0.181	0.869***	-0.0580
	(0.144)	(0.274)	(0.147)	(0.128)
Manufacturing as % GDP	-0.0729	-0.305	-0.386*	0.178
	(0.140)	(0.277)	(0.186)	(0.131)
Service as % GDP	-0.681*	0.319	0.471	0.0626
	(0.316)	(0.462)	(0.376)	(0.378)
Urban Pop. as % Pop.	-0.265	0.116	0.00694	0.392
	(0.636)	(0.683)	(1.116)	(0.642)
Age Dependency Ratio	0.402	0.333	0.343	0.508
	(0.461)	(0.576)	(0.397)	(0.445)
Constant	-13.55#	-23.67*	7.316	-21.02*
	(7.971)	(11.37)	(10.72)	(9.493)
N	710	710	710	710
# of nation	34	34	34	34
N per nations, min.	19	19	19	19
N per nation, avg.	20.88	20.88	20.88	20.88
N per nation, max.	21	21	21	21
R-squared	0.996	0.986	0.991	0.995
RMSE	0.108	0.172	0.134	0.113
chi2	178799.1	48752.3	81914.4	130538.1
P-value	0.000	0.000	0.000	0.000

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
# p<0.1 * p<.05 ** p<.01 *** p<.001 (two tailed).

2.12 FIGURES

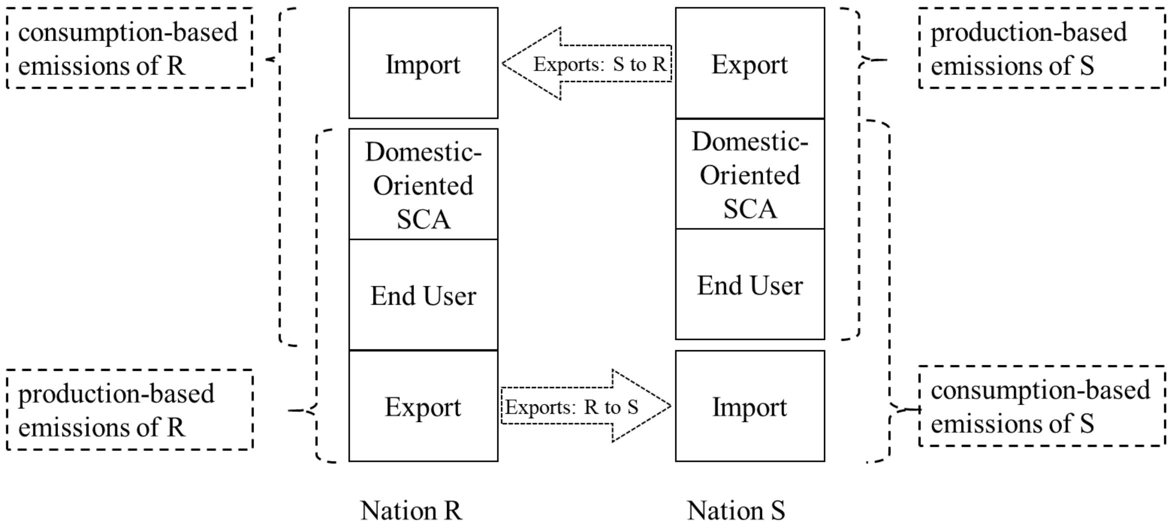

Figure 2.1 Conceptual Diagram of the 4 Emissions Components and Their Relationships with Production-Based Emissions Account and Consumption-Based Emissions Account, in A Simplified 2-Nation Model that Excludes Re-imports and Re-exports.

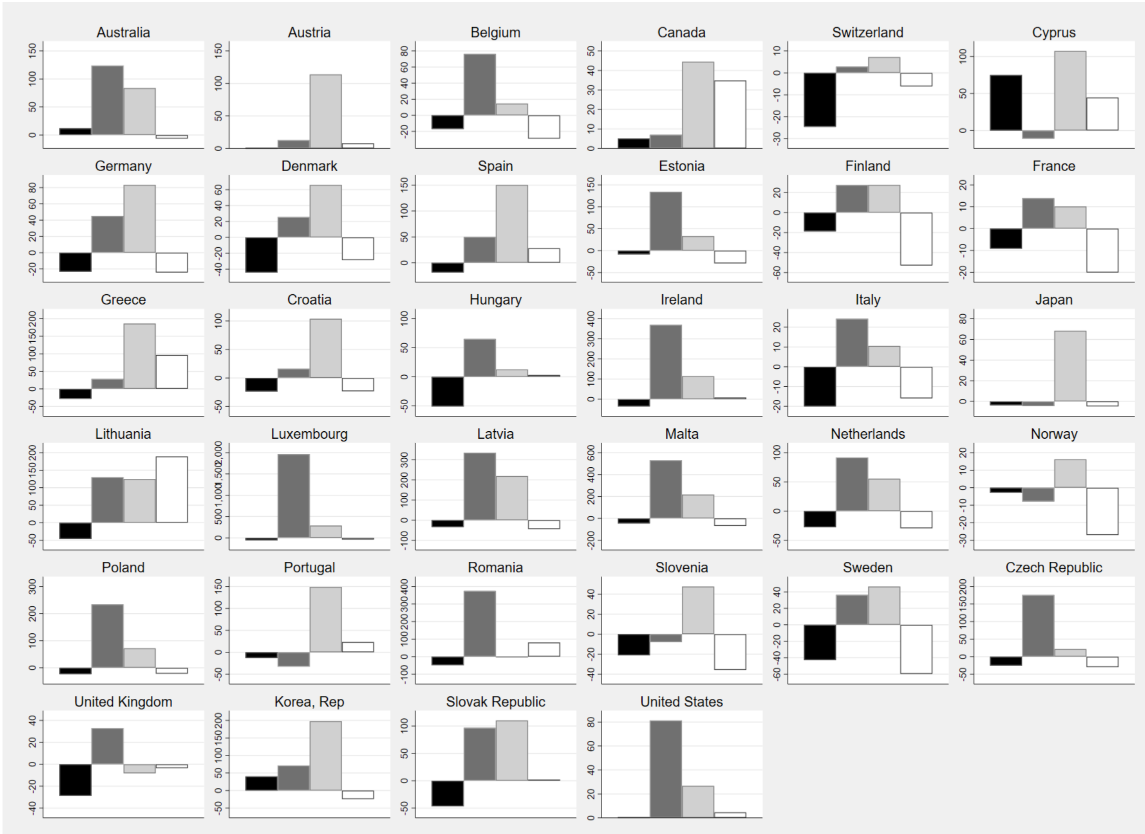

Figure 2.2 Change in GHG Emissions from 1995 to 2015 as a Percent of the 1995 Levels, for 4 Emissions Components of 34 High-Income Nations. Each Bar Chart Includes (a) a Black Bar Representing Emissions Generated by Domestic-Oriented Supply Chain Activities (DOSCA) ; (b) a Dark Grey Bar Representing Emissions Embodied in Imports; (c) a Light Grey Bar Representing Emissions Embodied in Exports; and (d) a White Bar Representing Direct End User Emissions.

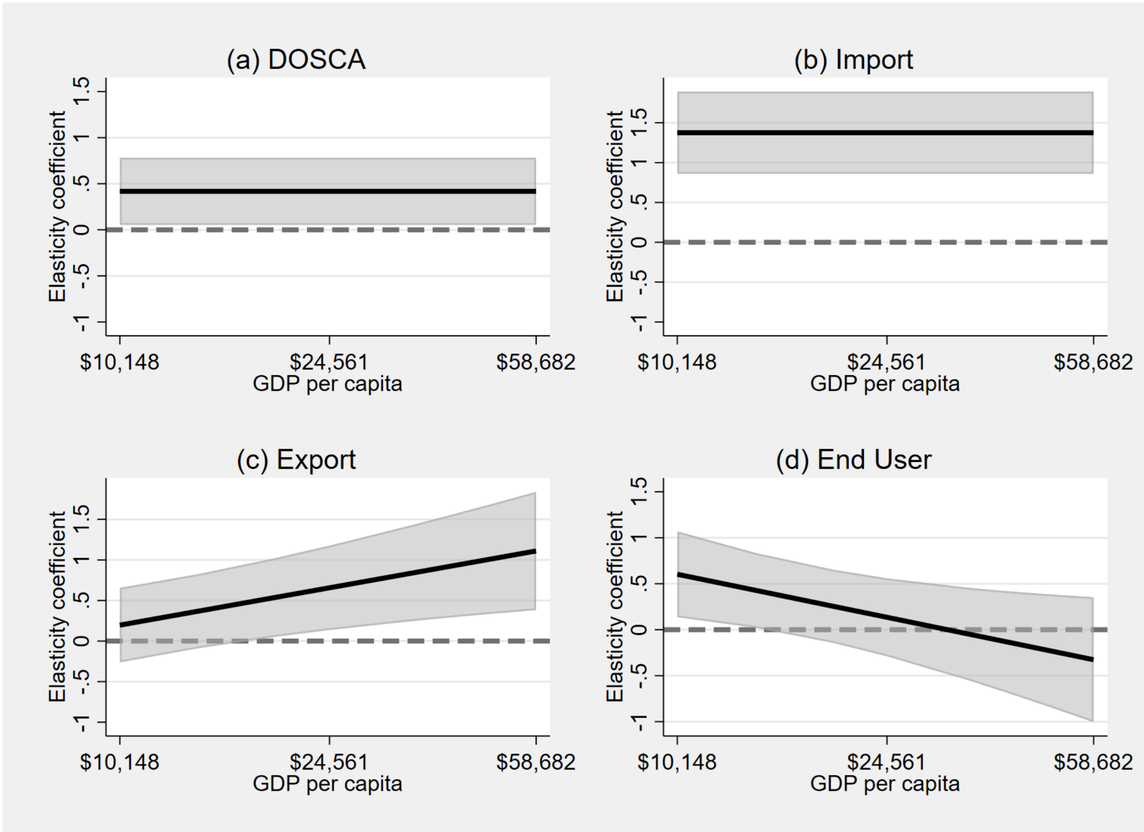

Figure 2.3 Average Marginal Effects of GDP Per Capita on (a) Emissions Generated by Domestic-Oriented Supply Chain Activities (DOSCA); (b) Emissions Embodied in Imports; (c) Emissions Embodied in Exports; and (d) Direct End User Emissions, based on Models 3, 6, 9, 12, Respectively, and Across 9 Decile Points of GDP Per Capita in the Sample. Shaded Areas are 95% Confidence Intervals.

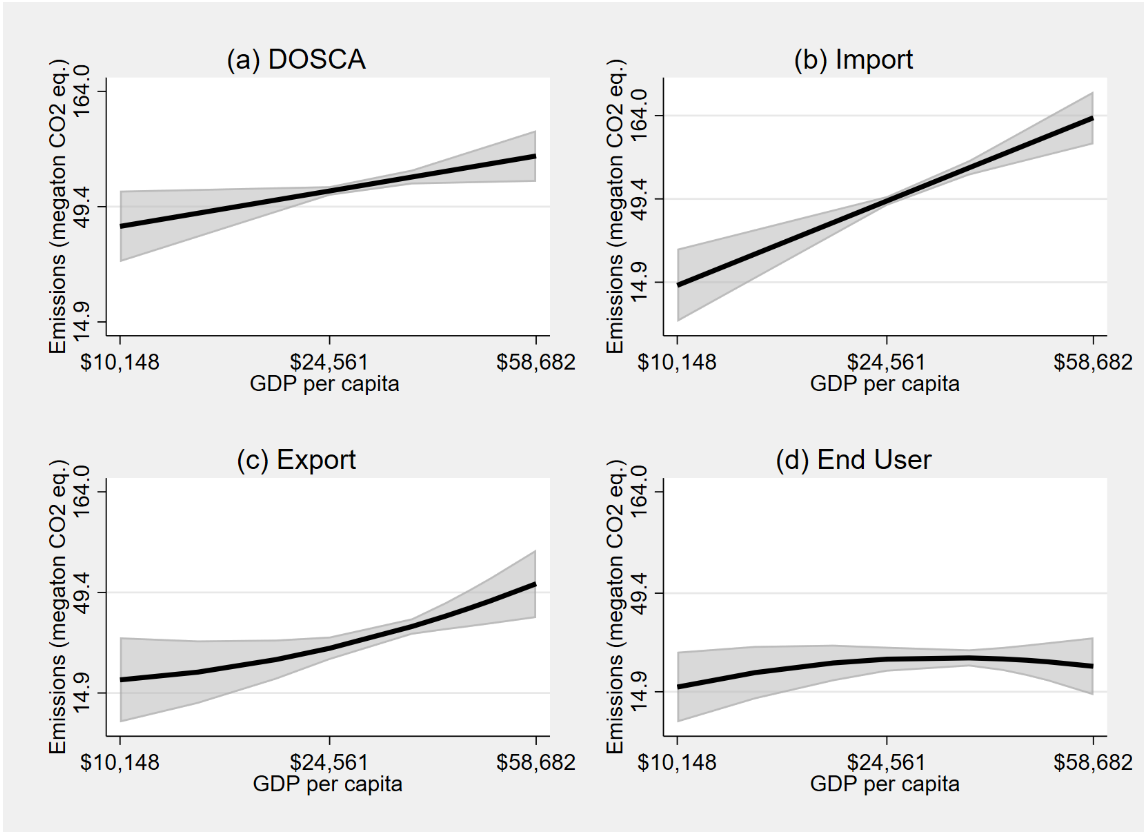

Figure 2.4 Average Predicted Values and 95% Confidence Intervals of (a) Emissions Generated by Domestic-Oriented Supply Chain Activities (DOSCA); (b) Emissions Embodied in Imports; (c) Emissions Embodied in Exports; and (d) Direct End User Emissions, Across the 9 Decile Points of GDP Per Capita in the Sample, based on Models 3, 6, 9, 12, Respectively.

Figure 2.5 Average Predicted Values of (a) Emissions Generated by Domestic-Oriented Supply Chain Activities (DOSCA); (b) Emissions Embodied in Imports; (c) Emissions Embodied in Exports; and (d) Direct End User Emissions, at the 1st, 5th (median), and 9th Deciles of GDP Per Capita in the Sample, based on Models 3, 6, 9, and 12. Percentages in the Parentheses Indicate the Shares of Each Component Relative to the Sum of All 4 Components at Each GDP Per Capita Level.

2.13 APPENDICES

2.13.1 Operationalizing the Four Emission Components of the MEP

I used the environmentally-extended multi-regional input-output (EE-MRIO) method (Miller and Blair 2009), and the EE-MRIO tables from the latest version of Exiobase 3 to calculate nations' four emission components (Stadler et al. 2018, 2021). Prior research has demonstrated that the EE-MRIO method and Exiobase 3 are well suited for analyzing GHG emissions and other environmental impacts of global supply chain activities (Bjelle et al. 2021; Bjørn et al. 2018; Dorninger et al. 2021; Hertwich 2021; Tukker et al. 2016). Emissions data calculated using the EE-MRIO method can be sensitive to the choice of EE-MRIO databases (Lenzen, Wood, and Wiedmann 2010; Owen et al. 2016; Rodrigues et al. 2018). Harmonizing environmental satellite accounts across EE-MRIO databases, which has been applied to Exiobase 3, can alleviate the data sensitivity (Moran and Wood 2014; Tukker, de Koning, et al. 2018). The high level of sectoral resolution of Exiobase also mitigates data uncertainties introduced by sectoral aggregation (Lenzen 2011; Stadler et al. 2018). For a full description of the build process of Exiobase 3 and its use in research, see Stadler et al (2018) and a special issue of *Journal of Industrial Ecology* edited by Tukker et al (2018).

I acquired industry by industry (ixi) EE-MRIO tables from Exiobase 3 for the period of 1995 to 2015, which covers 163 harmonized industrial sectors and 49 regions. Together these areas account for over 99% of global population in 2015. 1995 is the first year with data available, while 2015 is the latest year with industry-level energy-related emissions calculated based on real energy balances data as opposed to nowcasts. For each year, I utilized the technical coefficient matrix $\boldsymbol{A}$ provided by Exiobase. $\boldsymbol{A}$ is a 7987 by 7987 matrix (7987= 163 * 49, and is the number of industry-region pairs); its elements a_{ij}^{RS} (row indices *Ri*: *R*=1,…,49; *i*=1,…,163; column indices *Sj*: *S*=1,…,49; *j*=1,…,163) denote the output from industry *i* in Region *R* that is required as direct intermediate input for industry *j* in region *S* to produce one unit of output. Based on $\boldsymbol{A}$, I calculated a 7987 by 7987 multi-regional Leontief inverse matrix $\boldsymbol{L}$ following the Leontief IO model (Leontief 1970; Miller and Blair 2009).

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$$

where $\boldsymbol{I}$ is a 7987 by 7987 identity matrix. In the matrix $\boldsymbol{L}$, an element l_{ij}^{RS} represents the total output of industry *i* in region *R* that is required to satisfy, both directly and indirectly, a one-unit increase in the final demand for the output of industry *j* in region *S*.

Next, I constructed a 7987 by 49 final demand matrix $\boldsymbol{Y}$ based on the final demand data from Exiobase 3; its element y_j^{ST} (row indices *Sj*: S=1,…,49; *j*=1,…,163; column index *T*=1,…,49) denotes the final demand in region *T* for product *j* imported from region *S*. The *T*-th column of $\boldsymbol{Y}$, denoted by vector $\boldsymbol{y}^T$, represents the final demand in region *T* for each of the 163 products imported from each of the 49 regions including region *T* itself.

Then, for each region of final demand *T*, I calculated a partial output matrix $\boldsymbol{X}^T$ as:

$$\boldsymbol{X}^T = \boldsymbol{L}\widehat{\boldsymbol{y}^T}\boldsymbol{E}$$

where $\widehat{\boldsymbol{y}^T}$ is a 7987 by 7987 matrix resulting from the diagonalization of $\boldsymbol{y}^T$; $\boldsymbol{E}$ is a 7987 by 163 summation matrix created by stacking 49 identity matrices, each sized at 163 by 163, on top of one another. The resulted $\boldsymbol{X}^T$ is a 7987 by 163 matrix.

I then assemble all $\boldsymbol{X}^T$ side by side in the order of T=1,…,49 to create a 7987 by 7987 full output matrix $\boldsymbol{X}$ with elements denoted by x_{ij}^{RT} (row indices Ri: R=1,…,49; i=1,…,163; column indices Tj: T=1,…,49; j=1,…,163). x_{ij}^{RT} represents the total output of industry i located in region R that is required to satisfy, both directly and indirectly, the final demand in region T for product j produced anywhere in the world.

Next, I obtained a 1 by 7987 of emission intensity coefficient vector $\boldsymbol{s}$ for GHG emissions from the impacts extension of Exiobase 3; each element s_i^R represents the GHG emissions per monetary unit of output of industry i located in region R in a particular year. GHG emissions are operationalized as CO_2-equivalents using the Global Warming Potential 100 years approach (IPCC 2013) that accounts for six major greenhouse gases (CO_2, CH_4, N_2O, SF_6, HFCs and PFCs) and weights each based on its relative contributions to global warming over a 100-year period using CO_2 as the benchmark. As such, s_i^R can be viewed as a composite measure that captures the emission intensity of multiple types of GHG by each region-industry pair Ri. s_i^R does not account for GHG emissions related to land use, land-use change and forestry (LULUCF).

A GHG footprint matrix $\boldsymbol{F}$ is calculated as:

$$\boldsymbol{F} = \boldsymbol{s} \bigotimes \boldsymbol{X}$$

where $\bigotimes$ refers to the multiplication of $\boldsymbol{s}$ and $\boldsymbol{X}$ without summation along the columns of $\boldsymbol{X}$. In other words, each element in the n-th row of $\boldsymbol{X}$ is multiplied with the n-th element of $\boldsymbol{s}$. The resulted $\boldsymbol{F}$ is a 7987 by 7987 matrix, the elements of which are $f_{ij}^{RT} = s_i^R x_{ij}^{RT}$ (row indices Ri: R=1,…,49; i=1,…,163; column indices Tj: T=1,…,49;

j=1,…,163).[10] f_{ij}^{RT} represents the total GHG emissions (megaton CO_2-equivalents) generated by industry i in region R that is driven, both directly and indirectly, by the final demand in region T for product j produced anywhere in the world.

Regions' four emission components are calculated by aggregating selective elements of the footprint matrix $\boldsymbol{F}$. Emissions generated by DOSCA for region T are calculated by aggregating the GHG emissions generated by all industries i in region T in order to satisfy, both directly and indirectly, its domestic final demand for all products j, as in:

$$CO_2e\text{-}DO^T = \sum_{i,j=1,1}^{163,163} f_{ij}^{TT}$$

Emissions embodied in imports of region T are calculated by first aggregating the emissions generated by all industries i in all regions R in order to satisfy region T's final demand for all products j, and then deducting the part of emissions generated by all industries i in region T in order to satisfy its domestic final demand for all products j, as in

$$CO_2e\text{-}IM^T = \sum_{R,i,j=1,1,1}^{49,163,163} f_{ij}^{RT} - \sum_{i,j=1,1}^{163,163} f_{ij}^{TT}$$

Emissions embodied in exports of region T are calculated by first aggregating the emissions generated by all industries i in region T in order to satisfy all regions R's final demand for all products j, and then deducting the emissions generated by all industries i in region T i=n order to satisfy its domestic final demand for all products j, as in

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[10] This differs from a conventional matrix multiplication such as $\boldsymbol{m} = \boldsymbol{sX}$, where the product $\boldsymbol{m}$ is a 1 by 7987 vector with its element $m_j^T = \sum_{R,i=1,1}^{49,163}(s_i^R x_{ij}^{RT})$.

$$CO_2e\text{-}EX^T = \sum_{R,i,j=1,1,1}^{49,163,163} f_{ij}^{TR} - \sum_{i,j=1,1}^{163,163} f_{ij}^{TT}$$

For direct end user emissions, Exiobase 3 provides data on the magnitude of GHG emissions directly generated by 3 categories of final demand activities for each of the 49 regions, in the form of a 1 by 147 vector $\boldsymbol{f}_Y$; its elements ${f_Y}_c^T$ (column indices *Tc*: *T*=1,…,49; *c*=1,…,3) denote the direct GHG emissions of final demand category *c* in region *T*. The 3 final demand categories are: final consumption expenditure of households, final consumption expenditure of non-profit organizations serving households (NPISH), final consumption expenditure of general government. The total direct emissions of end user activities of region *T* were calculated by aggregating the direct GHG emissions generated by 3 final demand categories of region *T*, as in:

$$CO_2e\text{-}Y^T = \sum_{c=1}^{3} {f_Y}_c^T$$

The calculation of the four emission components was repeated for each of the sampled regions, and for each year from 1995 to 2015.

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2.13.2 Appendix Tables

Table A2.1 Descriptive Statistics

	N	Mean	S.D.	Min.	Max.
DOSCA Emissions	714	276.178	752.617	0.959	4759.021
Emissions Embodied in Imports	714	157.238	287.703	0.828	2013.607
Emissions Embodied in Exports	714	79.159	113.493	0.389	724.795
Direct Emissions of End User Activities	714	86.921	257.329	0.142	1596.208
GDP per capita	714	34834.015	21537.649	4775.307	111968.352
Imports of goods and services (% GDP)	714	48.356	28.043	7.708	187.165
Exports of goods and services (% GDP)	714	49.576	31.812	8.972	221.197
Manufacturing, value added (% GDP)	710	15.585	4.984	3.887	34.566
Services, value added (% GDP)	710	61.791	6.875	39.84	79.116
Total population	714	30123532.3	54075199.6	377419	320600000
Urban population (% Pop.)	714	73.316	11.813	50.622	97.876
Age dependency ratio	714	48.459	4.227	36.214	63.958

Table A2.2 Unstandardized coefficients for the regression of nations' 4 emission components, 1995–2015 on GDP per capita and all covariates: two-way fixed effects regression model estimates with country-clustered robust standard errors for 34 high-income countries.

	Fixed-Effects Model		Seemingly Unrelated Regression Models			
	DOSCA Emissions Model 1	**Emissions in Imports Model 2**	**DOSCA Emissions Model 3**	**Emissions in Imports Model 4**	**Emissions in Exports Model 5**	**Direct End User Emissions Model 6**
GDP Per Capita	0.277	1.335**	0.277	1.335***	0.728**	0.0625
	(0.249)	(0.419)	(0.240)	(0.404)	(0.269)	(0.222)
GDP Per Capita Squared	-0.114	-0.0323	-0.114	-0.0323	0.260**	-0.265*
	(0.121)	(0.161)	(0.117)	(0.155)	(0.0895)	(0.113)
Total Population	1.796**	1.558*	1.796**	1.558**	-0.311	1.285*
	(0.619)	(0.574)	(0.598)	(0.554)	(0.555)	(0.541)
Imports as % GDP	0.0759	0.617**	0.0759	0.617**	-0.282#	-0.160
	(0.155)	(0.205)	(0.149)	(0.198)	(0.170)	(0.134)
Exports as % GDP	-0.352*	-0.179	-0.352*	-0.179	0.871***	-0.0577
	(0.144)	(0.275)	(0.139)	(0.266)	(0.146)	(0.128)
Manufacturing as % GDP	-0.0746	-0.306	-0.0746	-0.306	-0.386*	0.178
	(0.143)	(0.288)	(0.138)	(0.278)	(0.186)	(0.131)
Service as % GDP	-0.903*	0.256	-0.903*	0.256	0.428	0.0535
	(0.436)	(0.444)	(0.421)	(0.428)	(0.379)	(0.381)
Urban Pop. as % Pop.	-0.231	0.125	-0.231	0.125	0.0136	0.393
	(0.680)	(0.691)	(0.656)	(0.667)	(1.115)	(0.643)
Age Dependency Ratio	0.554	0.376	0.554	0.376	0.373	0.514
	(0.442)	(0.495)	(0.427)	(0.478)	(0.390)	(0.446)
Constant	-20.91#	-24.93**	-20.65*	-25.67**	5.914	-21.31*
	(10.44)	(8.562)	(10.48)	(8.593)	(10.79)	(9.645)
N	710	710	710	710	710	710
# of nation	34	34	34	34	34	34
N per nations, min.	19	19	19	19	19	19
N per nation, avg.	20.88	20.88	20.88	20.88	20.88	20.88
N per nation, max.	21	21	21	21	21	21

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
# p<0.1 * p<.05 ** p<.01 *** p<.001 (two tailed).

3.0 CHAPTER 3: UNEVEN DECARBONIZATION: THE MULTIDIMENSIONAL RELATIONSHIP BETWEEN HIGH-INCOME NATIONS' RENEWABLE ENERGY DEPLOYMENT AND CARBON DIOXIDE EMISSIONS, 1995-2015

3.1 ABSTRACT

Renewable energy transition is crucial to reducing global CO_2 emissions. Using a multidimensional analytical framework, I systematically analyze the relationships between nations' renewable energy deployment and four components of CO_2 emissions with distinct implications for climate change mitigation: (1) emissions generated by domestic-oriented supply chain activities; (2) emissions embodied in exports; (3) direct emissions of end user activities, and (4) emissions embodied in imports. Primary attention is given to the first three components, which together constitute nations' production-based emission account. I analyze a panel dataset consisted of 34 high-income nations from 1995 to 2015. Results of seemingly unrelated regression models suggest that renewable energy deployment only mitigates emissions by domestic-oriented supply chain activities, and with increasing effectiveness over time; yet it remains ineffective in curbing the other three emission components. I discuss potential structural barriers that prevent the decarbonization effect of renewables from spilling over to the other emission components. These barriers must be overcome in order to achieve the full decarbonization potential of renewable energy deployment.

3.2 INTRODUCTION

In order to limit global warming to 1.5 °C, it requires a 45% reduction in global CO_2 emissions by 2030 relative to the 2010 level (UNFCCC 2021). This urgency underscores the importance of optimizing the decarbonization effect of renewable energy deployment, a major climate mitigation strategy (IPCC 2011). To this end, a large body of research has examined how renewable energy deployment affects nations' CO_2 emissions, yielding mixed findings on its decarbonization effect (e.g., Sovacool et al. 2020; Thombs 2017; Wang, Assenova, and Hertwich 2021; York 2012; York and McGee 2017). At the national level, a myriad of human activities leads to fossil fuel consumption and CO_2 emissions, including domestic consumer activities such as driving, as well as industrial production that serves both domestic and foreign consumers. Prior cross-national research has not systematically examined the decarbonization effect of renewable energy deployment on multiple components of nations' CO_2 emissions corresponding to different types of fossil fuel consumption activities. Such a systematic analysis can identify the types of activities that renewable energy deployment can most effectively decarbonize, and the types that are most resistant to its decarbonization effects, thereby informing the strategies for deploying renewables to optimize the effect for climate change mitigation.

This study seeks to address this gap by adopting the Multidimensional Emissions Profile (MEP) framework to the study of renewable energy-carbon emissions nexus. This framework situates a nation's contributions to global carbon emissions into 4 distinct components: (1) emissions generated by domestic-oriented supply chain activities, such as domestic industrial activities that serve domestic consumers; (2) emissions embodied in exports; (3) direct emissions of end user activities; and (4) emissions embodied in imports (see Chapter 2). Using seemingly unrelated regression modeling with fixed effects on a panel dataset of 34 high-income nations from 1995 to 2015, I analyze how nations' renewable energy consumption is associated with each of these emission components. The analyses address two sets of questions. First, compared across these emission components, which are more effectively mitigated by renewable energy deployment? Which components are less effectively mitigated? Second, for each emission component, how has the decarbonization effect of renewable energy deployment changed over time? The findings indicate that renewable energy deployment only mitigates the emissions generated by domestic-oriented supply chain activities, and with increasing effectiveness over time. Using this emission component as the benchmark, I discuss potential structural barriers to the mitigation of other emission components by renewables.

3.3 RENEWABLE ENERGY AND CO_2 EMISSIONS

The relationship between renewable energy deployment and CO_2 emissions is the focus of a large and growing body of research at both national and subnational levels (e.g., Adua, Zhang, and Clark 2021; Jebli and Kahia 2020; Thombs and Jorgenson 2020). A number of studies find that increasing renewable energy consumption in a nation can reduce its CO_2 emissions (Bilgili, Koçak, and Bulut 2016; Shafiei and Salim 2014; Shahnazi and Dehghan Shabani 2021; Sovacool et al. 2020; Wang et al. 2021). Dong et al (2018) focus on renewable energy consumption per unit of GDP, which is found to be negatively associated with CO_2 emissions across major geographic regions of the world, and the effect is greater in regions where renewable energy constitutes a larger share of total energy consumption.

However, much complexity exists in the relationships among renewable energy consumption, CO_2 emissions, and fossil fuel consumption. Some studies question whether renewable energy, as it has been deployed, can lead to the rapid and substantial emission abatement that is necessary to meet the global mitigation target. York (2012) finds that an one-unit increase in nations' renewable energy usage is associated with a reduction in fossil fuel usage by less than a quarter of a unit. This may be in part due to the fuel market rebound effect: renewable energy production increases overall energy supply, lowers energy price, which stimulates total energy consumption, including the consumption of fossil fuels (Hill, Tajibaeva, and Polasky 2016). Other studies find that the downward effect of renewable energy consumption (% total energy consumption) on CO_2 emissions is smaller in wealthier nations than in poorer nations (Thombs 2017; York and McGee 2017), which may be partly because in wealthier nations renewable energy consumption could displace nuclear energy as opposed to fossil fuel consumption (Greiner, York, and McGee 2022; Sovacool et al. 2020).

Whether and by how much renewable energy deployment reduces CO_2 emissions may depend on the extent to which increases in renewable energy consumption displace fossil fuel consumption. The aforementioned research challenges the assumption that innovation in renewable energy technologies can lead to a "creative destruction" in which renewable energies quickly displace fossil fuels through market competition (Schumpeter 1942). Davidson (2019:254) argues that "if left to the vagaries of creative destruction, renewables will not replace fossil fuels until those renewable energy technologies not only achieve price parity with fossil fuels, but also become so cheap that they justify the abandonment of the extraordinary levels of sunk costs that continue to be invested in the fossil fuel regime". Therefore, Davidson argues that in order to achieve the full potential of renewable energy for climate change mitigation, it requires a concurrent "exnovation" of the fossil fuel regime, namely the deliberate and concerted effort to phase out institutions, infrastructure, products, practices, and beliefs that sustain and legitimize the fossil-fuel based energy system.

The type of renewable energy and other socioeconomic factors also influence the impacts of renewables on nations' CO_2 emissions. Thombs (2018) finds substantial variation in the effects of multiple types of non-fossil-fuel energy on emissions, and that the effects of some renewables change over time. Hill et al (2016) note that investment in biofuel, a major component of the U.S. renewable fuel standard, may lead to increases in CO_2 emissions when accounting for the fuel market rebound effect. Additionally, McGee and Greiner (2019) find that the emission-reducing effects of renewable energy consumption is moderated by domestic income inequality. These studies together underscore that renewable energy transition and its effectiveness as an emission abatement measure are shaped by various political-economic, social, and technological factors (Jorgenson et al. 2019; Sequeira and Santos 2018; Smil 2016; Sovacool 2016; Sovacool and Geels 2016).

3.4 NATIONS' MULTIDIMENSIONAL EMISSIONS PROFILE

Most cross-national research to date on the renewable energy-carbon emissions nexus examines aggregate national emission outcomes and especially production-based account (PBA) that captures all emissions generated within a nation's territory. However, a nation's fossil fuel-burning and CO_2-emitting activities are not monolithic, but can instead be classified into distinct categories based on characteristics such as the stage of supply chain in which the activities occur, the type of fossil fuels consumed, or the economic sector in which the activities take place. Correspondingly, a nation's CO_2 emissions are constituted by multiple structural components, each with distinct implications for emissions abatement. To this end, Huang (see Chapter 2) proposes a Multidimensional Emissions Profile (MEP) framework for the systematic analysis of nations' multiple emission components, focusing on how these components are heterogeneously related to certain human drivers of emissions.

The MEP framework situates each nation's contributions to global carbon emissions into 4 distinct components: (1) emissions generated by domestic-oriented supply chain activities (DOSCA), such as domestic industrial activities that serve domestic consumers; (2) emissions embodied in exports; (3) direct emissions of end user activities; and (4) emissions embodied in imports. DOSCA emissions, emissions embodied in exports, and emissions embodied in imports are generated by supply chain activities outside the end use phase (see Chapter 2). Direct emissions of end user activities are generated by activities such as driving personal vehicles and household heating that burns fossil fuels on-site. This emission component excludes the emissions that are induced by end user activities but generated upstream in supply chains, such as the emissions generated by domestic power plants serving domestic households (which are a part of DOSCA emissions). Figure 3.1 illustrate the 4 components and their relationships with production-based account (PBA) and consumption-based emission account (CBA) (see also Steininger et al. 2014).

While these 4 emission components are connected through global supply chains, each of them can be viewed as a distinct point of decarbonization. At the national level, generally speaking, emissions embodied in imports are generated by foreign supply chain activities to fulfill a nation’s final demand. These foreign supply chain activities are, at best, indirectly influenced by the nation’s climate mitigation measures. Emissions embodied in exports are generated by domestic supply chain activities serving foreign final demand, which are more directly affected by domestic climate and energy policies, and might be subject to the indirect influence of foreign policies. Among the 4 components, DOSCA emissions and direct end user emissions are arguably under the most direct influence of domestic policies and are least affected by foreign policies.

At the organizational level, mitigating the three emission components generated outside the end use phase requires business organizations to reduce the emissions generated by their own operations. In contrast, mitigating direct end user emissions requires firms that produce consumer goods and services to offer products that facilitate the reduction of direct end user emissions (e.g., electric vehicles and solar-powered EV chargers) (Stern et al. 2016). At the household and individual levels, reducing emission components generated outside the end use phase requires changing consumer behaviors that do not generate emissions directly but are instead implicated in the emissions generated by upstream production processes (e.g., purchasing products that require fossil fuels to produce and deliver). Among the many challenges to fostering behavioral changes, mitigation strategies targeting these behaviors need to overcome the cognitive barrier that most consumers are unaware of the embodied emissions of consumer products, and the institutional and technical barriers of compiling and publicizing credible information on embodied emissions for a wide range of consumer products (Abrahamse et al. 2007; Taufique et al. 2022). In comparison, these barriers are present but relatively less inhibiting for changing consumer behaviors that contribute to direct end user emissions, such as driving personal vehicles, where consumer behaviors are more immediately linked to their emission outcomes (Stern et al. 2016).

3.5 MULTIDIMENSIONALITY IN THE RENEWABLE ENERGY-CARBON EMISSIONS NEXUS

The above account of the distinctions among the 4 emission components alludes to the potential heterogeneity in how these emission components respond to decarbonization measures such as renewable energy deployment. Renewables' impacts on these emission components may differ in magnitude, in direction, and in how the impacts change over time. In other words, unless proven otherwise, the renewable energy-carbon emissions nexus is likely a multidimensional process consisting of distinct relationships between renewables and each of these emission components. If renewable energy deployment is found to suppress the production-based account (PBA) of nations' emissions, it does not necessarily mean that the same decarbonization effect is achieved for all emission components. Similarly, if a null effect is observed between renewables and PBA, it does not necessarily suggest that renewables are unable to curb any emission components that constitute PBA; instead, it could mean renewables' decarbonization effect on some emission components are offset by renewables inadvertently boosting other components.

The research literature on the renewables-emissions nexus has not systematically examined how renewable energy deployment is heterogeneously associated with multiple structural components of a nation's contributions to global CO_2 emissions. Therefore, in this study I apply the MEP framework to conduct such an analysis. Compared across these emission components, which are more effectively mitigated by renewable energy deployment? Which components are less effectively mitigated? For each emission component, how has the decarbonization effect of renewable energy deployment changed over time? To answer these questions, I first conduct a baseline analysis of renewables' relationship with nations' PBA, and how the relationship changes over time. Then I analyze renewables' relationships with DOSCA emissions, emissions embodied in exports, and direct end user emissions, as well as how these relationships change over time. As noted in Figure 3.1, these 3 emission components together constitute PBA. The 4^{th} emission component, emissions embodied in imports, is excluded from the main analysis because a lack of theoretical ground to assume that a nation's domestic energy policies can directly influence the emissions embodied in imports, which are generated in foreign nations.[11] Nonetheless, I include this emission component in additional sensitivity analysis because it is an integral part of how nations contribute to global emissions

[11] This study's focus on PBA and its components is also consistent with the research literature's main focus. With few exceptions (e.g., Zhong, Jiang, and Zhou 2018) that examine indirect effects, the literature has not focused on the relationship between renewables and emissions embodied in imports.

(Davis and Caldeira 2010; Davis, Peters, and Caldeira 2011; Peters and Hertwich 2006; see also Chapter 2), and that many nations have seen substantial increase in emissions embodied in their imports during the past two decades (Peters et al. 2011; Wood et al. 2020; see also Figure 3.1 below). I analyze a sample of high-income nations, partly due to data availability constraints discussed in next section. The focus on high-income nations is also motivated by the facts that many high-income nations are major contributors to global carbon emissions (Andrew and Peters 2021), and they generally have greater financial and technological capability for renewable energy transition than lower-income nations (IPCC 2011).

3.6 DATA AND METHODS

3.6.1 Dependent Variables

The dependent variable for the baseline analysis is nations' production-based account (PBA) of CO_2 emissions. The main analysis focuses on 3 separate dependent variables (1) CO_2 emissions generated by domestic-oriented supply chain activities (DOSCA); (2) CO_2 emissions embodied in exports; and (3) direct CO_2 emissions of end user activities. Additional sensitivity analysis includes CO_2 emissions embodied in imports. These emission variables are calculated using the environmentally-extended multi-regional input-output (EE-MRIO) method and the EE-MRIO tables from the latest version of Exiobase 3 (Stadler et al. 2018, 2021).[12] All dependent variables capture CO_2 emissions generated from fossil fuel combustion and are measured in megatons. Technical details of data compilation and calculation are provided in the Appendix 3.12.1.

3.6.2 Independent Variables

The main independent variable of interest is renewable energy consumption as a percent of total final energy consumption. This measure accounts for multiple types of renewable energy, including hydroelectric, solar, wind, and biofuel. I use this relative measure of renewable energy consumption because it is more aligned with the conceptual focus on renewable energy transition, which more closely concerns the share of societal energy usage from renewable sources rather than the total amount of renewable energy consumed. This operationalization is also consistent with prior studies on the renewables-emissions nexus (e.g., Thombs 2017; York and McGee 2017).

I also include both the linear term and the square term of gross domestic product (GDP) per capita measured in constant 2010 U.S. dollars. Additional independent variables are total population, imports as a percent of GDP, exports as a percent of GDP, manufacturing value added as a percent of GDP, services value added as a percent of GDP, urban population as a percent of total population, and age dependency ratio (i.e.,

[12] DOSCA emissions and emissions embodied in exports and in imports are conceptualized and operationalized based on the multi-regional input-output (MRIO) method as opposed to the emissions embodied in bilateral trade (EEBT) method (see Chapter 2). The two methods differ in the allocation of the emissions generated by the internationally-traded intermediate goods. The EEBT method allocates this part of emissions to the nations that consume the intermediate goods, regardless of where the final goods (produced from said intermediate goods) are consumed. The MRIO method allocates this part of emissions to the nation where the final goods are consumed. See Peters et al (2011) for more information.

the population of people younger than 15 or older than 64 as a percent of the population of those between 15 and 64 years old). Trade openness (i.e., the sum of imports and exports as a percent of GDP) is also an important covariate (Jorgenson and Clark 2012; Thombs and Huang 2019). However, given that I use separate dependent variables for the emissions embodied in exports and imports, I elect to include imports (% GDP) and exports (% GDP) as separate independent variables (see also Chapter 2). Energy consumption per capita is not included because it is very highly correlated with GDP per capita. Data on all independent variables is acquired from the World Bank's World Development Indicators Database (https://databank.worldbank.org/source/world-development-indicators).

3.6.3 Sample

The overall sample is a balanced panel dataset consisted of 714 annual observations from the 34 high-income nations in the 21-year period of 1995 to 2015.[13] The sample includes 9 out of 10 biggest emitters among high-income nations in terms of total production-based CO_2 emissions from fossil fuel combustion in 2015.[14] The sample size is reduced to 710 observations in models that include manufacturing value added or services value added because the United States and Canada have missing data on these two variables for years 1995 and 1996.

[13] Sampled nations are Australia, Austria, Belgium, Canada, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, South Korea, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Sweden, United States.

[14] Based on data by Andrew and Peters (2021)

The sample includes all high-income nations, as per World Bank's country classification, that have data available for all variables.[15] A total of 43 nations also have data available on all dependent and independent variables. Among these 43 nations, 34 are high-income nations and 9 are non-high-income nations. The analysis excludes the 9 non-high-income nations, in order to avoid potential misleading results from a mixed sample, given that national income level significantly moderates the relationship between renewable energy consumption and CO_2 emissions (Thombs 2017; York and McGee 2017). Nonetheless, the emission measures of the sampled high-income nations do account for their trade with these non-high-income nations as well as the rest of the world. For example, although India is not a sampled nation, the exports from the United States to India are accounted for when calculating the total emissions embodied in the exports of the United States. Appendix Tables A3.1 and A3.2 report the descriptive statistics and correlation matrix of all dependent and independent variables in their original metrics for the sample.

3.6.4 Regression Modeling Techniques

For the baseline analysis, I estimate a set of fixed effects regression models for PBA that include both time-specific and nation-specific intercepts, in order to account for unobserved heterogeneity that is unique to each year and affects all nations equally, as well as the unobserved heterogeneity that is unique to each nation and invariant across the whole period of analysis. I estimate country-clustered robust standard errors in order

[15] World Bank country classification. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

to correct for autocorrelation and heteroskedasticity. All non-binary variables are transformed with natural logarithm, and hence the regression coefficients are elasticity coefficients that represent the percentage change in the dependent variable associated with a 1% increase in the independent variables, net of the effects of other independent variables.[16] The general model is specified as follows:

$$y_{it} = \beta x_{it} + u_i + w_t + e_{it}$$

where subscripts i and t represent nation and year respectively; and y_{it} is the outcome variable for nation i at year t; β is the vector of regression coefficients that correspond to the vector of time-varying predictor variables x_{it}; u_i is the nation-specific intercept for nation i; $w_t$is the year-specific intercept for year t; e_{it} is the unique residual for nation i at year t.

In one of the models for PBA, I examine changes over time in the relationship between renewables and PBA by including interaction terms between renewables and yearly dummy variables for 1996 to 2015, a modeling technique used in prior research (Huang 2018; Jorgenson 2012, 2014; Jorgenson and Clark 2012; Thombs and Huang 2019). The coefficient for the main effect of renewables is the slope for year 1995, the reference category. The coefficients for the interaction terms indicate if the association between renewables and emissions for each subsequent year differs from that of 1995 (Allison 2009).

For the main analysis, I estimate a seemingly unrelated regression (SUR) model that consists of 3 equations, one for each of the 3 main dependent variables: DOSCA emissions, emissions embodied in exports, and direct end user emissions. The model also

[16] The minimal value of renewable energy development is 0. Therefore, I add a constant of 1 to each observation of this variable before transforming it with natural logarithm.

includes nation and year fixed-effects, and nation-clustered robust standard errors. SUR model allows the error terms of the 3 equations to be correlated, and hence has greater efficiency in estimating parameters in each equation by using the information from all 3 equations (Srivastava and Giles 1987). The 3 emission components are generally interconnected by complex feedback loops including different types of supply chain processes and carbon leakage (Davis et al. 2011; Dietz 2017; Hu et al. 2019; Jarke and Perino 2017; Liu et al. 2007; Peters 2010), which are not explicitly accounted for in the model. Compared to estimating separate models for each emission component, SUR model better accounts for these potential underlying relationships among the 3 emission components (Srivastava and Giles 1987).

Then, I estimate another SUR model to examine how the associations between renewables and nations' 3 emission components have changed over time. The 3 equations of this model additionally include interactions between renewables and yearly dummy variables (the reference category is 1995), similar to the aforementioned model for PBA. In additional sensitivity analysis, I estimate 4-equation SUR models that include emissions embodied in imports as the dependent variable of the 4^{th} equation.

3.7 RESULTS

Turning first to descriptive statistics, I find that all but one nation in the sample increased the share of renewable energy in total final energy consumption from 1995 to 2015 (see Figure 3.2). The only exception is Norway, which, despite a slight decrease during this period, has the highest level of renewable energy consumption in the sample.

Meanwhile, out of the 34 sampled nations, 29 reduced their DOSCA emissions and 22 reduced direct emissions from end user activities during this period (see Figure 3.3). The reduction in the other 2 emission components are far less prevalent: 6 nations saw a reduction in emissions embodied in exports from 1995 to 2015, and only 3 nations experienced a reduction in emissions in imports. It appears that in most sampled nations the increase in renewable energy consumption occurred concurrently with a decrease in DOSCA emissions and in direct end user emissions, while emissions embodied in their exports and imports grew substantially at the same time.

The baseline regression analysis of PBA is reported in Table 3.1. Nation clustered robust standard errors are reported in parentheses. Elasticity coefficients are flagged for statistical significance in the table. Model 1 includes only renewable energy, GDP per capita, and total population. Model 2 includes other covariates. Model 3 includes the squared term of GDP per capita. Model 4 additionally includes the interactions between renewables and yearly binary variables, which are separately reported in the left-hand side of Figure 3.4. The right-hand side of Figure 3.4 plots the slope of renewables from 1995 to 2015, with shaded areas representing the 95% confidence intervals. The slope for year 1995 is the main effect of renewables, while the slope for each subsequent year is the sum of the main effect and the interaction term for that year. Models 1 through 3 suggest that, on average from 1995 to 2015, renewable energy consumption is negatively associated with PBA. Model 4 and Figure 3.4 show the slope remains negative throughout this period. The magnitude of the slope is largely stable before 2005 and then gradually increases especially after 2010.

The baseline analysis indicates an overall decarbonization effect of renewable energy deployment on PBA, and that the effect has become stronger since the late 2000s. Is the observed effect, and its enhancement over time, evenly distributed among the 3 components that constitute PBA? Are certain components more effectively mitigated than others by renewables? To answer these questions, I estimate 3-equation SUR models for DOSCA emissions, emissions embodied in exports, and direct end user emissions. The Breusch-Pagan test indicates that the residuals of the 3 equations are significantly correlated. Table 3.2 reports the first SUR model, which examines the average associations for the 1995 to 2015 period between renewables and each emission component. The results indicate that renewable energy consumption is negatively associated with DOSCA emissions; yet, it is not associated with the emissions embodied in exports or direct end user emissions.

Next, I estimate another 3-equation SUR model, which includes the interactions between renewables and year-specific dummy variables. Model estimates are reported in Table 3.3. Figure 3.5 presents renewable energy' slopes for the 3 emission components for each year from 1995 to 2015, with shaded areas representing the 95% confidence intervals.

Figure 3.5(a) suggests that the association between renewables and DOSCA emissions remains negative and significant throughout this period. Despite some fluctuations, the association generally increases in magnitude over time and especially since 2010. In 1995, a 1% increase in renewables is associated with a reduction in DOSCA emissions by 0.295%. In 2014, when the magnitude of the association is at its peak, a 1% increase in renewables is associated with a reduction in DOSCA emissions by

0.513%. Figure 3.5(b) shows that, for emissions embodied in exports, the point estimates of renewable energy's slope are negative during this period and remain relatively stable except for an initial dip. However, the slope is either statistically nonsignificant or borderline significant.[17] Figure 3.5(c) illustrates the changes in renewable energy's slope for direct end user emissions, which remains nonsignificant and relatively stable in magnitude from 1995 to 2015 (alpha=0.05).

Among covariates reported above in Table 3.2, the linear term of GDP per capita is positively associated with emissions in exports, but is not associated with DOSCA emissions or direct end user emissions (alpha=0.05). The squared term of GDP per capita is negatively associated with direct end user emissions, which indicates that the association between GDP per capita and direct end user emissions becomes negative and increasingly larger in magnitude as nations become wealthier. Additional unreported SUR models suggest that the squared term of GDP per capita is not associated with DOSCA emissions or emissions in exports. These findings indicate that economic growth has decoupled from DOSCA emissions and direct end user emissions but remain coupled with increases in emissions embodied in exports. Total population is positively and elastically associated with all 3 emission components. Exports (% GDP) is positively associated with emissions embodied in exports, and is negatively associated with DOSCA emissions. Manufacturing (% GDP) is positively associated with direct end user emissions, while service (% GDP) is negatively associated with DOSCA emissions. The

[17] Wald tests suggest that, for 10 years out of the 21 year-period, namely, 1996, 1998, 2002, 2005-2007, 2009, 2010, 2012, and 2013, the slopes of renewables are borderline significantly different than 0 ($0.03 \leq p < 0.05$ for 9 out of these 10 years; for 2009, $p=0.019$). For the other 11 years, the coefficients are nonsignificant at 0.05 alpha level.

coefficients for imports, urban population, and age dependency ratio are nonsignificant across all three emission components (alpha=0.05).

Appendix Tables A3.3 and A3.4 report 4-equation SUR models that include emissions embodied in imports as the 4th dependent variable, as part of the additional sensitivity analysis. The findings for DOSCA emissions, emissions embodied in exports, and direct end user emissions remain substantively similar to the reported 3-equation models. For emissions embodied in imports, the slope of renewable energy consumption is nonsignificant during the whole 1995 to 2015 period. GDP per capita is positively and elastically associated with emissions embodied in imports.

3.8 DISCUSSION AND CONCLUSION

This study examines the multidimensionality in the renewable energy-carbon emissions nexus for a sample of 34 high-income nations from 1995 to 2015. Drawing from the Multidimensional Emissions Profile (MEP) framework, I systematically analyze the relationships between nations' renewable energy consumption and 4 emission components with distinct implications for climate change mitigation. Consistent with the literature's focus on production-based account (PBA) of nations' CO_2 emissions, I primarily focus on the 3 emission components that constitute PBA: (1) emissions generated by domestic-oriented supply chain activities (DOSCA); (2) emissions embodied in exports; and (3) direct emissions of end user activities. The 4th component, emissions embodied in imports, is also considered in sensitivity analyses. The study seeks to identify emission components that are more effectively mitigated by renewable energy deployment, as well as components that are less effectively mitigated. Furthermore, the study investigates if the decarbonization effect of renewable energy deployment has changed over time for each emission components.

When the entire 1995 to 2015 period is considered, I find an overall decarbonization effect of renewable energy deployment on nations' PBA. However, this effect is not evenly distributed among the 3 components that constitute PBA. Renewable energy deployment is only effective in mitigating DOSCA emissions, which are emissions by domestic industrial and other supply chain activities that serve domestic final consumption. Renewable energy remains ineffective in curbing emissions embodied in exports and direct end user emissions. This suggests that the observed overall decarbonization effect of renewables is primarily attributed to the effect on DOSCA emissions. While renewables' overall decarbonization effect on PBA has improved over time from 1995 to 2015 and especially since the late 2000s, this improvement is once again primarily attributed to the improvement in renewables' effectiveness in mitigating DOSCA emissions. Despite such an improvement, renewables' inability to mitigate emissions embodied in exports and direct end user emissions has persisted throughout this period.

It is promising to observe an increasingly stronger decarbonization effect of renewables on PBA and more specifically on DOSCA emissions, which may be credited to the strengthening of policy and private sector support for renewable energy transition. The lack of similar suppressive effects on emissions embodied in exports and direct end user emissions, however, indicates the existence of structural barriers that prevent decarbonization from spilling over to these two emission components. These structural barriers prevent the fossil fuel consumption of export-oriented industries and domestic end users from being displaced by nations' increased renewable energy consumption. Moreover, it appears that the barriers cannot be overcome by simply strengthening the existent strategies of renewable energy deployment. It is crucial to identify and overcome these structural barriers in order to achieve the full decarbonization potential of renewable energy deployment. Below I explore what these barriers may be.

For emissions embodied in exports, one likely barrier is the preferential treatment of energy-intensive export-oriented industries in environmental policies. In order to maintain competitiveness in international trade, many nations either exempt energy-intensive export industries from carbon taxes, or provide them with tax rebates or reduced tax rates (Babiker et al. 2003; Böhringer and Rutherford 1997; OECD 2001). These preferential treatments reduce the incentives for energy-intensive export industries to reduce fossil fuel consumption and CO_2 emissions (Barker, Baylis, and Madsen 1993; Lin and Li 2011; OECD n.d.; Zhang and Baranzini 2004). Investment in renewable energy without proportional exnovation of the fossil fuel regime does little to curb fossil fuel consumption (Davidson 2019), in part because of the fuel market rebound effect: investment in renewables increase total energy supply, which can lower energy price—including the price of fossil fuel, thereby spurring fossil fuel use (Hill et al. 2016). Additionally, if not accompanied by adequate effort to suppress fossil fuel consumption, renewable energy deployment in nuclear-capable nations tends to crowd out nuclear power rather than fossil fuels (Greiner et al. 2022; Sovacool et al. 2020). This also sidesteps the decarbonization effect of renewable energy and is particularly relevant to high-income nations because they are more likely to be nuclear-capable than lower-income nations.[18]

Underlying these processes is that many practices that are normalized at a societal level, such as personal vehicle-based transportation and the ubiquity of plastics, together with the vast economic and political power of the fossil fuel industry, continue to legitimize the fossil fuel regime despite the growth in alternative energy deployment (Davidson 2019; Sicotte 2020; Sicotte and Seamon 2021; Smil 2016). Due to their preferential treatment in climate policies, export industries may be more likely than domestic-oriented industries to succumb to the fuel market rebound effect, the mutual displacement between renewable and nuclear energies, and the underlying inertia of the fossil fuel regime. It might also be the case that granting climate policy preference to export industries induces a form of carbon leakage from domestic-oriented industries to export industries. In order to recoup the sunk cost of the fossil fuel-based equipment and facilities made obsolete due to a transition to renewable energy in domestic-oriented industries, businesses may choose not to scrap these equipment and facilities but instead repurpose them for export-oriented production. These dynamics create an upward pressure on fossil fuel consumption that is disproportionally felt by export industries, which offsets the potential suppressive effect of renewable energy on emissions embodied in exports.

For direct end user emissions, the null effect of renewables may be due to a lack of effective mechanisms to translate increased renewable energy consumption into a reduction in direct fossil fuel consumption by end users. The main focus on renewable

[18] 19 out of the 34 sampled nations produced electricity from nuclear power at some point during the 1995 to 2015 period.

energy deployment so far has been electricity generation (Smil 2016), which may not have direct impacts on the direct fossil fuel consumption by end users such as households. As a reminder, direct end user emissions do not include emissions generated at powerplants providing electricity for household use, but only account for emission directly generated by end users, primarily including driving personal vehicles. The major types of renewables deployed in road transportation are biofuels like bioethanol and biodiesel, which are more carbon intensive relative to other renewables and hence have limited decarbonization potential (Hill et al. 2016). Biofuels are commonly deployed as blended fuels that contain a large share of fossil fuel (e.g., E10, the most common ethanol blend in the United States, contains 10% ethanol and 90% gasoline). Therefore, the deployment of biofuel in automobile-based transportation sustains fossil fuel consumption. When combined with the aforementioned fuel market rebound effect, the current ways of biofuel deployment may even increase carbon emissions by road transportation (Hill et al. 2016).

The observed suppressive effect of renewables on DOSCA emissions is used as a benchmark against which the other emissions components are discussed. However, renewable energy transition has by no means achieved the optimal effectiveness in mitigating DOSCA emissions. Although the observed suppressive effect became greater from 1995 to 2015, it remained inelastic. Each 1% increase in renewable energy consumption is associated with a reduction in DOSCA emissions by slightly over 0.5% at best. The magnitude of the effect found in this study is consistent with York's (2012) observation that each unit increase in renewable energy consumption only displaces fossil fuel consumption by a fraction of a unit. This finding also supports Davidson's (2019) argument that renewable energy deployment to date has not been matched with proportional efforts to exnovate the fossil fuel regime. It appears that the decarbonization effectiveness of renewables on domestic-oriented industries are also impeded by the inertia of the fossil fuel regime, the fuel market rebound effect, and the mutual displacement between renewables and nuclear energy, albeit to a lesser extent than export industries.

Turning briefly to emissions embodied in imports, I find that renewable energy consumption does not directly mitigate this emission component. This is to be expected because this emission component is generated outside of importing nations' territory, so that the importing nations' domestic renewable energy deployment may not have direct bearing on this component. I also find that emissions in imports is positively associated with economic growth, and more strongly so than the other 3 emission components. This means that as high-income nations become even wealthier, the emissions embodied in their imports become an increasingly major way in which they contribute to global CO_2 emissions. In 2015, emissions embodied in imports was the largest of the 4 emission components in half (17) of the sampled nations. This, combined with the null effect of renewables, highlights that it is imperative to mitigate the emissions embodied in imports for high-income nations through means other than renewable energy deployment.

The above discussion explores potential barriers to renewables' decarbonization effectiveness, in order to understand the observed heterogeneous relationships between renewables and multiple emission components. These barriers, as well as others not explicitly discussed here, warrant thorough investigations beyond the scope of this study. To this end, the present study highlights several avenues for future research: What social, economic, political, and technological barriers impede renewables' mitigation effect on emissions embodied in exports and direct emissions by end users? How do the barriers differ across nations and change over time? How can these barriers be overcome? How can renewables' mitigation effect on DOSCA emissions be further strengthened? Furthermore, this study focuses on high-income nations, in part due to the limited availability of data on nations' 4 emission components. As data availability improves, future researchers should also examine middle- and low-income nations, some of which have become major CO_2 emitters and energy consumers. Additionally, this study demonstrates how future research on the effectiveness of climate mitigation measures can benefit from using the Multidimensional Emissions Profile (MEP) framework.

In conclusion, this study finds that renewable energy consumption in high-income nations can mitigate CO_2 emissions generated by their domestic-oriented supply chain activities, and with increasing effectiveness over time. However, the decarbonization effect of renewables has not spilled over to emissions embodied in exports, emissions generated directly by end user activities, or emissions embodied in imports. The results underscore the existence of structural barriers that disproportionally hinder the displacement of fossil fuel consumption in the export sector as well as end user activities. These barriers must be overcome in order to achieve the full decarbonization potential of renewable energy deployment.

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3.10 TABLES

Table 3.1 Unstandardized coefficients for the regression of nations' PBA, 1995–2015, on renewable energy and selected independent variables: two-way fixed effects regression model estimates with country-clustered robust standard errors for 34 high-income countries.

	Model 1	**Model 2**	**Model 3**	**Model 4**
Renewable Energy (as % Total Energy)	-0.109**	-0.0981*	-0.0993*	-0.165***
	(0.0397)	(0.0397)	(0.0385)	(0.0435)
GDP Per Capita	0.379**	0.499**	0.448*	0.355*
	(0.119)	(0.142)	(0.216)	(0.140)
GDP Per Capita Squared			-0.0406	
			(0.104)	
Total Population	1.500***	1.653***	1.808***	1.125***
	(0.329)	(0.253)	(0.471)	(0.293)
Imports as % GDP		0.0642	0.0667	-0.0368
		(0.109)	(0.108)	(0.0932)
Exports as % GDP		-0.0535	-0.0538	-0.0355
		(0.114)	(0.114)	(0.107)
Manufacturing as % GDP		-0.303	-0.381	-0.384
		(0.270)	(0.353)	(0.268)
Service as % GDP		0.0872	0.0979	-0.361
		(0.386)	(0.391)	(0.423)
Urban Pop. as % Pop.		0.350	0.403	0.356
		(0.351)	(0.315)	(0.323)
Age Dependency Ratio		0.389		
		(0.493)		
Constant	-23.28***	-27.54***	-24.87**	-14.8
	(6.152)	(6.766)	(7.706)	(7.787)
N	714	710	710	710
# of nation	34	34	34	34
N per nations, min.	21	19	19	19
N per nation, avg.	21	20.88	20.88	20.88
N per nation, max.	21	21	21	21

Notes: Model 4 includes interactions between renewables and yearly dummy variables, which are separately reported in Figure 4; robust standard errors clustered by nation are reported in parentheses; all nonbinary variables are transformed with natural logarithm; all models include unreported country-specific and year-specific fixed effects;
* $p<.05$ ** $p<.01$ *** $p<.001$ (two tailed).

Table 3.2 Unstandardized coefficients for the regression of nations' 3 emission components, 1995–2015, on renewable energy and selected independent variables: seemingly unrelated regression model estimates with two-way fixed effects and country-clustered robust standard errors for 34 high-income countries.

	Seemingly Unrelated Regression Model		
	DOSCA Emissions	**Emissions in Exports**	**Direct End User Emissions**
Renewable Energy (as % Total Energy)	-0.132*	-0.108	-0.0587
	(0.0531)	(0.0728)	(0.0564)
GDP Per Capita	0.354	0.478*	-0.0851
	(0.205)	(0.226)	(0.274)
GDP Per Capita Squared			-0.350**
			(0.132)
Total Population	1.723***	1.719**	1.715**
	(0.375)	(0.528)	(0.651)
Imports as % GDP	0.176	-0.124	-0.160
	(0.154)	(0.185)	(0.184)
Exports as % GDP	-0.361*	0.841***	-0.143
	(0.151)	(0.181)	(0.170)
Manufacturing as % GDP	-0.158	-0.129	0.406*
	(0.167)	(0.192)	(0.162)
Service as % GDP	-0.925*	0.258	-0.110
	(0.403)	(0.466)	(0.513)
Urban Pop. as % Pop.	-0.242	0.107	0.526
	(0.615)	(0.651)	(0.744)
Age Dependency Ratio	0.389	0.844	0.512
	(0.475)	(0.442)	(0.556)
Constant	-22.69*	-36.25**	-28.61**
	(9.752)	(12.16)	(10.92)
N	710	710	710
# of nation	34	34	34
N per nations, min.	19	19	19
N per nation, avg.	20.88	20.88	20.88
N per nation, max.	21	21	21

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
* p<.05 ** p<.01 *** p<.001 (two tailed).

Table 3.3 Unstandardized coefficients for the regression of nations' 3 emission components, 1995–2015, on renewable energy, renewable energy's interaction with yearly dummy variables, and selected independent variables: seemingly unrelated regression model estimates with two-way fixed effects and country-clustered robust standard errors for 34 high-income countries.

	Seemingly Unrelated Regression Model					
	DOSCA Emissions		Emissions in Exports		Direct End User Emissions	
	β	S.E.	β	S.E.	β	S.E.
Renewable Energy (as % Total Energy)	-0.295***	(0.0525)	-0.0442	(0.0891)	-0.0979	(0.0700)
Renewable × 1996	0.0864**	(0.0302)	-0.124*	(0.0570)	0.0196	(0.0275)
Renewable × 1997	0.0827*	(0.0374)	-0.113	(0.0650)	0.0108	(0.0214)
Renewable × 1998	0.0947*	(0.0409)	-0.123	(0.0668)	0.0377	(0.0297)
Renewable × 1999	0.0588	(0.0324)	-0.0969	(0.0580)	0.0333	(0.0494)
Renewable × 2000	0.0371	(0.0351)	-0.105*	(0.0457)	0.00958	(0.0817)
Renewable × 2001	0.0329	(0.0310)	-0.121*	(0.0558)	0.0397	(0.0792)
Renewable × 2002	0.0334	(0.0326)	-0.123*	(0.0544)	0.0600	(0.0789)
Renewable × 2003	0.0315	(0.0362)	-0.127*	(0.0648)	0.0794	(0.0785)
Renewable × 2004	-0.00491	(0.0319)	-0.0965*	(0.0483)	0.0527	(0.0624)
Renewable × 2005	-0.0219	(0.0345)	-0.140*	(0.0571)	0.0599	(0.0887)
Renewable × 2006	-0.00737	(0.0440)	-0.136*	(0.0649)	0.0424	(0.0883)
Renewable × 2007	-0.0394	(0.0459)	-0.144*	(0.0621)	0.0773	(0.0996)
Renewable × 2008	-0.0859	(0.0600)	-0.126*	(0.0619)	0.0472	(0.107)
Renewable × 2009	-0.0794	(0.0687)	-0.170**	(0.0604)	0.0669	(0.110)
Renewable × 2010	-0.120*	(0.0549)	-0.151*	(0.0653)	0.0743	(0.117)
Renewable × 2011	-0.153**	(0.0570)	-0.164*	(0.0745)	0.0487	(0.112)
Renewable × 2012	-0.171**	(0.0650)	-0.183*	(0.0894)	0.0255	(0.118)
Renewable × 2013	-0.134	(0.0870)	-0.202*	(0.0884)	0.00882	(0.124)
Renewable × 2014	-0.218**	(0.0731)	-0.179*	(0.0741)	0.0363	(0.126)
Renewable × 2015	-0.166	(0.0913)	-0.169*	(0.0761)	0.00893	(0.128)
GDP Per Capita	0.115	(0.168)	0.387	(0.229)	-0.0928	(0.299)
GDP Per Capita Squared					-0.350**	(0.135)
Total Population	0.822**	(0.292)	1.368*	(0.547)	1.757**	(0.651)
Imports as % GDP	-0.0145	(0.116)	-0.177	(0.178)	-0.154	(0.223)
Exports as % GDP	-0.429**	(0.137)	0.822***	(0.177)	-0.140	(0.165)
Manufacturing as % GDP	-0.121	(0.125)	-0.133	(0.190)	0.414*	(0.162)
Service as % GDP	-1.055**	(0.389)	0.190	(0.460)	-0.103	(0.537)
Urban Pop. as % Pop.	-1.034	(0.529)	-0.205	(0.660)	0.616	(0.759)
Age Dependency Ratio	0.412	(0.433)	0.859*	(0.431)	0.483	(0.559)
Constant	-0.163	(8.082)	-27.72*	(12.59)	-29.59*	(11.58)
N	710		710		710	
# of nation	34		34		34	
N per nations, min.	19		19		19	
N per nation, avg.	20.88		20.88		20.88	
N per nation, max.	21		21		21	

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
* p<.05 ** p<.01 *** p<.001 (two tailed).

3.11 FIGURES

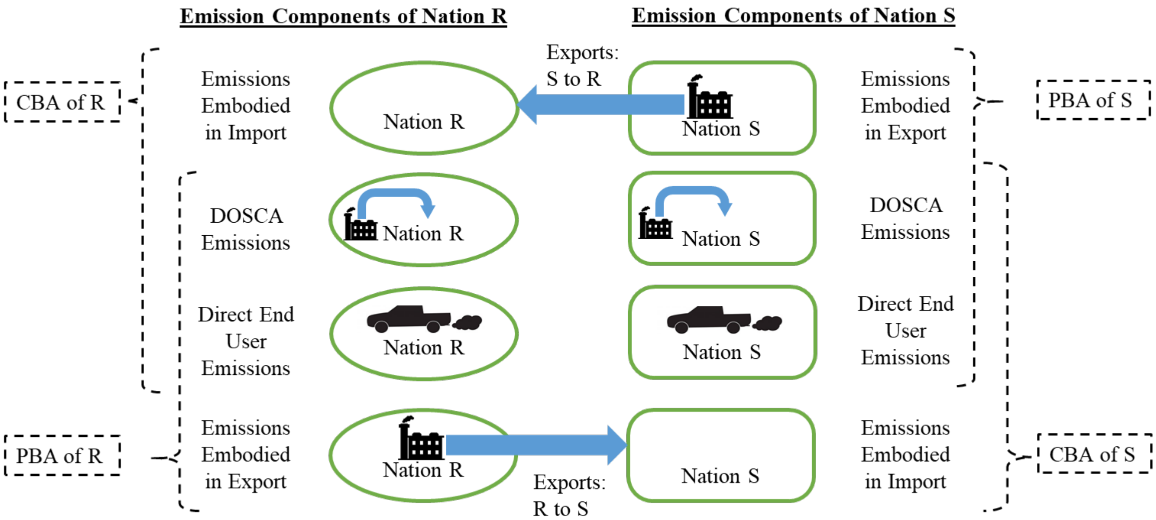

Figure 3.1 Conceptual Diagram of the 4 Emissions Components that Constitute the Multidimensional Emissions Profile (MEP) framework, in A Simplified 2-Nation Model that Excludes Re-imports and Re-exports.

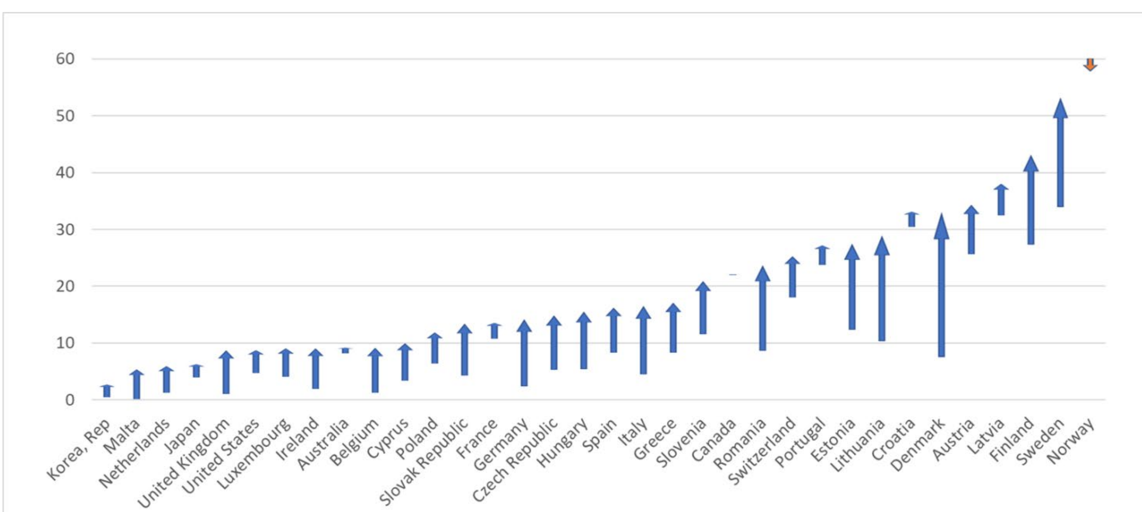

Figure 3.2 Changes in Renewable Energy Consumption as A Percent of Total Final Energy Consumption for 34 Sampled Nations, 1995-2015.

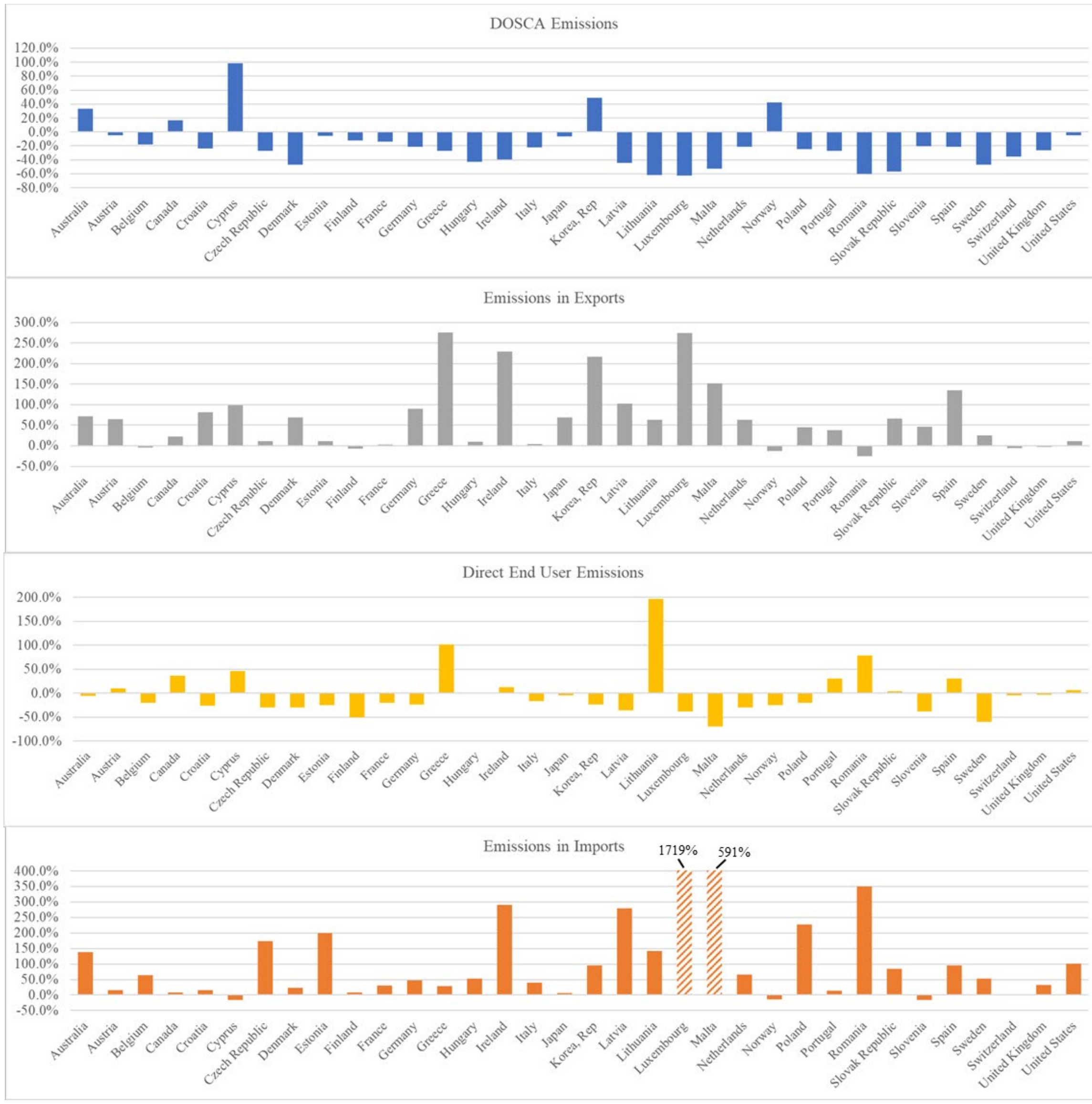

Figure 3.3 Percentage Change from 1995 to 2015 for 4 Components of CO_2 Emission: Emissions by Domestic-Oriented Supply Chain Activities (DOSCA), Emissions Embodied in Exports, Direct End User Emissions, and Emissions Embodied in Imports, for 34 Sampled Nations. Notes: axis scale varies across subplots; the emissions embodied in imports for Luxemburg and Malta are truncated due to extreme values.

	β	S.E.
Renewable, main effect 1995	-0.165***	(0.0435)
Renewable × 1996	0.00670	(0.00746)
Renewable × 1997	0.00400	(0.00790)
Renewable × 1998	0.0110	(0.00856)
Renewable × 1999	0.00664	(0.0113)
Renewable × 2000	-0.00906	(0.0208)
Renewable × 2001	-0.0135	(0.0165)
Renewable × 2002	-0.00702	(0.0184)
Renewable × 2003	-0.00754	(0.0193)
Renewable × 2004	-0.0177	(0.0199)
Renewable × 2005	-0.0399	(0.0217)
Renewable × 2006	-0.0379	(0.0248)
Renewable × 2007	-0.0483	(0.0263)
Renewable × 2008	-0.0677	(0.0338)
Renewable × 2009	-0.0740	(0.0383)
Renewable × 2010	-0.0824*	(0.0339)
Renewable × 2011	-0.106*	(0.0392)
Renewable × 2012	-0.134**	(0.0395)
Renewable × 2013	-0.129**	(0.0456)
Renewable × 2014	-0.147**	(0.0522)
Renewable × 2015	-0.135*	(0.0637)

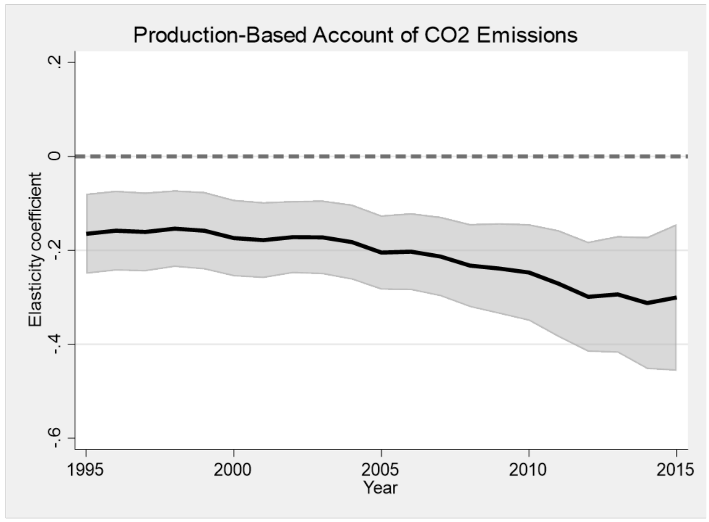

Figure 3.4 Average marginal effects of renewable energy consumption on PBA, based on the Model 4 reported in Table 3.1. Coefficients for the main effect of renewables and the interactions with yearly dummy variables are reported on the left-hand side. Shaded areas are 95% confidence intervals.

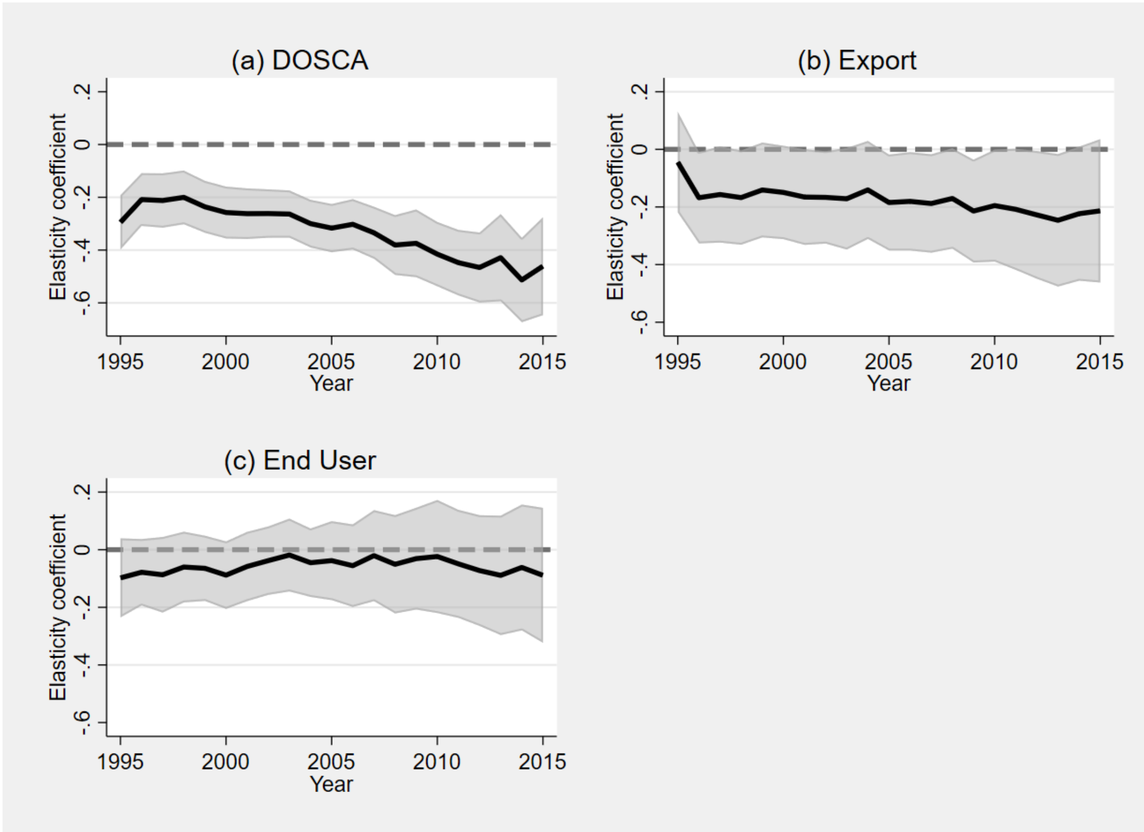

Figure 3.5 Average marginal effects of renewable energy consumption on (a) emissions generated by domestic-oriented supply chain activities (DOSCA); (b) emissions embodied in exports; and (c) direct end user emissions, for each year from 1995 to 2015, based on the SUR model reported in Table 3.3. Shaded areas are 95% confidence intervals.

3.12 APPENDICES

3.12.1 Calculating the 4 Components of CO_2 Emissions Using the EE-MRIO Approach

The calculation of the four components of CO_2 emissions follows procedures similar to those described in Chapter 2 Appendix 2.13.1 for the calculation of GHG emission measures. I used the environmentally-extended multi-regional input-output (EE-MRIO) method (Miller and Blair 2009), and the EE-MRIO tables from the latest version of EXIOBASE 3 to calculate nations' four emission components (Stadler et al. 2018, 2021). Prior research has demonstrated that the EE-MRIO method and EXIOBASE 3 are well suited for analyzing environmental impacts, including CO_2 and other GHG emissions, of global supply chain activities (Bjelle et al. 2021; Bjørn et al. 2018; Dorninger et al. 2021; Hertwich 2021; Tukker et al. 2016). Emissions data calculated using EE-MRIO method can be sensitive to the choice of EE-MRIO databases (Lenzen, Wood, and Wiedmann 2010; Owen et al. 2016; Rodrigues et al. 2018). Harmonizing environmental satellite accounts across EE-MRIO databases, which has been applied to EXIOBASE 3, can alleviate the data sensitivity (Moran and Wood 2014; Tukker, de Koning, et al. 2018). The high level of sectoral resolution of EXIOBASE also mitigates data uncertainties introduced by sectoral aggregation (Lenzen 2011; Stadler et al. 2018). For a full description of the build process of EXIOBASE 3 and its use in research, see Stadler et al (2018) and a special issue of *Journal of Industrial Ecology* edited by Tukker et al (2018). I acquired industry by industry (ixi) EE-MRIO tables from EXIOBASE 3 for the period of 1995 to 2015, which covers 163 harmonized industrial sectors and 49 regions.

Together these areas account for over 99% of global population in 2015. 1995 is the first year with data available, while 2015 is the latest year with industry-level energy-related emissions calculated based on real energy balances data from the IEA as opposed to nowcasts. For each year, I utilized the technical coefficient matrix $\boldsymbol{A}$ provided by EXIOBASE. $\boldsymbol{A}$ is a 7987 by 7987 matrix (7987= 163 * 49, and is the number of industry-region pairs); its elements a_{ij}^{RS} (row indices *Ri*: *R*=1,…,49; *i*=1,…,163; column indices *Sj*: *S*=1,…,49; *j*=1,…,163) denote the output from industry *i* in Region *R* that is required as direct intermediate input for industry *j* in region *S* to produce one unit of output. Based on $\boldsymbol{A}$, I calculated a 7987 by 7987 multi-regional Leontief inverse matrix $\boldsymbol{L}$ following the Leontief IO model (Leontief 1970; Miller and Blair 2009).

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-1}$$

where $\boldsymbol{I}$ is a 7987 by 7987 identity matrix. In the matrix $\boldsymbol{L}$, an element l_{ij}^{RS} represents the total output of industry *i* in region *R* that is required to satisfy, both directly and indirectly, a one-unit increase in the final demand for the output of industry *j* in region *S*. Next, I constructed a 7987 by 49 final demand matrix $\boldsymbol{Y}$ based on the final demand data from EXIOBASE 3; its element y_j^{ST} (row indices *Sj*: S=1,…,49; *j*=1,…,163; column index *T*=1,…,49) denotes the final demand in region *T* for product *j* imported from region *S*. The *T*-th column of $\boldsymbol{Y}$, denoted by vector $\boldsymbol{y}^T$, represents the final demand in region *T* for each of the 163 products imported from each of the 49 regions including region *T* itself.

Then, for each region of final demand *T*, I calculated a partial output matrix $\boldsymbol{X}^T$ as:

$$\boldsymbol{X}^T = \boldsymbol{L}\widehat{\boldsymbol{y}^T}\boldsymbol{E}$$

where $\widehat{\boldsymbol{y}^T}$ is a 7987 by 7987 matrix resulting from the diagonalization of $\boldsymbol{y}^T$; $\boldsymbol{E}$ is a 7987 by 163 summation matrix created by stacking 49 identity matrices, each sized at 163 by 163, on top of one another. The resulted $\boldsymbol{X}^T$ is a 7987 by 163 matrix.

I then assemble all $\boldsymbol{X}^T$ side by side in the order of T=1,…,49 to create a 7987 by 7987 full output matrix $\boldsymbol{X}$ with elements denoted by x_{ij}^{RT} (row indices Ri: R=1,…,49; i=1,…,163; column indices Tj: T=1,…,49; j=1,…,163). x_{ij}^{RT} represents the total output of industry i located in region R that is required to satisfy, both directly and indirectly, the final demand in region T for product j produced anywhere in the world.

Next, I obtained a 1 by 7987 of emission intensity coefficient vector $\boldsymbol{s}$ for airborne CO_2 emissions from fossil fuel combustion from the impacts extension of EXIOBASE 3; each element s_i^R represents the CO_2 emissions per monetary unit of output of industry i located in region R in a particular year.

A CO_2 footprint matrix $\boldsymbol{F}$ is calculated as:

$$\boldsymbol{F} = \boldsymbol{s} \otimes \boldsymbol{X}$$

where $\otimes$ refers to the multiplication of $\boldsymbol{s}$ and $\boldsymbol{X}$ without summation along the columns of $\boldsymbol{X}$. In other words, each element in the n-th row of $\boldsymbol{X}$ is multiplied with the n-th element of $\boldsymbol{s}$. The resulted $\boldsymbol{F}$ is a 7987 by 7987 matrix, the elements of which are $f_{ij}^{RT} = s_i^R x_{ij}^{RT}$ (row indices Ri: R=1,…,49; i=1,…,163; column indices Tj: T=1,…,49; j=1,…,163).[19] f_{ij}^{RT} represents the total CO_2 emissions (megatons) generated by industry i

[19] This differs from a conventional matrix multiplication such as $\boldsymbol{m} = \boldsymbol{sX}$, where the product $\boldsymbol{m}$ is a 1 by 7987 vector with its element $m_j^T = \sum_{R,i=1,1}^{49,163}(s_i^R x_{ij}^{RT})$.

in region *R* that is driven, both directly and indirectly, by the final demand in region *T* for product *j* produced anywhere in the world.

Regions' four emission components are calculated by aggregating selective elements of the footprint matrix ***F***. Emissions generated by DOSCA for region *T* are calculated by aggregating the CO_2 emissions generated by all industries *i* in region *T* in order to satisfy, both directly and indirectly, its domestic final demand for all products *j*, as in:

$$CO_2\text{-}DO^T = \sum_{i,j=1,1}^{163,163} f_{ij}^{TT}$$

Emissions embodied in imports of region *T* are calculated by first aggregating the emissions generated by all industries *i* in all regions *R* in order to satisfy region *T*'s final demand for all products *j*, and then deducting the part of emissions generated by all industries *i* in region *T* in order to satisfy its domestic final demand for all products *j*, as in

$$CO_2\text{-}IM^T = \sum_{R,i,j=1,1,1}^{49,163,163} f_{ij}^{RT} - \sum_{i,j=1,1}^{163,163} f_{ij}^{TT}$$

Emissions embodied in exports of region *T* are calculated by first aggregating the emissions generated by all industries *i* in region *T* in order to satisfy all regions *R*'s final demand for all products *j*, and then deducting the emissions generated by all industries *i* in region *T* i=n order to satisfy its domestic final demand for all products *j*, as in

$$CO_2\text{-}EX^T = \sum_{R,i,j=1,1,1}^{49,163,163} f_{ij}^{TR} - \sum_{i,j=1,1}^{163,163} f_{ij}^{TT}$$

For direct end user emissions, EXIOBASE 3 provides data on the magnitude of CO_2 emissions directly generated by 3 categories of final demand activities for each of the 49 regions, in the form of a 1 by 147 vector $\boldsymbol{f_Y}$; its elements f_{Yc}^{T} (column indices Tc: T=1,…,49; c=1,…,3) denote the direct CO_2 emissions of final demand category c in region T. The 3 final demand categories are: final consumption expenditure of households, final consumption expenditure of non-profit organizations serving households (NPISH), final consumption expenditure of general government. The total direct emissions of end user activities of region T were calculated by aggregating the direct CO_2 emissions generated by 3 final demand categories of region T, as in:

$$CO_2\text{-}Y^T = \sum_{c=1}^{3} f_{Yc}^{T}$$

The calculation of the four emission components was repeated for each of the sampled regions, and for each year from 1995 to 2015.

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3.12.2 Appendix Tables

Table A3.1 Descriptive Statistics

	N	Mean	S.D.	Min.	Max.
Production-Based Account (PBA)	714	355.757	924.823	1.994	5747.415
DOSCA Emissions	714	212.237	596.493	0.658	3825.635
Emissions Embodied in Exports	714	58.946	89.808	0.377	544.112
Direct Emissions of End User Activities	714	84.574	249.991	0.141	1549.552
Emissions Embodied in Imports	714	101.487	187.631	0.551	1341.968
Renewable Energy (% Energy Consumption)	714	14.774	13.236	0	60.188
GDP per capita	714	34834.015	21537.649	4775.307	111968.352
Imports of goods and services (% GDP)	714	48.356	28.043	7.708	187.165
Exports of goods and services (% GDP)	714	49.576	31.812	8.972	221.197
Manufacturing, value added (% GDP)	710	15.585	4.984	3.887	34.566
Services, value added (% GDP)	710	61.791	6.875	39.84	79.116
Total population	714	30123532.32	54075199.57	377419	320600000
Urban population (% Pop.)	714	73.316	11.813	50.622	97.876
Age dependency ratio	714	48.459	4.227	36.214	63.958

Table A3.2 Bivariate Correlation Matrix

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1)	Production-Based Account (PBA)	1												
(2)	DOSCA Emissions	0.9984	1											
(3)	Emissions Embodied in Exports	0.9022	0.8845	1										
(4)	Direct Emissions of End User Activities	0.993	0.9898	0.8678	1									
(5)	Emissions Embodied in Imports	0.9581	0.9486	0.9326	0.9458	1								
(6)	Renewable Energy (% Energy Consumption)	-0.2012	-0.1955	-0.2671	-0.1818	-0.2335	1							
(7)	GDP per capita	0.1134	0.1055	0.1506	0.1139	0.1625	0.1803	1						
(8)	Imports of goods and services (% GDP)	-0.3399	-0.3313	-0.4374	-0.3096	-0.3988	-0.1861	0.0796	1					
(9)	Exports of goods and services (% GDP)	-0.3263	-0.3205	-0.4	-0.2986	-0.3743	-0.1591	0.2518	0.9744	1				
(10)	Manufacturing, value added (% GDP)	-0.0162	-0.0163	0.0654	-0.045	-0.0192	-0.1495	-0.3625	-0.1163	-0.1132	1			
(11)	Services, value added (% GDP)	0.3502	0.3421	0.3452	0.3548	0.403	-0.2721	0.4761	0.1351	0.1733	-0.5893	1		
(12)	Total population	0.9587	0.951	0.9418	0.9393	0.973	-0.2612	0.0951	-0.4375	-0.4156	0.0437	0.36	1	
(13)	Urban population (% Pop.)	0.1727	0.1616	0.2935	0.1477	0.2273	-0.1581	0.5036	0.096	0.1627	-0.272	0.5112	0.1895	1
(14)	Age dependency ratio	0.1155	0.107	0.1061	0.1338	0.1746	0.3177	0.3228	-0.2312	-0.1883	-0.3192	0.3149	0.1534	0.3342

Table A3.3 Unstandardized coefficients for the regression of nations' 4 emission components, 1995–2015, on renewable energy and selected independent variables: seemingly unrelated regression model estimates with two-way fixed effects and country-clustered robust standard errors for 34 high-income countries.

	Seemingly Unrelated Regression Model			
	DOSCA Emissions	**Emissions in Exports**	**Direct End User Emissions**	**Emissions in Imports**
Renewable Energy (as % Total Energy)	-0.132*	-0.108	-0.0588	-0.0474
	(0.0531)	(0.0728)	(0.0563)	(0.0646)
GDP Per Capita	0.354	0.478*	-0.0899	1.347***
	(0.205)	(0.226)	(0.275)	(0.223)
GDP Per Capita Squared			-0.354**	
			(0.133)	
Total Population	1.723***	1.719**	1.730**	1.613**
	(0.375)	(0.528)	(0.652)	(0.581)
Imports as % GDP	0.176	-0.124	-0.160	0.628**
	(0.154)	(0.185)	(0.184)	(0.210)
Exports as % GDP	-0.361*	0.841***	-0.143	-0.146
	(0.151)	(0.181)	(0.170)	(0.293)
Manufacturing as % GDP	-0.158	-0.129	0.406*	-0.295
	(0.167)	(0.192)	(0.162)	(0.251)
Service as % GDP	-0.925*	0.258	-0.117	0.453
	(0.403)	(0.466)	(0.511)	(0.441)
Urban Pop. as % Pop.	-0.242	0.107	0.527	0.110
	(0.615)	(0.651)	(0.744)	(0.758)
Age Dependency Ratio	0.389	0.844	0.517	0.440
	(0.475)	(0.442)	(0.557)	(0.558)
Constant	-22.69*	-36.25**	-28.85**	-41.94***
	(9.752)	(12.16)	(10.97)	(12.55)
N	710	710	710	710
# of nation	34	34	34	34
N per nations, min.	19	19	19	19
N per nation, avg.	20.88	20.88	20.88	20.88
N per nation, max.	21	21	21	21

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
* p<.05 ** p<.01 *** p<.001 (two tailed).

Table A3.4 Unstandardized coefficients for the regression of nations' 4 emission components, 1995–2015, on renewable energy, renewable energy's interaction with yearly dummy variables, and selected independent variables: seemingly unrelated regression model estimates with two-way fixed effects and country-clustered robust standard errors for 34 high-income countries.

	Seemingly Unrelated Regression Model							
	DOSCA Emissions		Emissions in Exports		Direct End User Emissions		Emissions in Imports	
	β	S.E.	β	S.E.	β	S.E.	β	S.E.
Renewable Energy (as % Total Energy)	-0.295***	(0.0525)	-0.0442	(0.0891)	-0.0979	(0.0700)	0.0226	(0.0805)
Renewable × 1996	0.0864**	(0.0302)	-0.124*	(0.0570)	0.0196	(0.0275)	-0.166**	(0.0637)
Renewable × 1997	0.0827*	(0.0374)	-0.113	(0.0650)	0.0108	(0.0214)	-0.0870	(0.0798)
Renewable × 1998	0.0947*	(0.0409)	-0.123	(0.0668)	0.0377	(0.0297)	-0.0686	(0.0800)
Renewable × 1999	0.0588	(0.0324)	-0.0969	(0.0580)	0.0333	(0.0494)	-0.0713	(0.0812)
Renewable × 2000	0.0371	(0.0351)	-0.105*	(0.0457)	0.00961	(0.0817)	-0.0884	(0.0765)
Renewable × 2001	0.0329	(0.0310)	-0.121*	(0.0558)	0.0397	(0.0792)	-0.0912	(0.0692)
Renewable × 2002	0.0334	(0.0326)	-0.123*	(0.0544)	0.0600	(0.0789)	-0.12	(0.0674)
Renewable × 2003	0.0315	(0.0362)	-0.127*	(0.0648)	0.0795	(0.0785)	-0.128	(0.0671)
Renewable × 2004	-0.00491	(0.0319)	-0.0965*	(0.0483)	0.0527	(0.0624)	-0.110*	(0.0526)
Renewable × 2005	-0.0219	(0.0345)	-0.140*	(0.0571)	0.0600	(0.0887)	-0.107	(0.0573)
Renewable × 2006	-0.00737	(0.0440)	-0.136*	(0.0649)	0.0424	(0.0883)	-0.104	(0.0610)
Renewable × 2007	-0.0394	(0.0459)	-0.144*	(0.0621)	0.0774	(0.0996)	-0.0975	(0.0590)
Renewable × 2008	-0.0859	(0.0600)	-0.126*	(0.0619)	0.0473	(0.107)	-0.0704	(0.0655)
Renewable × 2009	-0.0794	(0.0687)	-0.170**	(0.0604)	0.0671	(0.110)	-0.120	(0.0859)
Renewable × 2010	-0.120*	(0.0549)	-0.151*	(0.0653)	0.0744	(0.117)	-0.110	(0.0824)
Renewable × 2011	-0.153**	(0.0570)	-0.164*	(0.0745)	0.0488	(0.112)	-0.0831	(0.0752)
Renewable × 2012	-0.171**	(0.0650)	-0.183*	(0.0894)	0.0257	(0.118)	-0.0953	(0.0777)
Renewable × 2013	-0.134	(0.0870)	-0.202*	(0.0884)	0.00898	(0.124)	-0.0995	(0.0759)
Renewable × 2014	-0.218**	(0.0731)	-0.179*	(0.0741)	0.0365	(0.126)	-0.131	(0.0725)
Renewable × 2015	-0.166	(0.0913)	-0.169*	(0.0761)	0.00914	(0.128)	-0.195*	(0.0906)
GDP Per Capita	0.115	(0.168)	0.387	(0.229)	-0.0955	(0.299)	1.285***	(0.251)
GDP Per Capita Squared					-0.353**	(0.136)		
Total Population	0.822**	(0.292)	1.368*	(0.547)	1.767**	(0.651)	1.452*	(0.653)
Imports as % GDP	-0.0145	(0.116)	-0.177	(0.178)	-0.154	(0.223)	0.614*	(0.241)
Exports as % GDP	-0.429**	(0.137)	0.822***	(0.177)	-0.140	(0.165)	-0.144	(0.297)
Manufacturing as % GDP	-0.121	(0.125)	-0.133	(0.190)	0.414*	(0.162)	-0.295	(0.259)
Service as % GDP	-1.055**	(0.389)	0.190	(0.460)	-0.107	(0.535)	0.500	(0.456)
Urban Pop. as % Pop.	-1.034	(0.529)	-0.205	(0.660)	0.617	(0.759)	-0.0211	(0.855)
Age Dependency Ratio	0.412	(0.433)	0.859*	(0.431)	0.486	(0.559)	0.407	(0.564)
Constant	-0.163	(8.082)	-27.72*	(12.59)	-29.75*	(11.59)	-38.20*	(15.39)
N	710		710		710		710	
# of nation	34		34		34		34	
N per nations, min.	19		19		19		19	
N per nation, avg.	20.88		20.88		20.88		20.88	
N per nation, max.	21		21		21		21	

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
* p<.05 ** p<.01 *** p<.001 (two tailed).

4.0 CHAPTER 4: HARNESS THE CO-BENEFITS AND AVOID THE TRADE-OFF: THE MULTIDIMENSIONAL TIME-VARYING RELATIONSHIP BETWEEN DOMESTIC INCOME INEQUALITY AND CARBON DIOXIDE EMISSIONS

4.1 ABSTRACT

Multiple causal pathways link nations' domestic income inequality to their CO_2 emissions. Using a multidimensional analytical framework, I systematically analyze the relationships between nations' domestic income inequality and four components of CO_2 emissions with distinct implications for climate change mitigation: (1) emissions generated by domestic-oriented supply chain activities; (2) emissions embodied in exports; (3) direct emissions of end user activities, and (4) emissions embodied in imports. I analyze a panel dataset consisted of 34 high-income nations from 2004 to 2015, and use two measures of income inequality: the Gini coefficient and the income share of the top 10%. Results of seemingly unrelated regression models suggest that the relationships between income inequality and CO_2 emissions change over time, vary across emission components, and differ between measures of income inequality. The results are indicative of variations in the causal pathways, both over time and across emission components.

4.2 INTRODUCTION

Growing income inequality has become a prominent issue during the COVID19 pandemic (Deaton 2021; Ferreira 2021). Meanwhile, reducing global CO_2 emissions remains an urgent task (UNFCCC 2021). Can policies seeking to address income inequality also synergistically generate the co-benefits of CO_2 emissions abatement? Is there instead a trade-off between these two objectives? A growing body of literature investigates the relationship between domestic income inequality and CO_2 emissions, highlighting a multitude of causal pathways. However, the literature has not systematically examined how income inequality may heterogeneously affect various structural components of nations' CO_2 emissions that are generated by different categories of human activities. How might the effect of income inequality differ in magnitude or even in direction across emission components? Are the pathways linking income inequality to emissions different across emission components? Is equality enhancement associated with a reduction in certain emission components but an increase in other components? This study seeks to address these questions.

Drawing from the Multidimensional Emissions Profile (MEP) analytical framework (Chapter 2), I decompose a nation's contributions to global CO_2 emissions into four distinct components: (1) emissions generated by domestic-oriented supply chain activities (DOSCA), such as domestic industrial activities that serve domestic consumers; (2) emissions embodied in exports; (3) direct emissions of end user activities; and (4) emissions embodied in imports. I use seemingly unrelated regression with two-way fixed effects to analyze the time-varying relationships between domestic income inequality and these four emission components for a sample of 34 high-income nations from 2004 to

2015. Income inequality is operationalized in two different ways: the Gini coefficient and the income share held by the top 10% of population. I find that the relationships between income inequality and nations' CO_2 emissions change over time, vary across emission components, and differ between measures of income inequality. The results are indicative of variations in the causal pathways, both over time and across emission components.

4.3 THEORETICAL PATHWAYS OF THE INCOME INEQUALITY-CARBON EMISSIONS RELATIONSHIP

Multiple pathways link domestic income inequality to carbon dioxide emissions (Cushing et al. 2015; Jorgenson, Schor, and Huang 2017; Ravallion, Heil, and Jalan 2000), which can be broadly divided into three groups. The first group focuses on power and political economy. Boyce (1994, 2003, 2007) proposes a "power-weighted social decision rule," which contends that social decisions affecting environmental outcomes, such as environmental regulations, are shaped by the relative power of those who benefit from environmental degradation and those who suffer from the degradation. When the group that benefits from environmental degradation is more powerful than those who suffer, the societal level of environmental degradation tends to increase. Studies have found that the wealthier segment of a society tends to be more shielded than the poorer population from various forms of environmental degradation (Brulle and Pellow 2006; Mohai, Pellow, and Roberts 2009), including carbon-intensive industrial facilities (Pattison, Habans, and Clement 2014). Through controlling and profiting from production facilities and organizations that generate environmental harms, the wealthy also benefit more from environmental degradation (Downey 2015), and are less supportive of environmental protection (Page, Bartels, and Seawright 2013; Page and Hennessy 2011). In the case of CO_2 emissions and climate change, the wealthy reap more benefits from the fossil fuel-based economic regime and are better protected from the impacts of climate change than the poor (Harlan et al. 2015; Malm 2016).

Higher income inequality means greater differential in economic and political power between the wealthy and the poor. The power differential translates into more disproportionate influence by the wealthy over social policies and organizational decisions, allowing the wealthy to undermine democracy and prioritize their economic interests in perpetuating the polluting production apparatus over the needs of the rest of the society for public goods such as environmental protection and climate change mitigation (Cushing et al. 2015; Downey 2015). Furthermore, greater income inequality erodes social trust and impedes collective actions such as environmental movements (Boyce 2003; Brechin 2016; Cushing et al. 2015; Ostrom 2008; Wilkinson and Pickett 2010). Overall, the political economy pathway suggests that greater income inequality may increase the societal level of environmental degradation including CO_2 emissions.

The second pathway focuses on how income inequality shapes consumption patterns. Greater income inequality can induce a "Veblen effect" where middle- and lower-class groups are pressured by heightened status competition to spend more in order to keep up with the lifestyle standard set by the upper class (Schor 1998; Veblen 1934). The increased competitive consumption can lead to increased CO_2 emissions. Moreover, Higher income inequality means a greater gap in disposable income between the wealthy early adopters of expensive innovative consumer products and the rest of the population. This gap slows down the diffusion of eco-friendly innovation in consumer products from a niche market for the wealthy to the mass market (Vona and Patriarca 2011). A related argument concerns how greater income inequality is associated with rising average working time (Bowles and Park 2005), which leads to growth in economic output, consumption, and the adoption of more ecologically intensive lifestyles (Fitzgerald 2022; Fitzgerald, Jorgenson, and Clark 2015; Fitzgerald, Schor, and Jorgenson 2018; Jalas and Juntunen 2015; Knight, Rosa, and Schor 2013; Schor 2008). In general, this pathway, hereafter referred to as the Veblen effect pathway, argues that higher income inequality is associated with increased CO_2 emissions.

The third pathway focuses on the marginal propensity to emit. When examining the role of income inequality in the income-emissions relationship, Ravallion, Heil, and Jalan (2000) find that greater domestic income inequality is associated with lower emissions, which they attribute to the decline in the marginal propensity to emit that accompanies an increase in household income. This argument is supported by a number of prior studies (Heil and Selden 1999; Holtz-Eakin and Selden 1995; Jakob et al. 2014; Seriño and Klasen 2015) and is viewed as a "stylized fact". Another dynamic that is consistent with Ravallion and colleagues' argument is a Keynesian model suggesting that the marginal propensity to consume also declines with income (Jorgenson et al. 2017). For each additional dollar of income, wealthier households generate less consumption and CO_2 emissions than poorer households. Following this pathway, reduction in income inequality by redistributing income from the wealthy to the poor is expected to increase the societal level of consumption and overall CO_2 emissions. Despite a focus on the marginal propensity to emit, Ravallion et al (2000) also acknowledge that the domestic income inequality-carbon emissions relationship is theoretically ambiguous and that multiple potential mechanisms (such as the political economy pathway theorized by Boyce and colleagues) pulling the relationship in different directions.

4.4 EMPIRICAL LITERATURE ON THE INCOME INEQUALITY-CARBON EMISSIONS RELATIONSHIP

A growing body of empirical research has examined the relationship between income inequality and carbon emissions, both at the subnational level (Fitzgerald 2022; Jorgenson et al. 2015, 2017), and cross-nationally (Grunewald et al. 2017; Jorgenson et al. 2016). Cross-national studies find that among high- and upper-middle-income nations, income inequality is positively associated with production-based emissions (Grunewald et al. 2017) and consumption-based emissions (Jorgenson et al. 2016). In lower-middle- and low-income nations, the association is negative or nonsignificant (Grunewald et al. 2017; Jorgenson et al. 2016). These studies indicate that macroeconomic context may shape which pathways take effect more prominently. In higher-income nations, greater income inequality may affect emission primarily via shaping the power distribution and through the Veblen effect dynamics, resulting in increasing emissions (Jorgenson et al. 2017). Conversely, in lower-income nations, income inequality affects emissions mainly following the marginal propensity to emit pathway. Grunewald et al (2017:254) argue that “in highly unequal poor societies a large share of the population lives essentially outside of the [fossil fuel-based] carbon economy and produces few emissions while the very rich already have lower marginal propensities to emit than middle income groups." Therefore, reducing income inequality in lower-income nations can bring more people into the fossil fuel-based economy and hence increase societal CO_2 emissions. Like the relationships between other anthropogenic drivers and CO_2 emissions (e.g., Dietz, Shwom, and Whitley 2020; Jorgenson and Clark 2012), the income inequality-emissions relationship also varies over time (Jorgenson et al. 2016), which may be indicative of temporal shifts in the causal pathways.

Prior research has also examined the broader relationships between social inequality and environmental outcomes for other aspects of inequality (Knight, Schor, and Jorgenson 2017; Thombs 2021), as well as other socioecological and public health outcomes (Jorgenson 2015; Jorgenson et al. 2020, 2021; Jorgenson, Dietz, and Kelly 2018; Kelly, Thombs, and Jorgenson 2021; McGee and Greiner 2019; Vogel et al. 2021; Wilkinson, Pickett, and Vogli 2010). Together, the literature highlights the multitude of pathways linking social inequality to socioecological well-being, and more specifically, linking nations' domestic income inequality to CO_2 emissions.

4.5 INCOME INEQUALITY AND NATIONS' MULTIDIMENSIONAL EMISSIONS PROFILE

Existing cross-national research on the inequality-emissions nexus focuses on aggregate emission measures such as production-based account (PBA) (Grunewald et al. 2017), and consumption-based account (CBA) of CO_2 emissions (Jorgenson et al. 2016), allowing studies to capture the "net effect" of domestic income inequality on the totality of emissions within a nation's territory, as well as on the totality of global emissions driven by a nation's consumption demand. However, existing literature has not systematically examined how the effect of income inequality may differ across components of a nation's emissions. At the national level, the numerous types of CO_2-emitting activities are not homogeneous but differ in important characteristics such as the economic sector and supply chain stage to which the activities belong. A nation's CO_2 emissions can be decomposed into distinct components based on some of these characteristics.

Huang (see Chapter 2) proposes a Multidimensional Emissions Profile (MEP) framework to systematically analyze these distinct emission components, especially how they are differentially affected by certain anthropogenic drivers of emissions. As illustrated in Chapter 3 Figure 3.1, the MEP framework situates a nation's contributions to global CO_2 emissions into four components: (1) emissions generated by domestic-oriented supply chain activities (DOSCA), such as domestic industrial activities that serve domestic consumers; (2) emissions embodied in exports, such as emissions by export-oriented industrial activities; (3) emissions embodied in imports, which are emissions generated by foreign production of goods that are imported and consumed by domestic consumers; and (4) direct emissions of end user activities. Direct emissions of end user activities are generated by activities such as driving personal vehicles and household heating that burns fossil fuels on-site. This emission component excludes the emissions that are induced by end user activities but generated upstream in supply chains, such as the emissions generated by domestic power plants serving domestic households (which are a part of DOSCA emissions). These four emission components, while interconnected via domestic and global supply chains, are distinct points of intervention for climate change mitigation (see Chapter 2). Cross-national studies find the four emission components are heterogeneously related to human drivers such as economic development (see Chapter 2), and mitigation measures such as renewable energy deployment (see Chapter 3).

The present study adopts the MEP framework to investigate how these four emission components may be heterogeneously related to nations' domestic income inequality. Such a systematic analysis allows for a more nuanced understanding of how income inequality affects emissions through multiple co-existing pathways that each concerns different emission components. The three aforementioned theoretical pathways concern different types of carbon-emitting activities, and correspondingly, different emission components. The political economy pathway primarily focuses on the production realm, while the Veblen effect pathway and the marginal propensity to emit pathway are more closely related to the consumption realm. From a nation's standpoint, emissions embodied in its exports belong to its production realm, as this component is generated by domestic production activities serving foreign final demand. Conversely, emissions embodied in a nation's imports belong to its consumption realm, same as direct end user emissions. DOSCA emissions of a nation pertain to both its production and consumption because its domestic producers and consumers both contribute to this emission component. Therefore, the political economy pathway may have more theoretical relevance to emissions embodied in exports and DOSCA emissions, while the Veblen effect pathway and the marginal propensity to emit pathway are more pertinent to direct end user emissions, emissions embodied in imports, and DOSCA emissions. Figure 4.1 illustrates this pattern in a conceptual diagram.

4.6 METHODS AND DATA

4.6.1 Dependent Variables

The analysis includes four dependent variables (1) CO_2 emissions generated by domestic-oriented supply chain activities (DOSCA); (2) CO_2 emissions embodied in exports; (3) direct CO_2 emissions of end user activities; and (4) CO_2 emissions embodied in imports. These emission variables are calculated using the environmentally-extended multi-regional input-output (EE-MRIO) method and the EE-MRIO tables from the latest version of Exiobase 3 (Stadler et al. 2018, 2021).[20] All dependent variables capture CO_2 emissions generated from fossil fuel combustion and are measured in megatons. Technical details of data compilation and calculation are provided in Chapter 3 Appendix 3.21.1.

[20] DOSCA emissions and emissions embodied in exports and in imports are conceptualized and operationalized based on the multi-regional input-output (MRIO) method as opposed to the emissions embodied in bilateral trade (EEBT) method (see Chapter 2). The two methods differ in the allocation of the emissions generated by the internationally-traded intermediate goods. The EEBT method allocates this part of emissions to the nations that consume the intermediate goods, regardless of where the final goods (produced from said intermediate goods) are consumed. The MRIO method allocates this part of emissions to the nation where the final goods are consumed. See Peters et al (2011) for more information.

4.6.2 Independent Variables

The main independent variables of interest are 2 measures of domestic income inequality. First, I use national-level Gini coefficient of household disposable income (post-tax, post-transfer), which measures overall income distribution in a nation. Data on the Gini indices are acquired from the Standardized World Income Inequality Database (SWIID) version 9.2 (Solt 2020). SWIID employs multiple imputation techniques on income inequality data from multiple international and national data sources in order to maximize the cross-national and -temporal comparability of existing inequality data (for more, see Solt 2020). As a result, SWIID is well-suited for cross-national analysis (Grunewald et al. 2017; Jorgenson et al. 2016). I multiply SWIID's Gini indices by 100 to acquire Gini coefficients, ranging from 0 (perfect equality) to 100 (perfect inequality). The second measure of domestic income inequality is the income share held by the top 10% of population, which is ranged from 0 to 100 (top 10% income earners capture all incomes) and is acquired from World Bank's World Development Indicators Database (https://databank.worldbank.org/source/world-development-indicators).

Given that the three aforementioned pathways can co-exist, it is possible that all of them can shape the two inequality measures' relationships with emissions, albeit not in an equal manner. According to Jorgenson and colleagues (2017), the relationship between emissions and income share of the top 10% may be more sensitive to the political economy and Veblen effects because this measure primarily captures the power of economic elites, as well as their emulative influence over the consumption practices of the rest of the population. On the other hand, the Gini coefficient measures the overall inequality in societal income distribution regardless in which income strata does the inequality occur. Therefore, Gini's relationship with emissions is likely less sensitive to the political economy and Veblen effects but more sensitive to the dynamics of the marginal propensity to emit (Jorgenson et al. 2017).

Additional independent variables include gross domestic product (GDP) per capita measured in constant 2010 U.S. dollars, total population, and urban population as a percent of total population, which are consistent with much prior cross-national research on carbon emissions. Data on these variables are also acquired from World Bank's World Development Indicators Database.

4.6.3 Sample

The overall sample is a balanced panel dataset consisting of annual observations for 34 high-income nations in the 12-year period of 2004 to 2015, yielding 408 observations in total.[21] In models for the income share held by the top 10%, the sample is reduced to an unbalanced panel dataset of 368 observations for the same 34 nations. The sample includes all high-income nations, as per World Bank's country classification, that have data available during this period,[22] including 9 out of 10 biggest emitters among high-income nations in 2015.[23] 2004 is selected as the starting point because the limited availability of income share data prior to this year.[24] 2015 is the latest year with available

[21] Sampled nations are Australia, Austria, Belgium, Canada, Switzerland, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Croatia, Hungary, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, South Korea, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Sweden, United States.
[22] World Bank country classification. https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups
[23] Based on total production-based CO_2 emissions calculated by Andrew and Peters (2021)
[24] Out of the 34 sampled nations, fewer than 19 of them have data available on income share before 2004. For each year since 2004, more than 26 nations have available data on income share.

EE-MRIO data from Exiobase 3 that is used to calculate the four decomposed emission variables.

I only focus on high-income nations because while there are 34 of them with data available for all variables, only 9 non-high-income nations meet the same criterion. This is mainly due to EE-MRIO data being only available for 9 non-high-income nations from Exiobase 3, which as a standalone sample is smaller than ideal for the regression modeling techniques used in this study. Given that the income inequality-CO_2 emissions relationship differs across nations at different income levels (Grunewald et al. 2017; Jorgenson et al. 2016), I choose not to combine both high-income nations and non-high-income nations in one sample in order to avoid spurious results. It is worth noting that the emission measures of the sampled nations do account for their trade with nations that are not in the sample. For instance, Australia's imports from Indonesia are included when calculating the total emissions embodied in the imports of Australia, even though Indonesia is not a sampled nation. Appendix Table A4.1 reports the descriptive statistics of all variables in their original metrics for the sample.

4.6.4 Regression Modeling Techniques

I estimate seemingly unrelated regression (SUR) models in Stata 17 that consist of 4 equations, one for each of the four main dependent variables: DOSCA emissions, emissions embodied in exports, direct end user emissions, and emissions embodied in imports. By allowing the error terms to be correlated among the four equations, SUR model uses information from all equations to improve the efficiency in estimating parameters in each equation (Srivastava and Giles 1987). It is appropriate for this study because the four emission components—the dependent variables—are interrelated with one another through various supply chain processes, carbon leakage, and other complex feedback loops (Davis, Peters, and Caldeira 2011; Dietz 2017; Hu et al. 2019; Jarke and Perino 2017; Liu et al. 2007; Peters 2010). These potential underlying relationships are better accounted for in a SUR model than in models separately estimated for each emission component (Srivastava and Giles 1987). These two inequality measures, the Gini coefficient and the income share of the top 10%, are analyzed in separate SUR models because they are highly correlated (correlation = 0.86).

I include both time-specific and nation-specific intercepts in each equation of the SUR models, in order to account for unobserved heterogeneity that is unique to each year and affects all nations evenly, as well as the unobserved heterogeneity that is unique to each nation and consistent across the whole period of analysis. I estimate country-clustered robust standard errors in order to correct for autocorrelation and heteroskedasticity.[25] I also include interactions between inequality and a series of yearly binary variables for 2005 to 2015. This modeling technique is used by prior research to examine changes over time in the relationship between a predictor and the outcome (Huang 2018; Jorgenson 2012, 2014; Jorgenson et al. 2016; Jorgenson and Clark 2012; Thombs and Huang 2019). The coefficient for the main effect of income inequality is the slope for year 2004, the reference category. The coefficients for the interaction terms indicate if and to what extent the slope for each subsequent year differs from that of 2004 (Allison 2009).

[25] Stata module *suregr* is used (Kolev 2021).

All non-binary variables are transformed with natural logarithm, and hence the regression coefficients are elasticity coefficients that represent the percentage change in the dependent variable associated with a 1% increase in the independent variables, net of the effects of other independent variables. The general model is specified as follows:

$$y_{it} = \beta_1 Inequality_{it} + \beta_2 Year2005_t + \cdots + \beta_{12} Year2015_t + \beta_{13} Inequality_{it} * Year2005_t + \cdots + \beta_{23} Inequality_{it} * Year2015_t + \beta_{24} GDPper\ capita_{it} + \beta_{25} Population_{it} + \beta_{26} Urban\ Population_{it} + u_i + e_{it}$$

where subscripts i and t represent nation and year respectively; and y_{it} is the outcome variable (CO_2 emissions) for nation i at year t; $\beta_1$is the main effect of income inequality measure for the reference category year 2004; $\beta_2$to $\beta_{12}$are time-specific intercept for year 2005 through 2015; $\beta_{13}$to $\beta_{23}$are the coefficients for the interaction between income inequality and each year from 2005 to 2015; $\beta_{24}$to $\beta_{26}$are the coefficients for GDP per capita, population, and urban population; u_i is the nation-specific intercept for nation i; e_{it} is the unique residual for nation i at year t.

4.7 RESULTS

Table 4.1 presents the 4-equation SUR model for the Gini coefficient. Elasticity coefficients are flagged for statistical significance, while nation clustered robust standard errors are reported in parentheses. The main effect of the Gini coefficient, which represents its slope for year 2004, is nonsignificant at the .05 alpha level for all four emission components. In the equations for DOSCA emissions and for emissions embodied in imports, the interactions between Gini and year are nonsignificant throughout the 2005 to 2015 period. For emissions embodied in exports, the interaction terms are nonsignificant from 2005 to 2010, and become positive and significant from 2011 to 2015. For direct end user emissions, the interaction terms are positive and significant for 2007, 2008, 2014, and 2015, and nonsignificant for the remaining years.

Based on the model output in Table 4.1, Figure 4.2 plots the slope (in terms of average marginal effect) of Gini for each of the four emission components from 2004 to 2015, along with the 95% confidence interval indicated by shaded areas.[26] As a reminder, the slope for each year from 2005 to 2015 is the sum of the main effect and corresponding interaction term. Although the model in Table 4.1 shows that in some years Gini's slopes for emissions in exports and end user emissions significantly differ from their respective levels in 2004, Figure 4.2 suggest that the slopes are not significantly different from 0 at the .05 alpha level throughout the period for all four emission components.

Table 4.2 presents the 4-equation SUR model for income inequality measured as the income share held by the top 10% of population. The main effect of the income share of the top 10% is nonsignificant for DOSCA emissions, emissions in exports, and emissions in imports, and is negative and significant for direct end user emissions at the .05 alpha level. The interactions between the income share of the top 10% and year are nonsignificant for DOSCA emissions and emissions in imports from 2005 through 2015. For emissions in exports, the interaction terms are positive and significant for 2009, and 2011 to 2015. For direct end user emissions, the interaction terms are positive and significant for 2007, 2014, and 2015.

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[26] Stata module *mimrgns* is used to calculate marginal effects for the Gini coefficient, which is a multiply imputed variable (Klein 2021).

Figure 4.3 illustrates the changes over time in the slopes of the income share of the top 10%, along with 95% confidence intervals showing whether the slopes are significantly different from 0. Most notably, subplot (b) indicates that the slope for emissions in exports is nonsignificant in 2004, then gradually increases in magnitude over time, and becomes positive and significant at the .05 level from 2011 to 2015. In 2015, a 1% increase in the income share of the top 10% is associated with a 1.316% increase in emissions embodied in exports. Subplot (a) indicates that the association between the income share of the top 10% and DOSCA emissions is nonsignificant during the studied period, with the only exception being 2010 when the slope is negative. Subplot (c) shows that the slope for direct end user emissions is negative and significant from 2004 to 2006, and from 2009 to 2011, and then trends upwards and becomes nonsignificant. In 2014 and 2015, the point estimates of the slope are positive but remain nonsignificant. Subplot (d) indicates that the slope for emissions in imports remains nonsignificant from 2004 to 2015.

A comparison between the results for the two income inequality measures shows both similarities and differences. For each emission component, its relationships with the two inequality measures change over time in similar ways. For instance, in the equation for emissions in exports, the interaction terms with years 2011 through 2015 are positive and significant for both inequality measures. In the equation for end user emissions, the interaction terms with years 2007, 2014, and 2015 are also positive and significant for both inequality measures. For DOSCA emissions and emission in imports, interactions with yearly binary variables are consistently nonsignificant. The similarities are also evident in the resemblance in the shape of subplots for each emission component in Figures 4.2 and 4.3 (e.g., by comparing subplot 4.2(b) to subplot 4.3(b)).

Despite these similarities, the two inequality measures differ in their relationships with CO_2 emissions, based on tests of statistical significance. As noted before, the associations between the Gini coefficient and emissions do not significantly differ from 0 (alpha=0.05) across the board, while the associations between the income share of the top 10% and emissions are significant for some of the emission components in certain periods. To examine whether the difference is due to variation in sample, I estimate a SUR model for the Gini coefficient using the same unbalanced sample used in the model for the income share of the top 10%, and then plot the marginal effects (see Appendix Table A4.2 and Appendix Figure A4.1). The results of this model are substantively similar to the original model with a fully balanced sample reported in Table 4.1 and Figure 4.2.

4.8 DISCUSSION AND CONCLUSION

This study examines the multi-dimensional time-varying relationship between domestic income inequality and CO_2 emissions, for a sample of 34 high-income nations from 2004 to 2015. Drawing from the Multidimensional Emissions Profile (MEP) framework (see Chapter 2), I situate a nation's CO_2 emissions into four components with distinct implications for climate change mitigation: (1) emissions generated by domestic-oriented supply chain activities (DOSCA); (2) emissions embodied in exports; (3) direct emissions of end user activities; and (4) emissions embodied in imports. I analyze the four emission components' time-varying relationships with Gini coefficient and the income share of the top 10%, seeking to understand how the effect of income inequality might differ across emission components.

The Gini coefficient is not associated with any of the four emission components from 2004 to 2015. The null findings for emissions embodied in exports are expected because this emission component concerns production, while Gini coefficient is more sensitive to the marginal propensity to emit pathway that is primarily about consumption. For the other three emission components—all of which are at least partially related to consumption—the null findings appear to contradict with the marginal propensity to emit pathway. The three theoretical pathways can co-exist. Hence it is possible that income inequality's positive effect on emissions via the marginal propensity to emit pathway is offset by income inequality's negative effect on emissions via the Veblen effect pathway, resulting in the observed null effects.

Turning to the income share of the top 10%, it is positively associated with emissions embodied in exports after 2010. The finding for emissions embodied in exports supports the political economy pathway: as a nation's economic elites possess more power relative to the non-elites, they are able to spur carbon-intensive export-oriented production that creates economic benefits for themselves while increasing the carbon emissions generated within the nation's territory. The relationship becomes positive after the 2008 Great Recession, which indicates that a post-recession economic recovery may aggravate the political economy pathway. With governments and society at large seeking economic recovery, political and public support for environmental protection and climate change mitigation waned (Geels 2013; Obani and Gupta 2016; Schor 2014). In this context, the wealthy elites can more easily translate their economic and political power into boosting carbon-intensive export-oriented production in the name of economic growth and job creation. While some sampled nations like Germany and the United Kingdom incorporated into their stimulus packages support for investment in energy efficiency and renewable energy, these efforts are ineffective in achieving and sustaining societal decarbonization (Jaeger, Westphal, and Park 2020; UNEP 2020). Additionally, Huang (see Chapter 3) finds that renewable energy deployment in high-income nations has largely failed to decarbonize their export sectors, likely because of the preferential treatment these sectors receive in environmental policies. In contrast, renewable energy deployment has been relatively effective in curbing DOSCA emissions (see Chapter 3), which might in part explain why a significant post-recession upward trend is not observed for the relationship between income inequality and DOSCA emissions.

The relationship between the income share of the top 10% and DOSCA emissions is relevant to both the political economy and the Veblen effects because both domestic production and consumption activities contribute to DOSCA emissions. However, the relationship is nonexistent for most of the studied period and is negative in 2010, which appears to contradict with both pathways. Moreover, the observed relationships between the income share of the top 10% and both direct end user emissions and emissions embodied in imports are either nonsignificant or negative in certain years, also inconsistent with the Veblen effect pathway. Similar to the findings for Gini coefficients, it might the case that the upward pressure that the income inequality puts on these emission components via the political economy pathway (for DOSCA emissions) and via the Veblen effect pathway (for DOSCA emissions, direct end user emissions, and emissions in imports) are offset, and at times outweighed by the downward pressure induced by the marginal propensity to emit pathway. Note that while relationships between emissions and the income share of top 10% more closely capture the political economy pathway and the Veblen effect pathway, they can still be influenced by the marginal propensity to emit pathways in that the marginal propensity to consume and emit is lower for the top 10% earners than for the rest of the population.

One period during which the negative relationship between the income share of top 10% and direct end user emissions is observed is 2009 to 2011, during and following the Great Recession. The main contributor to direct end user emissions is driving personal vehicles. Therefore, it appears that the Veblen effect, especially regarding the purchasing and driving of cars, was weakened during this period and thus unable to offset the negative relationship caused by the marginal propensity to emit pathway. In the United States, the purchase of new cars fell by 40% during the recession (U.S. Bureau of Economic Analysis 2022). This is because of the widespread financial hardship felt by lower- and middle-class populations due to structural unemployment, housing-bubble burst, and sovereign debt crises in many of the sampled nations. Lower- and middle-class populations adopted more frugal and energy conscious consumption behaviors amidst the hardship (Petev and Pistaferri 2012; Petev, Pistaferri, and Saporta-Eksten 2011; Shahiduzzaman and Layton 2015). Meanwhile, consumption fell more drastically for the top 10% of earners than for the bottom 10% of earners during the Great Recession (i.e., a decrease in consumption inequality), even as income inequality continued to rise (Meyer and Sullivan 2013).[27] Therefore, the emulative pull of top-earners is weaker during the

[27] This is likely because the decline in asset value during the recession affected the wealth of upper-class households more so than lower-class households who had very little assets to begin with.

recession and may not spur as much competitive consumption among the rest of the population compared to non-recession periods, especially regarding the purchase of cars. Meanwhile, the tendency for the marginal propensity to consume and to emit may become even stronger during the recession due to the concurrent rise in income inequality and fall in consumption inequality.

The negative effect of the income share of the top 10% on direct end user emissions peaked in 2011 and then gradually turned into a positive effect from 2012 to 2015 (though still nonsignificant as of 2015). This might be because the Veblen effect pathway became increasingly stronger as the Great Recession's impacts on consumption gradually subsided.

Unlike cars, the consumption of some recreational goods such as personal electronics remained stable or even increased during the recession (Petev et al. 2011). This might explain why a similar period of negative association from 2009 to 2011 is not found for the relationships between the income share of the top 10% and either DOSCA emissions or emissions embodied in imports. As a reminder, the consumption of these goods does not directly generate CO_2 emissions on site. Instead, the emissions are generated during the upstream production and power generation processes, and counted toward either DOSCA emissions or emissions embodied in imports depending on the location of production facilities and power plants.

The Great Recession, however, cannot explain the negative relationship between the income share of the top 10% and end user emissions for the period of 2004 to 2006. Therefore, although this study advances the understanding of the three pathways linking domestic income inequality to multiple emission components, further investigation is required to better understand what drives the changes in the income inequality-emissions relationships both over time and across emission components. Additionally, due to the limited availability of data on decomposed emission components and on income inequality, this analysis is limited to a sample of high-income nations for a 12-year period. As data will likely become increasingly more available in the future, researchers should also study lower- and middle-income nations, and for a longer time-period. This study also demonstrates the utility of the Multidimensional Emissions Profile (MEP) framework for research on human drivers of carbon emissions.

In conclusion, I find that the relationships between income inequality and nations' CO_2 emissions change over time, vary across emission components, and differ between measures of income inequality. Most notably, the income share of the top 10% is positively associated with emissions embodied in exports after 2010, and is negatively associated with end user emissions from 2004 to 2006, and from 2009 to 2011. The results are indicative of variations in the causal pathways between income inequality and CO2 emissions, both over time and across emission components. Can policies seeking to enhance income equality generate co-benefits for climate change mitigation? This study suggests that the answer is likely context specific. Policies seeking to curb a top-heavy income concentration, such as the Billionaire Minimum Income Tax (Hussein 2022), may facilitate the abatement of CO_2 emissions embodied in a nation's exports. Yet, such policies may at times inadvertently spur direct end user emissions of the nation, such as during economic recessions. In order to maximize income equality-enhancing policies' co-benefits for climate change mitigation and avoid potential trade-off, these policies must be implemented along with measures that curb consumers' direct fossil fuel consumption without compromising the well-being of lower-income populations.

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4.10 TABLES

Table 4.1 Unstandardized coefficients for the regression of nations' 4 emission components, 2004–2015, on the Gini coefficient and selected independent variables: seemingly unrelated regression model estimates with two-way fixed effects and country-clustered robust standard errors for 34 high-income countries.

	Seemingly Unrelated Regression Model			
	DOSCA Emissions	**Emissions in Exports**	**Direct End User Emissions**	**Emissions in Imports**
Gini Coefficient	-0.372	-0.172	-0.634	0.0216
	(0.419)	(0.498)	(0.416)	(0.444)
Gini Coefficient × 2005	0.165	0.230	0.0650	0.0141
	(0.123)	(0.160)	(0.135)	(0.148)
Gini Coefficient × 2006	0.170	0.0122	0.150	-0.0597
	(0.143)	(0.208)	(0.177)	(0.170)
Gini Coefficient × 2007	0.233	0.115	0.470*	0.124
	(0.160)	(0.230)	(0.183)	(0.181)
Gini Coefficient × 2008	0.255	0.180	0.413*	0.0970
	(0.226)	(0.232)	(0.200)	(0.210)
Gini Coefficient × 2009	0.0195	0.263	0.185	-0.0571
	(0.192)	(0.268)	(0.203)	(0.211)
Gini Coefficient × 2010	-0.155	0.429	0.0730	0.121
	(0.198)	(0.300)	(0.227)	(0.220)
Gini Coefficient × 2011	0.0219	0.615*	0.0737	0.258
	(0.202)	(0.266)	(0.293)	(0.249)
Gini Coefficient × 2012	0.234	0.670*	0.222	0.336
	(0.234)	(0.293)	(0.330)	(0.271)
Gini Coefficient × 2013	0.145	0.681*	0.437	0.0556
	(0.281)	(0.302)	(0.302)	(0.246)
Gini Coefficient × 2014	0.185	0.786**	0.747**	0.282
	(0.243)	(0.287)	(0.249)	(0.227)
Gini Coefficient × 2015	0.281	0.745*	0.791**	0.161
	(0.277)	(0.349)	(0.262)	(0.246)
GDP Per Capita	0.200	-0.0672	0.446*	1.370***
	(0.249)	(0.318)	(0.176)	(0.202)
Total Population	0.756	-0.0869	0.603	2.674***
	(0.662)	(0.583)	(0.783)	(0.746)
Urban Pop. as % Pop.	-1.015	-0.745	0.00771	0.582
	(1.304)	(1.454)	(1.151)	(1.252)
Constant	-3.486	10.30	-8.805	-57.78***
	(16.01)	(12.69)	(18.07)	(16.01)
N	408	408	408	408
# of nation	34	34	34	34
N per nations, min.	12	12	12	12
N per nation, avg.	12	12	12	12
N per nation, max.	12	12	12	12

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
* p<.05 ** p<.01 *** p<.001 (two tailed).

Table 4.2 Unstandardized coefficients for the regression of nations' 4 emission components, 2004–2015, on the income share of the top 10% and selected independent variables: seemingly unrelated regression model estimates with two-way fixed effects and country-clustered robust standard errors for 34 high-income countries.

	Seemingly Unrelated Regression Model			
	DOSCA Emissions	**Emissions in Exports**	**Direct End User Emissions**	**Emissions in Imports**
Income Share Held by Top 10%	-0.220	-0.00574	-0.635*	-0.0999
	(0.241)	(0.251)	(0.300)	(0.288)
Income Share Top 10% × 2005	0.305	0.135	0.0516	0.254
	(0.178)	(0.196)	(0.128)	(0.213)
Income Share Top 10% × 2006	0.136	0.245	0.0827	0.0386
	(0.195)	(0.250)	(0.235)	(0.200)
Income Share Top 10% × 2007	0.0570	0.350	0.426*	0.0768
	(0.224)	(0.227)	(0.200)	(0.204)
Income Share Top 10% × 2008	0.168	0.301	0.383	0.0761
	(0.291)	(0.276)	(0.261)	(0.232)
Income Share Top 10% × 2009	-0.00998	0.568*	0.144	0.0275
	(0.238)	(0.265)	(0.229)	(0.204)
Income Share Top 10% × 2010	-0.430	0.663	0.0482	0.239
	(0.234)	(0.362)	(0.313)	(0.225)
Income Share Top 10% × 2011	-0.170	0.853**	0.0354	0.250
	(0.242)	(0.285)	(0.373)	(0.277)
Income Share Top 10% × 2012	0.116	0.917***	0.371	0.354
	(0.264)	(0.275)	(0.388)	(0.322)
Income Share Top 10% × 2013	0.000457	1.016***	0.630	0.0159
	(0.281)	(0.272)	(0.367)	(0.277)
Income Share Top 10% × 2014	0.0471	1.180***	0.835**	0.437
	(0.278)	(0.338)	(0.280)	(0.249)
Income Share Top 10% × 2015	-0.0979	1.322**	0.933**	0.374
	(0.309)	(0.496)	(0.314)	(0.252)
GDP Per Capita	0.0540	-0.0483	0.443**	1.288***
	(0.209)	(0.231)	(0.166)	(0.192)
Total Population	0.605	-0.550	0.583	2.532**
	(0.645)	(0.579)	(0.884)	(0.833)
Urban Pop. as % Pop.	-1.737	-0.765	-0.455	0.205
	(1.246)	(1.228)	(1.150)	(1.354)
Constant	3.240	17.47	-6.535	-52.44**
	(15.31)	(12.56)	(19.70)	(16.83)
N	368	368	368	368
# of nation	34	34	34	34
N per nations, min.	3	3	3	3
N per nation, avg.	10.8	10.8	10.8	10.8
N per nation, max.	12	12	12	12

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
* $p<.05$ ** $p<.01$ *** $p<.001$ (two tailed).

4.11 FIGURES

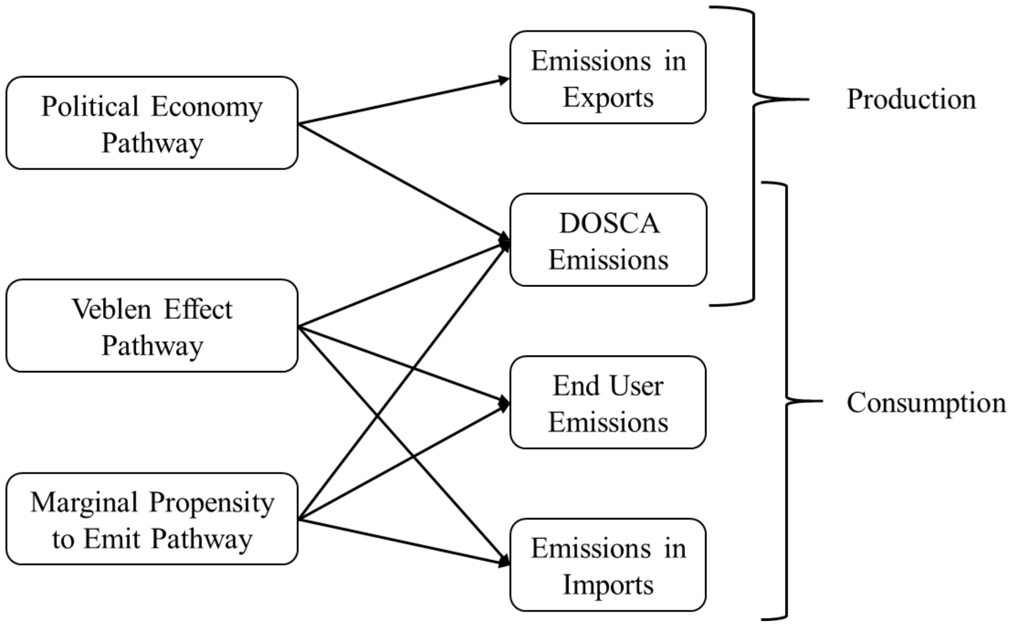

Figure 4.1 Conceptual Diagram of Income Inequality-CO_2 Emissions Relationships.

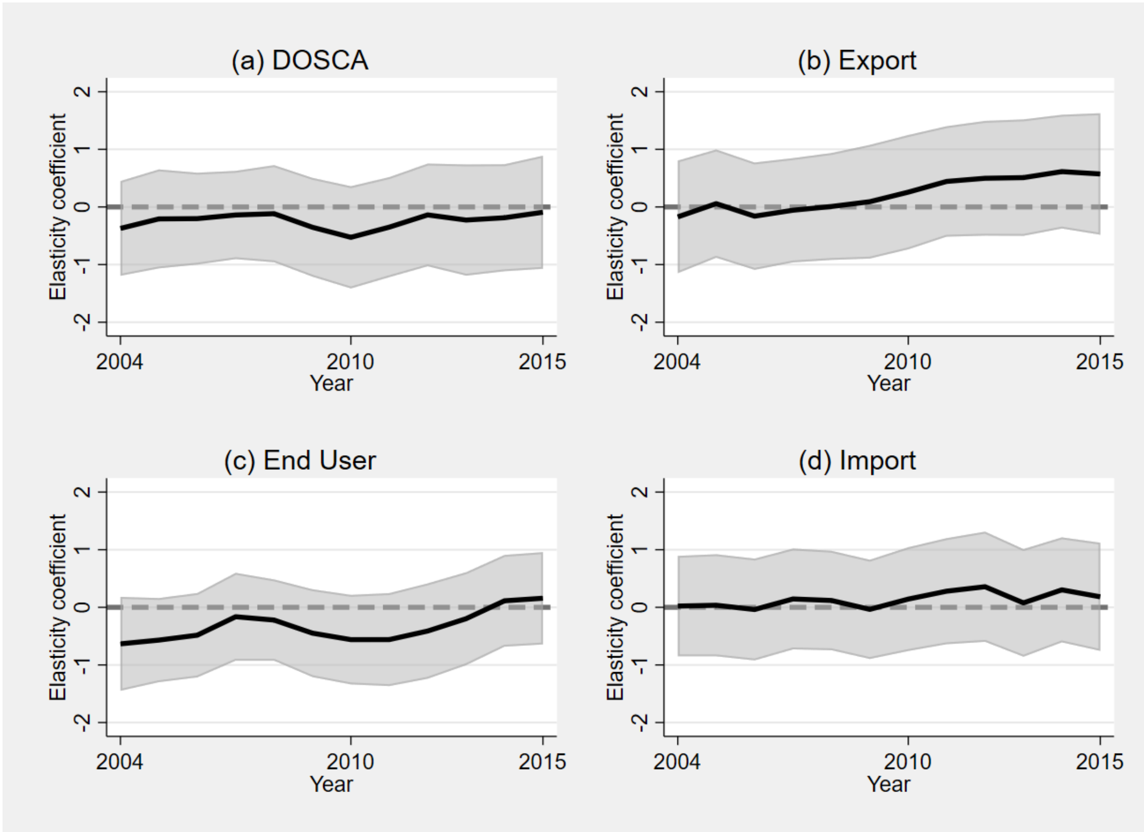

Figure 4.2 Average marginal effects of the Gini coefficient on (a) emissions generated by domestic-oriented supply chain activities (DOSCA); (b) emissions embodied in exports; (c) direct end user emissions; and (d) emissions embodied in imports, for each year from 2004 to 2015, based on the SUR model reported in Table 4.1. Shaded areas are 95% confidence intervals.

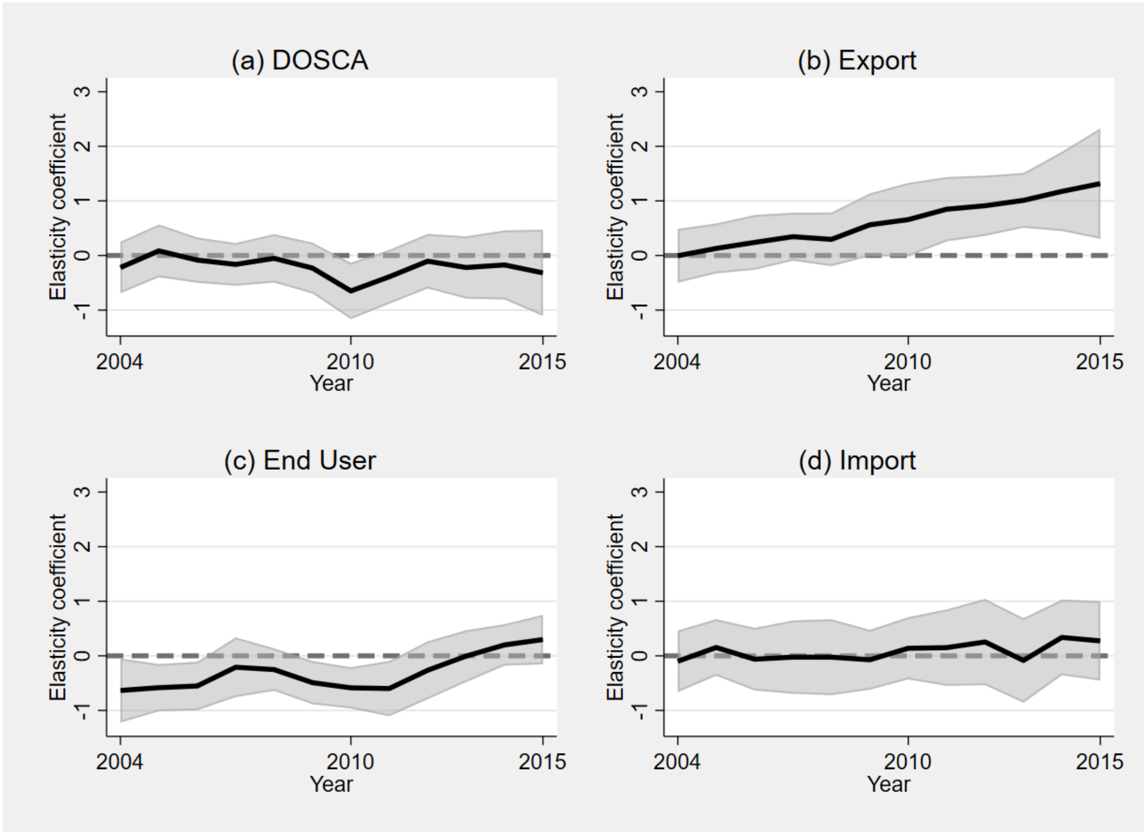

Figure 4.3 Average marginal effects of the income share of the 10% on (a) emissions generated by domestic-oriented supply chain activities (DOSCA); (b) emissions embodied in exports; (c) direct end user emissions; and (d) emissions embodied in imports, for each year from 2004 to 2015, based on the SUR model reported in Table 4.2. Shaded areas are 95% confidence intervals.

4.12 APPENDICES

4.12.1 Appendix Tables and Figures

Table A4.1 Descriptive Statistics

	N	Mean	S.D.	Min.	Max.
DOSCA Emissions	408	210.042	590.845	0.658	3825.635
Emissions Embodied in Exports	408	63.321	96.671	0.808	544.112
Direct Emissions of End User Activities	408	83.189	247.063	0.141	1538.284
Emissions Embodied in Imports	408	110.992	205.969	1.822	1341.968
Gini coefficient	408	29.741	3.577	22.738	38.924
Income Share of the top 10%	368	24.764	2.357	20.1	31.2
GDP per capita	408	37500.806	22197.446	6442.414	111968.352
Total population	408	30824661.5	55929867.51	401268	320600000
Urban population (% Pop.)	408	74.128	12.101	51.308	97.876

Note: the descriptive statistics for the Gini coefficient are calculated using Stata module *misum* (Klein 2011).

Table A4.2 Unstandardized coefficients for the regression of nations' 4 emission components, 2004–2015, on the Gini coefficient and selected independent variables: seemingly unrelated regression model estimates with two-way fixed effects and country-clustered robust standard errors for 34 high-income countries. The sample is restricted to N=368, identical to the sample used in the model for the income share of the top 10%.

	Seemingly Unrelated Regression Model			
	DOSCA Emissions	**Emissions in Exports**	**Direct End User Emissions**	**Emissions in Imports**
Gini Coefficient	-0.318	-0.0410	-0.717	0.158
	(0.379)	(0.467)	(0.404)	(0.409)
Gini Coefficient × 2005	0.186	0.302*	0.0308	0.0565
	(0.129)	(0.136)	(0.121)	(0.150)
Gini Coefficient × 2006	0.104	0.151	0.120	-0.00525
	(0.141)	(0.198)	(0.186)	(0.169)
Gini Coefficient × 2007	0.197	0.284	0.421*	0.119
	(0.169)	(0.193)	(0.168)	(0.180)
Gini Coefficient × 2008	0.179	0.285	0.341	0.112
	(0.229)	(0.217)	(0.198)	(0.219)
Gini Coefficient × 2009	-0.0884	0.361	0.121	-0.00823
	(0.176)	(0.218)	(0.189)	(0.201)
Gini Coefficient × 2010	-0.283	0.522*	-0.0106	0.123
	(0.193)	(0.265)	(0.204)	(0.205)
Gini Coefficient × 2011	-0.136	0.705**	-0.0446	0.219
	(0.196)	(0.225)	(0.297)	(0.248)
Gini Coefficient × 2012	0.0627	0.793**	0.0927	0.295
	(0.211)	(0.249)	(0.330)	(0.271)
Gini Coefficient × 2013	-0.0219	0.752**	0.326	0.0571
	(0.253)	(0.266)	(0.301)	(0.247)
Gini Coefficient × 2014	0.0329	0.860**	0.647**	0.267
	(0.251)	(0.273)	(0.236)	(0.228)
Gini Coefficient × 2015	0.0341	0.831*	0.684**	0.199
	(0.248)	(0.360)	(0.262)	(0.241)
GDP Per Capita	0.0381	-0.103	0.418*	1.292***
	(0.213)	(0.289)	(0.183)	(0.208)
Total Population	0.537	-0.355	0.508	2.590**
	(0.665)	(0.626)	(0.863)	(0.841)
Urban Pop. as % Pop.	-1.731	-0.829	-0.256	0.229
	(1.276)	(1.569)	(1.193)	(1.326)
Constant	4.908	15.16	-5.474	-54.44**
	(15.94)	(13.40)	(19.47)	(17.23)
N	368	368	368	368
# of nation	34	34	34	34
N per nations, min.	3	3	3	3
N per nation, avg.	10.8	10.8	10.8	10.8
N per nation, max.	12	12	12	12

Notes: robust standard errors clustered by nation are reported in parentheses;
all nonbinary variables are transformed with natural logarithm;
all models include unreported country-specific and year-specific fixed effects;
* p<.05 ** p<.01 *** p<.001 (two tailed).

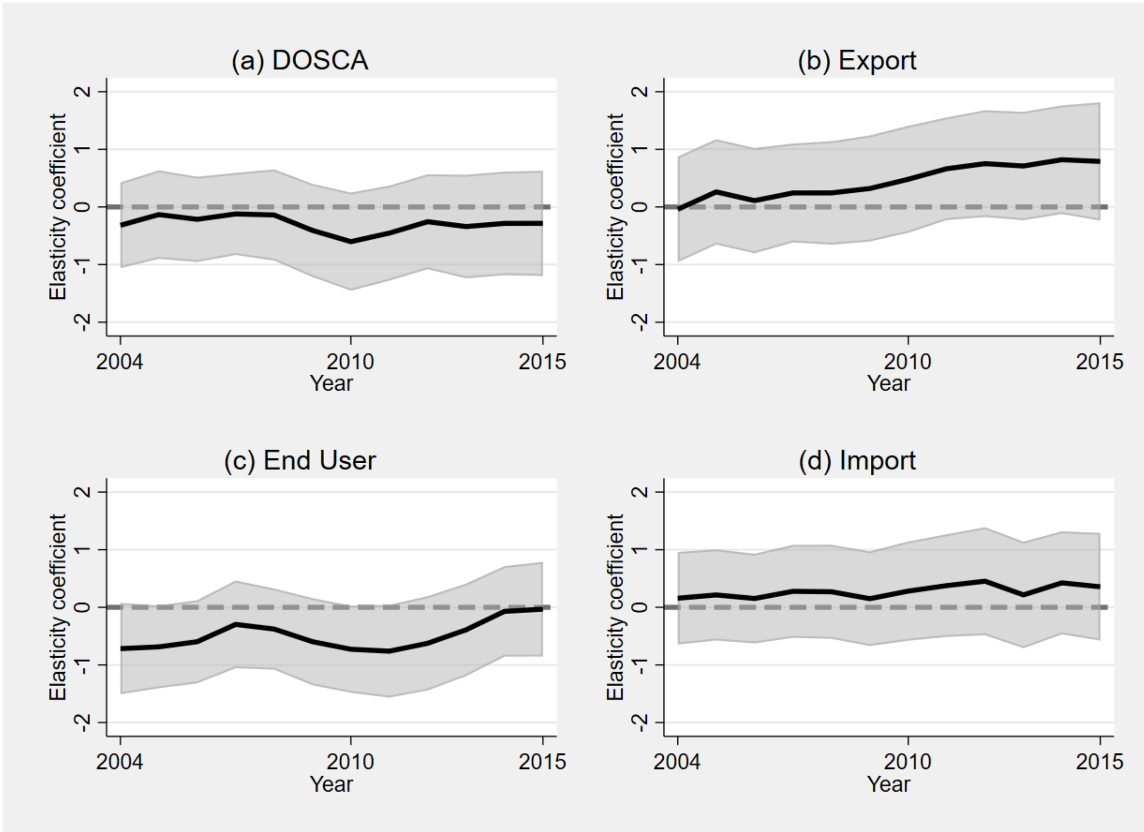

Figure A4.1 Average marginal effects of the Gini coefficient on (a) emissions generated by domestic-oriented supply chain activities (DOSCA); (b) emissions embodied in exports; (c) direct end user emissions; and (d) emissions embodied in imports, for each year from 2004 to 2015, based on the SUR model reported in Appendix Table A4.2 (unbalanced sample, N=368). Shaded areas are 95% confidence intervals.

5.0 CONCLUSION

5.1 MITIGATING GLOBAL CLIMATE CHANGE

Global climate change is among the greatest crises facing humanity in the 21st century (IPCC 2021). In order to mitigate the worsening impacts of climate change and limit global warming to below 1.5 °C, global CO_2 emissions must be reduced by 45% by 2030 relative to the 2010 level, along with substantial reduction in other greenhouse gases (GHGs) (IPCC 2018; UNFCCC 2021). Despite the urgency, climate actions have been lacking at the national level in many countries. At the onset of the Glasgow Climate Conference in 2021, nations' collective contributions, pledges, and commitments to emission abatement were still insufficient to meet the global target, underscoring the need for more climate actions by the world's nations (Bansard et al. 2021; UNEP 2021).

What are the social, economic, political, technological, and cultural forces that influence GHG emissions at the national level? Whether and how can changes in these forces lead to emission abatement? A large and sophisticated body of social science research on human drivers of emissions seek to answer these two questions and inform climate policies (Blanco et al. 2014; Jorgenson et al. 2019; Rosa and Dietz 2012). Foundational to this literature are the IPAT/STIRPAT framework and the similarly specified Kaya identity, both of which identify population (P), affluence (A), and technology (T) as three main drivers of human impacts on the environment (Dietz 2017; Dietz and Rosa 1994; Kaya 1990; York, Rosa, and Dietz 2003). In cross-national empirical analyses, the STIRPAT model is widely used to identify human drivers of emissions, estimate their effects, test hypotheses, and inform policy efforts. A group of anthropogenic forces have been empirically identified as key drivers of emissions, including affluence, population, urbanization, trade, and militarization, while the fossil fuel-based energy system is the biggest direct source of GHG emissions (Dietz, Shwom, and Whitley 2020; Jorgenson et al. 2019; Rosa and Dietz 2012). As an alternative of fossil fuel, renewable energy is widely viewed as an integral part of the strategy for climate change mitigation (IPCC 2011). Meanwhile, climate change mitigation is contextualized by and interacts with existing social inequality (Harlan et al. 2015), such as domestic income inequality. Researchers underscore the importance of identifying potential double-dividend measures that enhance income equality and reduce emissions at the same time (Grunewald et al. 2017; Jorgenson et al. 2016; Jorgenson, Schor, and Huang 2017).

Most cross-national empirical studies on relationships between anthropogenic forces and carbon emissions focus on aggregate emission measures such as production-based accounts (PBA) that capture all emissions generated in a nation's territory (UNFCCC 1997), and consumption-based accounts (CBA) that capture the totality of global emissions driven by a nation's consumption demand (Davis and Caldeira 2010; Peters and Hertwich 2008). These studies advance the understanding of the "net effect" of a certain human force on the totality of a nation's emissions defined based on PBA or CBA, and are instrumental to climate change research and policy considerations.

However, the existing literature has not systematically examined how the effects of certain anthropogenic forces may differ across components of a nation's emissions. At the national level, a myriad of activities contributes to GHG emissions. These activities are not homogeneous but differ in important characteristics such as the economic sector and supply chain stage to which they belong. Accordingly, a nation's GHG emissions can be divided into multiple distinct components based on some of these characteristics. Given the differences between emission components, it is likely that their relationships with a certain human force differ in magnitude or even in direction. If such heterogeneity is found, it can inform the unique strategy that might be required to effectively mitigate each emission component. Yet, analyses using PBA or CBA are unable to detect such heterogeneity.

In this dissertation, I address these gaps in the literature. In Chapter 2, I propose a new analytical framework of Multidimensional Emissions Profile (MEP) for the systematic analysis of four structural components of nations' emissions and how they are related to anthropogenic forces. I then apply this framework to analyze the national affluence-GHG emissions nexus in high-income nations over the period of 1995 to 2015. In Chapter 3, I draw upon the MEP framework to investigate how renewable energy deployment is related to nations' multiple emissions components, and how the relationships change over time from 1995 to 2015 in high-income nations. In Chapter 4, I examine the time-varying relationships between domestic income inequality and the four emission components in high-income nations from 2004 to 2015. The empirical findings from all three chapters show heterogeneity among the four emissions components in how they are associated with anthropogenic forces, hence supporting the validity of the MEP framework. The heterogeneity bears important theoretical, substantive, and policy implications regarding the roles of economic development, renewable energy deployment, and domestic income inequality in the pursuit of climate change mitigation.

As a whole. this dissertation contributes to the research literature and policy considerations on human drivers of climate change and mitigation. Below I briefly summarize the MEP framework and the empirical analyses, and then discuss the contributions of this dissertation with more depth.

5.2 MULTIDIMENSIONAL EMISSIONS PROFILE

The MEP framework situates each nation's contributions to global carbon emissions into 4 distinct components: (1) emissions generated by domestic-oriented supply chain activities (DOSCA), such as domestic industrial activities that serve domestic consumers; (2) emissions embodied in imports; (3) emissions embodied in exports; and (4) direct emissions of end user activities. DOSCA emissions, emissions embodied in exports, and emissions embodied in imports are generated by supply chain activities outside the end use stage. Direct emissions of end user activities are generated by activities such as driving personal vehicles, and household electricity generation and heating that burns fossil fuels on-site. This emission component does not account for the emissions that are driven by end user activities but generated outside the end use stage, such as the emissions generated by domestic power plants serving domestic households.

As leverage points for climate change mitigation, these four emission components differ from one another at multiple levels. At the national level, emissions embodied in imports are generated by foreign supply chain activities to fulfill a nation's final demand. These foreign supply chain activities are, at best, indirectly influenced by the nation's domestic policies. In contrast, emissions embodied in exports are generated by domestic supply chain activities serving foreign final demand, which are more directly affected by domestic policies, and might be indirectly impacted by foreign policies. In comparison, DOSCA emissions and direct end user emissions are most directly affected by domestic policies and least affected by foreign policies. At the organizational level, mitigating the three emission components generated outside the end use stage requires business organizations to reduce the emissions generated by their own operations. In contrast, mitigating direct end user emissions requires firms to offer consumer products and services that facilitate the reduction of direct end user emissions (Stern et al. 2016). At the household and individual levels, reducing emission components generated outside the end use stage requires changing consumer behaviors that are implicated in the emissions generated by upstream production processes. Mitigation strategies targeting these behaviors need to overcome the cognitive barrier that most consumers are unaware of the embodied emissions of consumer products, and the institutional and technical barriers of compiling and publicizing credible information on embodied emissions for a wide range of consumer products (Abrahamse et al. 2007; Taufique et al. 2022). In comparison, these barriers are less inhibiting for changing consumer behaviors that contribute to direct end user emissions (Stern et al. 2016).

These distinctions allude to the potential heterogeneity in how the emission components are affected by anthropogenic forces that drive or mitigate emissions, including national affluence (i.e., economic development), renewable energy deployment, and domestic income inequality. Each of these forces is empirically examined in a chapter.

5.3 OVERVIEW OF EMPIRICAL ANALYSES

The analyses in this dissertation focus a sample of 34 high-income nations, for both methodological and substantive reasons. As discussed extensively in Chapter 2, I calculate the values of the four emission components (i.e., the dependent variables) using the environmentally-extended multi-regional input-output (EE-MRIO) method (Miller and Blair 2009). The calculation is based on the EE-MRIO data from Exiobase 3 (Stadler et al. 2018, 2021), which provides data for 49 geographic regions (including nations and non-nation regions). Among them, 34 high-income nations and 9 non-high-income nations also have available data on independent variables. The 9 non-high-income nations as a standalone sample is too small for the regression modeling techniques used in the analyses. Moreover, combining high-income nations and non-high-income nations together as a mixed sample may generate spurious results because prior studies find relationships between human drivers and emission outcomes tend to differ substantially between high-income nations and lower-income nations (Grunewald et al. 2017; Jebli and Kahia 2020; Jorgenson et al. 2016; Jorgenson and Clark 2012; Thombs 2017; York and McGee 2017). Therefore, I elect to focus only on the 34 high-income nations.

Despite only including high-income nations, this sample is substantively meaningful. Many high-income nations are major contributors to global carbon emissions. The sample includes 9 out of 10 biggest emitters of among high-income nations. Besides, prior studies find that if there would be nations where growth in affluence is decoupled from growth in emissions, they would more likely be high-income nations than in lower-income nations (Jebli and Kahia 2020; Jorgenson and Clark 2012; Schmalensee, Stoker, and Judson 1998; Thombs 2018). Moreover, high-income nations generally have greater financial and technological capability for a renewable energy transition than lower-income nations (IPCC 2011).

In Chapter 2, I apply the MEP framework to empirically analyze the affluence/emissions nexus, a focal point of climate mitigation research and policies. There is a major debate on the relationship between national affluence and carbon emissions. Some studies argue that national affluence is positively associated with the scale of resource consumption, which in turn is positively related to carbon emissions (Dietz 2017; Jorgenson et al. 2019; Rosa and Dietz 2012; Schnaiberg 1980). Others contend that social changes such as environmental regulations, renewable energy deployment, energy efficiency improvement, and environmental movements are capable of offsetting the upward pressure on emissions caused by increased affluence and resource consumption (Grossman and Krueger 1995; Mol 2000; Mol, Spaargaren, and Sonnenfeld 2014; Rosa and Dietz 2012). The majority of cross-national empirical studies find positive relationship between affluence and emissions (Dietz and Rosa 1997; Dong et al. 2018; Jorgenson and Clark 2012; Khan et al. 2021; Liddle 2015; Lohwasser, Schaffer, and Brieden 2020; Thombs 2018; Thombs and Huang 2019; Wang, Assenova, and Hertwich 2021), while a smaller number of studies find the relationship to be negative for high-income nations (Dogan and Aslan 2017; Schmalensee et al. 1998).

The empirical literature primarily relies on aggregate emission measures such as PBA and CBA. Different from prior research, I investigate how national affluence is associated with multiple components of nations' emissions in potentially heterogeneous ways, by using the MEP framework. Results of panel regression analyses with two-way fixed effects indicate that as high-income nations grow even wealthier, affluence is increasingly decoupled from direct emissions of end user activities but remains positively associated with the other three emission components in various ways.

In Chapter 3, I apply the MEP framework to investigate how high-income nations' renewable energy deployment is related to their emission components. While some prior studies find that renewable energy consumption is negatively associated with CO_2 emissions (Bilgili, Koçak, and Bulut 2016; Shafiei and Salim 2014; Shahnazi and Dehghan Shabani 2021; Sovacool et al. 2020; Wang et al. 2021), others studies question whether renewables can displace fossil fuel consumption at the scale and pace required to meet necessary mitigation targets (Davidson 2019; Hill, Tajibaeva, and Polasky 2016; York 2012). Most cross-national research to date on the renewable energy-carbon emissions nexus examines PBA. An understudied area is how renewables' overall effect on PBA may be heterogeneously distributed among specific emission components. I address this gap in Chapter 3. I first conduct a baseline analysis of renewables' time-varying relationship with nations' PBA. Then I analyze renewables' time-varying relationships with DOSCA emissions, emissions embodied in exports, and direct end user emissions. These 3 emission components together constitute PBA. Results of panel regression models with two-way fixed effects suggest that renewable energy deployment is effective in mitigating DOSCA emissions, and with increasing effectiveness over time from 1995 to 2015; yet it remains ineffective in curbing the other emission components.

In Chapter 4, I examine how domestic income inequality is related to nations' four emission components that constitute the MEP. Prior research on this relationship identifies three major theoretical pathways that link domestic income inequality to CO_2 emissions: the political economy pathway (Boyce 1994, 2003, 2007), the Veblen effect pathway (Schor 1998; Veblen 1934), and the marginal propensity to emit pathway (Ravallion, Heil, and Jalan 2000). Given that prior cross-national studies rely on aggregate emissions measures such as PBA (Grunewald et al. 2017), and CBA (Jorgenson et al. 2016), they are unable to further unpack how the effect of income inequality might vary across emission components, and whether the pathways linking income inequality to emissions are different across emission components. I argue that the three aforementioned theoretical pathways concern different types of carbon-emitting activities, and correspondingly, different emission components in the MEP framework. Specifically, political economy pathway mainly concerns emissions embodied in exports and DOSCA emissions, while the Veblen effect pathway and the marginal propensity to emit pathway are more relevant to direct end user emissions, emissions embodied in imports, and also DOSCA emissions.

I also operationalize income inequality in two different ways: the Gini coefficient and the income share held by the top 10% of population. The former is more sensitive to the marginal propensity to emit pathway and the latter is more sensitive to the political economy and the Veblen effect pathways (Jorgenson et al. 2017). Results of seemingly unrelated regression models suggest that the relationships between income inequality and nations' CO_2 emissions change over time, vary across emission components, and differ between the two measures of income inequality.

5.4 IMPLICATIONS FOR CLIMATE CHANGE MITIGATION

The findings for this dissertation bear implications for research and policy considerations on climate change mitigation. For the national affluence-GHG emissions nexus (Chapter 2), the heterogeneity across emission components suggests that the emission-suppressing mechanisms that are theorized to accompany growing affluence may be more effective in curbing direct end user emissions but remain inadequate in mitigating the other three emission components: DOSCA emissions, emissions embodied in imports, and emissions embodied in exports—all three of which are generated by supply chain activities outside the end use stage. This is problematic because these three emission components together account for the absolute majority of high-income nations' contributions to global emissions. Emissions embodied in imports, in particular, increasingly become the largest emission component as high-income nations grow wealthier. If high-income nations aim to reduce GHG emissions while maintaining growth in affluence, it is necessary for them to achieve absolute decoupling between affluence and these three emission components, especially emissions embodied in imports. However, absolute decoupling is only observed for direct end user emissions, the fourth and the smallest emission component. Therefore, the findings underscore the importance for high-income nations to shift the focus of their climate mitigation policy agenda from direct end user emissions to emissions generated by both domestic and foreign supply chain activities outside the end use stage. This shift would require targeting not only consumers but also multiple entities along supply chains (World Economic Forum 2021).

For the renewable energy-CO_2 emissions nexus (Chapter 3), the heterogeneity across emission components indicates that while renewables can more effectively curb DOSCA emissions and increasingly so over time, there exist structural barriers that prevent renewable energy deployment from mitigating emissions embodied in exports and direct end user emissions. For emissions embodied in exports, one likely barrier is the preferential treatment of energy-intensive export-oriented industries in climate and environmental policies such as carbon tax (Lin and Li 2011). For direct end user emissions, there is a lack of effective mechanisms to translate increased renewable energy consumption into a reduction in direct fossil fuel consumption by end users. Notably, the deployment of biofuels as blended fuels in road transportation perpetuates rather than displaces fossil fuel consumption (Hill et al. 2016). Underlying these barriers is the continuous legitimization of the fossil fuel regime by normalized societal practices such as personal vehicle-based transportation and the ubiquity of plastics (Davidson 2019; Sicotte 2020; Sicotte and Seamon 2021; Smil 2016). It is crucial to overcome these structural barriers in order to achieve the full decarbonization potential of renewable energy deployment.

For the income inequality-CO_2 emissions nexus (Chapter 4), the observed heterogeneity is indicative of the variations, both across emission components and over time, in the causal pathways that link carbon emissions to domestic income inequality. Equality-enhancing policies that seek to curb the income concentration among top earners, such as the Billionaire Minimum Income Tax (Hussein 2022), may curb the disproportional power of wealthy elites who collectively control most of the production facilities and business organizations in a nation. As a result, the environmental impacts of these facilities and organizations, including carbon-intensive export-oriented industries, can be more effectively regulated, which in turn could lead to a reduction in CO_2 emissions embodied in the nation's exports. However, such policies may at times, such as during economic recessions, increase the fossil fuel consumption by bottom earners and thus increase direct end user emissions of the nation. Therefore, in order to better harness the climate mitigation co-benefits of equality-enhancing policies and avoid potential trade-offs, these policies need to be accompanied by measures that curb consumers' direct fossil fuel consumption without compromising the well-being of lower-income populations.

Overall, this dissertation research underscores the multidimensionality in how nations contribute to global carbon emissions, and in how nations' emissions are related to anthropogenic forces. National affluence, renewable energy deployment, and income inequality do not evenly affect the emission components. Instead, they curb some emission components but spur others. Climate policies targeting these anthropogenic forces should optimize their decarbonization benefits while neutralizing the mechanisms through which they drive growth in emissions.

5.5 LIMITATIONS AND FUTURE DIRECTIONS

The findings in each of the empirical chapters inform avenues for future research. In Chapter 2, I raise these questions that warrant further investigation: What are the specific emission-suppressing mechanisms accompanying growing affluence that contribute to the absolute decoupling between affluence and direct end user emissions?

How can these mechanisms be adapted to mitigate the other three emission components? In Chapter 3, I explore potential barriers that cause renewable energy deployment to unevenly affect the emission components, and call for future research to more thoroughly examine these barriers: What social, economic, political, and technological barriers impede renewables' mitigation effect on emissions embodied in exports and direct emissions by end users? How do the barriers differ across nations and change over time? How can these barriers be overcome? How can renewables' mitigation effect on DOSCA emissions be further strengthened? In Chapter 4, I call for further investigation into the mechanisms that drive the changes in the income inequality-emissions relationships both over time and across emission components. Moreover, while Chapter 4 focuses on the period of 2004 to 2015 due to the limited data availability on income inequality measures, future research should examine the relationships over a longer time span. Similarly, data availability issues limit the sample to high-income nations for across all three empirical chapters. As data will likely become increasingly more available in the future, it will be imperative for researchers to study lower- and middle-income nations, some of which have become major emitters.

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