Low-Carbon Transition: How Successful and at What Cost?

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Abstract

Global climate change is widely recognized as the most severe threat facing humankind. Combating the climate threat depends critically on the transition from unsustainable high-carbon economic growth to sustainable low-carbon development. This dissertation presents three scientific essays that endeavor to provide methodological innovations for evaluating and monitoring the low-carbon transition.

The first essay focuses on the evaluation of the marginal abatement costs for greenhouse gases, which is fundamental to effective climate policy. The motivation of this essay stems from the observation that most empirical studies using frontier estimation methods grossly over-estimate the marginal abatement costs due to three sources of upward bias from ignoring input-side abatement options, inefficiency, and noisy data. To address the overestimation issue, we clarify the conceptual distinction between the shadow price and marginal abatement cost and develop a novel data-driven estimation approach based on convex quantile regression. Compared to the traditional approaches, convex quantile regression is more robust to random noise, the choice of the direction vector, and heteroscedasticity. An empirical application to U.S. electric power plants provides empirical evidence and demonstrates the advantages of the proposed approach.

The second essay is motivated by a surprising paucity of well-developed studies investigating environmental productivity growth in consumption (a necessary condition for a smooth transition toward low-carbon consumption). This essay seeks to develop an environmental total-factor productivity index specific to the use of consumer durable goods. We first analyze the particular features of consumer durables (taking the passenger car as an example) compared to conventional production units, based on which we elaborate how to model the production activity during the use phase of consumer durables. Then, we present an overview of the existing approaches to measuring environmental productivity change and describe how they can be applied in the current context. Finally, we use a unique data set that covers all registered passenger cars in Finland to illustrate the interpretation of the proposed index.

The third essay extends the second by further examining the driving factors behind decreasing CO₂ emissions of new passenger cars. This essay develops a novel decomposition method to break down the change in the average CO₂ emissions of new passenger cars into underlying factors such as technology, efficiency, and policy measures. Our decomposition draws insights from the traditional index decomposition analysis and frontier-based decomposition of productivity growth and satisfies several desirable properties. An empirical application to the Finnish register data sheds light on why and how the CO₂ emissions of new cars decreased from year 2002 to 2014.

Keywords Climate change; Climate policy; Data-driven analytics; Environmental performance; Frontier estimation; Low-carbon consumption behavior; Nonparametric regression; Production theory; Sustainable transportation

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Preface

Eventually, the journey of Ph.D. studies comes to an end, and it is high time to review my reflections on the entire trip. I would personally consider the four-year-long trip as a voluntary “exile” in a place where you isolated yourself from the previous comfort zone, devoted yourself to the endless search of scientific truth, and adapted yourself to solitude and perseverance. Nevertheless, the exile has been an unforgettable life experience that incites my ambition to be an internationally renowned scholar, and I have received encouragement and support from many individuals and institutions.

First of all, I would like to express my sincere gratitude to my supervisor, Professor Timo Kuosmanen, for his excellent guidance throughout the research work. I would not have been able to complete this dissertation without him. I have benefited a lot from the collaboration with Timo. I also enjoyed the conversations very much with him, whether in the office, bar, stadium, or museum.

Apart from my Ph.D. supervisor, I will not forget to convey my deep gratitude to my Master’s supervisor, Professor Peng Zhou, for his unconditional constant support from the very beginning of my research career, which dates back to more than eight years ago. He enlightened my passion for research and is always there to answer my questions.

I am pleased to say thank you to the preliminary examiners, Dr. Kenneth Løvold Rødseth and Dr. Hervé Dakpo. Their constructive comments have greatly helped me to improve the presentation of this dissertation. I also feel privileged to have Dr. Rødseth as the opponent for the public defense.

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It has been an honor and enjoyable experience to work with my outstanding colleagues, Abolfazl Keshvari, Antti Saastamoinen, Yaping Mao, Peng Xu, Sheng Dai, Weimu You, Yuan Virtanen, Wenjie Fan, Mingyang Zhang, and Linyu Liu. My profound thanks go to my dear friends, Qiqi Zhang, Wenzhong Zhang, Ben Yin, Yan Wang, and Xiaoxu Liu, without whom I would have been unlikely to avoid falling into depression during my Ph.D. journey.

I will always be indebted to my late grandparents, my parents, sister, brother-in-law, and two lovely nephews. They give me unconditional moral support and motivation to accomplish my personal goals. Finally, yet importantly, I dedicate this dissertation to my gorgeous girlfriend, Yanqing Lin. Your deep love always encourages me to strive for the ultimate success.

Espoo, 19 September 2019,

Xun Zhou

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List of Abbreviations

BOD	Biochemical Oxygen Demand
CNLS	Convex Nonparametric Least Squares
CO ₂	Carbon Dioxide
DEA	Data Envelopment Analysis
DMU	Decision-Making Unit
EU	European Union
IPCC	Intergovernmental Panel on Climate Change
LP	Linear Programming
MAC	Marginal Abatement Cost
NO _x	Nitrogen Oxides
SBM	Slacks-Based Measure
SFA	Stochastic Frontier Analysis
SO ₂	Sulfur Dioxide
StoNED	Stochastic Nonparametric Envelopment of Data
TFP	Total-Factor Productivity
VRS	Variable Returns to Scale

List of Essays

This thesis consists of an overview and of the following scientific essays which are referred to in the text by their Roman numerals.

- I** Kuosmanen, Timo; Zhou, Xun. Shadow Prices and Marginal Abatement Costs: Convex Quantile Regression Approach. Revision Submitted to *Operations Research*, September 2019.
- II** Zhou, Xun. Environmental Productivity Growth in Consumer Durables. In *Pang R., Bai X., Lovell K. (eds) Energy, Environment and Transitional Green Growth in China*, Springer, Singapore, April 2018.
- III** Zhou, Xun; Kuosmanen, Timo. What Drives Decarbonization of New Passenger Cars? Submitted to *European Journal of Operational Research*, July 2019.

Author's Contribution

Essay I: "Shadow Prices and Marginal Abatement Costs: Convex Quantile Regression Approach"

The author of the dissertation was the second author of this essay. He was responsible for the literature review, the data collection and processing, and the coding and running of the convex quantile regression approach. He also visualized the results and was responsible for the initial analysis and discussion of the findings.

Essay II: "Environmental Productivity Growth in Consumer Durables"

The author of the dissertation was the sole author of this publication.

Essay III: "What Drives Decarbonization of New Passenger Cars?"

The author of the dissertation was the first author of this essay. The research was designed by him, and he was responsible for the literature review, the data collection and processing, and the coding and running of the decomposition methods. He also visualized the results and was responsible for the initial analysis and discussion of the findings.

1. Motivation

“We are the first generation that can end poverty, the last that can end climate change.”

— Ban Ki-moon

Global climate change is widely recognized as the most severe challenge facing humankind. With the increasingly high atmospheric concentration of greenhouse gases (mainly represented by carbon dioxide, CO₂), climate change has led to frequent and intense extreme weather events around the globe, raised sea levels, and endangered all species living on this planet. This change may continue to induce profound and disastrous consequences on the ecosystem and the entire human society (see, e.g., Stern, 2007; World Meteorological Organization, 2019).

The majority of the international community has responded to the climate threat with urgent and firm actions (e.g., the United Nations Framework Convention on Climate Change in 1992, the Kyoto Protocol in 1997, and the Paris Agreement in 2015). The central goal of the climate actions is to promote a transition from unsustainable high-carbon economic growth to sustainable low-carbon development. The low-carbon transition would be the inevitable course of the global economy to counter the climate threat and protect humankind (as well as other species) from hazardous effects posed by climate change.

Meanwhile, however, there is widespread concern that combating climate change might profoundly undermine economic growth due to the fact that economic growth is still tightly coupled to fossil energy consumption. Furthermore, some skeptics argue that the claim of climate change is an ‘expensive hoax’ fabricated by individual countries and interest groups in order to gain unfair competitive advantages and achieve special interests. From their perspective, moreover, climate actions would be a lose-lose proposition for both developed and developing countries; climate actions would impose extra economic costs on developed countries, while vulnerable countries and groups would be first inflicted by a stagnant economy before they could benefit from climate actions.

Despite concern and skepticism, the low-carbon transition is an irresistible

development trend due to the risk that the world will one day run out of fossil fuels, not to mention the climate threat. However, of course, there is no free lunch; making progress toward a low-carbon economy could be costly (Nordhaus and Boyer, 1999; Nordhaus, 2019). In order to make the low-carbon transition process as smooth as possible, a government must balance climate change mitigation and economic development. Ideally, a successful low-carbon transition should be economically viable and cost-effective and able to enhance human well-being

Under these circumstances, it is fundamental to estimate how much reducing CO₂ emissions can cost for a decision-making unit (DMU), i.e., CO₂ abatement cost. According to literature surveys by Zhou et al. (2014) and Huang et al. (2016), frontier estimation methods have been one of the most commonly used approaches to estimating the marginal abatement costs (MACs) of CO₂ emissions (as well as various environmental pollutants). However, in this dissertation (Essay I), I will argue that most empirical studies using frontier estimation methods grossly over-estimate the MACs of CO₂, which are usually 10–100 times higher than the market prices of tradeable CO₂ permits in emission trading (Kuosmanen and Zhou, 2018). While the market prices and MACs may differ for many reasons, including market failure and government failure, the difference is far from marginal and calls for an explanation.

Another important research topic is to assess how successful the low-carbon transition of a DMU has been over time. In recent decades, there has been vast and growing research interest in developing reasonable indicators to assess the progress of low-carbon transitions, which consider trade-offs between CO₂ reduction and economic benefit as well as synergies with other development goals. But given the complexity of the tasks, much still remains to be done, especially in the field of consumption (Kortelainen and Kuosmanen, 2007; Zhou, 2018). For instance, there is a surprising paucity of well-developed studies investigating environmental total-factor productivity (TFP) growth in the use of consumer durables—a necessary condition for a smooth low-carbon transition in consumption. Moreover, no systematic decomposition of changes in the CO₂ emissions of consumer durables into a series of driving factors is available in the literature. This is clearly another significant research gap that needs to be filled, as a comprehensive understanding of the driving factors is critically important going forward to promote low-carbon consumption.

This dissertation set out to develop reliable quantitative approaches in order to address the identified research gaps and shortcomings in the evaluation and monitoring of the low-carbon transition. We anticipate that the methodological innovations proposed in this dissertation would support the evidence-based policymaking in the low-carbon transition across the globe.

The rest of the dissertation proceeds as follows. Chapter 2 introduces the fundamental methodological framework of the dissertation, based on which our methodological innovations are developed. Chapter 3 critically reviews the empirical literature related to this dissertation and highlights the research

gaps and shortcomings addressed here. Chapter 4 lists the critical research questions that prompt this dissertation. Chapter 5 responds to the questions by summarizing the main findings of this thesis work. Chapter 6 discusses the policy implications of our results and suggests revenues for future research. Following these chapters are the references and the three original scientific essays.

2. Methodology

This chapter is intended to prepare the reader for the production theory, which establishes the foundation for this dissertation. Note that the first three sections of this chapter are adapted from a previous work of the author of the dissertation (for which he was the second and co-corresponding author): Zhou et al. (2014, Sections 2–3), and the last section is drawn from Essay II.

2.1 Production Technology

Consider a joint-production process in which a productive entity employs an input vector $\mathbf{x} \in \mathbb{R}_+^N$ to produce a desirable output vector $\mathbf{y} \in \mathbb{R}_+^M$ and an undesirable output vector $\mathbf{b} \in \mathbb{R}_+^K$. Note that the input vector can include both energy and non-energy inputs, and undesirable outputs may refer to greenhouse gases and a variety of pollutants. The production technology can be represented by the output possibility set $P(\mathbf{x}) = \{(\mathbf{y}, \mathbf{b}) : \mathbf{x} \text{ can produce } (\mathbf{y}, \mathbf{b})\}$ or the input requirement set $I(\mathbf{y}, \mathbf{b}) = \{\mathbf{x} : \text{producing } (\mathbf{y}, \mathbf{b}) \text{ requires } \mathbf{x}\}$.

In the joint-production process, inputs and desirable outputs are generally assumed to be strongly (freely) disposable (Färe and Primont, 1995), which can be respectively expressed in terms of the output possibility set¹ as

$$\mathbf{x}' \geq \mathbf{x} \text{ implies } P(\mathbf{x}') \supseteq P(\mathbf{x}) \quad (2.1)$$

$$(\mathbf{y}, \mathbf{b}) \in P(\mathbf{x}) \text{ and } \mathbf{y}' \leq \mathbf{y} \text{ imply } (\mathbf{y}', \mathbf{b}) \in P(\mathbf{x}) \quad (2.2)$$

Under the circumstance of environmental regulations (e.g., climate policy), undesirable outputs cannot be freely disposable, i.e., the productive entity has to undertake a certain amount of costs to reduce undesirable outputs. This situation corresponds to the ‘weak disposability’ assumption:

$$(\mathbf{y}, \mathbf{b}) \in P(\mathbf{x}) \text{ and } 0 \leq \theta \leq 1 \text{ imply } (\theta \mathbf{y}, \theta \mathbf{b}) \in P(\mathbf{x}) \quad (2.3)$$

¹Alternatively, the strong disposability assumption can be equally well expressed in terms of the input requirement set (Hailu and Veeman, 2000). This also applies to the assumptions of weak disposability and null-jointness introduced below.

Furthermore, undesirable outputs will be inevitably produced unless the entire production process is terminated. This is the so-called ‘null-jointness’ assumption:

$$\text{if } (\mathbf{y}, \mathbf{b}) \in P(\mathbf{x}) \text{ and } \mathbf{b} = \mathbf{0}, \text{ then } \mathbf{y} = \mathbf{0} \quad (2.4)$$

Weak disposability and null-jointness are the classical assumptions that make the production technology $P(\mathbf{x})$ an environmental production technology (or polluting technology) in the conventional production theory (Färe et al., 1993; Färe and Primont, 1995; Chung et al., 1997).²

To characterize the environmental production technology, distance functions are generally used in the literature. The Shephard distance functions proposed by Shephard (1970) provide the theoretical foundation for measuring the efficiency and productivity of productive entities. Following Färe et al. (1993) and Coggins and Swinton (1996), we define the following Shephard output distance function with undesirable outputs taken into account:

$$D_o(\mathbf{x}, \mathbf{y}, \mathbf{b}) = \inf\{\theta > 0 : (\mathbf{y}/\theta, \mathbf{b}/\theta) \in P(\mathbf{x})\} \quad (2.5)$$

where θ is the value of the output distance function that measures the maximum degree by which $(\mathbf{y}, \mathbf{b})$ can be proportionally increased given $\mathbf{x}$.

Likewise, according to Färe and Primont (1995) and Hailu and Veeman (2000), the Shephard input distance function incorporating undesirable outputs can be defined as follows:

$$D_i(\mathbf{y}, \mathbf{b}, \mathbf{x}) = \sup\{\phi > 0 : (\mathbf{x}/\phi) \in I(\mathbf{y}, \mathbf{b})\} \quad (2.6)$$

where ϕ is the value of the input distance function that measures the maximum degree by which $\mathbf{x}$ can be proportionally reduced given $(\mathbf{y}, \mathbf{b})$.

The Shephard output distance function $D_o(\cdot)$ attempts to increase the desirable and undesirable outputs at the same rate, which may not be consistent with the common desire of public and policymakers to reduce undesirable outputs and increase desirable outputs simultaneously. To “allow for the possibility of crediting firms for the reduction of bad outputs”, the more general directional distance function is proposed (Chambers et al., 1996). Following Chung et al. (1997) and Färe et al. (2005), we formulate the directional output distance function as follows:

$$\tilde{D}_o(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}_y, -\mathbf{g}_b) = \sup\{\beta : (\mathbf{y} + \beta\mathbf{g}_y, \mathbf{b} - \beta\mathbf{g}_b) \in P(\mathbf{x})\} \quad (2.7)$$

where $(\mathbf{g}_y, -\mathbf{g}_b)$ is a direction vector that indicates the direction by which the output combination are scaled, and β is the value of the directional distance function that measures the largest amount by which $\mathbf{b}$ can be deflated and $\mathbf{y}$ can be inflated given $\mathbf{x}$. Recently, the directional distance function has received increasing attention in energy and environmental studies, mainly owing to its flexibility (Zhou et al., 2008).

²See, e.g., Murty et al. (2012); Cherchye et al. (2013); Rødseth (2016, 2017), for recent developments on modeling polluting technology.

Note that there are two fundamental properties that any distance function must possess: feasibility and monotonicity (disposability). In addition, the Shephard distance functions must satisfy the linear homogeneity property, and the directional distance function shall meet the translation property and homogeneity of degree -1 in the direction vector (see, e.g., Färe and Grosskopf, 2000; Färe et al., 2005, for further discussion).

2.2 Estimation Methods

Having introduced the environmental production technology, we turn to describe two vis-à-vis estimation approaches, namely parametric and nonparametric frontier estimation methods, which can be used to evaluate a distance function.

Parametric Methods The parametric methods use a pre-defined functional form to characterize the distance function. Along this line of research, translog (Färe et al., 1993) and quadratic (Färe et al., 2005) are the two commonly-used functional forms. In practice, the translog functional form is generally accompanied by choice of Shephard distance functions, while the quadratic functional form is usually used for characterizing the directional distance function.

Once the functional form is determined, we can use linear programming (LP) or stochastic frontier analysis (SFA) to generate the parameters of distance functions. Aigner and Chu (1968) propose a deterministic LP model for calculating the parameters of distance functions, which has later been widely employed in the shadow price estimation. The objective of the LP model is to seek a set of parameters that minimizes the sum of deviations of the distance function value from the frontier of the environmental production technology. The constraint conditions cover the feasibility, monotonicity (disposability), linear homogeneity or translation property of the distance function to be estimated (Hailu and Veeman, 2000; Färe et al., 2005).

However, a limitation of the deterministic parametric method lies in that it assumes away random noise. This limitation can be overcome by the SFA method (Aigner et al., 1977; Meeusen and Van den Broeck, 1977). Nevertheless, contrary to the deterministic method, the stochastic method does not completely satisfy the monotonicity property, thus imposing inconvenience on setting *a priori* inequality restrictions for the distance function (Rezek and Campbell, 2007).

Nonparametric Methods In addition to the parametric methods, distance functions can also be evaluated by nonparametric ones. A classical nonparametric method for estimating distance functions is data envelopment analysis (DEA) developed by Charnes et al. (1978). The key advantages of DEA over the parametric methods lie in its nonparametric orientation that does not require any parametric specification of the functional form and its strong axiomatic foundation in the axiomatic theory of production. By far, there have been a

number of extensions and variants of DEA developed in the literature, including slacks-based measures (SBM) (Tone, 2001; Fukuyama and Weber, 2009), context-dependent DEA (Seiford and Zhu, 2003; Cook and Zhu, 2008), and network DEA (Färe and Grosskopf, 2000; Kao, 2014), to name but a few.

However, a major shortcoming of DEA is that it is essentially a deterministic method that assumes away random noise. In order to simultaneously impose the axiomatic properties required by the distance functions and deal with stochastic noise in a nonparametric way, one can resort to convex nonparametric least squares (CNLS) (Kuosmanen, 2008) or stochastic nonparametric envelopment of data (StoNED) (Kuosmanen and Kortelainen, 2012) where CNLS serves as the first stage. It is worth noting that Kuosmanen and Johnson (2010) demonstrate that DEA can be treated as a special case of CNLS with shape and sign constraints.

2.3 Shadow Price Derivation

An important theoretical application of the production theory that relates to this dissertation is the estimation of shadow prices and MACs for undesirable outputs. Färe et al. (1993) propose a seminal framework for shadow pricing undesirable outputs by incorporating undesirable outputs into the Shephard output distance function and estimating the shadow prices using parametric programming, and then the estimated shadow prices are considered as the MACs for undesirable outputs. This line of thought has led to several important variants of the original shadow pricing framework (e.g., Turner, 1995; Boyd et al., 1996; Hailu and Veeman, 2000; Lee et al., 2002; Färe et al., 2005; Rødseth, 2013; Lee et al., 2014) and a number of publications that report shadow price estimates for undesirable outputs (see Chapter 3).

The derivation of shadow prices is built upon the relationship between a distance function and its dual form. According to Färe et al. (1993); Hailu and Veeman (2000) and Färe et al. (2005), the dual functions of the output-oriented and input-oriented distance functions are the revenue and cost functions, respectively. The revenue function is the optimal solution to a revenue-maximization problem

$$R(\mathbf{x}, \mathbf{p}) = \max_{(\mathbf{y}, \mathbf{b})} \{\mathbf{p}'\mathbf{y} + \mathbf{r}'\mathbf{b} : D_o(\mathbf{x}, \mathbf{y}, \mathbf{b}) \leq 1 \text{ or } \bar{D}_o(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}_y, \mathbf{g}_b) \geq 0\} \quad (2.8)$$

where $\mathbf{p} \in \mathbb{R}_+^M$ is the price vector of desirable outputs and $\mathbf{r} \in \mathbb{R}_+^K$ denotes the price vector of undesirable outputs. In contrast to $R(\mathbf{x}, \mathbf{p})$, the cost function is the optimal solution to a cost-minimization problem

$$C(\mathbf{y}, \mathbf{b}, \mathbf{w}) = \min_{\mathbf{x}} \{\mathbf{w}'\mathbf{x} : D_i(\mathbf{y}, \mathbf{b}, \mathbf{x}) \geq 1\} \quad (2.9)$$

where $\mathbf{w} \in \mathbb{R}_+^N$ is the input price vector.

Through applying the Lagrangian method, the envelope theorem, and the Shephard lemma, the shadow pricing formulas for undesirable output j via the

Shephard output distance function, the Shephard input distance function, and the directional output distance function are respectively derived as follows:

$$r_j = p_i \cdot \frac{\partial D_o(\mathbf{x}, \mathbf{y}, \mathbf{b}) / \partial b_j}{\partial D_o(\mathbf{x}, \mathbf{y}, \mathbf{b}) / \partial y_i} \quad (2.10)$$

$$r_j = p_i \cdot \frac{\partial D_i(\mathbf{y}, \mathbf{b}, \mathbf{x}) / \partial b_j}{\partial D_i(\mathbf{y}, \mathbf{b}, \mathbf{x}) / \partial y_i} \quad (2.11)$$

$$r_j = p_i \cdot \frac{\partial \vec{D}_o(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}_y, -\mathbf{g}_b) / \partial b_j}{\partial \vec{D}_o(\mathbf{x}, \mathbf{y}, \mathbf{b}; \mathbf{g}_y, -\mathbf{g}_b) / \partial y_i} \quad (2.12)$$

By using p_i in the above formulas, we assume that the market price of desirable output i is known and equal to its shadow price. Note that the distance functions in the shadowing pricing formulas can be estimated by alternative methods as introduced in Section 2.2.

However, the shadow pricing framework described above is the conventional view, which will be critically discussed and challenged in Essay I.

2.4 Productivity Decomposition

Another critical application of the production theory discussed in this dissertation is the measurement of environmental productivity change.

In the literature, environmental productivity change in multiple-input or multiple-output settings is generally assessed by TFP indices. The estimation of environmental TFP is quite challenging because one must somehow manage to aggregate the inputs and the outputs but without readily available price data for environmental bads (see, e.g., Kuosmanen, 2013, for a more detailed discussion). In this context, the Malmquist TFP index proposed by Caves et al. (1982) (or one of its many variants such as the Malmquist-Luenberger index proposed by Chung et al. 1997) has been the most common environmental TFP indicator, because it does not require price data for environmental bads, but rather employs shadow prices of technology distance functions.

Assume for the moment that the Shephard output and input distance functions defined in Equations (2.5–2.6) have been estimated by one method or another, we can respectively derive the output- and input-oriented Malmquist indices of environmental productivity change as follows:

$$MO(t, t+1) = \left[\frac{D_o^t(\mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{b}^{t+1})}{D_o^t(\mathbf{x}^t, \mathbf{y}^t, \mathbf{b}^t)} \times \frac{D_o^{t+1}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{b}^{t+1})}{D_o^{t+1}(\mathbf{x}^t, \mathbf{y}^t, \mathbf{b}^t)} \right]^{1/2} \quad (2.13)$$

$$MI(t, t+1) = \left[\frac{D_i^t(\mathbf{y}^t, \mathbf{b}^t, \mathbf{x}^t)}{D_i^t(\mathbf{y}^{t+1}, \mathbf{b}^{t+1}, \mathbf{x}^{t+1})} \times \frac{D_i^{t+1}(\mathbf{y}^t, \mathbf{b}^t, \mathbf{x}^t)}{D_i^{t+1}(\mathbf{y}^{t+1}, \mathbf{b}^{t+1}, \mathbf{x}^{t+1})} \right]^{1/2} \quad (2.14)$$

It is said that there is environmental TFP growth from period t to $t+1$ if the value of $MI(t, t+1)$ or $MO(t, t+1)$ is greater than unity, and environmental productivity decline if the value is less than unity.

Alternatively, we can derive the Malmquist index based on the directional output distance function defined in Equation (2.7), which is generally referred to as the Malmquist-Luenberger index (Chung et al., 1997):

$$ML(t, t+1) = \left[\frac{1 + \bar{D}_o^t(\mathbf{x}^t, \mathbf{y}^t, \mathbf{b}^t; \mathbf{g}_y^t, -\mathbf{g}_b^t)}{1 + \bar{D}_o^t(\mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{b}^{t+1}; \mathbf{g}_y^{t+1}, -\mathbf{g}_b^{t+1})} \times \frac{1 + \bar{D}_o^{t+1}(\mathbf{x}^t, \mathbf{y}^t, \mathbf{b}^t; \mathbf{g}_y^t, -\mathbf{g}_b^t)}{1 + \bar{D}_o^{t+1}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1}, \mathbf{b}^{t+1}; \mathbf{g}_y^{t+1}, -\mathbf{g}_b^{t+1})} \right]^{1/2} \quad (2.15)$$

Likewise, $ML(t, t+1)$ indicates environmental productivity growth from period t to $t+1$ if its value is greater than unity, and environmental productivity decline if the value is less than unity.

The Malmquist indices can be decomposed into two components, namely technical change (TC) and efficiency change (EC) (Nishimizu and Page, 1982; Chung et al., 1997). Taking the input-oriented Malmquist index as an example, the decomposition proceeds as below:

$$MI(t, t+1) = MITC(t, t+1) \times MIEC(t, t+1) \quad (2.16)$$

$$MITC(t, t+1) = \left[\frac{D_i^{t+1}(\mathbf{x}^t, \mathbf{y}^t)}{D_i^t(\mathbf{x}^t, \mathbf{y}^t)} \times \frac{D_i^{t+1}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1})}{D_i^t(\mathbf{x}^{t+1}, \mathbf{y}^{t+1})} \right]^{1/2} \quad (2.17)$$

$$MIEC(t, t+1) = \frac{D_i^t(\mathbf{x}^t, \mathbf{y}^t)}{D_i^{t+1}(\mathbf{x}^{t+1}, \mathbf{y}^{t+1})} \quad (2.18)$$

The technical change component accounts for the shift of production frontier over time: there is technical progress from period t to $t+1$ if $MITC(t, t+1) > 1$, and technical regress if $MITC(t, t+1) < 1$. As for the efficiency change component $MIEC(t, t+1)$, a value greater (or less) than unity indicates that the evaluated production unit is catching up to (or moving farther from) the frontier. It is worth mentioning that Färe et al. (1994) propose a third component: *scale efficiency change* under variable returns to scale (VRS). Yet, no consensus has been reached on the derivation and interpretation of this component. See Färe et al. (1997) and Ray and Desli (1997) for a critical exchange on this issue and Lovell (2003) for a more detailed discussion.

Note, however, that it is not self-evident how the TFP measurement and decomposition could be applied in the context of consumer durables, and what kind of adjustments or revisions might be needed. These issues will be critically examined and discussed in Essays II and III.

3. Survey of Empirical Literature

In the previous chapter, we introduce the production theory and its two application domains that underlie the dissertation. In this chapter, we present a brief but critical survey of the empirical literature concerning the two domains. The objective of the survey is to clarify the structure of the empirical literature and pinpoint the research gaps and shortcomings addressed in this dissertation. Note that the first section of this chapter is mainly based on and adapted from Zhou et al. (2014, Section 4) and the second section is drawn from Essay II.

3.1 MAC Estimation

There exist multiple different approaches to estimating MACs, including *engineering approaches* such as power system optimization models and mitigation technology assessment (e.g., Kesicki and Strachan, 2011; Kesicki, 2013), *simulation-based approaches* such as integrated assessment models and computable general equilibrium models (e.g., Nordhaus and Boyer, 1999; Klepper and Peterson, 2006; Nordhaus, 2019), and *data-driven approaches* such as econometric approaches and frontier estimation methods (Zhou et al., 2014). Different approaches to estimating MACs are useful in different contexts, and each methodology has its own advantages and disadvantages (Lee et al., 2014; Huang et al., 2016). Considering the recent growth of analytics and evidence-based decision making, we expect frontier estimation methods to play a more prominent role in the future environmental policy and management.

Table 3.1 summarizes shadow pricing studies using frontier estimation methods in terms of their key features, including the type of study, undesirable output(s), DMUs, and the estimation method. Notably, the scope of undesirable outputs has been expanded over time. Earlier studies mainly focused on air and water pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), suspended particulate, and biochemical oxygen demand (BOD). Shadow prices of these pollutants are calculated to approximate their MACs for policy support as a consequence of growing stringent environmental regulations across the world. Later, the international communities have been aware of the huge risk arising

from global climate change to the survival and development of human beings. Reducing greenhouse gases (particularly CO₂ emissions) has evolved as one of the most crucial issues in the world. Consequently, estimating the shadow prices of CO₂ and other greenhouse gases, which shares the same shadowing pricing procedure as local pollutants, has attracted the attention of many researchers.

Table 3.1. Studies on Shadow Pricing Undesirable Outputs with Frontier Estimation Methods
(Extended from Zhou et al., 2014).

Publication	Type	Undesirable output(s)	DMUs	Methodology
Färe et al. (1993)	M+A	BOD, TSS, TSP, SO _x	U.S. paper and pulp mills	T/ODF/PD
Turner (1995)	M+A	SO ₂	U.S. electric plants	SV- ODF/N/DEA
Coggins and Swinton (1996)	A	SO ₂	U.S. coal-burning electric plants	T/ODF/PD
Boyd et al. (1996)	M+A	SO ₂	U.S. coal-burning electric plants	DDF/N/DEA
Swinton (1998)	A	SO ₂	U.S. coal-burning electric plants	T/ODF/PD
Kwon and Yun (1999)	A	SO _x , NO _x , TSP, CO ₂	South Korea's bunker-C & coal-burning electric plants	T/ODF/PD
Hailu and Veeman (2000)	M+A	BOD, TSS	Canada's pulp and paper industry	T/IDF/PD
Reig-Martinez et al. (2001)	A	Watery muds, used oil	Spain's ceramic pavement firms	T/ODF/PD
Lee et al. (2002)	M+A	SO _x , NO _x , TSP	South Korea's fossil-fueled electric plants	DDF/N/DEA
Boyd et al. (2002)	A	NO _x	U.S. glass plants	DDF/N/DEA
Murty and Kumar (2002)	A	BOD, COD	India's water polluting firms	T/ODF/PD&PS
Aiken and Pasurka (2003)	A	SO ₂ and PM-10	U.S. manufacturing industries	T/ODF/PD
Lee (2005)	M+A	SO ₂	U.S. coal-burning electric plants	T/IDF/PD
Atkinson and Dorfman (2005)	M+A	SO ₂	U.S. electric utilities	T/IDF/P- Bayesian
Maradan and Vassiliev (2005)	A	CO ₂	Developed and developing countries	DDF/N/DEA
Färe et al. (2005)	M+A	SO ₂	U.S. electric utilities	Q/DDF/PD&PS
Färe and Grosskopf (2006)	A	Human-risk leaching runoff of pesticides	U.S. agricultural sector	Q/DDF/PD
Vardanyan and Noh (2006)	M+A	SO ₂	U.S. electric generating units	T/ODF, H-ODF& Q/DDF/PD
Murty et al. (2006)	A	BOD, COD, TSS	India's sugar firms	T/IDF/PD
Rezek and Campbell (2007)	M+A	Mercury, SO ₂ , NO _x , CO ₂	U.S. coal-burning electric plants	CD/ODF/P- GME
Van Ha et al. (2008)	A	BOD, COD, TSS	Vietnam's household-level paper recycling units	T/ODF/PD&PS
Ke et al. (2008)	A	SO ₂	China's provincial regions	T/ODF/PD
Park and Lim (2009)	A	CO ₂	South Korea's electric plants	T/ODF/PD
Hernández-Sancho et al. (2010)	A	Nitrogen, TSS, phosphorus, BOD, COD	Spain's wastewater treatment plants	T/ODF/PD
Kaneko et al. (2010)	A	SO ₂	China's thermal power sector	DDF/N/DEA
Lee (2011)	A	CO ₂	South Korea's fossil-fueled electric generators	T/ODF/PD
Wang et al. (2011)	A	CO ₂	China's provincial regions	DDF/N/DEA
Wei et al. (2012)	A	CO ₂	China's provincial regions	DDF/N/SBM

Choi and Ang (2012)	M+A	CO ₂	China's provincial regions	DDF/N/SBM
Färe et al. (2012)	A	SO ₂ , NO _x	U.S. coal-burning electric plants	Q/DDF/PD
Lee and Zhang (2012)	A	CO ₂	China's manufacturing industries	T/IDF/PD
Matsushita and Yamane (2012)	A	CO ₂ , low-level wastes	Japan's electric companies	Q/DDF/PD
Yuan et al. (2012)	A	CO ₂	China's industrial sectors	DDF/N/DEA
Wei et al. (2013)	A	CO ₂	China's electric enterprises	Q/DDF/PD
Rødseth (2013)	M	-	Enhancing the general shadow-pricing procedure	Q/DDF/PD
Chen (2013)	A	CO ₂	China's industrial sectors	DDF/N/DEA
Mekaroonreung and Johnson (2014)	M+A	SO ₂ , NO _x	U.S. bituminous coal-burning electricity plants	DDF/N/CNLS, StoNED
Zhang et al. (2014b)	A	CO ₂	China's provincial regions	Q/DDF&T/ODF/PD
Du and Mao (2015)	A	CO ₂	China's coal-burning electric plants	Q/DDF/PD
Molinos-Senante et al. (2015)	A	CO ₂	Spain's wastewater treatment plants	Q/DDF/PD
Zhou et al. (2015)	A	CO ₂	Shanghai's manufacturing industries	Q/DDF, T/ODF&T/IDF/PD, DDF/N/DEA
Tang et al. (2016a)	A	Nitrogen, COD, phosphorus	China's regional agricultural sectors	Q/DDF/PD
Tang et al. (2016b)	A	Greenhouse gases	Australia's farms	T/IDF/PD
Wang and He (2017)	A	CO ₂	China's regional transportation sectors	DDF/N/DEA
Wang et al. (2017)	A	CO ₂	China's regional iron and steel industries	Q/DDF/PD
Peng et al. (2018)	A	CO ₂	China's thermal power sector	Q/DDF/PD

Note: M=Methodological study; A=Application study; T=Translog function; Q=Quadratic function; CD=Cobb-Douglas; ODF=Shephard output distance function; IDF=Shephard input distance function; DDF=Directional output distance function; PD=Parametric deterministic; PS=Parametric stochastic; N=Nonparametric; SV=Sub-vector; GME=General maximum entropy; COD=Chemical oxygen demand; TSP= total suspended particulate; TSS=total suspended solids.

Consider next the methodological aspect. The general shadow pricing procedure described in Section 2.3 has been followed by most of the studies. The variation in the methodological aspect mainly arises from the choice of distance functions and estimation methods. Evidently, the majority of earlier studies employed the Shephard distance functions while recent studies preferred the directional distance function. Along with the trend of transferring from the Shephard to the directional distance function, the nonparametric estimation method that lets the data speak for themselves has been increasingly applied. However, the parametric method that needs a pre-defined functional form keeps being a popular approach to shadow pricing. Furthermore, whether to use the deterministic or stochastic method is an issue worth considering as well. The deterministic method completely satisfies the monotonicity, which facilitates researchers to set *a priori* inequality restrictions on the distance function. On the contrary, the stochastic method permits hypothesis testing and measurement of random noise. In practice, however, the deterministic methods still

predominated compared to the stochastic methods. Apart from the above variations in methodology, the shadow pricing framework for undesirable outputs continues to be improved and extended by many researchers (see, e.g., Atkinson and Dorfman, 2005; Rezek and Campbell, 2007; Mekaroonreung and Johnson, 2014; Rødseth, 2013; Lee et al., 2014; Lee and Zhou, 2015; Lee and Wang, 2019) and the present thesis work.

Despite a large number of shadow pricing studies, we observe that empirical MAC estimates of CO₂ emissions using frontier estimation methods are usually 10–100 times higher than the market prices of CO₂ allowances in emissions trading. For example, the prices of CO₂ allowances fluctuated within the range of €5 – €15 per tonne in the European Union, \$12 – \$15 per tonne in California, and €5 – €10 per tonne in Beijing in years 2014–2018 (see the Appendix of Essay I for further details). For comparison, a recent study by Lee and Wang (2019) reviews 11 published studies with MAC estimates of CO₂ in different countries ranging between \$16–\$476 per tonne. While the market prices and shadow prices cited above are not directly comparable, we find it disturbing that the shadow price estimates tend to be always far above the observed price range of CO₂ permits, and not just marginally but by factor 10–100.

Some have questioned the traditional shadow pricing framework about its shortcomings and provided several extensions. Firstly, the shadow price generally denotes the opportunity cost to reduce the undesirable output in terms of less production of the desirable output. This might be inconsistent with the actual operation of business firms which have many other options to reduce undesirable outputs. Lee (2005) attempts to compute the shadow price of SO₂ by measuring the opportunity cost of reducing sulfur in terms of forgone capital inputs, based upon a translog input distance function estimated by the parametric deterministic method. Further, Rødseth (2013) constructs a production model in which alternative compliance strategies of a DMU are incorporated, and the MACs calculated through a parametric directional distance function approach represent the least costly way to reduce undesirable outputs among the alternative abatement options. Secondly, the estimation of shadow prices based on the efficient frontier will likely yield higher MAC estimates for inefficient units located far below the efficient frontier. This important fact is recognized by Lee et al. (2002) and they introduce a correction factor in the directional distance function approach. Unfortunately, this correction factor implicitly imposes strong arbitrary assumptions about the adjustment path to the frontier.

3.2 Environmental TFP Measurement

In recent decades, a large number of studies on environmental TFP have appeared across various sub-disciplines of economics (e.g., energy economics, environmental economics, ecological economics, agricultural economics, production economics, mathematical economics, and econometrics) as well as in other re-

lated disciplines such as operations research, management science, engineering, and public administration. Note that there are several similar notions of environmental productivity in the literature, including environmentally sensitive productivity, green TFP, environmental performance, and various forms of eco-efficiency.

In these studies, production units (or DMUs) of interest are usually *plants* or *firms*, *sectors* or *industries*, *regions*, and *countries* (see Table 3.2). To our knowledge, however, there is a paucity of well-developed studies investigating environmental TFP growth in consumption, especially the consumption of durable goods (Kortelainen and Kuosmanen, 2007; Zhou, 2018). This is somewhat surprising because, during their use phase, consumer durables such as passenger cars, washing machines, refrigerators, and other home appliances are in fact production units that consume energy and resources (and hence generate environmental pollutants) to provide services for consumers.

Table 3.2. Summary of Some Environmental TFP Studies.

Classification of DMUs	DMUs	Publication	TFP index
Plant/firm	Sweden's paper and pulp mills	Chung et al. (1997)	Malmquist-Luenberger
Plant/firm	China's fossil-fueled electric plants	Zhang and Choi (2013)	Malmquist
Plant/firm	Iran's gas-burning electric plants	Arabi et al. (2017)	Malmquist-Luenberger
Plant/firm	China's fossil-fueled electric plants	Song et al. (2017)	Malmquist-Luenberger
Plant/firm	China's coal-burning electric plants	Yu et al. (2017b)	Luenberger
Plant/firm	China's iron and steel enterprises	He et al. (2013)	Malmquist & Malmquist-Luenberger
Plant/firm	China's automobile manufacturers	Du et al. (2017a)	Malmquist-Luenberger
Plant/firm	China's airlines	Liu et al. (2017)	Malmquist
Sector/industry	OECD countries' agriculture	Kuosmanen (2013)	Malmquist
Sector/industry	China's agriculture	Lin and Fei (2015)	Malmquist
Sector/industry	China's transportation industry	Zhang et al. (2015)	Malmquist
Sector/industry	China's transportation industry	Yu et al. (2017a)	Malmquist-Luenberger
Sector/industry	China's light manufacturing industries	Emrouznejad and Yang (2016)	Malmquist-Luenberger
Sector/industry	China's nonferrous metals industry	Shao and Wang (2016)	Malmquist & Malmquist-Luenberger
Sector/industry	China's manufacturing industries	Yao et al. (2016)	Malmquist
Sector/industry	China's paper and pulp industry	Yu et al. (2016)	Malmquist-Luenberger
Provincial regions	China's provincial regions	Zhang et al. (2011)	Malmquist-Luenberger
Provincial regions	China's provincial regions	Du et al. (2017b)	Malmquist-Luenberger
Provincial regions	China's provincial regions	Sueyoshi et al. (2017)	Malmquist
Countries	OECD countries	Färe et al. (1994)	Malmquist
Countries	World's top CO ₂ emitting countries	Zhou et al. (2010)	Malmquist
Countries	Developed and developing countries	Aparicio et al. (2017)	Malmquist-Luenberger
Countries	OECD countries	Shen et al. (2017)	Luenberger

A possible reason for this research gap is that services provided by consumer durables go unmeasured in economic censuses, and thus the environmental TFP of consumer durables has gained little attention in the literature of efficiency and productivity analysis.¹ However, we cannot ignore the importance of consumer durables in providing services for consumers and in casting pressure on the natural environment. For instance, the use of passenger cars—the main category of consumer durables—is a very convenient and flexible means of transportation in daily life but also an important contributor to emissions of greenhouse gases

¹Note the difference between TFP and partial indicators such as the fuel economy (l/100km) or CO₂ level (g/km) of cars.

and air pollutants. Therefore, environmental productivity growth in consumer durables, which balances sustainability and human well-being, is fundamentally important for a successful low-carbon transition in consumption and calls for in-depth studies.

Since consumer durables are, in fact, production units during their use phase, we can, in principle, estimate environmental TFP change in consumer durables within the existing productivity analysis framework described in Section 2.4. Note, however, that this framework was originally developed for conventional production units; a mechanical application to consumer durables may encounter problems or even lead to biased or inaccurate estimates because consumer durables differ from conventional production units in a number of important respects. Therefore, to investigate environmental TFP change in consumer durables warrants a rigorous modeling of the environmental production technology for the use phase of consumer durables.

Further, environmental TFP growth does not guarantee a decrease in CO₂ emissions due to the rebound effect. If the absolute change in CO₂ emissions, rather than the unit-invariant TFP index, is of interest, it is particularly important to figure out the mechanisms through which regulatory measures (e.g., climate policy) and social-economic environment can influence CO₂ emissions from new consumer durables (e.g., new passenger cars). Empirical studies have identified such pathways as consumer choices and available technology (e.g., Meyer and Wessely, 2009; Kok, 2013; MacKenzie and Heywood, 2015) as well as test manipulation (e.g., Dings, 2013; Tietge et al., 2016; Fontaras et al., 2017). However, no systematic decomposition of the change in the CO₂ emissions of new consumer durables to these pathways is available in the literature. This is clearly a major research gap that needs to be filled, as a comprehensive understanding of the pathways can greatly facilitate evidence-based policymaking in decarbonizing new consumer durables.

4. Research Questions

Through the literature survey in the previous chapter, we identify the following important research questions of interest:

- Q1. Are MACs always equivalent to the shadow prices of bad outputs in terms of forgone good outputs?
- Q2. How to adjust the MAC estimation for inefficiency and stochastic noise?
- Q3. What are the particular features of consumer durables compared to conventional production units?
- Q4. How to model the production activity during the use phase of consumer durables and measure the environmental TFP change?
- Q5. What are the mechanisms through which regulatory measures and social-economic environment influence CO₂ emissions from new passenger cars?
- Q6. How to decompose the changes in CO₂ emissions of new passenger cars to underlying factors such as technology, efficiency, and policy measures?

This dissertation examines Q1 and Q2 in Essay I, Q3 and Q4 in Essay II, and Q5 and Q6 in Essay III.

5. Summary of Results

In the previous chapter, we present the research questions of interest that guide this dissertation. The purpose of the present chapter is to shed light on the questions by reporting and synthesizing the major results obtained from the three scientific essays.

5.1 Essay I: A Novel Data-Driven Approach to MAC Estimation

Essay I is motivated by the observation that empirical MAC estimates of CO₂ using frontier estimation methods such as DEA and parametric programming are usually 10–100 times higher than the market prices of tradable CO₂ allowances. In this essay, we argue that the gross overestimation of MACs is due to three reasons. First, assuming downscaling of production as the only abatement option ignores abatement through increasing the input use. Second, estimating shadow prices on the frontier ignores the impact of inefficiency. Third, estimating the frontier by deterministic methods ignores the upward bias due to noise in empirical data.

We have developed a novel data-driven approach based on convex quantile regression to estimate shadow prices and MACs for undesirable outputs such as CO₂. The proposed approach effectively addresses the three sources of upward bias in the traditional shadow pricing approach. Based on the results of Essay I, my answer to Q1 is “no”. Specifically, drawing a clear conceptual distinction between shadow prices and MACs, we redefine the MAC as the least-cost alternative among multiple abatement options, including the conventional option to downscale activity, but also the capital investment (e.g., cleaner technology, end-of-pipe abatement technologies) and increasing the variable input (e.g., fuel switch, improving the quality of operation and maintenance) as alternative abatement options.

My answer to Q2 is as follows: We apply convex quantile regression to estimate shadow prices not only on the efficient frontier but also in the interior of the production possibility set. The proposed quantile approach ensures that the shadow prices and MACs for bad outputs are estimated at the actual level of

performance of the evaluated units. The local estimation approach makes the proposed quantile approach less sensitive to the choice of the direction vector as there is no need to project inefficient firms to the efficient frontier. In contrast to the deterministic DEA, which is known to be sensitive to noise in empirical data, the convex regression approach takes both noise and inefficiency explicitly into account in the estimation of quantiles. Indeed, the quantiles differ from each other specifically due to heteroscedastic inefficiency and noise.

In the empirical part of Essay I, the proposed convex quantile approach to marginal abatement cost estimation was applied to a sample of U.S. electric power plants. The main purpose of this application was to demonstrate using high-quality plant-level data used by numerous empirical studies that our proposed approach yields systematically lower marginal abatement cost estimates than the traditional DEA approach. The median of the conventional DEA estimates is 660 times higher than our corresponding estimate obtained by convex quantile regression. If one takes the input-side abatement alternatives into account in DEA estimation, following our definition of marginal abatement cost, the median DEA estimate is still 61 times higher than our quantile based estimate. While we recognize the need for further research on convex quantile regression, in our view, the empirical application clearly demonstrates that the three innovations proposed in this paper are revolutionary rather than evolutionary.

5.2 Essay II: An Environmental TFP Index Specific to Consumer Durables

Essay II starts with identifying four particular features of consumer durables compared to conventional production units.

- 1) In a region under consideration, the total fleet of a category of consumer durables can reach a huge size and face the dynamics involving entry of new consumer durables and exit of older ones at each moment.
- 2) Consumer durables are not DMUs—their environmental productivity are not influenced by themselves but regulators, producers, consumers, and ambient conditions.¹
- 3) Real-world data on environmental costs (fuel consumption and emissions) at the consumer durable level tend to be unavailable or difficult to obtain.²

¹For example, fuel consumption of passenger cars on roads are affected by driving behavior, vehicle maintenance, and ambient conditions (e.g., temperature, road, traffic flow, altitude, and weather) (VCA, 2016). As a result, even given cars of the same make and model, the actual amounts of fuel consumption may vary significantly.

²Estimation of real-world fuel consumption and CO₂ emissions of consumer durables, passenger cars in particular, has attracted a lot of attention. See, e.g., André et al. (2006); Alvarez and Weilenmann (2012); Dings (2013); Zhang et al. (2014a).

- 4) A consumer durable usually uses a single type of fuel (gasoline, diesel, or electricity). The amount of fuel consumption directly determines the level of its CO₂ emissions.

This summary of the particular features of consumer durables, therefore, answers Q3.

My answer to Q4 is the following: In Essay II, the particular features of consumer durables are explicitly taken into account to develop a Malmquist-type environmental TFP index specific to the use of consumer durables. More specifically, our specification of the polluting technology for passenger cars—a typical example of consumer durables—considers CO₂ emissions as the input and transportation services as the outputs, thereby breaking the direct proportionality between fuel consumption and CO₂ emissions. We sort individual passenger cars into the corresponding car models and use a representative car of each yearly cohort in order to make it possible to interpret and compute the Malmquist-type index based on large-sized and unbalanced panel data.

In order to illustrate the interpretation of the proposed index, we apply it to investigate the environmental productivity change in new gasoline cars in Finland from 2002 to 2014. The empirical study has found that the environmental TFP of new gasoline cars in Finland grew at an average rate of 3.22% per year between 2002 and 2014. Over 95% of the growth was due to the technical progress that occurred in models of new gasoline cars over the years. Although the contribution of Finnish car consumers to the growth was, on average, rather modest, they played an important role around year 2008 when Finland introduced a CO₂-based vehicle registration tax.

5.3 Essay III: A Novel Decomposition of CO₂ Emissions from New Passenger Cars

This essay extends Essay II by developing a new decomposition method to gain insights into the driving factors behind the decarbonization of new passenger cars. Our decomposition offers three major benefits compared to previous works (and answers Q5 and Q6 as well). First, it systematically breaks down the change in the average CO₂ emissions of new passenger cars to components representing changes in the available technology, carbon efficiency of consumer choices, vehicle attributes, fuel mix, and test manipulation. Second, it combines insights from the traditional index decomposition analysis with a frontier-based decomposition. Note that the main difference to the existing frontier-based decomposition is that our decomposition effectively avoids any scale efficiency component. Estimating the technology frontier by CNLS allows us to handle stochastic noise without a need to assume *a priori* any particular functional form for the emissions generating function. Third, the proposed decomposition satisfies the desirable properties of time reversal, factor reversal, and zero-value robustness.

In the empirical part of this essay, the proposed decomposition is applied to unique Finnish register data for years 2002–2014 to quantify the driving factors behind the decarbonization of the Finnish new car fleet. Our results demonstrate that technical change was the most important pathway of decreasing CO₂ emissions, and the technical progress in new cars remains the strongest driver even when we adjust for the test manipulation. Our decomposition also helps to understand better the impact of the CO₂-based vehicle registration tax that was introduced in Finland in 2008. While the tax had a rather modest effect on the carbon efficiency of consumer choices, at least, it helped to slow down the increasing demand for heavier and more powerful cars.

5.4 Synthesis

In summary, this dissertation has

- 1) developed a novel data-driven approach to MAC estimation, which eliminates three sources of upward bias (Essay I);
- 2) enhanced the environmental TFP index approach to incorporate the low-carbon transition in consumption (Essay II);
- 3) proposed a novel decomposition method that breaks down the change in the average CO₂ emissions of new passenger cars into a series of systematically defined components (Essay III).

The linkages between the three essays are illustrated in Figure 5.1.

Figure 5.1. Conceptual Framework of the Dissertation.

6. Policy Implications and Future Research

In the previous chapter, we summarize the major results of the dissertation. The present chapter proceeds to discuss the policy implications of our findings and suggest possible revenues for future research.

6.1 Policy Implications

It is worth emphasizing that the systematic over-estimation of MACs has profound and far-reaching policy implications. If the policymakers believe that CO₂ abatement is prohibitively expensive, they are less likely to consider mitigation options, and are more likely to favor adaptation strategy, or simply accept the damage cost due to climate change. For example, the perceived high economic cost of the Kyoto Protocol (see, e.g., Nordhaus and Boyer, 1999) was the main reason why the U.S. did not commit to the Kyoto targets. If better estimation methods enable empirical researchers to identify affordable abatement options (not only through downscaling production but also through capital investment and increased input use) and adjust for inefficiency in production, new empirical evidence could convince policymakers around the world to pursue a more ambitious low-carbon transition called for by the Intergovernmental Panel on Climate Change (IPCC).

In terms of the low-carbon transition in consumption (specifically the Finnish new car fleet in this dissertation), the critical role of technological progress demonstrated by the technical change component in Essay II or the available technology component in Essay III clearly highlights the importance of the technical standards at the EU level. Strict emissions standards in such major markets such as the EU or the USA will influence car manufacturers around the world. In contrast, as far as car technology is concerned, the possibilities of a single EU member state such as Finland are very limited. However, an individual state can considerably influence consumer choices by national policy instruments such as taxes and subsidies. Achieving further environmental TFP growth in passenger cars or decrease in the fleet average CO₂ emissions will have to heavily rely on technical progress, but also employ effective policy

instruments to incentivize consumers to choose carbon-efficient models and counter the demand for heavier and more powerful cars. We believe that the empirical analysis in Essays II and III helps to put the relative contributions of better technology and the CO₂-based vehicle registration tax to an appropriate perspective. Such empirical evidence is critically important going forward as Finnish policymakers are planning and designing future policy instruments. Further, we hope that the empirical evidence can also help other states and countries to develop better policy measures to promote a successful low-carbon transition in consumption.

6.2 Avenues for Future Research

In the following, we indicate several fascinating avenues for future research, both in theoretical and empirical domains.

- 1) Extending the convex quantile regression approach to estimate the marginal abatement cost curve.
- 2) Examining the statistical properties and performance of convex quantile regression, both in theory and in terms of systematic Monte-Carlo simulations.
- 3) Extending the convex quantile regression approach to other environmental bads (e.g., SO₂, NO_x, PM-2.5).
- 4) Extending the convex quantile regression approach from the plant and firm level studies to sectors, industries, regions, and countries.
- 5) Investigating environmental TFP growth in other kinds of consumer durables (e.g., refrigerators, washing machines).
- 6) Applying alternative estimation methods and/or productivity indices to the emerging study of consumer durables.
- 7) Extending the novel decomposition method to electric vehicles.
- 8) Extending the novel decomposition method to model the dynamics of the entire fleet of vehicles, not only the new passenger cars.
- 9) Extending the novel decomposition method to trucks, vans, and buses.

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