INTERCONNECTIONS BETWEEN REGIONAL INDUSTRIAL STRUCTURE AND ENERGY CONSUMPTION PATTERNS

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INTERCONNECTIONS BETWEEN REGIONAL INDUSTRIAL STRUCTURE AND ENERGY CONSUMPTION PATTERNS

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To My Husband Chen Chen

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LIST OF SYMBOLS AND ABBREVIATIONS

CES	Constant elasticity of substitution
CET	Constant elasticity of transformation
CGE	Computable general equilibrium
FE	Fixed-effect
GSP	Gross state product
IDA	Index decomposition analysis
IO	Input-output
LMDI	Logarithmic mean divisia index
NAICS	North American Industry Classification System
RCD	Revealed comparative dependence
SAC	Structural adjustment cost
SAM	Social accounting matrix
SDA	Structural decomposition analysis
WAP	Weighted average proximity
wRCD	Weighted revealed comparative dependence

SUMMARY

Two critical components of sustainability are maintaining the development of the human system and preserving nature's supporting systems. To reconcile these two components, we need to be able to evaluate the performance of the systems, and to understand how they interact with each other. As a large percentage of human activities are economic in nature, a key measure for the society's robustness is its industrial structure. To connect economic activities with the ecosystem, the society's energy consumption provides much information, as it establishes a linkage between resource exploitation (energy source extraction) with pollution generation (greenhouse gas emission).

In this dissertation, I investigate the interconnection between regional industrial structure and energy consumption patterns at the U.S. state level. I start by exploring the "stage", i.e., by characterizing the U.S. state level industrial structure through a simple measure. This step looks at regional dependence on sectors and economic robustness purely from the economic perspective. I then bring the industrial structure into context with an economy's energy consumption. Two major components of my research are dedicated to addressing their interconnection: isolating the historical impact of industrial structure on energy use patterns through accounting for sector interaction, and predicting the response of an economy towards an energy efficiency shock.

The study consists of three major parts. In the first part, I evaluate the difference in industrial structure and economic resilience level across U.S. states. I first develop an indicator, revealed comparative dependence (RCD), to compare regions' level of dependence on different sectors. Based on RCD, I further use a weighted version of RCD

(wRCD) to measure how much a sector contributes to the industrial structure diversity of an economy. I then calculate the industrial structure diversity indices for each state economy. The diversity indices are used as state-level economic resilience scores, allowing for state ranking. Results show that resilient ranking is not directly correlated with the size of a regional economy. In terms of structural patterns, more resilient states are likely to depend more on manufacturing sectors, while less resilient states tend to focus on natural resource-oriented sectors. Between 1997 and 2010, while the balance of the national output composition did not changed significantly, state resilience rankings fluctuated noticeably.

Second, I bring the industrial structure into context with energy consumption. This is done through an examination of how historical regional industrial structure transition determines industrial energy use at the U.S. state level. As in the first part, RCD is used to compare regional dependence on various sectors. Incorporating RCD into index decomposition analysis, I show that state-specific structural transition against the national trend has significantly changed state-level industrial energy use. I then test the real contribution of industrial structure change to energy use, highlighting the role of developing dependence on energy-efficient sectors, as well as the secondary effect triggered by sector interaction. First, building on RCD, I construct a measure to characterize the interaction between sectors. I then develop the industrial structure network which allows us to explicitly consider specific industrial structural transitions and sector interaction in the panel regression test. Second, I use fixed-effect panel regression to reveal the extent to which industrial energy use change is due to industrial structural change. This investigation shows that above all, energy use reduces as a region increases dependence on service sectors. Additionally, sectors with stronger interaction indirectly boost energy use. The implication is that energy policy makers need to consider not only the benefit of sectors with low energy intensity, but also the secondary effect on energy use triggered by sector interaction.

As a third effort, I move beyond establishing the interconnection between industrial structure and historical energy use. I further explore how the industrial structure determines the fluctuation of energy consumption under external shocks. Specifically, I try to predict economy-wide energy rebound effects, which measures lost part of ceteris paribus energy saving from increased energy efficiency. To achieve this goal, I develop a computable general equilibrium (CGE) model for Georgia, USA. The model adopts a highly disaggregated sector profile and highlights the substitution possibilities between different energy sources in the production structure. These two features allow me to better characterize the change in energy use in face of an efficiency shock, and to explore in detail how a sector-level shock propagates throughout the industrial structure to generate aggregate impacts. I find that with economy-wide energy efficiency improvement on the production side, economy-wide rebound is moderate, while changes in GDP and consumption are orders of magnitude smaller than the scale of the efficiency gain. Energy price levels fall very slightly, yet sectors respond to these changing prices quite differently in terms of local production and demand. Energy efficiency improvements in a particular sector (epicenter) induce quite different economy-wide impacts, depending on how the epicenter sector interacts with other sectors. In general, we can expect rebound if the epicenter sector is an energy production sector, a direct upstream / downstream sector of energy production sectors, a transportation sector or a sector with high production elasticity. This analysis offers valuable insights for policy makers aiming to achieve energy conservation through increasing energy efficiency.

This study establishes the linkage between regional industrial structure and energy consumption from different perspectives. From the scientific perspective, it improves the fundamental understanding of how industrial structure and energy consumption are intricately connected to each other. From the policy perspective, it informs policy makers of the importance of considering sector interaction when designing energy policies, as well as the effectiveness of efficiency measures in achieving energy conservation. Given the progress of my dissertation, I further recommend a few directions for future research. Major suggestions include expanding the time horizon and incorporating regional technology data for the historical trend analysis, evaluating rebound effects from the end-use consumption side, comparing rebound effects and industrial structure shift in different regions, investigating the mechanism of impact propagation from individual epicenter sectors, and incorporating structural adjustment cost in the CGE model.

CHAPTER 1

INTRODUCTION

Meeting human needs and preserving nature's life support systems simultaneously is a fundamental goal in sustainability studies [1-3]. To achieve this goal requires that researchers across disciplines harness various perspectives ranging from the natural and social sciences to engineering and medicine. As researchers scrutinize the complex interactions between social, economic and ecological systems [4-11], a crucial subset of topics revolves around how economic activities utilize resources and generate pollution [12-19]. For these evaluations, an economy's industrial structure is a crucial determinant on the social side [20-25]. On the ecosystem side, energy consumption particularly stands out as a key indicator. This is because energy consumption establishes a linkage between resource exploitation (energy source extraction) with pollution generation (greenhouse gas emission) [26-29].

From the economic perspective, an economy's industrial structure alone can offer much valuable information for evaluating sustainability. This is because above all, the economic aspect of sustainable development implies sustained, inclusive and equitable economic growth [30]. For an economy to function well on a consistent basis, it needs respond robustly enough in the face of adversity. In this sense, a healthy industrial structure is essential. Yet more profoundly, the industrial structure is characterized by the kinds of production activities that dominate the economy, and inevitably reflects how the society, as a whole, consumes nature's resources, generates environmental impact and in turn affects the entire ecosystem.

From the environmental perspective, an indicator constantly under scrutiny is an economy's energy consumption. Access to energy to a large extent sets the boundary for an economy's production potential [31]. In turn, energy consumption indicates the level of resource exploitation and human impact on nature's supporting systems. As energy use is inevitably traced back to economic activities, an economy's energy consumption pattern is deeply interconnected with its industrial structure.

1.1 Industrial Structure and Economic Resilience

In the economic aspect of sustainability, an important indicator is economic resilience. It is the foundation for sustained, inclusive and equitable economic growth. Indeed, the World Economic Forum listed major systematic financial failure, income disparity and chronic fiscal imbalances as some of the most severe global risks [32]. The resilience of an economy is fundamental for reducing the society's vulnerability in the face of adversity. Economic resilience ensures that a regional economy can respond quickly and maintain key functions in the event of disturbance. A prerequisite for improving economic resilience, however, is to evaluate regional economic resilience and identify more resilient structural patterns. Therefore, we need a measure for economic resilience that is easy to calculate and comparable across regions.

Traditionally, measuring economic resilience has been challenging. This is because unlike in lab experiments, we cannot exert "manmade" shocks to real economic systems and observe responses. This means that case studies are rare, not to mention that individual case studies do not provide the basis for comparison across regions. With various simulation techniques, some studies have measured the sensitivity and reaction of an economy towards shocks against a single "equilibrium state" [33] or "development path" [34], often using econometric models, input-output (IO) models, and computable general equilibrium (CGE) models. Much work has been done to evaluate economic resilience at the international, national [35-39] and regional [34, 40-45] levels. However, these studies have mostly been conducted for a single region or a few regions.

However, one way around these difficulties is to indirectly investigate economic resilience by looking at the economy's industrial structure itself. This approach builds upon a line of literature on the relationship between industrial structure diversity and economic development. Existing studies have tried to explain this relationship with three theories. The first theory focuses on the spillover effect between sectors. Therefore, the industrial structure diversity today can contribute to increased productivity and economic growth tomorrow [46, 47]. The second theory centers on the necessity of long-term industrial structure diversification. It argues that developing new sectors over time is necessary for absorbing labor that has become redundant in existing sectors due to productivity increase and demand saturation [48]. The third theory thinks of industrial structure diversity as a risk-spreading strategy. The fundamental argument is that greater diversity in the industry portfolio protects and economy from external shocks in demand [49, 50], which is similar to the purpose behind corporate diversification [51]. Among the three theories, the third theory is especially relevant for establishing the linkage between difference in regional industrial structure and economic resilience.

Therefore, it is possible to break away from the commonly used resilience measurements, and to indirectly measure economic resilience by quantifying the difference in industrial structure across economies. This also renders characterizing the industrial structure in itself valuable for sustainability evaluation.

Yet from a more holistic perspective, the industrial structure provides the stage for, and sets constraints on, an economy's energy consumption patterns. Addressing these interconnections is the prerequisite to achieving sustainability [4, 52].

1.2 Dynamic Interconnections between Industrial Structure and Energy Consumption

In general, energy consumption management can target three key factors: economic growth rate, energy-efficient technologies or industrial structure [53]. At the regional level, managing the industrial structure has been a prevalent approach, which usually operates through prioritizing sectors with low energy intensity. However, the industrial structure reckons on the interaction between sectors. This means that prioritizing energy efficient sectors inefficient by ignoring that sector interaction has secondary effect on energy use. While a sector with low energy intensity by nature reduces regional energy use, the sector's growth can trigger production in related sectors and change total energy use in an unknown direction. Therefore, a prerequisite for sound energy policies is to understand the dynamic interconnection between regional industrial structure shift and trend in energy use, especially the secondary effect from sector interaction.

The industrial structure differs across regions and evolves over time. These horizontal and vertical differences may offer a way to explain how industrial structure shift leads to change in an economy's energy consumption. In terms of the horizontal differences, comparing the importance of the same bundle of sectors across regions can indicate the extent to which sectors interact with each other. In terms of the vertical differences, the expansion of sectors with different energy intensities over time alters an economy's total energy consumption in different directions.

1.3 Energy Efficiency Improvement and Economy-wide Energy Rebound

To fully characterize an economy's energy consumption pattern requires more than identifying its benchmark energy use. It is also crucial to predict how an economy's energy use fluctuates with external shocks. A particularly interesting question is: how does energy-efficiency enhancing technological change affect economy-wide energy consumption?

While national and regional governments increasingly resort to energy efficiency improvement to save energy, their good intentions do not guarantee desirable results. For example, the U.S. Department of Energy is actively promoting energy-efficient light bulbs [54], yet historical studies show that energy use for lighting has increased with every lighting efficiency improvement [55]. More broadly speaking, energy efficiency improvement can lead to less than proportionate reduction, or even increase, in energy use. This phenomenon is termed the rebound effect [56].

For policy makers, observing and responding to rebound effects can be quite challenging. First, the true magnitude of the rebound is difficult to isolate, as various factors are at play in shaping energy price and energy consumption. The changing price level of one sector can affect another sector's production and consumption. Therefore, the actual impact of sector-level energy efficiency improvements on economy-wide energy use is always hidden beneath aggregate numbers. Moreover, even if the rebound effect can be observed, policy makers have to consider other factors. Higher efficiency often means higher productivity, leading to GDP and income growth. Therefore, energy conservation and welfare improvement may seem at odds with each other. In other words, sustainability on the ecosystem side is not easily reconciled with sustainability on the economic side.

The economy-wide rebound effects are, to a large extent, constrained by the economy's industrial structure. In this particular context, the industrial structure is the combined outcome of various determinants, such as input-output transactions between sectors, households' and the government's spending structure, and capital and investment decisions. All the above factors, to some extent, affect how energy efficiency improvement propagates through the industrial structure and generates aggregate impact. The impact, in turn, shifts the regional industrial structure towards a new equilibrium. For a comprehensive characterization of how the industrial structure drives economy-wide rebound effects, computable general equilibrium (CGE) modeling is a promising approach.

1.4 Investigating Economy-wide Energy Rebound with Computable General Equilibrium Modeling

Computable general equilibrium (CGE) modeling has proved suitable for economic and environmental policy appraisal because of its theoretical foundation and modeling structure [57-60]. On one hand, CGE is grounded in economic theory in terms of its treatment of production and consumption behaviors and market equilibrium. On the other hand, CGE, by relying on numerical simulations, can effectively deal with circumstances that are too complex for analytical solutions. Since CGE can be parameterized to reflect the structure of a particular economy, it can estimate the order of magnitude of effect from a particular exogenous disturbance. In addition, CGE characterizes feedbacks and interdependencies between different sectors, making the modeling structure especially appropriate for measuring system level effects. In fact, CGE models are already widely used for investigating energy rebound effects at the national level [61, 62] and should be able to indicate the approximate magnitude of regional-level rebound effects.

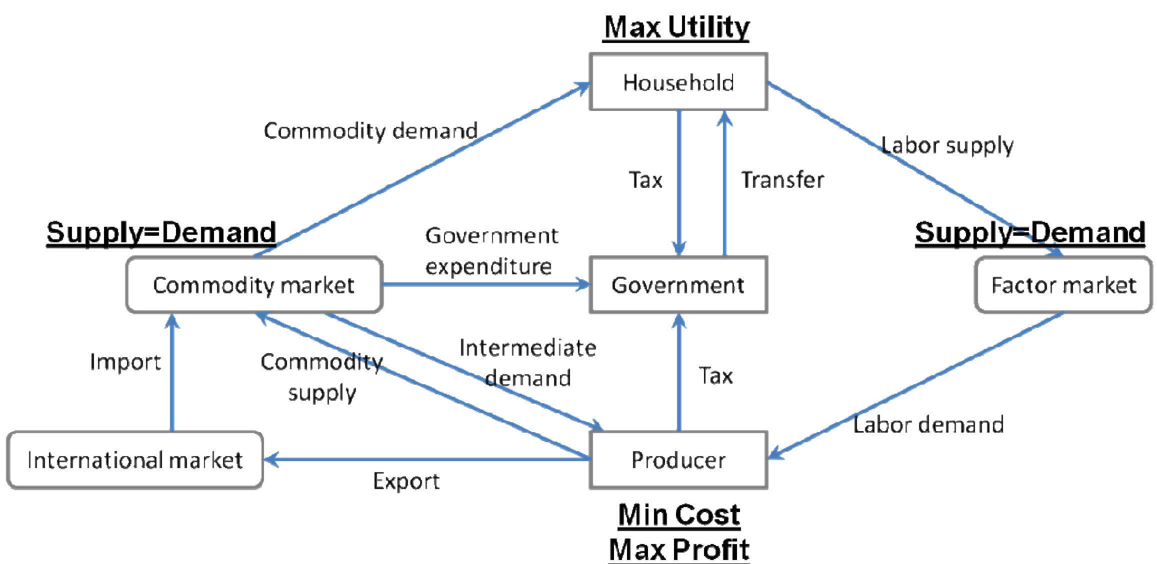


Figure 1.1. Interactions between agents in a CGE model

Figure 1.1 demonstrates the interaction between different agents in a CGE model. The model includes three agents (producer, household and government) and three markets (factor market, local commodity market and international market). The producer sources labor from the factor market and intermediate inputs from the commodity market. The producer then uses labor, intermediates and other inputs to produce commodities, which are then traded in the local and international commodity markets. The household supplies labor in the factor market and purchases goods from the commodity market. Both the household and the producer pay taxes to the government. The government in turn makes expenditures in the commodity market and redistributes income by making transfer payments to households. An international market that accepts exports from local production and supplies import to the local commodity market completes the model of the economy. The local commodity market is a composite of domestically produced goods and imports. When all markets clear, the model is said to have reached general equilibrium.

Building and working with a CGE model involves the following steps. After specifying agent interactions, the model explicitly defines the behavior of all parts of the economy including consumers, producers and markets with stated equations or "functional forms". Although the fundamental structure of all CGE models are determined by general equilibrium theory, they are actually flexible regarding the exact functional form and sector disaggregation level. Choice of behavior functions and market closure criteria are followed by calibration based on the social accounting matrix (SAM) specific to a certain economy. The calibrated model can then investigate different scenarios that simulate external shocks, or in other words, economic policies.

1.5 Motivation and Scope

Understanding the interconnections between industrial structure and energy consumption is crucial to promoting sustainability. However, past research on the topic has been incomplete. First, the industrial structure varies across regions and over time. Information drawn from these variations has yet to be used to explain how sector interaction and region-specific industrial structure shift alter regional energy use patterns. Second, a region's industrial structure constraints how economy-wide energy use responds to energy efficiency improvement. However, investigations on economy-wide energy rebound effects [56, 63-66] have never been conducted in the context of comprehensive industrial structure network, which is essential for tracing the propagation of an energy efficiency shock through the industrial structure.

The motivation for my research is to offer a comprehensive characterization of the interconnection between an economy's industrial structure and energy consumption. From the scientific perspective, I hope to improve the fundamental understanding of how industrial structure and energy consumption are intricately connected to each other. From the policy perspective, I hope to inform policy makers of the importance of considering sector interaction when designing energy policies, as well as the effectiveness of efficiency measures in achieving energy conservation. I carry out all the analysis at the U.S. state level to allow for easy comparison across states. I start by exploring the "stage", i.e., by characterizing the U.S. state level industrial structure through a simple measure. This step looks at resilience, a key measure for sustainability, purely from the economic perspective. I then bring the industrial structure into context with an economy's energy consumption. Two major components of my research are dedicated to addressing their interconnection: isolating the historical impact of industrial structure on energy use patterns through accounting for sector interaction, and predicting the response of an economy towards an energy efficiency shock. Specifically, this dissertation addresses the following topics:

1) Develop and easy indicator to compare regions' level of dependence on different sectors, setting the foundation for the horizontal and vertical comparison of industrial structure throughout the dissertation;

2) Based on the sector dependence indicator, quantify the difference in U.S. state level industrial structure diversity and comparatively evaluate their economic resilience;

3) Explore how the dynamic evolvement of regional industrial structure alters energy use patterns while accounting for the influence of sector interaction; and

4) Investigate the economy-wide energy rebound effects from energy efficiency improvement, emphasizing the propagation of impact through the industrial structure.

Chapter 2 is devoted to evaluating the difference in industrial structure and economic resilience level across U.S. states. I first develop an indicator, revealed comparative dependence (RCD), to compare regions' level of dependence on different sectors. Based on RCD, I further use a weighted version of RCD (wRCD) to measure how much a sector contributes to the economic structural diversity of an economy. I then calculate the economic structural diversity indices for each state economy. The diversity indices are used as state-level economic resilience scores, allowing for state ranking. Results show that resilient ranking is not directly related to the size of a regional economy. In terms of structural patterns, more resilient states are likely to depend more on manufacturing sectors, while less resilient states tend to focus on natural resource-oriented sectors. Between 1997 and 2010, while the balance of the national output composition did not changed significantly, state resilience rankings fluctuated noticeably.

In Chapter 3, I examine how historical regional industrial structure transition determines industrial energy use at the U.S. state level. As in Chapter 2, RCD is used to compare regional dependence on various sectors. Incorporating RCD into index decomposition analysis, I show that state-specific structural transition against the national trend has significantly changed state-level industrial energy use. I then test the real contribution of industrial structure change to energy use, highlighting the role of developing dependence on energy-efficient sectors, as well as the secondary effect triggered by sector interaction. First, building on RCD, I construct a measure to characterize the interaction between sectors. I then develop the industrial structure network which allows us to explicitly consider specific industrial structural transitions and sector interaction in the panel regression test. Second, I use fixed-effect panel regression to reveal the extent to which industrial energy use change is due to industrial structural change. Above all, energy use reduces as a region increases dependence on service sectors. Additionally, sectors with stronger interaction indirectly boost energy use. The implication is that energy policy makers need to consider not only the benefit of sectors with low energy intensity, but also the secondary effect on energy use triggered by sector interaction.

Chapter 4 is dedicated to investigating economy-wide energy rebound effects. To achieve this goal, I develop a computable general equilibrium (CGE) model for Georgia, USA. The model adopts a highly disaggregated sector profile and highlights the substitution possibilities between different energy sources in the production structure. These two features allow me to better characterize the change in energy use in face of an efficiency shock, and to explore in detail how a sector-level shock propagates throughout the industrial structure to generate aggregate impacts. I find that with economy-wide energy efficiency improvement on the production side, economy-wide rebound is moderate, while percentage changes in GDP and consumption are orders of magnitude smaller than the scale of the efficiency gain. Energy price levels fall very slightly, yet sectors respond to these changing prices quite differently in terms of local production and demand. Energy efficiency improvements in a particular sector (epicenter) induce quite different economy-wide impacts, depending on how the epicenter sector interacts with other sectors. In general, we can expect rebound if the epicenter sector is an energy production sector, a direct upstream / downstream sector of energy production sectors, a transportation sector or a sector with high production elasticity. This analysis offers valuable insights for policy makers aiming to achieve energy conservation through increasing energy efficiency.

Chapter 5 concludes. Based on the progress of my study, I further suggest a few directions for further research. Major suggestions include expanding the time horizon and incorporating regional technology data for the historical trend analysis, evaluating rebound effects from the end-use consumption side, comparing rebound effects and industrial structure shift in different regions, investigating the mechanism of impact propagation from individual epicenter sectors, and incorporating structural adjustment cost in the CGE model.

CHAPTER 2

ECONOMIC DIVERSITY AND ECONOMIC RESILIENCE: A REGIONAL COMPARATIVE ANSLYSIS

2.1 Introduction

The industrial structure by itself provides valuable information for evaluating sustainability. For one, the industrial structure provides constraints under which all economic activities, both production and consumption, take place. For another, the industrial structure, to a large extent, determines the energy consumption patterns of an economy. In this chapter, I focus on the industrial structure of an economy without bringing it together with energy consumption. Using the underlying information drawn from the industrial structure alone, I investigate a key aspect of sustainability: economic resilience.

Based on comparing regional industrial structure, I develop an indicator for regional economic resilience especially suited for large-scale inter-region comparison. Inconveniently, unlike in lab experiments, we cannot exert "manmade" shocks to economic systems and observe responses. This means that case studies are rare, not to mention that individual case studies do not provide the basis for comparison across regions. Therefore, I take an indirect approach, evaluating not economic response to disturbances, but an economy's intrinsic structural diversity that potentially increases resilience. The national economic output composition serves as the benchmark, against which every regional economy is compared. My economic resilience indicator has two major advantages. First, built upon economic structural diversity, the indicator does not require actual historical shocks or simulation of shocks. Second, the indicator is not data-intensive. In fact, calculation requires only readily available economic output data at the sector level for each studied region.

For developing the resilience indicator, I use a working definition of economic resilience, characterizing it as the capability to maintain system function in the event of disturbance [32]. In fact, the concept of economic resilience is not yet consistently defined and is a derivation from the discussion on engineering and ecological resilience. When resilience first appeared in the engineering realm, it focused on the stability of a system at a pre-determined equilibrium point, the resistance to a disturbance and the speed of return to equilibrium. The notion later infiltrated the discipline of ecology as a metric for assessing ecosystem dynamics, referring to the amount of change required to divert the ecosystem from one set of mutually reinforcing processes and structures (a stable state) to another [67, 68]. When the scope of resilience studies expanded to encompass social and economic aspects, the focus was social-ecological systems analysis [9, 69-74], which was mainly concerned with the interaction between human and natural systems. As the analogy between ecological and economic systems became more established, the resilience framework also gained popularity in studies of regional economic systems [75]. However, primitive usage of the term mostly resorted to its literal or intuitive meanings, ambiguously referring to a system's tendency to take risks or resistance against external shocks or inner crisis in general [36, 76, 77]. Later researchers began to characterize regional economies with the engineering resilience and ecological resilience frameworks, and shifted towards evolutionary viewpoints also while recognizing that the evolutionary depictions of economic resilience lacked testable hypothesis [75, 78, 79]. Here our working definition focuses not on an economy's ability to return exactly to its previous equilibrium, but structural diversity that allows the economy to find alternative routes to maintain essential functions.

The discussion on ecological resilience and biodiversity has provided a potential analogy and framework for empirical evaluation of economic resilience. This is especially important when it is impractical to observe how systems actually respond to perturbations. In ecosystems, the diversity of functional groups provides a cross-scale resilience [67]. The influences of functional groups of the ecosystem overlap and reinforce each other [80], creating redundancy and robustness throughout the system [81]. Having redundancy means that risks and benefits can spread to different segments of the systems, thus diluting the overall impacts. In an analogy to ecosystem resilience, economic resilience results from the diversity of a regional economy. This is because economic diversity creates redundancy, thus giving the economy a greater chance of finding alternative routes to maintain key functions when some of its segments fail. Indeed, the diversity of species has always been considered a key measure for the resilience of natural ecosystems [82-84] as well as artificial ecosystems (crop land, managed forests, fisheries for example) [85-90]. Further research has demonstrated that the concept of resilience and its linkage to diversity can be used across disciplines [91, 92], including the study of economic systems. For studying regional economies, existing research has used structural diversity as a key indicator for resilience [93-95]. Following this practice, in this chapter, I indirectly measure economic resilience by comparing the diversity of entire regional economies.

Regarding the aspect of industrial structure to examine, I choose a region's sectoral output composition. After all, among the key factors that define a good economic structure, a balanced output structure is one of the most important. The diversity of output composition to a large extent determines regional economic resilience. This is because once a region over-specializes in a specific area of the economy, it can be difficult to transfer the systems and know-how to other sectors [96]. Consequently, the region does not have the flexibility to respond quickly in face of adversity. In fact, output clustering in a few major sectors has shown to be a dangerous sign. For example, Pittsburgh, US was a steel center during and shortly after World War Two, at the cost of severe air pollution. With the falling price of global steel, and realizing the precariousness of such an economic structure, the city has shifted its economic base to education, tourism and services and has achieved a more balanced economy [33]. Other regions, however, may not be so lucky. Detroit of U.S. was once a prosperous automobile manufacturing center. However, its automobile giants failed to respond to consumer needs for improved air quality and mileage, and gradually lost market share. As a result, the city itself is now bankrupt following the decline of its automobile industry [97]. The same story applies internationally. The three Northeastern Provinces of China were once the nation's major economic center with their large share of heavy manufacturing industries. However, lacking adaptive capability to changing economic situations, their economic base has inevitably imploded, and has remained so for over two decades despite the central government's favorable policies [98]. Another example is the African country Angola. Having always benefited from rich oil resources, the country has failed to develop economic diversity. Therefore, its economic prosperity is still largely determined by fluctuation in oil prices [96]. All the examples above imply that economic diversity, particularly output structure diversity, is a critical aspect in economic resilience.

Therefore, a region's economic diversity, represented through output structure, can indirectly implicate economic resilience. A diversity indicator will also offer a firsthand basis for large-scale comparative analysis of regional economies, where exhaustive individual case studies are not practical.

In this chapter, I examine the economic resilience of 50 U.S. states and Washington D.C.. Section 2.2 is devoted to constructing a simple measure for economic structure diversity called weighted Revealed Comparative Dependence (*wRCD*). Using *wRCD*, I calculate diversity indices for each state's economy. The diversity indices are used as economic resilience scores for each state. In Section 2.3, I apply the resilience scores to analyzing the structural patterns of U.S. state economies of different levels of resilience, and further investigate resilience ranking in two different cross sections. Section 2.4 offers conclusions and discusses limitations of the research.

2.2 Methods and Data

My goal is to compare the economic structure diversity of a large number of economies, which can be quite challenging from the conventional sense. For one, a large sample size renders pair-wise comparison inefficient, not to mention that data requirements can be prohibitive. For another, it is often difficult to separate the impact of regional factors from national trends. Here I provide a simple solution by comparing all states' sectoral output composition to the national output composition, using a measure for regional dependence on sectors termed Revealed Comparative Dependence (*RCD*). Building on the *RCD* indicator, I further construct an indicator named weighted RCD (*wRCD*) to measure sectors' contribution to an economy's structural diversity.

2.2.1 Weighted Revealed Comparative Dependence (*wRCD*)

Revealed Comparative Dependence (*RCD*). I first develop the index *RCD* to compare economic dependence on the same sector across regions. Formally, *RCD* is defined as the GDP share of particular sectors in particular regional economies as compared to the sector's average share in all economies (in this case the US national economy):

$$RCD_{s,r} = \frac{O_{s,r} / \sum_s O_{s,r}}{\sum_r O_{s,r} / \sum_r \sum_s O_{s,r}} \tag{2.1}$$

where s is the sector index; r is the region index; $O_{s,r}$ represents GDP of sector s in region r; $\sum_s O_{s,r}$ is the total GDP of all sectors in region r; $\sum_r O_{s,r}$ is the GDP of sector s summed across all the regions; and $\sum_r \sum_s O_{s,r}$ is the total GDP of all the sectors across all the regions.

I then define weighted Revealed Comparative Dependence (*wRCD*) of a particular sector in a particular economy, which measures how much the sector contributes to the economic structure diversity of that economy. While RCD only compares different regions' dependence on the same sector, *wRCD* further compares the share of different sectors in the same regional economy. Mathematically, *wRCD* is defined as the quadratic of the GDP share of particular sectors in particular regional economies divided by the sector's average share in all economies (in this case the US national economy):

$$wRCD_{s,r} = \frac{O_{s,r}}{\sum_s O_{s,r}} RCD_{s,r} = \left(\frac{O_{s,r}}{\sum_s O_{s,r}} \right)^2 / \left(\frac{\sum_r O_{s,r}}{\sum_r \sum_s O_{s,r}} \right) \qquad (2.2)$$

Since all regions have the same number of sectors, the sum of squares of one region's sector output share ($\sum_s \left(\frac{O_{s,r}}{\sum_s O_{s,r}} \right)^2$) provides a measure of variance for the share of different sectors in the same region. Conceivably, lower variance means that a region's economic output is more evenly distributed across sectors. Given this standard, in an economy with the most balanced output structure, the value of $\sum_s \left(\frac{O_{s,r}}{\sum_s O_{s,r}} \right)^2$ should be 1/n (n being the number of sectors). However, the real situation is that different sectors always have different levels of output. Besides, certain economic output structures will allow the economy to function more robustly (For example, the real estate sector should be larger than the construction sector; the construction sector should be larger than, say, truck transportation). Because the national economy is considered to be more properly structured than its components (state economies), I use sectors' national share as a benchmark to compare state economies. Specifically, I use sectors' national share to offset the impact of the national industrial structure on regional output composition. That is, if a sector takes a huge share in the national economic output structure, it is more likely that the sector is also relatively crucial to a regional economy.

As an example, think of two sectors *a* and *b* in two regions *r* and *q*. *a* and *b* account for 10% and 1% of region *r*'s GDP respectively, while accounting for 1% and 10% in region *q*'s GDP. The sum of squares of these two sectors' share of output is the same for both regions (0.01001). However, the result does not tell us which region has a better, more balanced output structure. Suppose that for the national economy, *a* and *b* respectively produce 10% and 1% of the nation's economic output. This allows us to calculate *wRCD* for *a* and *b* in the two regions, which turn out to be 0.1 and 0.01 for region *r*, and 0.001 and 1 for region *q*. The difference in output structure manifests through the *wRCD* values. Very large *wRCD* means that a sector has a large share in the national economy, and even a larger share in the regional economy, and vice versa. The sum of *wRCD* for sector *a* and *b* be turns out to be 0.11 and 1.001 for region *r* and *q* respectively. The smaller the sum, the closer a regional economy is to the national economy, the more balanced the structure.

It is noteworthy that *RCD* only compares economic dependence on the same sector across regions. Therefore, two sectors with similar *RCD* values in one region could mean that one sector is highly important in both the region and the nation whereas the other one may be trivial both regionally and nationally. Alternatively, *wRCD* captures a particular region *r*'s dependence on different sectors and different regions' dependence on particular sector *s*.

wRCD summed across sectors within region *r*, or total weighted *RCD* (*twRCD*), measures the region's overall economic structure diversity:

$$\mathrm{twRCD}_r = \sum_s \mathrm{wRCD}_{s,r} \tag{2.3}$$

Higher *twRCD* value suggests that the robustness of a regional economy is more dependent on one or a few sectors, which we characterize as low economic diversity. In particular, a *twRCD* value of 1 indicates that the regional economy mirrors the national economy with the exact same structure. As a hypothetical example, suppose sector *a* and sector *b* both have an *RCD* value of 2 in region *r*, which means that the shares of sector *a* and *b* in region *r* are twice their shares in the national economy. Say sector *a* occupies 5% of the national GDP, which is a relatively large share. Therefore, $RCD_{a,r}$ implies that *a* is even more crucial for region *r*, being responsible for 10% of the regional GDP. On the other hand, suppose sector *b* is trivial in region *r*'s economic structure with 0.01% of the regional GDP share and is responsible for 0.005% of the national economy. The importance of sectors *a* and *b* to region *r* is captured not in *RCD* but in *wRCD*. Hence both *RCD* and the weight, which is a sector's national share, need to be high to achieve high *wRCD*. A few, or even one exceptionally high *wRCD* values will drive up a region's *twRCD* value, which we consider a sign of low economic diversity caused by economic dependence on major sectors.

Note that both wRCD and *twRCD* are ordinal indices. For three regions r_1, r_2 and r_3 with *twRCD* values of 1.5, 2 and 3, we know that r_1 possesses greater economic diversity than r_2, and that r_2 possesses greater diversity than r_3. However, we cannot come to the conclusion that the structural difference between r_1 and r_2 is smaller than between r_2 and r_3. This means rescaling *twRCD* values for all regions does not change the validity of comparative results. Therefore, for better intuitive interpretation, I further convert the calculated diversity indicator *twRCD* to the scale of 0 to 1 (labeled $twRCD_{rescale}$), with higher value representing greater diversity. The same principle applies to *wRCD*. Since *wRCD* only serves to compare sectors in terms of contribution to industrial structure imbalance, rescaling does not compromise the validity of the index. Therefore, for easy comparison, I also rescale wRCD values for all sectors in all regions between 0 and 1 (labeled $wRCD_{rescale}$), with higher values representing that a region depends more heavily on a sector compared with other regions and other sectors.

2.2.2 Modeling Economic Resilience

My measure of regional economic resilience builds upon an analogy between an economic system and an ecosystem. Think of specialized knowledge that makes a person a more efficient and productive worker. The specialization also makes the person vulnerable by locking him/her in a labor market that can disappear overnight. A similar paradox applies to both the ecosystem and the economic system. Across both systems, specialization that is beneficial for efficient production undermines resilience [78].

Therefore, ecological/economic diversity, which can be seen as a portfolio that protects an ecosystem/region from external shocks, to a large degree determines ecological/economic resilience. In fact, research in finance has shown that a strong clustering, or low diversity, in financial networks can be a warning sign [99]. The same intuition holds beyond the financial network for a regional economy. Although large clusters of businesses of the same industry can be effective at increasing regional GDP, these clusters make the region more vulnerable to input shortage, changes in policies and shifts in consumer demands. For example, Silicon Valley brings big revenue to California. However, if the world's silicon reserve began to shrivel, or if Chinese consumers no longer demanded American-designed electronic devices, the decline of the Silicon Valley would significantly harm the Californian economy. In fact, the Silicon Valley did perform poorly during USA's business downturn of the early 2000s, largely because of a poorly diversified economic base [100].

Based on the above analogy, I indirectly evaluate economic resilience by measuring the diversity of a regional economy. I use the *twRCD* indicator rescaled between 0 and 1 ($twRCD_{rescale}$) as an indirect measure for resilience, with higher value representing greater diversity and potentially greater resilience.

2.2.3 Data

I apply the methodology described above to a dataset of annual GDP detailed to 64 sectors (Table 2.1) for 50 US States and Washington D.C. I choose 1997 to compare to 2010 because 1997 was the first year to adopt the NAICS industry profile and the dataset is available through the Bureau of Economic Analysis (BEA) website [101].

Table 2.1. Sector indices, names and corresponding NAICS codes

Sector Index	Sector Name	NAICS Codes
1	Crop and animal production (Farms)	111-112
2	Forestry, fishing, and related activities	113-115
3	Oil and gas extraction	211
4	Mining (except oil and gas)	212
5	Support activities for mining	213
6	Utilities	22/221
7	Construction	23
8	Wood product manufacturing	321
9	Nonmetallic mineral product manufacturing	327
10	Primary metal manufacturing	331
11	Fabricated metal product manufacturing	332
12	Machinery manufacturing	333
13	Computer and electronic product manufacturing	334
14	Electrical equipment, appliance, and component manufacturing	335
15	Motor vehicle, body, trailer, and parts manufacturing	3361-3363
16	Other transportation equipment manufacturing	3364-3369
17	Furniture and related product manufacturing	337
18	Miscellaneous manufacturing	339
19	Food and beverage and tobacco product manufacturing	311-312
20	Textile mills and textile product mills	313-314
21	Apparel and leather and allied product manufacturing	315-316
22	Paper manufacturing	322
23	Printing and related support activities	323
24	Petroleum and coal products manufacturing	324
25	Chemical manufacturing	325
26	Plastics and rubber products manufacturing	326
27	Wholesale trade	42
28	Retail trade	44-45
29	Air transportation	481
30	Rail transportation	482
31	Water transportation	483
32	Truck transportation	484
33	Transit and ground passenger transportation	485
34	Pipeline transportation	486
35	Other transportation and support activities	487-488, 492
36	Warehousing and storage	493
37	Publishing industries	511, 516
38	Motion picture and sound recording industries	512
39	Broadcasting and telecommunications	515, 517
40	Information and data processing services	518-519
41	Federal Reserve banks, credit intermediation and related services	521-522
42	Securities, commodity contracts, investments	523
43	Insurance carriers and related activities	524
44	Funds, trusts, and other financial vehicles	525

45	Real estate	531
46	Rental and leasing services and lessors of intangible assets	532-533
47	Legal services	5411
48	Computer systems design and related services	5415
49	Other professional, scientific and technical services	5412-5414, 5416-5419
50	Management of companies and enterprises	55/551
51	Administrative and support services	561
52	Waste management and remediation services	562
53	Educational services	61/611
54	Ambulatory health care services	621
55	Hospitals and nursing and residential care facilities	622-623
56	Social assistance	624
57	Performing arts, spectator sports, museums, and related services	711-712
58	Amusement, gambling, and recreation	713
59	Accommodation	721
60	Food services and drinking places	722
61	Other services, except government	81
62	Federal civilian	NA
63	Federal military	NA
64	State and local government	NA

2.3 Results and Discussion

2.3.1 Comparative Economic Diversity and Resilience

Figure 2.1(a) shows the frequency distribution of states based on $twRCD_{rescale}$ values in 2010, indicating that the majority of states have relatively low $twRCD_{rescale}$ values, with over 50% above 0.95, and over 75% above 0.9. Since low $twRCD_{rescale}$ suggests lower economic structure diversity, Figure 2.1(a) implies around one fourth of the states with relatively low structural diversity and more vulnerable to external disturbances.

I further look at sectoral $wRCD_{rescale}$ values for different states. This is shown through a comparison of Illinois, Georgia, and Alaska, each respectively representing states with high, medium, and low $twRCD_{rescale}$ values (Figure 2.1(b)). Note that for $wRCD_{rescale}$ values between 0 and 1, higher values indicate that a region depends more heavily on a sector compared with other regions and other sectors. With each data point representing a sector (Table 2.1), Figure 2.1(b) shows that Illinois has a well-balanced economic structure with all sectoral $wRCD_{rescale}$ values ranging between 10^{-6} and 10^{-1}. Georgia performs almost equally well except that one sector (oil and gas extraction) is trivial in terms of economic importance. On the other hand, Alaska's sectors are highly scattered in a wide $wRCD_{rescale}$ range, implying a quite unbalanced economic output structure. Its *twRCD* value before rescaling is driven up by two sectors (pipeline transportation and oil and gas extraction) with *wRCD* values higher than 0.1. Therefore, Alaska's $twRCD_{rescale}$ value turns out to be very low. Failure of normal function of these two sectors is likely to significantly disturb the normal structure of the entire economy.

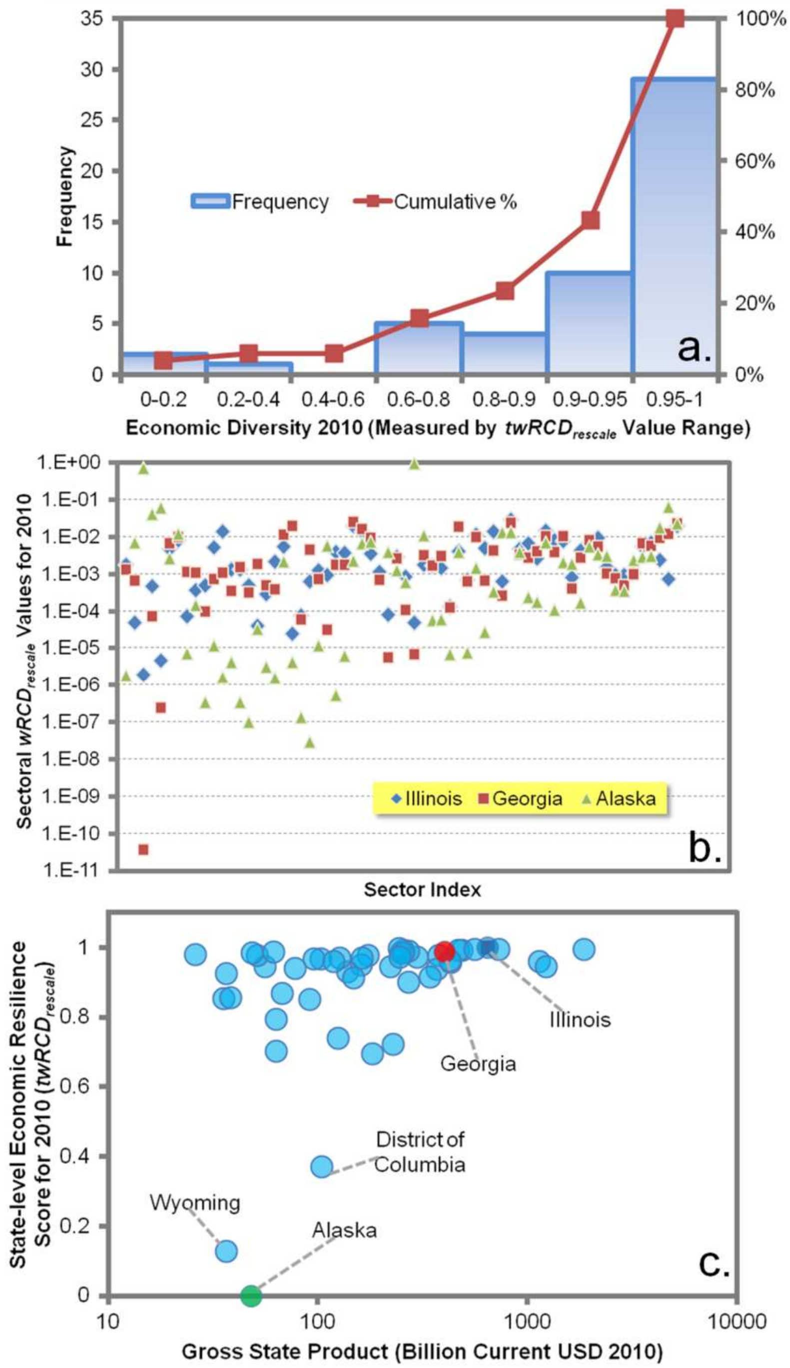


Figure 2.1. Basic economic diversity and resilience measures for the year 2010. (a) Frequency and cumulative distribution of states based on $twRCD_{rescale}$ value ; (b) Comparison of sectoral $wRCD_{rescale}$ between three states (Sector names, indices and

corresponding NAICS codes available in Table 2.1); (c) economic resilience score and regional GDP.

Figure 2.1(c) displays the economic resilience score ($twRCD_{rescale}$) against state-level GDP (Refer to Appendix A for economic resilience scores). The distribution of states indicates that while large economies are usually resilient, small economies are not necessarily un-resilient. Therefore, economic resilience is not directly correlated with the size of the economy. I have further ranked the states by GDP and compared these rankings to resilience rankings (Table 2.2). For example, in 2010, Florida ranks No. 5 by $twRCD_{rescale}$, indicating a high level of diversity. It also ranks No. 4 by GDP share in the national economy (5.06%). On the other hand, Vermont ranks No. 15 by $twRCD_{rescale}$, which also implies relatively high diversity. However, its GDP share in the national economy is only 0.18%, ranking last among the 51 studied regions. Still, Texas has a large GDP share in the national economy (ranking No.2, 8.53%), while by resilience the state only ranks No. 31.

Table 2.2. State GDP ranking and resilience ranking for 1997 and 2010

State Name	1997				2010			
	GDP share in the national economy (%)	GDP share rank	Resilience rank	Difference in rank (resilience rank – GDP rank)	GDP share in the national economy (%)	GDP share rank	Resilience rank	Difference in rank (resilience rank – GDP rank)
Alabama	0.1838	50	15	-39	1.2012	26	17	-9
Alaska	0.3410	45	51	-28	0.3329	46	51	5
Arizona	0.6837	35	20	-28	1.7188	20	11	-9
Arkansas	1.6068	22	23	-17	0.7170	35	24	-11
California	0.3415	44	8	-17	12.824	1	4	3
Colorado	0.3672	43	5	-15	1.7690	18	8	-10
Connecticut	1.8616	17	22	-15	1.5412	24	30	6
Delaware	1.9038	16	45	-12	0.4366	40	44	4
District of Columbia	0.1934	49	50	-12	0.7210	34	49	15
Florida	1.2315	26	6	-11	5.0592	4	5	1
Georgia	0.9512	30	13	-11	2.7938	11	13	2
Hawaii	0.7007	34	43	-10	0.4675	39	40	1
Idaho	0.7247	32	27	-9	0.3866	43	32	-11
Illinois	0.2321	48	1	-9	4.4671	5	1	-4
Indiana	0.4391	41	30	-8	1.8816	16	39	23
Iowa	1.8515	18	34	-8	0.9617	30	35	5
Kansas	0.8884	31	25	-6	0.8801	31	22	-9
Kentucky	1.8487	19	38	-5	1.1193	28	29	1
Louisiana	0.2373	47	44	-5	1.5802	23	46	23
Maine	1.5479	23	28	-3	0.3568	44	16	-28
Maryland	4.9415	4	14	-3	2.0570	15	19	4
Massachusetts	4.1601	6	12	-3	2.6194	12	18	6
Michigan	0.1759	51	41	-2	2.5513	13	34	21
Minnesota	2.7048	12	2	0	1.8665	17	9	-8
Mississippi	1.6582	21	24	1	0.6655	36	23	-13
Missouri	4.7755	5	4	1	1.6948	22	2	-20
Montana	3.6390	8	39	1	0.2537	48	36	-12
Nebraska	1.8289	20	40	1	0.6318	37	43	6
Nevada	0.4107	42	48	3	0.8675	32	45	13
New Hampshire	2.8672	10	33	3	0.4249	42	10	-32
New Jersey	0.4598	39	9	4	3.3568	7	6	-1
New Mexico	0.6146	36	46	4	0.5398	38	33	-5
New York	1.1715	28	29	4	7.8979	3	27	24
North Carolina	0.3042	46	31	5	2.9667	9	28	19
North Dakota	0.9893	29	37	5	0.2457	50	42	-8

Ohio	2.5508	13	16	5	3.2363	8	7	-1
Oklahoma	12.5648	1	19	7	1.0261	29	38	9
Oregon	0.4568	40	32	7	1.2615	25	48	23
Pennsylvania	0.5749	38	3	8	3.8837	6	3	-3
Rhode Island	1.1750	27	17	8	0.3375	45	14	-31
South Carolina	4.0299	7	35	9	1.1279	27	21	-6
South Dakota	0.6070	37	42	13	0.2661	47	41	-6
Tennessee	1.2507	25	10	13	1.7624	19	12	-7
Texas	2.0341	15	26	15	8.5254	2	31	29
Utah	0.7096	33	7	15	0.8216	33	26	-7
Vermont	1.4015	24	11	20	0.1793	51	15	-36
Virginia	2.7653	11	18	20	2.9381	10	25	15
Washington	2.2363	14	36	22	2.3817	14	37	23
West Virginia	7.2808	3	47	23	0.4359	41	47	6
Wisconsin	7.9955	2	21	27	1.7056	21	20	-1
Wyoming	3.5271	9	49	32	0.2533	49	50	1

2.3.2 State-level Economic Resilience Ranking Over Time

I first examine the U.S. resilience map in 2010 (Figure 2.2(a)) to compare state-level economic resilience in a given year. Here we identify a state's key sectors by ranking *wRCD* from high to low, which indicates their importance in terms of contribution to diversity. As a result, sectors consistently essential for the 20 most resilient as well as 20 least resilient states would be real estate, state and local enterprises, wholesale trade and retail trade. While the 20 most resilient states also show dependence on ambulatory health care and hospital services, the 20 least resilient states are comparatively more dependent on construction. The above comparison helps identify signals that potentially imply a resilient economic structure. Difference in *wRCD* indicates that real estate, state and local enterprises and trade always take on a large share in all regional economies. However, in terms of output composition, if a state exhibits greater focus on health care rather than infrastructure building, the state is more likely to be already built out with better established infrastructure, economically diversified and resilient.

State-level economic resilience scores use the national economic structure as the benchmark. Therefore, before comparing resilience ranking over time, I have examined how the national structure has evolved during the study period. , The standard deviation of national sector share slightly increased from 0.0205 in 1997 to 0.0211 in 2010. Because of the small sample size (64 sectors), the standard deviation alone cannot lead to stronger statistical conclusions. However, it does imply that the national industrial output composition has not significantly become more or less imbalanced during the study period. Besides, the distribution of sector sizes remains roughly the same from between 1997 and 2010. Appendix B presents more details in terms of the change in national industrial structure.

Resilience ranking for the same state also changes over time. Between 1997 (Figure 2.2(a)) and 2010 (Figure 2.2(b)), while a few of the most resilient states (Illinois, Pennsylvania and Georgia) and a few low-resilience states (Alaska and West Virginia) have retained their ranks, all the other states have changed more or less in resilience ranking. New Hampshire have jumped the most from No. 33 to No. 10 in resilience ranking, followed by South Carolina (14 places, No. 35 to No. 21), New Mexico (13 places, No. 46 to No. 33) and Maine (12 places, No. 28 to No. 16), all of which increased in resilience ranking by more than 10 places. States that have fallen the most in resilience ranking include Utah (19 places, No. 7 to No. 26), Oklahoma (19 places, No. 19 to No. 38), and Oregon (16 places, No. 32 to No. 48).

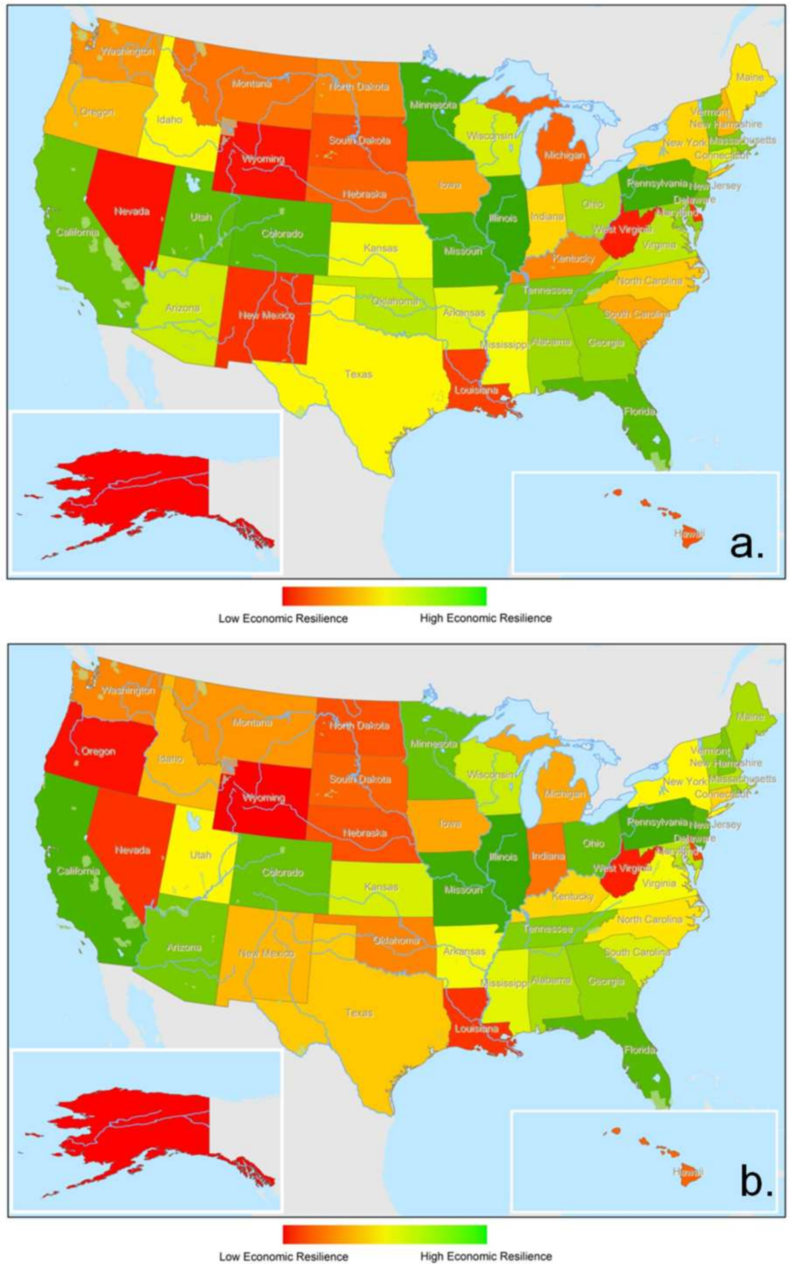


Figure 2.2. Economic resilience map in 1997 and 2010. (a) Economic resilience ranking for 1997; (b) Economic resilience ranking in 2010.

States that have moved most significantly in resilience ranking show distinct patterns of structural change. I look at New Hampshire and Utah, two states with the most significant change in resilience ranking. Between 1997 and 2010, if New

Hampshire's sectors are ranked by w*RCD*, I find that light manufacturing industries including paper manufacturing, apparel manufacturing and printing became much less essential to the state's economic structure. Alternatively, sectors that grow the most in *wRCD* ranking include rental and leasing services and securities and investments. For Utah, sectors that jumped the most in *wRCD* ranking include information and data processing services, chemical manufacturing, funds and trusts. On the other hand, motor vehicle manufacturing and rail transportation fell most heavily in *wRCD* ranking. This means that the above sectors have grown / shrunk significantly compared against the national economic structure, as well as compared to other sectors' share in the same region.

2.4 Conclusions

I developed a simple measure, Revealed Comparative Dependence (*RCD*), to compare regions' level of dependence on sectors. Based on *RCD*, I further developed the weighted Revealed Comparative Dependence (*wRCD*) indicator to evaluate state-level economic resilience across states and over time. This measure, based on economic structural diversity, addresses the intrinsic potential of resilience and is inspired by the ecological resilience concept. The bottom line is, across both the ecological and economic system, diversity creates functional redundancy, and allows the system to resist perturbations by maintaining key functions. Resilience ranking based on rescaled total weighted *RCD* ($twRCD_{rescale}$) has identified economic structures that are potentially more robust towards external shocks, providing policy makers a primer to investigate the cause and characteristics of more resilient structural patterns in more detail. Nevertheless, I recognize the limitations of the work. First, this resilience score is an indication of potential economic robustness without actually simulating external shocks. This simulation can be an interesting research topic itself if state-level input-output tables are available at a large scale. Second, although I vertically compare economic resilience between 1997 and 2010, the methodology does not provide a definite pathway for developing better regional economic structure. Third, the results provide no implications for the social welfare difference generated by different economic structures and therefore is not a well-rounded measure of economic resilience.

CHAPTER 3

REGIONAL INDUSTRIAL STRUCTURE AND ENERGY CONSUMPTION: DECOMPOSITION AND PANEL REGRESSION ANALYSIS

3.1 Introduction

In this chapter, I use historical data to identify the key forces in shaping regional energy use, specifically, the impact of expanding low energy-intensity sectors, and the impact of one sector's growth on other sectors. I have developed the *RCD* indicator, a simple measure to compare regional dependence on different sectors over time. Based on RCD, I am able to approximate the different levels of interaction between sectors and "map" out the entire industrial structure network. The network allows me to explicitly consider whether a sector that interacts more heavily with other sectors has had a stronger influence over regional energy use. In this way, I move beyond establishing the correlation between industrial structural transition and energy use change to identifying the real contribution of industrial structural transition.

Previous studies have contributed much to establishing the correlation between change in the industrial structure and the energy use trend. The predominant methods are structural decomposition analysis (SDA) and index decomposition analysis (IDA) [102-104]. SDA uses the input-output framework to account for structural changes. So far extensive SDA has been conducted for major energy consumers including the U.S. [105, 106], the European Union [107, 108] and China [109-111]. On the other hand, IDA requires aggregated production information at the sector level. Being less data demanding, IDA is more suitable for multi-period and multi-regional analysis, and has now become the dominant tool in monitoring key indices in energy use trends [112]. Various IDAs are available at the national level for different countries [106, 113-124]. However, there has been a lack of regional analysis, with the only exception being Metcalf (2008) [124] for U.S. states between 1970 and 2001, and Hasanbeigi et. al. (2012) [125] for California. Besides, studies using the approach have stopped at identifying aggregate contribution of output composition change, without distinguishing the large-scale national trend from region-specific structural shift. Yet most importantly, decomposition analysis, being mainly an accounting tool, cannot reveal factors' *ceteris paribus* impacts. This means that the actual contribution of expanding energy-efficient sectors and the subsequent triggering effect to other sectors are mixed together. I will address all three issues in this chapter.

My account of sector interaction builds upon previous studies on the industrial structure network. In fact, sectors interact highly heterogeneously in the industrial structure network, and region-specific dependence on different sectors result in very different energy use patterns. Fundamentally, any economic network is made of constantly interacting agents and built on interdependencies [126]. A network of sectors depicting the industrial structure is no exception. In addition to a complex topological structure, it shows heterogeneity in the intensity of inter-sector connections and collective dynamic behaviors [127]. Empirical research has demonstrated that sectors have different degrees of centrality [128], as well as different levels of economic proximity to each other [129-131]. Hidalgo et al. (2007) [129] used the proximity concept to demonstrate the interconnection between sectors and the evolution of region-specific industrial structure. However, examination of the causality between structural evolution and energy use is missing from the literature. I believe that given the constraint of industrial structure network, sectors with heterogeneous functions trigger different changes in energy use as a regional economy evolves. That is, despite a sector's own energy intensity, sectors with higher centrality and proximity to neighbors will indirectly affect energy use by interacting with their neighbors.

In this chapter, I investigate the historical interaction between regional industrial structure and industrial energy use in three sequential steps. My focus is industrial energy, or energy use associated with a state's economic output, for 50 U.S. states and Washington D.C. from 1997 to 2010. That is, energy use that cannot be linked to GDP (e.g., personal vehicle transportation, direct household energy use) is beyond the scope of this study. In Section 3.2, I incorporate the RCD indicator developed in Section 2.2 in an index decomposition analysis (IDA) to show that region-specific industrial structure shift, when separated from the national trend, significantly contributes to change in industrial energy use. I then explore in detail the role of heterogeneous sectors in shaping regional industrial energy use in Section 3.3 and 3.4. To depict heterogeneous sector interaction, my second step in Section 3.3 is to construct the product space map, a network of sectors to describe the industrial structure of the U.S.. The intensity of a sector's interaction with its neighbors indicates the heterogeneity in terms of function in the network. Those with more intensive interaction are termed hub sectors. After demonstrating how regions are located and relocate over time on the product space map, my third step is to use this information to further test the *ceteris paribus* contribution of region-specific industrial structure change to regional industrial energy use change with econometric methods (Section 3.4). I identify two potentially responsible factors: regional dependence on energy, manufacturing and service sectors in general; regional dependence on hub sectors. I then conclude and briefly discuss the policy implications for this chapter in Section 3.5.

3.2 Region-specific Industrial Structure Shift and Energy Use Change

In this section, I demonstrate that the trend of regional industrial energy use due to industrial structure shift can be split into two factors: the change in national output composition and region-specific sectoral dependence. By comparing historical U.S. state-level data, my analysis shows the significance of sectoral dependence in shaping energy use. Comparing regional industrial structure over a large number of samples has been challenging. For one, a large sample size renders pair-wise comparison inefficient, not to mention that data requirements can be prohibitive. For another, it is often difficult to separate the impact of regional factors from national trends in determining energy use. While IDA partly solves the problem, existing analysis has stopped at the point of identifying sectoral output share. Here I provide a simple solution by comparing all states' sectoral output composition to the national output composition, using the *RCD* measure for regional dependence on sectors that I developed earlier in Section 2.2. *RCD* is then used in index decomposition analysis (IDA) as an individual factor that accounts for historical change in energy use.

3.2.1 Methodology

While my final goal is to explore the real contribution of region-specific industrial structure shift to industrial energy use, I first quantify the role of economic growth, technological change and industrial structure shift in shaping regional industrial energy use through index decomposition analysis (IDA).

Assume E to be a region's total industrial energy use. The general IDA identity is given by

$$E = \sum_s E_s = \sum_s x_{1,s} x_{2,s} \cdots x_{n,s} \tag{3.1}$$

where s represents sectors; $x_{1,s}$, $x_{2,s}$, $\cdots x_{n,s}$ represents n determinant variables for energy use in sector s such as the region's total GDP, the share of sector s in the region's total GDP, and energy intensity of sector s. Therefore, n is also the number of determinant effects for a region's total energy use.

Between period *0* and period *T*, industrial energy use changes from $E^0 = \sum_s E_s{}^0 = \sum_s x_{1,s}{}^0 x_{2,s}{}^0 \cdots x_{n,s}{}^0$ to $E^T = \sum_s E_s{}^T = \sum_s x_{1,s}{}^T x_{2,s}{}^T \cdots x_{n,s}{}^T$. Additive decomposition focuses on the difference:

$$\Delta E_{tot} = E^T - E^0 = \Delta E_{x_1} + \Delta E_{x_2} + \cdots + \Delta E_{x_n} \quad (3.2)$$

where E_{x_i} is the additive effect associated with factor *i*.

IDA can also be calculated in the multiplicative form, which focuses on percentage change of energy use. We present the multiplicative formulae and results in Appendix C.

The standard IDA identifies three determinant effects for regional energy use [132] (*n* equals 3 in equation (3.2)), namely, activity, structure and intensity effects. The activity effect assesses the effect of total output change. The structure effect measures the effect of output composition shift. The intensity effect estimates the aggregated effect of change in sectoral energy use per unit output, or sectoral energy intensity. These three effects are calculated given regional sectoral GDP and sectoral energy intensity for two different years.

Building upon the standard three-factor IDA, I further split the structure effect into two: region-specific structural shift effect and national composition effect. The former describes energy use change due to shift of region-specific dependence (*RCD*) on key sectors. The latter depicts energy use change due to national output composition change. In this sense, regional industrial energy use can be described by four determinants in equation (3.1): the region's total GDP, the region's *RCD* on sector *s*, the share of sector *s* in the national economy, and energy intensity of sector *s*. Region-specific structural shift can thus be distinguished from the national trend. This division of effects is plausible because a sector's share of output in a region equals its *RCD* value for the region multiplied by the sector's share of output in the national economy. As an example, if a sector's regional share reduces by half while the sector's national share also reduces by half, then there is no region-specific structural shift, only the national composition trend shift. Alternatively, if a sector's regional share reduces by half while the sector's national share remains constant, there is only region-specific structural shift.

A number of IDA index approaches are available [132], among which I choose the logarithmic mean Divisia index (LMDI) method. LMDI is currently the most widely used IDA approach and has several clear advantages from the application viewpoint. These advantages include simple interpretation of results, easy conversion between multiplicative and additive results, easy-to-develop decomposition formulae, good handling of zeros values, etc [133]. A detailed derivation of the index is beyond the scope of this chapter. However, calculation formulae are available in Appendix D.

3.2.2 Data Source

I investigate U.S. state-level industrial energy use disaggregated to 64 sectors with yearly data from 1997 to 2010 (Refer to Table 2.1 for a complete list of sector names). State-level sectoral GDP data is available through the Bureau of Economic Analysis (BEA) website [101]. Because BEA started adopting the North American Industry Classification System (NAICS) only in 1997, I have chosen the study period so that sector disaggregation is consistent between different years. Sectoral energy intensity data comes from the MRIO database developed by Sydney University [134, 135]. The database provides yearly updates of sectoral energy use per million U.S. dollars specific to the U.S.. I match the sector schemes between state GDP and energy intensity data at the 4-digit NAICS sector profile (Refer to Appendix E).

3.2.3 Decomposition Results for Regional Industrial Energy Use (1997-2010)

Decomposition of energy use untangles the contribution of economic growth, technological change and industrial structure transition. The impact of industrial structure transition manifests itself in the aggregated form of output composition shift, as well as in separated forms of national composition trend and region-specific structure shift against the national trend. I performed IDA of industrial energy use between 1997 and 2010 for all 50 U.S. states and Washington D.C. (Complete IDA results available in Appendix C).

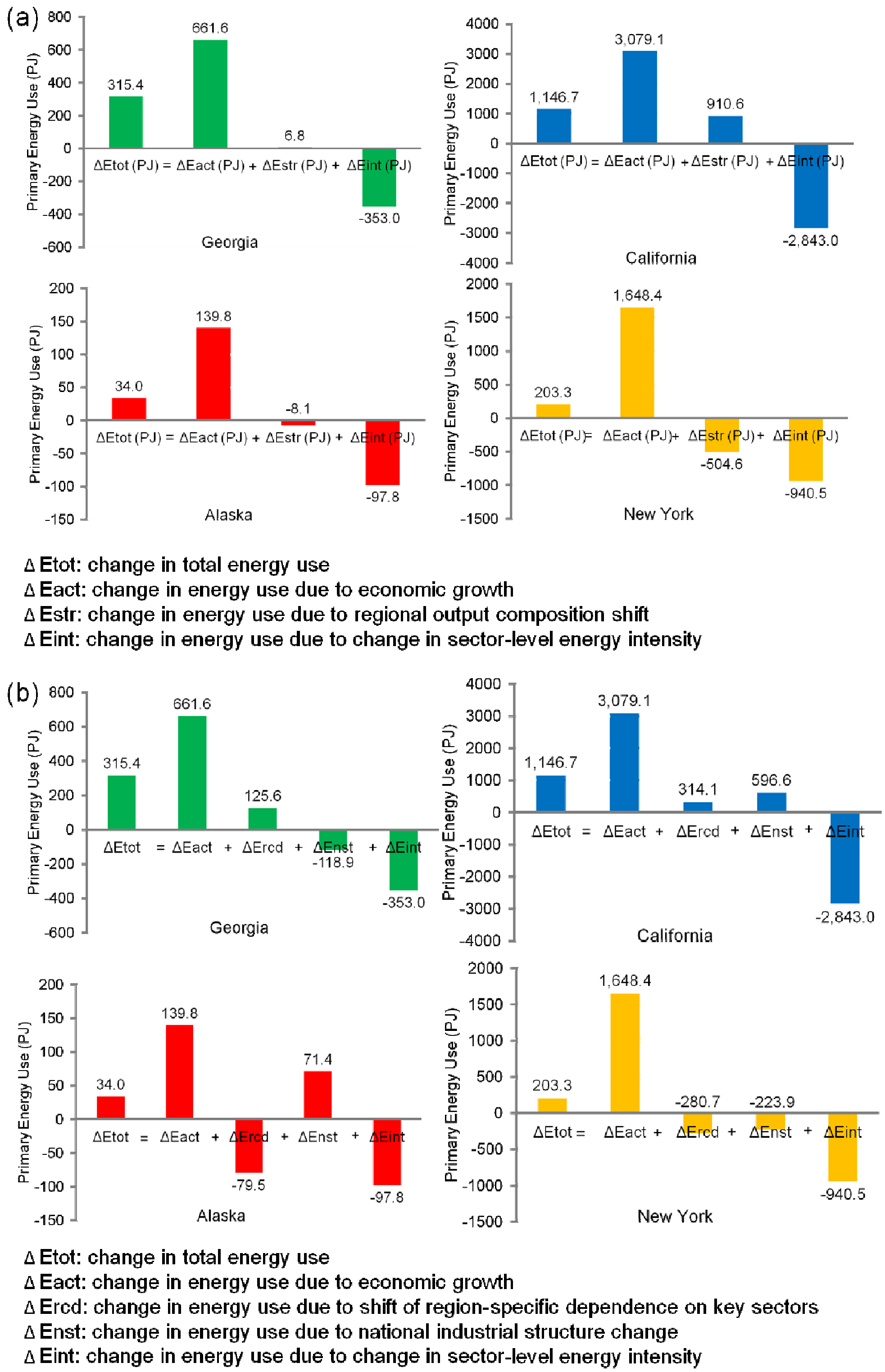


Figure 3.1. IDA results of industrial energy use between 1997 and 2010 for four states. (a) Industrial structure transition shown as a single output composition shift effect; (b)

Industrial structure transition shown as the combined effect of region-specific structure shift and national output composition trend.

Figure 3.1(a) compares IDA results for four states by considering structural change as aggregated output composition shift, while Figure 3.1(b) separates region-specific structure shift from the national trend by RCD. I chose the states to highlight the heterogeneity of regions. The effect of economic growth, represented by increased GDP (ΔEact) in both figures, is always highly positive. Meanwhile, technological change, represented by change in sectoral energy intensity (ΔEint), always drives energy use downwards, but not enough to offset the growth effect. On the other hand, industrial the structure effects can have positive or negative impact on energy use. The sum of the regional-specific structural effect (ΔErcd) and the national composition effect (ΔEnst) in Figure 3.1(b) would equal the output composition effect (ΔEstr) in Figure 3.1(a). Georgia, for example, would have experienced 661.6 PJ (30.7%) increase in energy use from economic growth, 353.0 PJ (13.3%) decrease from energy efficiency improvement, but only 6.8 PJ (0.3%) increase from output composition change. With total industrial primary energy use increasing by 315.4 PJ (13.6%) from 1997 to 2010, the composition effect seems trivial. However, when we separate region-specific structural shift from the national trend, the contribution of industrial structure transition becomes much more apparent. For Georgia, positive region-specific effect and negative national trend effect offset each other (Figure 3.1(b)), bringing the total output composition effect to nearly zero. Alaska shows a similar pattern of change, except that output composition shift serves to slightly reduce energy use (Figure 3.1(a), 8.1 PJ, i.e. 2.2%). This is because the national structure trend dramatically boosts energy use, but region-specific structural development keeps energy use relatively stable (Figure 3.1(b)). For California and New York, output composition shift plays a more significant role in Figure 3.1(a). The reason is that the national and regional effects work in the same direction for California, both serving to increase energy consumption. Contrarily, both effects appear to suppress energy use in New York (Figure 3.1(b)).

IDA results prove that region-specific industrial structure shift against the national trend, represented by change in *RCD*, affects energy use. Despite the usefulness of IDA for depicting trends, it is fundamentally a descriptive, or accounting tool [53]. In other words, analysis in this section stops at coupling the factors of interest with total energy use. The direction and magnitude of the effect, however, are determined by a region's original industrial structure and its change over time, as well as the nature of the specific sectors that becomes more important to the region. In addition, IDA fails to account for the specific structural transitions that play the most critical role in changing regional energy use. Therefore, I resort to econometric methods to explore the *ceteris paribus* impact of regional industrial structure shift to industrial energy use. Before building the regressors, I need to quantify the different levels of interaction between sectors, as well as to track how regions have changed their dependence on sectors over time. That is why I first depict regional economic structures and track their transitions over time against the national "backdrop" in the next section. Then I use panel data regression to unveil the *ceteris paribus* impact of regional industrial structure shift.

3.3 Inter-sector Proximity and Product Space

Based on *RCD*, I depict the interconnection between sectors with an indicator called proximity, followed by visualizing inter-sector proximity through a network called product space map. Using the product space map as the national industrial structure "backdrop", I compare regional industrial structure across states and over time. This will be the foundation for exploring how regional industrial energy use responds to transition of regional industrial structure.

3.3.1 Depicting Regional Industrial Structure

3.3.1.1 Inter-sector Proximity

Inter-sector proximity quantifies how closely different sectors are connected to each other. The proximity concept I use, as an extension of Hidalgo et al.'s original definition of proximity [129], is based on the idea that if two sectors are related because they 1) require similar institutions, infrastructure, physical factors, technologies or some combination thereof, or 2) interact frequently through local business transactions, their products will tend to be produced in tandem. Proximity between sector *i* and sector *j* is formally defined by the following equation:

$$\Phi_{i,j} = \min\left\{P(KEY_{i,r} \mid KEY_{j,r}), P(KEY_{j,r} \mid KEY_{i,r})\right\} \tag{3.3}$$

where $\Phi_{i,j}$ is the proximity between sector *i* and sector *j*; $KEY_{i,r}$ is the indicator that sector *i* is a key sector for region *r* ($RCD_{i,r}$ >1); $P(KEY_{i,r} \mid KEY_{j,r})$ is the conditional probability that sector *i* is a key sector for a region given that sector *j* is a key sector for the same region. $P(KEY_{i,r} \mid KEY_{j,r})$ is calculated through dividing the number of regions that specialize in both sector *i* and sector *j* by the number of regions that specialize in sector *j*. Conceivably, $P(KEY_{i,r} \mid KEY_{j,r}) = 1$ means that every region specializing in sector *j* also specializes in sector *i*. This outcome suggests sector *i* and sector *j* must be very similar in their nature or incur very frequent interactions.

Using the minimum of $P(KEY_{i,r} \mid KEY_{j,r})$ and $P(KEY_{j,r} \mid KEY_{i,r})$ fulfills two purposes: First, it ensures that the proximity measure is symmetrical. That is, if sector *i* is closely related to sector *j*, sector *j* is also closely related to *i*. Second, if only one region specializes in sector *j*, the conditional probability of specializing in any other sector *i* given sector *j* would be equal to 1. The reverse is not true. Taking the minimum would eliminate this problem.

3.3.1.2 Product Space Map

Since proximity characterizes the interconnection between sectors, calculation of proximity between all sectors can generate a network representation of the entire production structure. The network, which I call the "product space map", depicts not any specific region, but rather the level of similarity and interaction between sectors at the national level. Therefore, nodes in the network represent sectors and links represent proximity above a certain threshold value (Details for constructing the network available in the Appendix F). Usually the threshold is chosen so that the average degree of nodes (the number of connections a node has) in the network is 4.

Regions' locations on the product space map are detailed visualizations of their industrial structures. I define a region as located on a node if the sector represented by that node is a key sector (*RCD*>1) for that region. Therefore, regions are distinguished from each other based on the nodes they occupy. In addition, the same region's location on the product space map changes over time as its output composition changes with respect to the national output composition. This allows me to compare regional industrial structures both across regions and over time.

3.3.1.3 Hub Sectors

Given the product space map, I further identify the heterogeneous functions of sectors by defining "hub sectors", which are sectors that interact strongly with their neighbors. For any sector *s*, immediate neighbors of *s* are sectors directly connected to *s* on the product space map; secondary neighbors of *s* are sectors directly connected to *s*'s immediate neighbors but not to *s* itself. I define the weighted average proximity of *s* (WAP_s) as the average proximity of *s* to its immediate neighbors weighted by the neighbor sectors' national GDP. Alternatively, $WAP_{x\text{-}s}$ is the GDP-weighted average *WAP* of *s*'s immediate neighbors to *s*'s secondary neighbors. If $WAP_s > WAP_{x\text{-}s}$, I call sector *s* a hub sector; otherwise, we call sector *s* a non-hub sector.

A hub sector tends to attract local economic activities around it. Depending on the energy intensity of the hub sector and the type of economic activities it tends to attract, I hypothesize that having more hub sectors as key sectors would affect regional industrial energy use. I test this hypothesis in later sections.

3.3.2 The U.S. Product Space Map and Hub Sectors for 2010

Figure 3.2 is the product space map for U.S. based on state-level sectoral GDP in 2010. Nodes represent sectors and links represent proximity. I first calculated the maximum spanning tree that includes all 64 nodes maximizing the tree's added proximity, and then added proximity links equal or above 0.59. The proximity threshold is chosen so that the network has an average degree of 4, resulting in a clean layout. The layout is generated through an edge-weighted spring-embedded algorithm, which treats nodes as equally charged particles and links as springs and manages to minimize the total force in the layout. Details regarding the construction of the product space map are available in Appendix F.

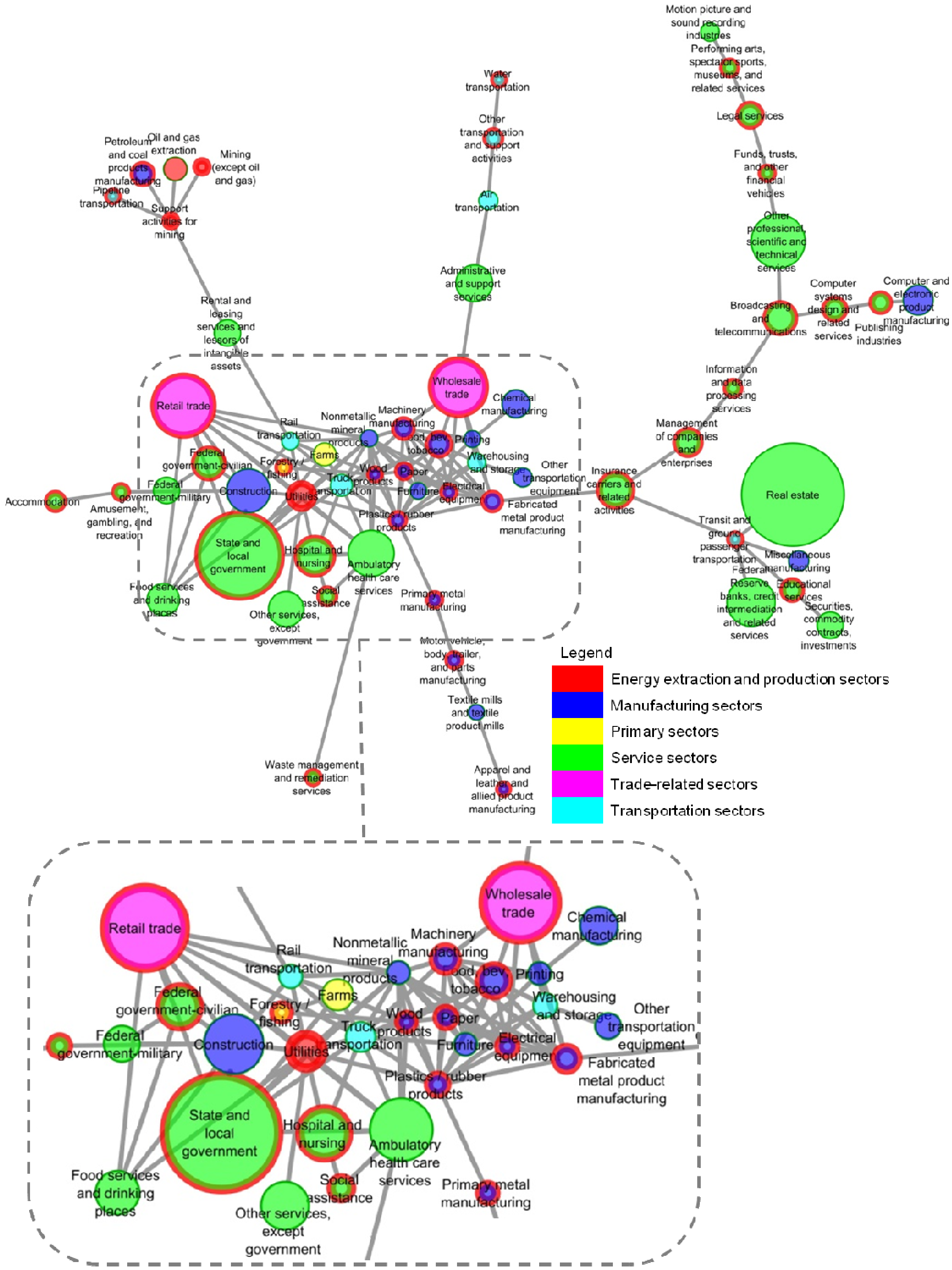


Figure 3.2. Product space map of the U.S. based on state-level sectoral GDP in 2010. Node size represents the sector's total national economic output. Hub sectors are highlighted in red.

The product space map shows that sectors are highly clustered. The core of the network is a large cluster of manufacturing sectors (blue), showing high proximity within the cluster as well as to some service sectors (green). Service sectors are clustered into two large groups. On the lower left side are sectors related to hospitality, entertainment, and public service. These sectors depend much on infrastructure and input of physical capital, which means they interact heavily with construction, manufacturing, trade and the utility sector. On the right side are sectors largely related to information, finance and management. Being less demanding in capital, this cluster is somewhat segregated from the rest of the network. Energy-related sectors are largely located on the upper left, interacting mostly with pipeline transportation and petroleum / coal product manufacturing. The only exception of energy sectors is the utility sector, which is very much the center of the network although the size of the sector is not particularly large.

Sectors play different roles in the industrial structure, potentially exerting secondary impacts on total energy use beyond their own energy intensity. First, some sectors possess more links than others. If these high-degree sectors (e.g., utilities, some manufacturing) expand, they can stimulate a variety of related service and manufacturing sectors. The potential effect on total energy use can be complex as a result. In addition, some sectors interact more intensively with their neighbors than other sectors do. This gives them greater capability for triggering production in neighbor sectors, and thus stronger influence on total energy use. While this heterogeneity is not directly observable from the product space map, it is related to proximity and can be calculated with the hub sector indicator.

Hub sectors (highlighted in red in Figure 3.2) can affect regional industrial structure and energy use in a complex manner. By definition, a hub sector's immediate neighbors interact more strongly with the hub sector than with the hub sector's secondary neighbors. Hence if a hub sector and a non-hub sector expand at the same rate, the former will have a stronger influence on its neighbors than the latter. The implication on energy use management, therefore, is that policies focusing on industrial structure should consider not only a sector's energy intensity, but also whether the sector is a hub. For example, compare the hospital and nursing sector and ambulatory health care services sector, neither of which is very energy-intensive (ranking No. 50 and No. 29 in energy intensity among the 64 sectors). While both are connected to more energy-intensive sectors (utilities, truck transportation, etc), the hospital and nursing sector, being a hub sector, has a stronger stimulating effect on the more energy-intensive sectors by its growth. Therefore, developing ambulatory health care services might be more beneficial for reducing energy use, although the sector consumes energy more intensively than hospital and nursing.

3.3.3 Region's Location and Transition on the Product Space Map

Industrial structures differ significantly across states. Figure 3.3 maps four states with distinctive industrial structures on the product space map, with nodes highlighted in black representing a state's key sectors ($RCD>1$). These are imposed on the national product space map shown in Fig. 3.2. Georgia (Figure 3.3(a)) particularly specializes in manufacturing, while Alaska (Figure 3.3(c)) depends heavily on energy, transportation and capital-demanding service industries. Although California (Figure 3.3(d)) and New York (Figure 3.3(e)) are both service-oriented states, California has a relatively bigger share of forestry and agricultural sectors. New York, on the other hand, relies more heavily on financial services. Conceivably, a state's industrial structure determines its energy profile, as well as constraining its future path of development.

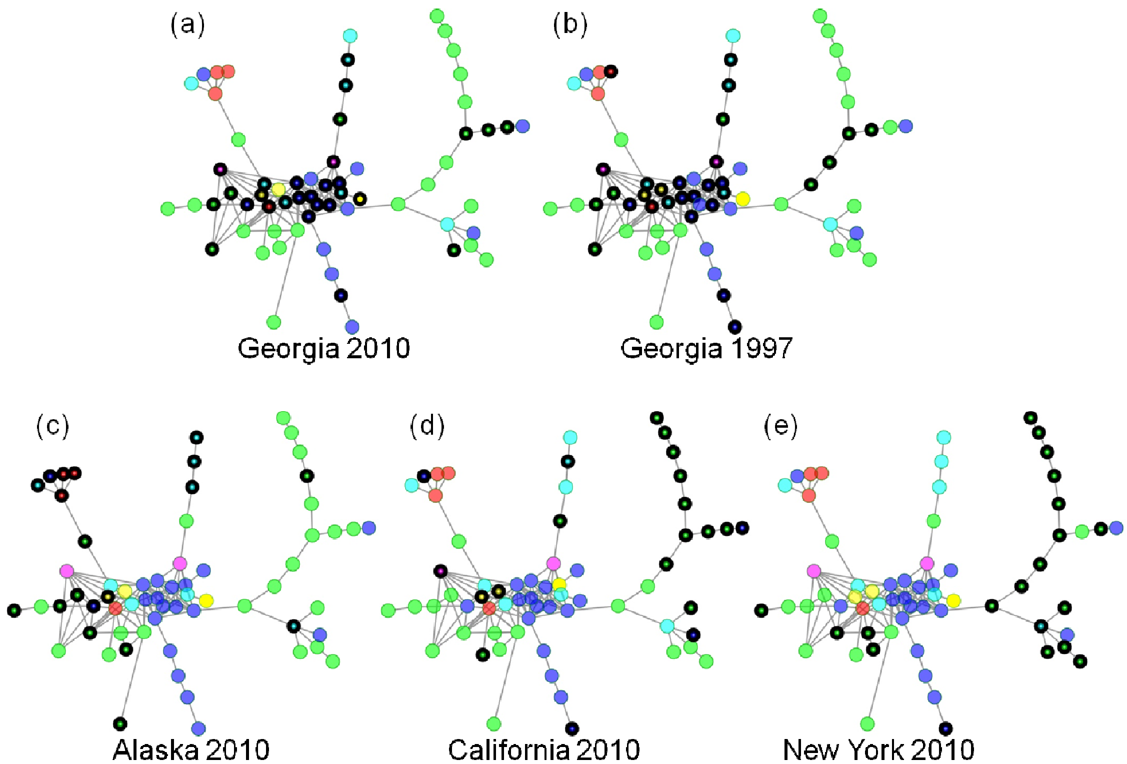


Figure 3.3. Comparison of product space across states and over time. Nodes highlighted in black represent states' key sectors in a given year. These are imposed on the national product space map shown in Fig. 3.2.

The same region's industrial structure changes over time. For instance, from 1997 (Figure 3.3(b)) to 2010 (Figure 3.3(a)), Georgia has developed new key sectors including furniture manufacturing, transportation equipment manufacturing, publishing and banking. Meanwhile, the state has lost specialization in mining, farming, apparel manufacturing, information services and enterprise management services (I calculate RCD for different cross sections but use the same product space map layout between 1997 and 2010. I have regressed proximity in 2010 against proximity in 1997, and found the coefficient (0.983) quite close to one, and an R-squared value of 0.915. This indicates the relative stability of proximity values. Refer to Appendix F for details.). For Alaska, the only newly developed key sectors are rental services and waste management, while state and local governmental service has changed into a non-key sector. California's structural change has been more dramatic, developing dependence on publishing industries, broadcasting and telecommunications, information and data processing, and funds and trusts, while losing specialization in transportation equipment manufacturing, air transportation, warehousing, rental services and management of enterprises. New York has had the most stable industrial structure, with the only new key sector being accommodation and no key sectors lost. Note that this change based on *RCD* is completely stripped from the national trend. Whether or not the change in *RCD* alters a state's key sector profile, we can couple this region-specific industrial structure transition with change in energy use (as shown in the decomposition analysis). Considering the growth and decline of hub sectors may affect energy use in a different way from non-hub sectors, I next investigate how newly developed key sectors and key-hub sectors contribute to regional industrial energy use through panel regression analysis.

3.4 The Contribution of Region-specific Industrial Structure Change to Industrial Energy Use

In this section, I explore the *ceteris paribus* contribution of region-specific industrial structure shift to change in industrial structure use with econometric methods. The econometric analysis builds upon the identified regional key sectors over time, as well as the key sectors' nature such as own energy intensity and interaction with neighbor sectors.

3.4.1 Panel Data Regression

Panel data regression is especially suitable for analyzing the *ceteris paribus* effect of region-specific structural shift on energy use. Because I suspect that unobserved historical factors for each region (region heterogeneity) affect regional energy use, correlation between regional structural shift and energy use change cannot be used to uncover a causal relationship. However, for the cross section of regions, I have several years of data. Differencing the same region's energy use in different years eliminates the unobserved time-constant factors that are probably correlated with the explanatory variables of interest [136] such as the number and category of key sectors for a region. This allows me to identify extent to which variation in regional energy use is due to variation in the independent variables that we hope to investigate. The specific model Iuse is a fixed-effect (FE) panel model that controls for heteroskedasticity [137].

With the FE panel model, I focus on the effect of two factors on regional industrial energy use: 1) the number of key sectors (*RCD*>1) per region; 2) the number of key sectors that are hub sectors (key-hub sectors) per region. I further break down the number of key sectors / key-hub sectors into energy, manufacturing and service sectors individually, with the purpose of untangling the true driving force of regional energy use. The rationale for choosing these two factors is as follows. First, the number of key sectors matters because a region's location on the product space map changes over time, and the IDA shows that change in *RCD* is coupled with change in energy use. In addition, the number of key-hub sectors is important since the nature of a sector is determined by not only its own energy intensity, but also its impact on other sectors, as well as the kind of economic activity it attracts. For example, if a service sector is a hub sector, it may induce the production of a variety of energy-intensive sectors, even though it does not consume much energy itself. A region developing higher *RCD* on this service hub sector could possibly incur an increase of energy use rather than a decrease.

3.4.2 Panel Regression Results

To fully capture the chronological change in regional industrial structure, I investigate yearly state-level data from 1997 to 2010. Regarding the explanatory variables, I examine a state's key sectors by total number and category, the impact of these key sectors being hub sectors (key-hub sectors), as well as regional economic growth.

Table 3.1. Effect of region-specific industrial structure change on regional energy use

Regressor \ Regression Index	(1)	(2)	(3)	(4)	(5)
Number of key sectors in:					
-Total	-0.011 (-3.33)	_	-0.013 (-3.75)	_	_
-Energy	_	_	_	0.039 (2.63)	0.042 (2.80)
-Manufacturing	_	_	_	0.014 (1.91)	0.013 (1.86)
-Service	_	_	_	-0.031 (-7.01)	-0.032 (-7.04)
-Transportation	_	_	_	0.002 (0.15)	_
-Agriculture	_	_	_	-0.034 (-1.71)	_
-Trade	_	_	_	-0.039 (-1.96)	_
-Transportation, agriculture and trade	_	_	_	_	-0.010 (-1.10)
Number of key sectors that are hub sectors (key-hub) in:					
-Total	_	-0.0004 (-0.19)	0.004 (1.97)	_	_
-Energy	_	_	_	0.046 (4.20)	0.048 (4.37)
-Manufacturing	_	_	_	-0.006 (-1.38)	-0.004 (-1.15)
-Service	_	_	_	0.011 (3.29)	0.012 (3.41)
-Transportation	_	_	_	-0.010 (-1.43)	_
-Agriculture	_	_	_	0.019 (1.77)	_
-Trade	_	_	_	0.028 (2.40)	_
-Transportation, agriculture and trade	_	_	_	_	-0.006 (-0.79)
log GSP	0.148 (2.47)	0.182 (3.09)	0.135 (2.23)	0.123 (1.99)	0.113 (1.74)
Intercept	12.253 (16.43)	11.599 (16.45)	12.409 (16.43)	12.460 (16.18)	12.853 (15.48)
Observations	714	714	714	714	714
R-squared (overall)	0.749	0.898	0.724	0.530	0.460
F statistics	13.12	4.90	9.41	22.72	18.20

Notes: Regression results report coefficients for each regressor. t-statistics are in parentheses. Results are robust to heteroskedasticity. Dependent variable: natural log of yearly industrial total energy use (logTE) from 1997 to 2010. Sample size: 50 U.S. states and Washington D.C. over the 1997-2010 period, 714 observations in total. Regressors: log GSP – natural log of real gross state output (2009 price).

Columns (1) to (3) in Table 3.1 prove that developing new key sectors and key-hub sectors significantly changes energy use, even when the impacts of energy, manufacturing and service sectors are mixed together. All tests control for economic growth, represented by natural log of gross state output (*loggsp*). Columns (1) and (2) individually test the effect developing new key sectors (*keysec*) and key-hub sectors (*keyhub*), while Column (3) simultaneously controls both. Based on Column (3), developing one more key sector would reduce regional industrial energy use by 1.3%. Given the same number of newly developed key sectors, the effect of one more key sector being hub is barely significant (t=2.0). Besides, the magnitude of impact seems trivial (0.4% increase in energy use). While the implication is that diversification of industrial structure serves to reduce energy use, the true impact may not be diversification *per se*, but transition towards certain types of sectors (e.g., shifting focus to service industries). In addition, the effect of developing specialization in hub sectors has also been muffled by the contradictory impact from service, manufacturing and energy sectors. To unravel the true impact of structural transition, I split *keysec* and *keyhub* into different categories (Column (4) and (5) in Table 1). Sectors of primary interest include energy, manufacturing and service. Other sectors (transportation, primary and trade) are first tested individually (Column (4)) and eventually combined into one group (Column (5)). Their individual as well as collective impact on energy use stands relatively minor (Refer to Appendix G for more complete regression results). According to Column (5), developing one more key sector in the service category reduces regional energy use by 4.2% on average, while a newly developed key sector in the energy category boosts energy use by 3.9%. Given the same level of diversification and the same composition of new key sectors, a hub energy sector increases total energy by 4.8% than a non-hub energy sector does. With the same *ceteris paribus* assumption, a hub service sector increases total energy use by 1.2% more than a non-hub service sector. Counter intuitively, diversifying towards manufacturing does not have a significant impact. Nor does the number of hub manufacturing sectors matter if the rest of the structural transition portfolio is held constant.

To understand the economic impact of the structural changes in the US economy, let’s consider a few examples. Wisconsin developed one key sector in energy between 1997 and 2010, boosting energy use by around 4%. Yet this boosting effect is more than offset by 4 more key sectors developed in service, which reduced almost one fifth of the state's energy use. New York developed 6 more key sectors that are hub service sectors, which would result in over 7% decrease in energy use. Colorado lost 3 key sectors that are hub service, causing over 3.6% increase in energy use. Even more significantly, Pennsylvania saw over 12% increased energy use as 3 hub energy sectors have become key sectors since 1997.

Regression results demonstrate that transition towards a new key sector has both direct and indirect effects on total energy use. A service sector, being usually less energy-intensive, by nature reduces energy use. However, if the service sector is a hub sector, it has stronger stimulating effects to its immediate neighbors on the product map than if it is a non-hub sector. While some hub service sectors mainly have connections in service, others interact heavily with manufacturing, utilities, transportation and trade. The growth of these sectors drives the economy towards a more energy-intensive output composition. The same mechanism holds for a hub energy sector. On the other hand, manufacturing plays a bonding role between energy and service sectors. A hub manufacturing sector thus has somewhat equal boosting power towards its neighboring energy and service sectors. Consequently, while a new key-hub sector in manufacturing still induces more growth than a non-hub manufacturing sector, induced energy use is to some extent smaller due to the simultaneous growth of energy and service sectors.

A noteworthy point is that whether a sector is hub can change over time, giving the regression results somewhat different interpretations. If the hub status of a specific sector has not changed during the studied period, the analysis is exactly the same as shown above. That is, for the same number of newly developed key sectors, more hubs in energy and service result in higher energy use. Alternatively, if a specific sector has changed from non-hub to hub, a region specializing in this sector would still have one more hub sector even if *RCD* on this sector remained the same. This means that the sector has developed stronger interconnection with its neighbors, possibly boosting the output of other energy-intensive sectors. The result is also increased energy use. In both situations, validity of the regression results remains. That said, the policy implication that transiting towards non-hub sectors benefits energy use mitigation is only valid in short to medium terms.

3.5 Conclusions

In this chapter, I investigated the linkage between region-specific industrial structure shift and total industrial energy use, and proved that sectors play heterogeneous roles in shaping regional industrial energy use. I used a simple indicator, revealed comparative dependence (*RCD*), to separate region-specific industrial structure shift from the national trend. The separated effect is highly significant and alters industrial energy use differentially across states. In addition, I visually demonstrated that sectors play different roles in terms of interaction in the industrial structure network. Because regions focus on different sectors from each other and over time, fixed effect panel regression showed that hub energy and hub service sectors have more profound effects in driving up energy use than their non-hub counterparts. The policy implication, therefore, is that regional industrial development strategies have as an important impact as the general national environment in energy use management. As policy makers decide on priority sectors to develop, they need to consider not only the energy intensity of a sector itself, but its interaction with others that triggers a secondary effect in total industrial energy use. Nevertheless, I recognize the limitations of our research and spaces for improvement. First, by taking the minimum in calculating proximity (equation (3.3)), we have underestimated the interconnection between sectors, and therefore have underestimated the systematic structural change that sectors can induce. Second, longer time periods would yield more variance in industrial structure change, therefore, giving better panel regression results. In addition, if region-specific technology data were available, I would be able to reveal more facts about how region-specific technological improvement affects regional energy use. Finally, while regression results use historical data to reveal the contribution of increased hub sector dependence to increased energy use, it does not predict that developing specialization in non-hub sectors will reduce energy use in the future.

CHAPTER 4

REGIONAL ENERGY REBOUND EFFECT: THE IMPACT OF ECONOMY-WIDE AND SECTOR-LEVEL ENERGY EFFICIENCY IMPROVEMENT IN GEORGIA, USA

4.1 Introduction

In this chapter, I explore how sector-level energy efficiency improvement propagates its impact through the economic structure and generates economy-wide rebound. I develop a regional computable general equilibrium (CGE) model, with a detailed treatment of energy input in the production function, and a highly disaggregated sector profile incorporating 69 sectors. The first feature allows me to explore fuel substitution in detail as energy efficiency and sector price levels change. The second feature allows me to trace energy and economic changes to more micro scales. Applying the model to Georgia, USA, I investigate changes in the region's aggregate energy use, price level, GDP and consumption through two types of scenarios: 1) *economy-wide* energy efficiency improvements; 2) *sector-level* energy efficiency improvements. Type 1 scenario sheds light on the true magnitude of the economy-wide energy rebound, as well as the tradeoff between economic growth, consumer welfare and energy conservation. Type 2 scenarios further isolate the different impacts of individual sectors on aggregate energy and economic indicators. By tracking the price level and production scale in every sector, we understand the process of permeation and diffusion of sectoral shocks through the economic structure.

This study builds upon existing theoretical literature on energy rebound effects. The notion of rebound started with Jevons [138] in the discussion on UK's coal consumption. Yet complete rebound theories were established by modern economists including

Khazzoom [139], Brookes [140] and Saunders [56, 141, 142]. Borenstein [143] offered a well-rounded microeconomic explanation for rebound effects. Here we define rebound effect as the lost part of ceteris paribus energy conservation from increased energy efficiency [144]. Theoretically, increased efficiency reduces energy prices. Associated to this price reduction are three types of effects. First, on the single-sector scale, price reduction triggers increased usage. Second, reduced price in one energy service enlarges purchasing power in other services, possible causing a further increase in energy usage. Third, on the macro scale, a structural effect caused by shifting spending patterns also affects system-wide energy demand, though this secondary effect can increase or reduce energy usage. Collectively, the effects above are usually found to reduce the potential benefit from increased energy efficiency, and are therefore termed "the rebound effect".

Yet the measurement of rebound is ultimately an empirical question, with far less than complete answers. Some studies only scrutinize the impact of energy efficiency improvement at the single-sector level [145-150]. At the higher macroeconomic level, Howells et al.[66] did incorporate macroeconomic feedbacks in a rebound analysis for South Korea, but with shocks that only arise from the electricity generation sector. Berkhout et al. [144] investigated multiple single-sector shock scenarios for the Netherlands' rebound effects, but only for a six-commodity case. Schipper and Grubb [63] compared rebound effects for IEA countries by breaking down the economy into 10 manufacturing sectors, 5 transportation sectors and the service sector, yet their simulation only covered economy-wide energy efficiency improvement. A more comprehensive series of rebound study for the Scotland economy [64, 65, 151, 152] did use a 25-sector industry profile, but the analysis was still based upon general technological change that increases economy-wide energy efficiency. Saunders [153] analyzed historical rebound evidence for 30 U.S. sectors, covering both sector-level and aggregate results, but the study did not match the empirical results with a clear mechanism. The sector-level simulations in this chapter are more comprehensive than any existing empirical study, tracing aggregate rebound back to the interaction between sectors, and offering policy makers a comparative basis for identifying the breakthrough point to achieve energy conservation through efficiency measures.

The rest of the chapter is organized as follows. In section 4.2, I introduce how I calculate economy-wide rebound effects. I also present the CGE model, highlighting the model's sector breakdown and treatment of energy sources in the production structure, two features that significantly facilitate our analysis of sector contribution to regional energy rebound. In section 4.3, I analyze the impact of both economy-wide and sector-specific energy efficiency improvement on regional energy use and key economic indicators. I then focus on sectors with highly heterogeneous impacts, and explore how sector-level efficiency shocks propagate through the economic structure and generate aggregate impacts. I conclude and discuss policy implications in section 4.4.

4.2 Methodology

4.2.1 Calculating Rebound Effects

The rebound effect measures, in percentage terms, the extent to which energy savings fail to fall in proportion with the scale of energy efficiency improvement. Theoretically, calculating the rebound effect is straightforward. For example, assume that energy efficiency increases by 10%. This means that only 90% of the original energy use is required to provide the same amount of output or service. Reduced energy use against the benchmark scenario is equivalent to a reduction in energy price, which in turn drives energy use up. This "bounce-back" phenomenon is the cause for rebound. If energy use reduces only by 4%, then 6% energy saving is lost compared with the 10% expected energy saving. This indicates a 60% rebound effect. Along the same line, a rebound effect of 100% means that energy use was not reduced at all. A rebound effect over 100%

implies *backfire*, which means energy use actually increases with increased energy efficiency.

For empirical calculation, defining the *ceteris paribus* condition is crucial. In an economy-wide setting, practically any non-zero elasticity value would cause rebound effect. This means that for the benchmark no-rebound scenario, change in price levels should not trigger any change in household consumption structure, or the production input mix of any sector. Suppose that energy efficiency increases by 10% in one sector, the benchmark economy-wide energy saving is simply 10% of this sector's energy use. If the sector accounts for 2% of the economy's total energy use, then economy's benchmark energy saving is 0.2%. This number is then compared with the actual energy saving that allows for substitution possibilities to yield the magnitude of rebound.

4.2.2 CGE Model Description

Here I develop a regional CGE model (Refer to Appendix H for condensed mathematical formulations) to systematically evaluate the impacts of technological change that increases energy efficiency at the sector level. Regarding the market structure, I assume that agents in our region of study are price takers in the competitive market. The market includes two exogenous transacting agents besides the domestic market: rest of the country and rest of the world. The domestic market is where all household consumption, government expenditure and non-energy intermediates for production are sourced. Imports and locally produced goods are imperfect, or Armington substitutes to each other [154]. Locally produced goods are used for local consumption and export. I treat this choice as a production possibility frontier represented by a constant elasticity of transformation (CET) function. Relevant to this study, this treatment of import and export will account for energy leakage due to inter-region transactions. Population is assumed fixed, which is valid in the short-to-medium term analysis. The following texts discuss agent behaviors and dynamic specifications in more detail.

Both the household module and the producer module take on a nested behavior structure, allowing higher flexibility in substitutive possibilities. They can be constant elasticity of substitution (CES) or Leontief which is usually introduced between non-energy intermediates in the production module.

Household consumption in each period is modeled in a two-level nested structure. The representative household consumes energy and non-energy goods connected by a CES utility function. Different non-energy goods are connected by a Cobb-Douglas utility function, as is the case for energy goods. Each good in the domestic market is an Armington composition of locally supplied goods and imports. Between periods, we assume an intertemporal elasticity of consumption, which allows the household to maximize its intertemporal utility through consumption in each period. Government expenditure adopts a similar structure, transforming market commodities into public goods.

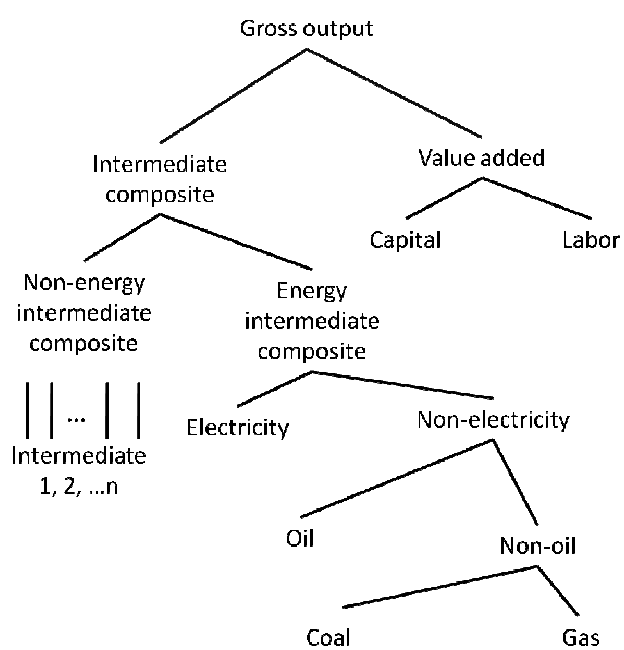


Figure 4.1. Nested production structure with a detailed treatment of energy intermediate

Production takes on a multi-level nested structure (Figure 4.1). Since I am interested in how the industrial structure transforms under technological change that increases energy efficiency, I introduce in the production structure an energy module that is further disaggregated into different energy sources. The relationship between energy and non-energy intermediates is assumed to be CES, with the choice of the elasticity parameter matching the widely used GTAP energy model [155]. Other nested levels also adopt convenient functional forms such as CES and Leontief.

Another crucial part of the model is how I introduce energy in the production structure. I identify four energy sources through the final use form: electricity, oil, coal and gas. These energy sources are again connected in a nested structure to allow substitution possibilities. While there is no consensus as to where the energy composite should be introduced in the nested production structure [156] , I adopt the approach used by Hanley et al. (2009) [65], introducing energy as a intermediate rather than value added. Given that energy is a produced input, it seems most natural to position it with other produced intermediates [157]. I identify energy intermediates as the final product of the following sectors: electricity generation, transmission and distribution; petroleum refining; coal mining; natural gas distribution. Similarly, non-energy intermediates always come from sector-level final products. For treatment of non-energy intermediates, I have adopted the standard Leontief input-output assumption for less strict data requirements and faster calculation speed.

In terms of the level of detail in the market structure, I have chosen a highly disaggregated sector profile. While existing CGE studies hardly break down the economy into more than 20 sectors, I run the model with 69 sectors (Refer to Appendix I for the list of sectors and corresponding NAICS codes). I design the sector profile at such a disaggregated level to ensure enough detail in the industrial network structure. This in turn allows me to trace how the impact of an idiosyncratic shock propagates through the industrial network and generates aggregate changes. In this case, we can observe how increased energy efficiency in one sector affects every other sector's production level, market demand and price, as well as sector-level energy use. In evaluating energy-saving projects targeting efficiency gains, the more disaggregated the industrial structure, the easier it is for policy makers to consider tradeoffs between prioritized sectors in terms of price, production and demand.

Regarding the dynamics, consumers consider their intertemporal welfare from consumption, and investment in production sectors matches consumers' lifetime saving choices. I make the following assumptions: 1) capital stock updates in each period from the last period's stock after accounting for depreciation and investment from local industries as well as foreign transactors. 2) Local investment matches consumer saving. 3) For the consumer with an initial endowment of capital stock, saving is implicit through the consumer's intertemporal consumption choices (refer to Appendix J for detailed description of how capital updates between periods). Each period is viewed as one year. The equilibrium generated without any policy implementation will be the benchmark that depicts the steady state of the economy given the status quo. The new equilibrium generated with a policy shock will be the counterfactual used to study the impact of exogenous shocks.

For calibration, I have calibrated the pilot model to Georgia based on the state's social accounting matrix (SAM) in 2010. The SAM, obtained from the Economic Impact Analysis Tools (IMPLAN) [158] database, was restructured to match our sector specification and agent behaviors. Elasticity parameter choices are crucial for a CGE model. Dozens of elasticity parameters define the behavior of producers, consumers and the government when the economy faces a shock. Therefore, I have chosen important elasticity parameters either based on econometric studies or existing CGE models. A complete list of parameter choices is available in Appendix K.

4.2.3 Simulation Scenarios

For the numerical simulations, I assume an exogenous energy efficiency improvement either occurs across all productive sectors, or in individual production sectors. Results based on the one-time shock describe the new equilibrium when the economy has fully responded, which means all changes in all variables are due to the energy efficiency shock.

I consider two simulation scenarios. First, I consider uniform energy efficiency improvement in all productive sectors. This economy-wide energy efficiency improvement informs us of the impacts of general technological change on energy use, production, demand and price at both the economy-wide scale and sector level. However, all the sectors' heterogeneous contributions to shaping the new equilibrium are lumped together in the economy-wide energy efficiency improvement scenario. Second, I consider energy efficiency improvement in individual sectors (epicenters). This allows me to compare the impacts of different sectors on aggregate economic outcome as well as on other sectors. I then identify relevant sectors that I can use to explore how epicenters' activity propagates through the economic structure.

4.3 Results and Discussion

I consider an exogenous 10% energy efficiency improvement in productive sectors at the energy composite level of the nested production structure. Because energy efficiency is defined as the amount of energy used to produce a unit of product (or service), increased energy efficiency implies using less energy to produce the same amount of product (or service) [159]. Therefore, 10% energy efficiency improvement in our analysis is equivalent to using 10% less energy to produce the same amount of output at the sector level.

I analyze two types of scenarios. The first type assumes that the energy efficiency improvement applies to all production sectors, i.e. *an economy-wide shock*. The second type assumes that only one sector (epicenter sector) benefits from increased energy efficiency, i.e. *a sector-specific shock*. Because I disaggregate the economy into 69 sectors (Refer to Appendix I for sector profile), I run 69 simulations of the second type, improving energy efficiency in one single sector at a time. Simulating an economy-wide shock provides a benchmark for the scale of impact on various economic and energy indicators relative to the magnitude of the shock. Sector-specific shocks allow me to investigate how the impact of small idiosyncratic shocks propagates through the economic structure.

I run the simulation over 10 periods, with each period representing one year. In the discussions below, I only report results for the final year in the studied period, which represents changes in economic and energy indicators after the economy has fully adjusted. Given an energy efficiency shock, the economy almost always reaches a new equilibrium after the first period. This is because energy accounts for a relatively small portion among production factors (compared to capital and labor for example), allowing the economy to adjust quickly.

4.3.1 Benchmark Scenario – Economy-wide Energy Efficiency Improvement

Economy-wide impacts on regional GDP and household consumption are orders of magnitude smaller than the energy efficiency shock (Figure 4.2). Given a 10% economy-wide shock in energy efficiency for production activities, total energy used for production reduces by 8.51%, less than 10%. This indicates that energy rebound does exist on the order of 15% for production, but not to the extent of backfire. On the other hand, household consumption increases very little, only by 0.52%, and GDP grows even less, by 0.27%. While counter-intuitive at first sight, low growth induced by the energy efficiency shock is plausible considering the role of energy in the economy. On one hand, GDP and consumption should grow since increased efficiency has increased the economy's productivity. On the other hand, energy plays a relatively minor role among all costs incurred in production activities. This means that the total impact on production would be relatively minor. Besides, we are not considering energy efficiency improvement in end-use consumption. Therefore, household consumption increases only because of reduced prices and increased household real income, both of which are bounded to be small given the nature of the efficiency shock.

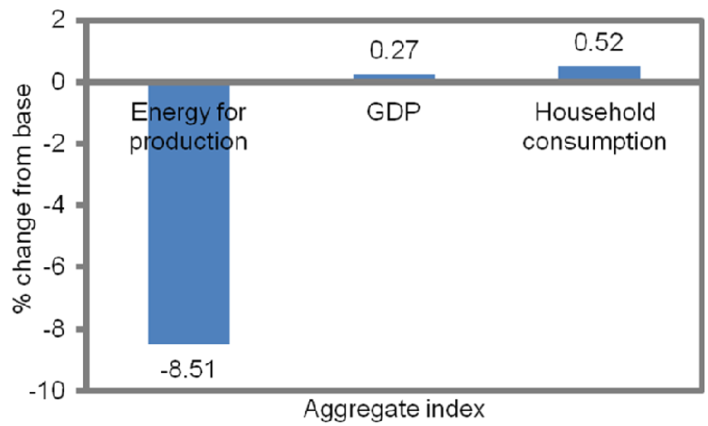


Figure 4.2. Aggregate economic changes induced by 10% economy-wide increased energy efficiency for production

The rebound effect in terms of economy-wide energy consumption differs among energy sources. Note that with CGE models, all quantity variables are represented through dollar spending (Refer to Appendix L for Georgia's energy spending composition). Therefore, I have found energy product cost data from other sources (Table 4.1), and have converted economy-wide spending on energy to energy quantity. Figure 4.3 shows that in the scenario without rebound, the consumption of electricity, petroleum and natural gas falls by around 5%. The use of coal, on the other hand, drops by nearly 10%, close to the scale of the efficiency improvement. This is because the economy's coal consumption can be almost exclusively traced back to production activities, while electricity, petroleum and natural gas are also widely consumed for end-use purposes. Ranking the rebound effect across energy sources, we have -9.8% for coal, 11.6% for electricity, 13.9% for natural gas and 30.9% for petroleum. Rebound for electricity, natural gas and petroleum is positive, but not large enough to generate backfire. Coal is distinct in that increased efficiency further drives down the demand, indicating that industries tend to shift towards alternative energy forms as energy efficiency increases.

Table 4.1. Energy production cost coefficients and data source

Energy source	**Production cost (producer price, 2010 dollars per million BTU)**	**Data source**
Electricity	28.52	Source: EIA (http://www.eia.gov/forecasts/aeo/tables_ref.cfm) Table 8. Electricity Supply, Disposition, Prices, and Emissions Combined cost for generation, tranmission and distribution equals average price
Oil	22.57	Source: EIA (http://www.eia.gov/forecasts/aeo/tables_ref.cfm) Table 12. Petroleum Product Prices
Gas	4.37	Source: EIA. Henry hub price (http://www.eia.gov/dnav/ng/hist/rngwhhdA.htm)
Coal	1.77	Source: EIA (http://www.eia.gov/forecasts/aeo/MT_coal.cfm)

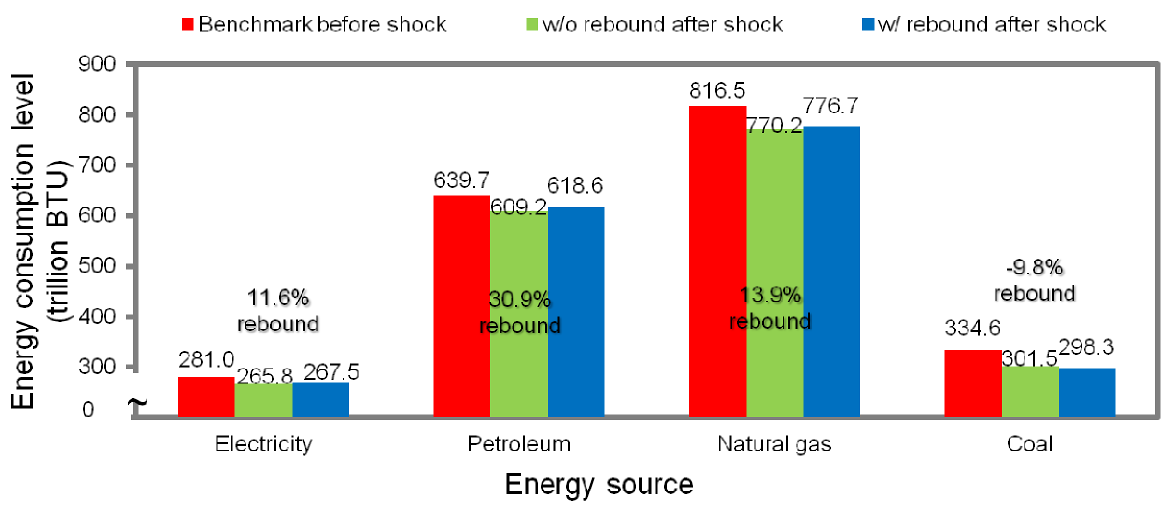


Figure 4.3. Rebound effect by energy sources

I calculate total rebound in both dollar spending and energy units. In total, non-electricity energy spending (by 2010 price standard) reduces by 3.84% given the efficiency shock. Total non-electricity energy spending rebound stands at 24.8%. Alternatively, if measured in energy units (btu), total non-electricity energy consumption falls by 5.43%, with 11.5% rebound. The results indicate that while natural gas consumption has the largest impact on *energy consumption*, the high cost of petroleum grants it greater influence on *energy spending*. For electricity, gross consumption as well as spending reduces by 4.78%, with 11.6% rebound. In general, my estimates are lower than a previous study on industrial energy use efficiency for the United Kingdom by Allan and Hanley, et al. (2007) [151], who identify rebound effects of the order of 30% to 50%. Still, my results echo recent theoretical analysis in supporting low to moderate rebound [143, 160].

Besides changing energy consumption quantity, the efficiency shock also changes energy prices. As energy efficiency increases, local energy prices naturally fall. The prices of coal and oil reduce by 0.91% and 0.97%, respectively. The prices of electricity and gas reduce by only 0.77% and 0.75%, respectively. Figure 4.4 demonstrates the various factors affecting local energy prices. As a most direct effect, increased energy efficiency on the production side reduces energy demand for production, driving down energy prices (Path ABL, Figure 4.4). Besides, as energy is used for producing energy, the production cost for energy decreases with increased energy efficiency, which also tends to reduce energy prices (ACL). However, energy price reduction induces end-use consumers to increase energy consumption (LJ). It also causes producers to substitute energy for other production factors (LK). These effects drive up energy demand and keep energy prices from falling (JM, KJM). Another direct effect of increased energy efficiency is reduced final commodity prices from various sectors (AD). As locally produced commodities become cheaper, local demand (DFH, DGH) as well as export demand for these commodities increases (DE). The result is increased scale of local commodity production (EI, HI), which drives up demand for all production factors, including energy. The aggregate impact, again, is that energy prices are prevented from falling (IJM).

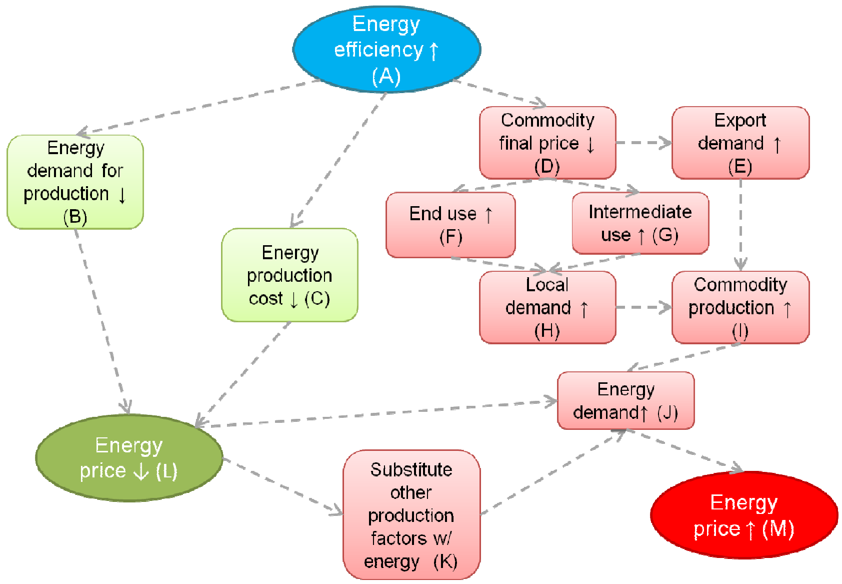
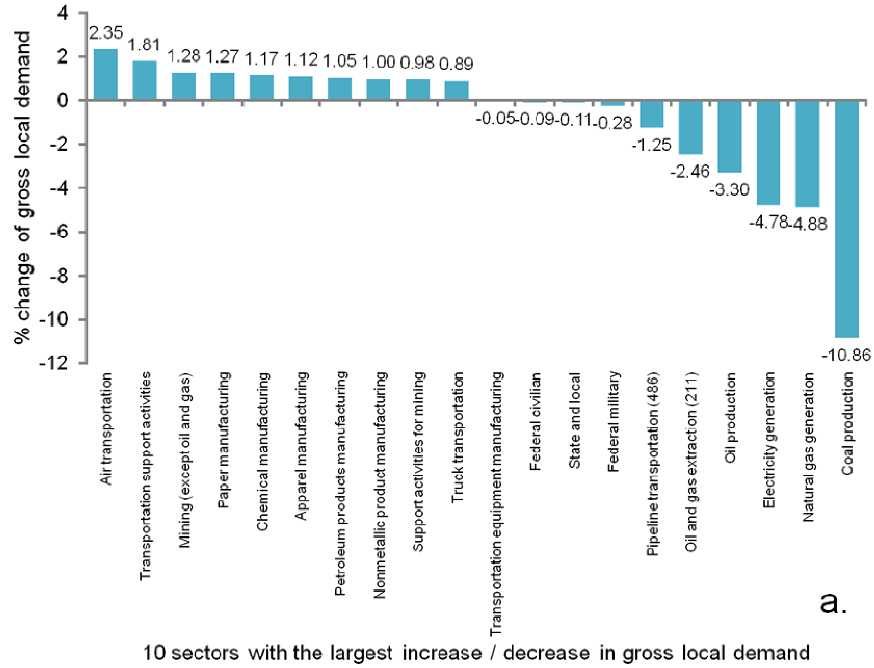


Figure 4.4. Factors affecting local energy prices

In local sectoral markets, the economy-wide efficiency shock induces change in local demand and production, as well as reducing local commodity prices. In terms of local commodity demand, air transportation, transportation support activities, mining, paper manufacturing and chemical manufacturing experience the largest boost, while energy production sectors see the largest decrease (Figure 4.5(a)). As with local market prices, all commodity prices fall because of reduced production costs. Sectors affected most heavily are air transportation, petroleum and coal products manufacturing, pipeline transportation, paper manufacturing and nonmetallic mineral product manufacturing (Figure 4.5(b)). Still, local production structure adjusts differently from local demand. Petroleum and coal products manufacturing grows by over 14%, far exceeding other sectors. For air transportation, chemical manufacturing and paper manufacturing, production scale grows by 3.94%, 2.66% and 2.56% respectively. Conceivably, energy production sectors still take the largest fall, especially gas, oil and electricity production (Figure 4.5(c)).


% change of gross local demand
4
2
0
-2
-4
-6
-8
-10
-12
2.35
1.81
1.28
1.27
1.17
1.12
1.05
1.00
0.98
0.89
-0.05
-0.09
-0.11
-0.28
-1.25
-2.46
-3.30
-4.78
-4.88
-10.86
Air transportation
Transportation support activities
Mining (except oil and gas)
Paper manufacturing
Chemical manufacturing
Apparel manufacturing
Petroleum products manufacturing
Nonmetallic product manufacturing
Support activities for mining
Truck transportation
Transportation equipment manufacturing
Federal civilian
State and local
Federal military
Pipeline transportation (486)
Oil and gas extraction (211)
Oil production
Electricity generation
Natural gas generation
Coal production
a.
10 sectors with the largest increase / decrease in gross local demand


% drop in local market price
3.5
3
2.5
2
1.5
1
0.5
0
3.20
2.14
1.60
1.38
1.31
1.28
1.24
1.16
1.13
1.10
Air transportation
Petroleum products manufacturing
Pipeline transportation
Paper manufacturing
Nonmetallic mineral product manufacturing
Truck transportation
Apparel manufacturing
Oil and gas extraction
Primary metal manufacturing
Support activities for mining
b.
10 sectors with the largest drop in local market price

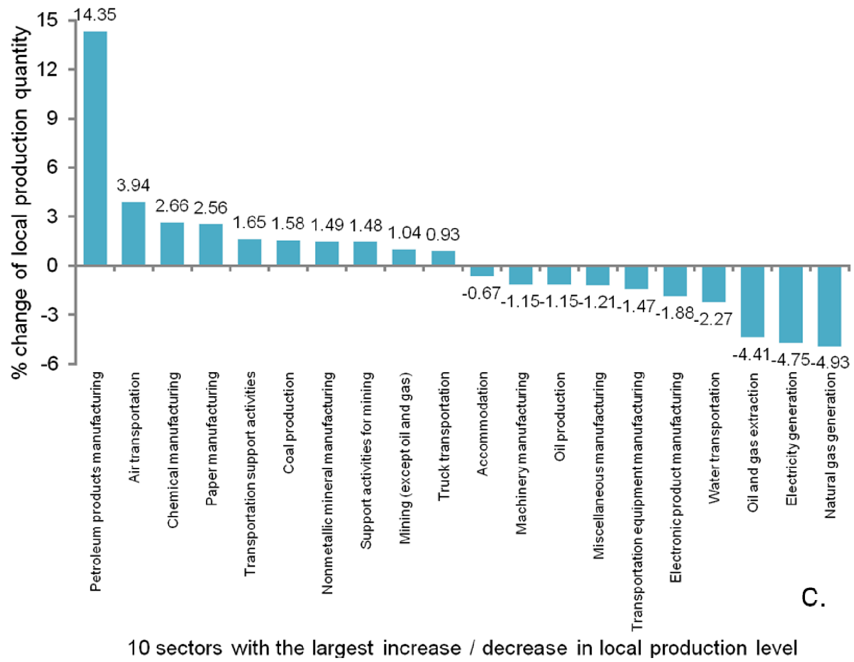


Figure 4.5. Impact on local sectoral markets. (a) Sector with the largest increase / decrease in local demand; (b) Sectors with the largest drop in local market price; (c) Sectors with the largest increase / decrease in local production

I have identified several parameters important for the CGE model's simulation results. These include the elasticity between value-added and intermediate inputs, the elasticity between energy and non-energy intermediate inputs, the elasticity between different energy inputs, and the capital adjustment coefficient. I carry out sensitivity analysis by varying the values of these parameters and compare key economic and energy indicators from the model results (Table 4.2-4.7).

Table 4.2. Impact of 10% economy-wide production energy efficiency improvement by varying the elasticity between value-added and intermediate inputs

Indicator	Low (0.3)	Central (0.5)	High (0.7)
GDP growth (%)	0.20	0.27	0.34
Household consumption growth (%)	0.52	0.52	0.52
Percentage change in capital investment (%)	0.31	0.37	0.42
Percentage change in energy for production (%)	-8.74	-8.51	-8.29
Percentage change in non-electricity energy consumption (%)	-3.98	-3.84	-3.71
Non-electricity rebound (%)	22.15	24.75	27.35
Percentage change in coal consumption (%)	-11.27	-10.86	-10.46
Coal rebound (%)	-13.88	-9.83	-5.76
Percentage change in oil consumption (%)	-3.43	-3.30	-3.17
Oil rebound (%)	28.18	30.88	33.57
Percentage change in gas consumption (%)	-4.99	-4.88	-4.77
Gas rebound (%)	12.04	13.92	15.77
Percentage change in electricity consumption (%)	-4.86	-4.78	-4.69
Electricity rebound (%)	10.01	11.58	13.15

Table 4.3. Impact of 10% economy-wide production energy efficiency improvement by varying the elasticity between energy and non-energy intermediate inputs

Indicator	Low (0.1)	Central (0.3)	High (0.5)
GDP growth (%)	0.27	0.27	0.27
Household consumption growth (%)	0.52	0.52	0.52
Percentage change in capital investment (%)	0.37	0.37	0.37
Percentage change in energy for production (%)	-8.52	-8.51	-8.44
Percentage change in non-electricity energy consumption (%)	-3.85	-3.84	-3.81
Non-electricity rebound (%)	24.66	24.75	25.47
Percentage change in coal consumption (%)	-10.87	-10.86	-10.84
Coal rebound (%)	-9.87	-9.83	-9.56
Percentage change in oil consumption (%)	-3.30	-3.30	-3.26
Oil rebound (%)	30.77	30.88	31.75
Percentage change in gas consumption (%)	-4.88	-4.88	-4.86
Gas rebound (%)	13.87	13.92	14.26
Percentage change in electricity consumption (%)	-4.78	-4.78	-4.74
Electricity rebound (%)	11.50	11.58	12.19

Table 4.4. Impact of 10% economy-wide production energy efficiency improvement by varying the elasticity between electricity and non-electricity energy intermediates

Indicator	Low (0.5)	Central (1)	High (1.5)
GDP growth (%)	0.27	0.27	0.27
Household consumption growth (%)	0.52	0.52	0.52
Percentage change in capital investment (%)	0.37	0.37	0.37
Percentage change in energy for production (%)	-8.51	-8.51	-8.51
Percentage change in non-electricity energy consumption (%)	-3.85	-3.84	-3.84
Non-electricity rebound (%)	24.64	24.75	24.87
Percentage change in coal consumption (%)	-10.87	-10.86	-10.86
Coal rebound (%)	-9.84	-9.83	-9.83
Percentage change in oil consumption (%)	-3.30	-3.30	-3.29
Oil rebound (%)	30.77	30.88	30.98
Percentage change in gas consumption (%)	-4.89	-4.88	-4.87
Gas rebound (%)	13.73	13.92	14.10
Percentage change in electricity consumption (%)	-4.76	-4.78	-4.79
Electricity rebound (%)	11.84	11.58	11.33

Table 4.5. Impact of 10% economy-wide production energy efficiency improvement by varying the elasticity between oil and non-oil (gas and coal composite)

Indicator	Low (1)	Central (2)	High (3)
GDP growth (%)	0.27	0.27	0.27
Household consumption growth (%)	0.52	0.52	0.52
Percentage change in capital investment (%)	0.37	0.37	0.37
Percentage change in energy for production (%)	-8.51	-8.51	-8.51
Percentage change in non-electricity energy consumption (%)	-3.84	-3.84	-3.84
Non-electricity rebound (%)	24.75	24.75	24.75
Percentage change in coal consumption (%)	-10.84	-10.86	-10.89
Coal rebound (%)	-9.54	-9.83	-10.13
Percentage change in oil consumption (%)	-3.31	-3.30	-3.29
Oil rebound (%)	30.66	30.88	31.10
Percentage change in gas consumption (%)	-4.84	-4.88	-4.92
Gas rebound (%)	14.58	13.92	13.25
Percentage change in electricity consumption (%)	-4.78	-4.78	-4.78
Electricity rebound (%)	11.58	11.58	11.58

Table 4.6. Impact of 10% economy-wide production energy efficiency improvement by varying the elasticity between coal and gas

Indicator	Low (1)	Central (2)	High (3)
GDP growth (%)	0.27	0.27	0.27
Household consumption growth (%)	0.52	0.52	0.52
Percentage change in capital investment (%)	0.37	0.37	0.37
Percentage change in energy for production (%)	-8.51	-8.51	-8.51
Percentage change in non-electricity energy consumption (%)	-3.84	-3.84	-3.84
Non-electricity rebound (%)	24.75	24.75	24.75
Percentage change in coal consumption (%)	-10.91	-10.86	-10.82
Coal rebound (%)	-10.30	-9.83	-9.37
Percentage change in oil consumption (%)	-3.30	-3.30	-3.30
Oil rebound (%)	30.88	30.88	30.88
Percentage change in gas consumption (%)	-4.87	-4.88	-4.89
Gas rebound (%)	14.05	13.92	13.78
Percentage change in electricity consumption (%)	-4.78	-4.78	-4.78
Electricity rebound (%)	11.58	11.58	11.58

Table 4.7. Impact of 10% economy-wide production energy efficiency improvement by varying the capital adjustment cost coefficient

Indicator	Low (0.1)	Central (0.2)	High (1)
GDP growth (%)	0.27	0.27	0.27
Household consumption growth (%)	0.52	0.52	0.52
Percentage change in capital investment (%)	0.37	0.37	0.37
Percentage change in energy for production (%)	-8.51	-8.51	-8.51
Percentage change in non-electricity energy consumption (%)	-3.84	-3.84	-3.84
Non-electricity rebound (%)	24.75	24.75	24.75
Percentage change in coal consumption (%)	-10.86	-10.86	-10.86
Coal rebound (%)	-9.83	-9.83	-9.84
Percentage change in oil consumption (%)	-3.30	-3.30	-3.30
Oil rebound (%)	30.88	30.88	30.88
Percentage change in gas consumption (%)	-4.88	-4.88	-4.88
Gas rebound (%)	13.92	13.92	13.91
Percentage change in electricity consumption (%)	-4.78	-4.78	-4.78
Electricity rebound (%)	11.58	11.58	11.58

I find that simulation results do not change significantly when the above parameters vary. As the elasticity between value-added and intermediate inputs increases (Table 4.2), the economy gains more structural flexibility. This is because it is easier to substitute between value-added and intermediate inputs increases when their relative prices change. As a result, the economy-wide production energy efficiency improvement has a larger boosting effect to GDP, consumption and investment. To achieve the higher GDP and consumption growth, energy use also increases compared with the central scenario, thus the larger rebound effects. However, between low, central and high elasticity values, the change in key economic and energy indicators are not large. The impact of elasticity gradually decreases at lower level of the production structure (Table 4.3-4.6). Regarding the capital adjustment coefficient, we set the high value at 1, a large increase against the central scenario (0.2). The impact on model results still turns out to be almost negligible (Table 4.7). Therefore, our choice of the capital adjustment coefficient is valid even though there is no consensus on the appropriate value from existing literature.

With the economy-wide energy efficiency shock on the production side, I have identified moderate economy-wide energy rebound effects, and minor boosting effect to regional GDP and consumption level. Energy price levels reduce slightly, while the commodity prices of other sectors respond quite differently. In terms of local production level and demand, energy production sectors and their direct upstream / downstream sectors, along with some energy-intensive sectors (e.g., air transportation, chemical manufacturing, paper manufacturing), are the most sensitive to the energy efficiency shock.

The above simulation provides much information about the magnitude of economy-wide impact induced by general technological change, specifically economy-wide energy efficiency improvement. However, the impacts of individual sectors are hidden in the aggregate results. Therefore, in the next section, I compare the economy-wide impacts induced by energy efficiency improvement in individual sectors.

4.3.2 Economy-wide Impact of Energy Efficiency Improvement in Individual Sectors

Given the same energy efficiency shock, different sectors generate different economy-wide impacts. For each simulation, I assume that energy efficiency increases by 10% in one single sector, which we term the *epicenter sector*. These scenarios are quite plausible, since technological breakthrough in an industry can often result in increased energy efficiency. To calculate the ripple effects of shock at the epicenter, the CGE model calculates change in various indicators including regional GDP, household consumption, energy spending, as well as sector level price, local demand and local production level. I then compare and rank the same indicators across 69 epicenter sectors. The comparative results will indicate how the impact of sectoral shocks propagates through the economic structure and generates aggregate changes.

Naturally, shocking individual epicenter sectors generates economy-wide impacts that are orders of magnitude smaller than shocking all production activities. Yet these scenarios allow me to single out the impact of every individual sector as the epicenter sector, and to identify sectors with large economy-wide implications. I focus our analysis on two relevant indicators: percentage reduction in economy-wide non-electricity energy use and rebound effect. The former represents an epicenter sector's total influence on the scale of regional non-electricity energy consumption. The latter implies an epicenter sector's production elasticity, its stimulation to other sectors' production and final demand. I plot economy-wide rebound effect against percentage change in economy-wide non-electricity energy use for all 69 epicenter sectors (Figure 6). Each data point represents the epicenter sector in a simulation. While most sectors are self-contained and the impact does not expand far from the epicenter, I am most interested in those few very distinct sectors that are able to affect the whole economy. First, I find that sectors generating the greatest reduction in energy use are those that consume the most energy in the first place. For example, sectors ranking top five in reducing economy-wide non-electricity use are construction, air transportation, chemical manufacturing, administrative and support activities, and truck transportation. Sectors that rank top five in benchmark non-electricity energy consumption are air transportation, chemical manufacturing, construction, administrative and support activities, and truck transportation — the same five sectors. The consistent rankings indicate that targeting these sectors is the most effective approach to economy-wide energy saving, partly due to their large energy consumption baseline, and partly due to the moderate rebound effect they induce. Second, I find that sectors generating the largest rebound effect fall into four categories: energy production sectors, direct upstream / downstream sectors of energy production sectors, transportation sectors, or sectors with very high own-price production elasticity. Note that some sectors may have two or more of the above features. Energy production sectors naturally generate large rebound, as increased efficiency directly reduces energy prices and lead people to use more energy. Direct upstream / downstream sectors of energy production sectors significantly affect energy production, also easily affecting energy prices. Transportation sectors have central structural positions in the economy, connecting various economic activities. This means transportation sectors are quite capable of extending their impact through the economic structure. High production elasticity of a sector implies that demand for its product increases significantly when the price of its product falls. If other sectors that use a lot of its product as intermediate are energy intensive, the epicenter sector with high production elasticity can potentially generate very large rebound effects.

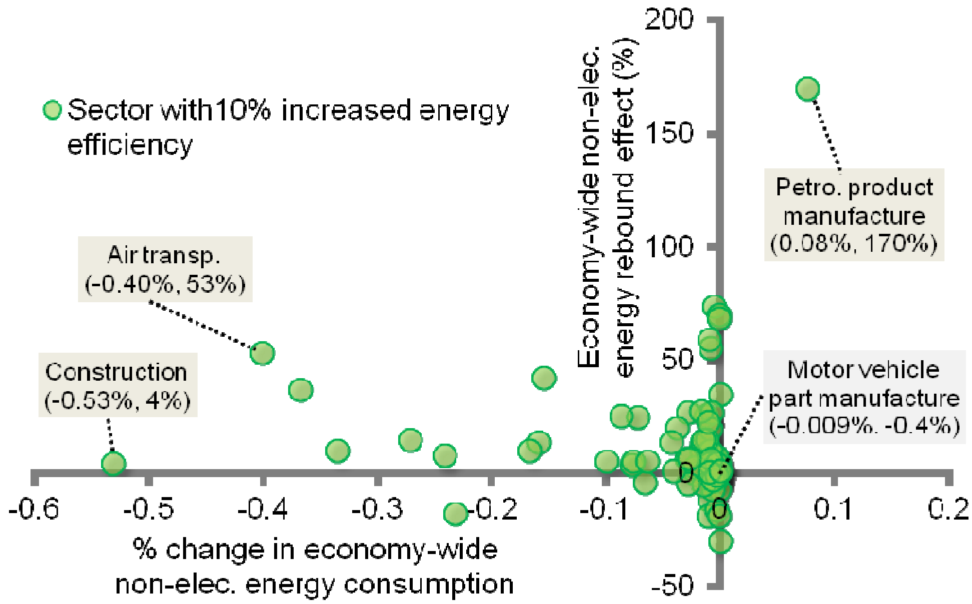


Figure 4.6. Economy-wide non-electricity rebound and energy use reduction generated by 10% increased energy efficiency in individual sectors.

However, no single rule dictates how much energy reduction or rebound a sector can trigger. The story is more nuanced. Therefore, based on non-electricity reduction and rebound, I select three distinct sectors to analyze their impact on energy and economic indicators in greater detail.

4.3.3 Simulation Scenario Case Studies

I choose three distinct sectors, covering different levels of non-electricity reduction and rebound, to look into their impact on economy-wide energy use and economic indicators. These sectors are construction (large reduction in energy use, small rebound), air transportation (large reduction in energy use, large rebound) and petroleum product manufacturing (small reduction in energy use, large rebound). I particularly focus on how the impact of an efficiency shock on these sectors extends to other sectors, propagates through the economic structure, and generate aggregate results. Compared with these very distinct sectors, most other sectors have potential for neither significant energy saving nor high rebound (e.g., motor vehicle part manufacturing in Figure 4.6). I do not analyze energy production sectors because the mechanism of their impact on the economy is straightforward.

The high level of disaggregation of the model allows this exercise to be repeated in detail for any sector. Policy and decision makers could choose alternative sectors and run the same analysis that we do below.

Construction

Given a 10% energy efficiency improvement shock, the construction sector reduces economy-wide non-electricity energy consumption by 0.53%, the highest among all the 69 sectors. It also achieves relatively high electricity reduction at 0.15%, ranking No. 10 among the 69 sectors. Energy efficiency improvement in construction triggers very little rebound—4% for non-electricity (Ranking No. 42) and 6% for electricity (Ranking No. 18). It also has a relatively large boosting effect on regional GDP (Ranking No. 4) and household consumption (Ranking No. 5).

Among all the 69 sectors, targeting construction is the most effective way to reduce economy-wide energy consumption. This is the combined result of the sector's high benchmark energy consumption and low rebound. First, the benchmark energy spending of construction ranks No. 3 among the 69 sectors. Secondly, construction triggers very little within-sector rebound, 3.7% for non-electricity and 3.4% for electricity. The most important reason for low within-sector rebound is the sector's low production elasticity. Specifically, as the shock reduces the sector's price level by 0.34%, its production level locally in Georgia only increases by 0.27%. The sector's production elasticity of 0.81 stands quite low compared with many sectors with production elasticity over 10 (e.g., oil and gas extraction; accommodation, etc.). In turn, low production elasticity can be traced back to two causes: 1) reduction in the sector's price level does not significantly stimulate people's consumption in the sector (Figure 4.4, Path ADF); 2) reduction in the sectors price level does not cause other sectors to use a lot more of this sector's product as intermediate input (Figure 4.4, Path ADG). In other words, the sector's structural influence is limited [161]. Indeed, direct household spending on construction remains close to zero before and after the shock. Intermediate use of construction also increases very little. The construction sector itself sees the largest growth in the intermediate use of construction, but even this growth accounts for less than 0.01% of the construction sector's benchmark production. Economy-wide, increased use as intermediate serves to increase the production level of construction by merely 0.002%. Counter-intuitively, while the production scale of construction itself only increases by 0.27%, it increases the production scale of another three sectors by more than 0.2%, and six other sectors between 0.1% and 0.2%. This explains the relatively high growth rates in GDP and household consumption. Nevertheless, sectors affected the most by construction do not rank high by energy spending, hence the low economy-wide rebound.

<u>Air transportation</u>

With the same 10% energy efficiency improvement, air transportation induces relatively large economy-wide rebound in primary energy use (53%, ranking No. 7), but still achieves high economy-wide energy saving (0.40%, ranking No.2). Regional GDP even shrinks by 0.004%, contrary to 64 other epicenter sectors that trigger GDP growth. However, household consumption sees the largest growth (0.12%) among all simulations. These contrasting changes suggest that energy saving in air transportation has caused greater reduction in local energy production than can be compensated for by increased productivity. At the same time, reduced price level, mostly in air fare and energy, has given consumers more income for purchasing other products.

The energy-intensive nature of air transportation, plus the sector's importance in Georgia's economy in particular, allows it to achieve significant energy reduction even with high rebound effect. The energy intensity of transportation ranks top three among the 69 sectors. In the mean time, its benchmark total energy spending exceeds all other sectors in Georgia's economy. The 10% energy efficiency improvement reduces the sector's price level by 3.5%, much greater than the same energy efficiency gain would reduce the price of other sectors. As a result, local production scale of air transportation increases by 5.22%. A production elasticity of 1.48 is higher than the construction sector, but still lower than most other sectors. However, because of the sector's high energy intensity, within-sector rebound already stands at 53%.

Nevertheless, air transportation is unique in terms of how it affects other sectors' production scale and energy consumption, as well as household consumption structure. The only sector that benefits from significant growth is transportation support activities (1.47%). Following are pipeline transportation (0.26%) and food and drinking services (0.18%). As both transportation support and food and drinking services rank relatively high in terms of energy spending, they further increase the magnitude of economy-wide rebound. However, over half of the 69 sectors cut production. Those taking the heaviest blow are some manufacturing sectors (e.g., primary metal product manufacturing, electronic product manufacturing and machinery manufacturing) and the petroleum production sector. An important reason is that less mobile production factors, particularly labor and capital, tend to move towards the air transportation sector, reducing the production capability of other sectors. In this particular case, the reduced production scales of more than half of the sectors have more than offset the growth of others. Hence the negative net impact on GDP. While household consumption of sectoral products increases by more than 0.1% in over half of the sectors, the increased consumption mostly comes from import rather than locally supplied commodities.

Petroleum product manufacturing

Petroleum product manufacturing is the only sector that causes backfire in non-electricity energy consumption. With 170% economy-wide rebound, 10% energy efficiency improvement in the sector actually increases the economy's non-electricity energy use by 0.08%. Although petroleum product manufacturing is one of Georgia's smallest sectors (ranking No. 60 by production scale), it still has a moderate impact on GDP (0.002%, ranking No. 29) and household consumption (0.002%, ranking No.41) as an epicenter sector. This is largely because petroleum product manufacturing is the most energy-intensive sector, thus more responsive to energy efficiency shocks.

Petroleum product manufacturing is distinct in that 1) it has very high own price elasticity; 2) it is a direct downstream sector of petroleum refining, our defined oil production sector. As the efficiency shock reduces the sector's price level by 1.53%, its local production grows by an impressive 16.36%. Production elasticity of 10.72 is much higher than the two sectors we analyzed earlier. Yet more importantly, petroleum product manufacturing is heavily interconnected with the oil production sector. 47% percent of its intermediate spending goes to the oil production sector, implying high rebound potential. In fact, with within-sector rebound at 162%, production expansion has already more than offset the energy savings from energy efficiency improvement. As a comparison, most sectors of small production scale have potential for neither significant energy saving or large rebound. For example, motor vehicle part manufacturing, as an epicenter sector, only reduces regional non-electricity energy use by 0.009%, while inducing an -0.4% economy-wide rebound.

Because of its small size, petroleum product manufacturing does not have a strong influence on other sectors, nor does it significantly affect GDP or household consumption. Even though the sector is highly energy intensive, its total energy use is still moderate compared with construction or air transportation. Therefore, while petroleum product manufacturing induces a huge rebound effect, gross impact on economy-wide energy use remains relatively small.

In this section, we have singled out three sectors to look into the nuances of why they generate different energy savings and rebound effects. The construction sector, with its large size in Georgia's economy and low production elasticity, allows significant energy savings without inducing large rebound effects. Air transportation, with large benchmark energy consumption, is also effective as an epicenter for energy conservation. However, the sector's high energy intensity and relatively high production cause significant rebound. Petroleum product manufacturing takes a small share in Georgia's economic output. Yet due to its heavy interconnection with an energy production sector, petroleum product manufacturing, as an epicenter, has the potential to induce backfire in energy use.

4.4 Conclusions

In this chapter, I investigate energy rebound effects at the regional level. By looking into both economy-wide and sector-specific energy efficiency improvement, I manage to demonstrate the magnitude of aggregate impact, as well as the heterogeneous contribution of individual sectors to economy-wide energy use reduction and rebound. The case studies further shed light on how sectoral shocks propagate to generate aggregate outcomes.

When general technological change increases economy-wide energy use efficiency, aggregate GDP and consumption growth would be orders of magnitude smaller than the scale of the efficiency gain. This is because energy use accounts for a relatively small portion in most sectors' production input. Therefore, if policy makers hope to boost economic growth through increasing efficiency, they should target more essential production factors such as capital or labor efficiency. Economy-wide rebound effects are moderate, implying that energy saving can be achieved through efficiency measures. At the sector level, energy price fluctuation turns out to be minor, partly due to the open nature of a regional economy. Sectors respond quite differently in terms of price level, local production and demand. Their responses alter the regional industrial structure, and should be taken into consideration in energy policy decisions.

When sector-specific technological change induces sector-level energy efficiency improvement, the economy-wide impacts can be quite different depending on the epicenter sector. How much total energy saving can be achieved is largely determined by the epicenter sector's initial energy use, while the magnitude of rebound is affected by several factors. Energy production sectors or their direct upstream / downstream sectors, transportation sectors or sectors with high production elasticity can all induce large rebound effects. My analysis traces how an energy efficiency shock to the epicenter sector diffuses through other sectors to induce aggregate changes. This can help policy makers identify the pivotal points that enable the propagation of sector-level shocks, so that *ex ante* measures can be taken to mitigate rebound. Still, efforts to save energy through increased energy efficiency are most effective targeting sectors that result in large energy use reduction and small rebound, such as the construction sectors.

Nevertheless, I recognize the caveats in this work. First, I have not distinguished between renewable and nonrenewable energy sources for electricity generation. This is because in the original SAM used for constructing the CGE, all electricity generation activities are lumped together into one single sector. However, if renewable energy sector data are available, this exercise could be easily modified to investigate changes in renewable energy consumption at both the aggregate and sector level. Second, this model has not considered population migration in the CGE model. Yet I am more interested in the economy's response in short-to-medium terms, during which population migration does not play an essential role. Still, the simulations in this study provide important insights for policy makers in terms of the tradeoff between rebound, energy conservation and economy growth triggered by sectoral energy efficiency improvement. With other regional SAMs available, this model can also be applied to other regions and address a wide range of policy questions.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

The human society exerts its influence on the ecosystem through economic activities. While the robustness of an economy manifests through its industrial structure, human impact on nature is well represented by an economy's energy consumption patterns. Therefore, evaluating the industrial structure and unraveling its interconnection with energy consumption is crucial for achieving sustainable development.

In this dissertation, I have addressed the topic from several perspectives. First, I start with an exploratory analysis on the industrial structure itself, developing an easy measure, revealed comparative dependence (*RCD*), to compare regional dependence on sectors. Building on the *RCD* measure, I have indirectly evaluated the economic resilience of U.S. states by quantifying their economic diversity. Second, I bring the measure for industrial structure into context with energy consumption patterns. RCD is used to characterize sector interactions, which are then used to explain the historical trend of regional energy consumption. I have found that while the expansion of low energy intensity sectors does reduce energy use, these sectors' level of interaction with other sectors also plays a key role in determining energy use. Besides addressing the historical interconnection between regional industrial structure and energy consumption level, as a third step, I investigate how regional structure affects an economy's response towards energy efficiency improvements, i.e., the economy-wide rebound effect. My regional CGE model has proved that production-side energy efficiency improvement induces moderate rebound effects, while feeding back into the industrial structure by changing sectoral production scale in different directions. I have also identified sectors being able to trigger different levels of energy saving and energy rebound, and have explored the mechanism for their impact propagation throughout the industrial structure.

Based on the progress of this dissertation, I recommend the following potential directions for future research.

5.1 Expand Time Horizon and Incorporate Regional Technology Data for Historical Trend Analysis

If future data is available, I recommend expanding the time horizon for the decomposition analysis and fixed effect regressions in Chapter 3. This will likely provide a more statistically convincing proof of the influence of sector interaction on energy consumption. Indeed, the data used in Chapter 3 extend only 14 years (1997-2010), which means limited variation, especially in terms of the change of dependence on sectors. Because of the requirement of uniform sector profile throughout the studied period, it would be beneficial to conduct the same analysis in Chapter 3 for years beyond 2010 against 1997. More significant industrial structural shift will probably explain the energy consumption trend better.

Due to data limitations, Chapter 3 has assumed uniform technology across regions throughout the analysis. This means that the energy intensity of the same sector remains the same in all the regions studied. This assumption is not necessarily true. For example, because of different regulations, the automobile fuel economy in California can be much lower than, say, Texas. If region-specific sectoral energy intensity data were available, the IDA would offer a more accurate regional estimation of the variation in energy consumption explained by technological change. Moreover, the fixed-effect panel regression analysis could increase the total explained variance in energy consumption by accounting for the technology factor.

5.2 Evaluate Rebound Effects from Consumption Side

Chapter 4 has focused on investigating the impact of energy efficiency improvement on the production side. Another way to evaluate rebound effects is to assume energy efficiency shocks on the end-use consumption side. The fundamental principle is that consumers receive the same level of service, or utility, from less energy consumption. This could be due to increased household lighting and heating efficiency, increased personal transportation fuel economy, etc. The yielded change in aggregate and sector-level economic and energy indicators could then be compared to results in Chapter 4. The comparison could inform policy makers whether increasing energy efficiency on the production side or increasing energy efficiency on the end-use side is more effective for energy conservation.

5.3 Compare Rebound Effects and Industrial Structure Shift in Different Regions

The current CGE model can be easily adapted to other states if state-level social accounting matrices (SAMs) are available. Conducting the same analysis in Chapter 4 for different states and comparing results will provide a more complete portrayal of the interconnection between industrial structure and energy consumption. For example, states could be selected covering different resilience rankings in Chapter 2 and factor decomposition results in Chapter 3. The CGE model should be calibrated to these individual states for the same year. Simulation would introduce the same level of energy efficiency shock in the same segment for each economy. Conceivably, these state economies would respond very differently in terms of aggregate production, consumption level and structure, output composition, as well as energy use patterns. The indicators above would reflect, from many aspects, the sensitivity of different regional economies towards the same shock, and thus be reflective of regional economic resilience. The results could also further prove the validity of our initial economic resilience analysis. Moreover, policy makers can prioritize regions in terms of introducing energy efficiency measures based on the comparative results.

5.4 Investigate Mechanism of Impact Propagation from Individual Epicenters

While I did investigate the impact propagation of shocking individual epicenter sectors in Chapter 4, the propagation effects are admittedly minor. This is because energy inputs account for a relatively small portion in most sectors' production input mix. Consequently, 10% increased efficiency in using energy simply does not trigger much change in the production structure, not to mention extending the impact to other sectors.

However, the impact of shocking individual epicenters does propagate through the industrial structure, and the magnitude of propagation can be quite different depending on the epicenter sector. This phenomenon can be studies by exerting a stronger shock on the sector – on sectoral output for example. Given that we have identified hub sectors in Chapter 3, shocking a hub sector would probably yield a greater impact propagation ratio than shocking a non-hub sector. After all, on the product space map in Chapter 3, a non-hub sector's immediate neighboring sectors interact more intensively with their other neighbors than with the non-hub sector. These different degrees of interaction suggest greater difficulty of impact propagation through the industrial structure network.

5.5 Incorporate Structural Adjustment Cost in CGE Model

While the CGE model presented in Chapter 4 is already relatively comprehensive, it follows the standard practice of all existing CGE models in terms of using the Leontief input-output relationship to characterize non-energy intermediate inputs in the production structure. For a more accurate characterization of the economy's response towards external shocks, I recommend breaking away from the standard Leontief method, and incorporating in the CGE model an additional adjustment cost when the firm changes its intermediate use for production.

The firm's adjustment cost is the additional cost involved changing the input mix for production besides the cost of input itself. When market demand or input price changes in an industry, firms adjust their production scale by adjusting input mix. This in turn affects the demand of capital, labor and product from other industries. Consequently, there is cascading effect in the entire economy, including commodity price, consumer choices, and the change in demand and choice of input mix of other industries. Since every bit of shifting requires adjustment cost due to the necessary change in infrastructure, physical capital, knowledge, labor, etc, it is crucial to incorporate adjustment cost for a more accurate estimation of the impact of exogenous shocks. While adjustment cost in changing primary production factors (capital, labor, etc.) has been relatively well studied [162-165], adjustment cost in changing the quantity of intermediate from other industries has hardly been addressed. I term this cost structural adjustment cost (SAC) because it is related to a region's input-output structure and hence prevalent between industries.

A simple example demonstrates the importance of SACs. Suppose a computer manufacturing firm makes its laptops mainly from aluminum and plastic. Suddenly energy efficiency improvement in the aluminum industry significantly reduces the price of aluminum, making it even cheaper than plastic. The firm thus has an incentive to substitute aluminum for plastic. However, the switching would require a different design for the laptop, more processing facilities for aluminum, different assembly techniques that the workers need to master, negotiation with the contracted plastic supplier, etc. All of the above constitute the SACs, forcing the firm to balance the tradeoff and limit the switch. Without considering SACs, the company would quickly change its input mix dramatically.

SACs can potentially significantly improve the estimation of a CGE model. Below I use energy efficiency improvement to demonstrate the importance of SACs. When energy efficiency increases in a specific industry, firms in the industry are tempted to substitute energy for other primary production factors (capital and labor) and non-energy intermediates. Since non-energy intermediates are drawn from every industry in an input-output framework, SACs affect the industry's entire supply chain. This creates secondary effect by offering every other industry incentives to change their intermediate mix, where SACs again play an important role. The situation further complicates when energy efficiency boost takes place in multiple industries. There will be economy-wide incentive to use more energy-intensive intermediates because these intermediates tend to become cheaper due to reduced production cost. Consequently, the general equilibrium effect can be enormous. Neglecting SACs means overestimating the structural flexibility of a regional economy.

Still, no existing CGE models, regardless of their goals, have introduced SACs in the production module. While capital and labor adjustment is usually considered in dynamic or semi-dynamic CGE models [64, 166-168], SACs between industries are hard to quantify. However, I demonstrate below that SACs can be approximated by quantifying how closely industries are related to one another.

SACs are, to a large extent, determined by the ex-ante relationship between the involved sectors. Comprehensibly, if two sectors are similar in terms of production factors or if they already incur frequent transactions, they tend to adjust more easily to the changing quantity of intermediate between one another. Based on this intuition, it is possible to characterize SACs through the inter-sector proximity indicator, which has already been developed in Chapter 3 to measure how closely different sectors are connected to each other.

As for introducing SACs to the regional CGE model, it would be natural to adopt the commonly adopted assumption that adjustment cost is proportional to the square of change in input [162]. This quadratic function accounts for proximity between industries. Because proximity measures the easiness of transferring production between industries, the proximity indicator can enter the adjustment function as a denominator. Therefore, at the same price level and the same level of input change, the higher the proximity, the lower the adjustment cost.

The improved production structure in the CGE model could generate more accurate estimation of various impacts that arise from an energy efficiency shock. Moreover, SAC provides the basis for more accurately tracking the diffusion process of impacts of exogenous shocks that originate from one or a few of an economy's sectoral markets.

APPENDIX A

ECONOMIC RESILIENCE SCORES

Based on *twRCD* values, the economic resilience scores for each state are scaled from 0 to 1 for easier presentation. Results are shown in Table A.1 with higher scores representing more resilient economies, and states ranking from the most resilient to the least. We present results for both 1997 and 2010.

Table A.1. State economic resilience scores and ranking, 1997 and 2010

State Name	**1997**		**2010**	
	Resilience score	Resilience rank	Resilience score	Resilience rank
Alabama	0.985695	15	0.978559	17
Alaska	0	51	0	51
Arizona	0.979547	20	0.986399	11
Arkansas	0.975693	23	0.967001	24
California	0.994904	8	0.994963	4
Colorado	0.997013	5	0.99233	8
Connecticut	0.97812	22	0.947069	30
Delaware	0.896815	45	0.795006	44
District of Columbia	0.5788	50	0.371098	49
Florida	0.995412	6	0.994694	5
Georgia	0.988819	13	0.986209	13
Hawaii	0.918144	43	0.86842	40
Idaho	0.971021	27	0.946062	32
Illinois	1	1	1	1
Indiana	0.969512	30	0.901546	39
Iowa	0.959509	34	0.930134	35
Kansas	0.973217	25	0.969555	22
Kentucky	0.952973	38	0.951584	29
Louisiana	0.900103	44	0.721838	46
Maine	0.969988	28	0.979305	16
Maryland	0.987654	14	0.972853	19
Massachusetts	0.99024	12	0.977721	18
Michigan	0.944219	41	0.937996	34
Minnesota	0.998608	2	0.991481	9
Mississippi	0.973958	24	0.969043	23
Missouri	0.997014	4	0.996843	2
Montana	0.947612	39	0.926698	36
Nebraska	0.944814	40	0.851018	43
Nevada	0.79766	48	0.740864	45

New Hampshire	0.967814	33	0.98886	10
New Jersey	0.992527	9	0.994182	6
New Mexico	0.871878	46	0.941828	33
New York	0.969829	29	0.96128	27
North Carolina	0.968823	31	0.958435	28
North Dakota	0.953544	37	0.854108	42
Ohio	0.98495	16	0.992964	7
Oklahoma	0.980362	19	0.914552	38
Oregon	0.968743	32	0.695275	48
Pennsylvania	0.998394	3	0.995001	3
Rhode Island	0.981504	17	0.985413	14
South Carolina	0.956459	35	0.96998	21
South Dakota	0.932871	42	0.855917	41
Tennessee	0.991923	10	0.986241	12
Texas	0.971096	26	0.946563	31
Utah	0.994973	7	0.961572	26
Vermont	0.991477	11	0.979615	15
Virginia	0.981472	18	0.962517	25
Washington	0.95461	36	0.916003	37
West Virginia	0.852697	47	0.702954	47
Wisconsin	0.978212	21	0.972269	20
Wyoming	0.595401	49	0.127875	50

APPENDIX B

NATIONAL SECTORAL OUTPUT BETWEEN 1997 AND 2010

Since state-level economic resilience scores use the national economic structure as the benchmark, it is valuable to examine how the national economic structure has evolved over the years (Figure B.1). From 1997 to 2010, real national GDP grew by 34.24%. However, not all sectors experienced the same growth. Some sectors more than doubled in size (financial services, mining and supporting activities, petroleum product manufacturing); while some shrank by half (Apparel manufacturing, motor vehicle manufacturing and textile mills). In general, industries related to petroleum and information technology saw the greatest growth, while all sectors that shrank in actual size are manufacturing industries, especially light manufacturing. Regarding sector share in the national economy, growth in share is not related to the original size of the sector. The largest increase of share happened in service industries including professional, scientific and technical services, federal banks, ambulatory healthcare services, hospitals and state and local government enterprises. Alternatively, retail and wholesale trade, motor vehicle manufacturing, construction and fabricated metal manufacturing faced the greatest decline in their importance in the national economic structure. Table S4 compares the national output composition between 1997 and 2010. We list sectoral share of national output for the two years, the change of sectoral share, and also real sectoral GDP growth. In total, standard deviation of national sector share increased from 0.0205 in 1997 to 0.0211 in 2010, suggesting that the national composition has not become significantly more or less imbalanced during the studied period.

Table B.1. National sectoral output between 1997 and 2010

State	Sector share 1997 (%)	Sector share 2010 (%)	Sector share change (%)	Sector output growth (%)
Crop and animal production (Farms)	1.06	0.87	-0.20	9.46
Forestry, fishing, and related activities	0.25	0.23	-0.02	24.26
Oil and gas extraction	0.67	1.08	0.42	117.50
Mining (except oil and gas)	0.32	0.36	0.04	50.61
Support activities for mining	0.16	0.31	0.15	159.23
Utilities	2.05	1.98	-0.08	29.21
Construction	4.19	3.64	-0.56	16.46
Wood product manufacturing	0.32	0.15	-0.17	-35.43
Nonmetallic mineral product manufacturing	0.48	0.22	-0.25	-37.64
Primary metal manufacturing	0.57	0.30	-0.28	-30.69
Fabricated metal product manufacturing	1.32	0.80	-0.52	-18.63
Machinery manufacturing	1.21	0.82	-0.40	-9.55
Computer and electronic product manufacturing	1.88	1.64	-0.24	16.82
Electrical equipment, appliance, and component manufacturing	0.55	0.29	-0.26	-28.42
Motor vehicle, body, trailer, and parts manufacturing	1.16	0.45	-0.71	-47.98
Other transportation equipment manufacturing	0.66	0.61	-0.05	23.91
Furniture and related product manufacturing	0.34	0.17	-0.17	-32.45
Miscellaneous manufacturing	0.56	0.58	0.01	37.59
Food and beverage and tobacco product manufacturing	1.62	1.52	-0.10	26.06
Textile mills and textile product mills	0.33	0.13	-0.20	-46.17
Apparel and leather and allied product manufacturing	0.30	0.08	-0.22	-63.49
Paper manufacturing	0.65	0.37	-0.27	-22.37
Printing and related support activities	0.45	0.21	-0.23	-35.73
Petroleum and coal products manufacturing	0.53	0.88	0.35	124.11
Chemical manufacturing	1.82	1.64	-0.18	20.83
Plastics and rubber products manufacturing	0.69	0.46	-0.23	-10.24
Wholesale trade	6.35	5.55	-0.79	17.46
Retail trade	7.13	6.09	-1.04	14.59
Air transportation	0.65	0.46	-0.19	-4.94
Rail transportation	0.24	0.22	-0.02	25.80
Water transportation	0.08	0.10	0.01	53.28
Truck transportation	0.97	0.83	-0.14	15.07

Transit and ground passenger transportation	0.18	0.19	0.01	41.74
Pipeline transportation	0.09	0.12	0.03	85.57
Other transportation and support activities	0.69	0.71	0.02	38.75
Warehousing and storage	0.27	0.30	0.04	52.96
Publishing industries	0.99	0.97	-0.02	31.56
Motion picture and sound recording industries	0.38	0.41	0.03	44.07
Broadcasting and telecommunications	2.49	2.34	-0.15	26.24
Information and data processing services	0.36	0.53	0.17	97.78
Federal Reserve banks, credit intermediation and related services	3.00	3.88	0.89	73.90
Securities, commodity contracts, investments	1.43	1.25	-0.18	17.78
Insurance carriers and related activities	2.50	2.67	0.17	43.50
Funds, trusts, and other financial vehicles	0.12	0.24	0.12	167.90
Real estate	11.15	11.65	0.51	40.36
Rental and leasing services and lessors of intangible assets	1.29	1.30	0.02	36.15
Legal services	1.32	1.42	0.10	44.48
Computer systems design and related services	0.91	1.27	0.36	87.04
Other professional, scientific and technical services	3.86	4.84	0.98	68.30
Management of companies and enterprises	1.50	1.83	0.33	63.34
Administrative and support services	2.32	2.62	0.29	51.18
Waste management and remediation services	0.26	0.32	0.06	64.28
Educational services	0.81	1.16	0.35	92.06
Ambulatory health care services	3.02	3.77	0.75	67.72
Hospitals and nursing and residential care facilities	2.61	3.23	0.62	66.23
Social assistance	0.47	0.66	0.19	87.85
Performing arts, spectator sports, museums, and related services	0.45	0.55	0.10	64.53
Amusement, gambling, and recreation	0.52	0.42	-0.10	9.39
Accommodation	0.85	0.75	-0.10	19.13
Food services and drinking places	1.82	2.15	0.34	59.25
Other services, except government	2.71	2.47	-0.23	22.76
Federal civilian	2.40	2.36	-0.04	32.20
Federal military	1.05	1.37	0.32	75.31
State and local government	8.64	9.17	0.53	42.55

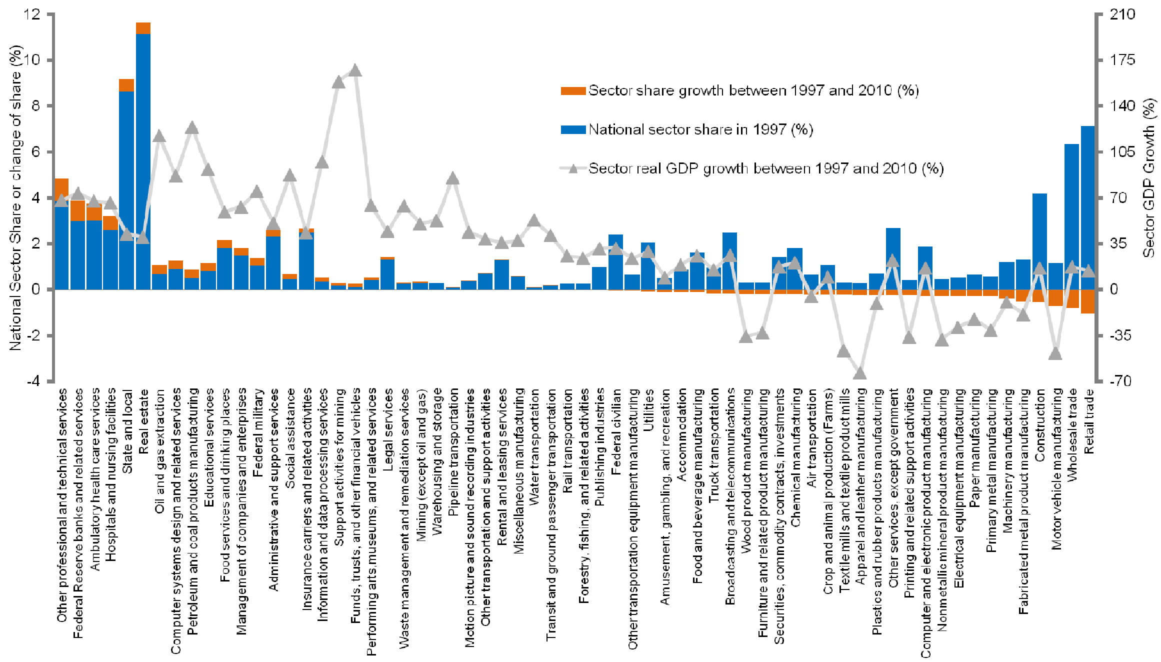


Figure B.1. National sector growth and share change between 1997 and 2010

In addition, we look at the distribution of sector shares in the national economy with histograms (Figure B.2). In both 1997 and 2010, sector shares roughly follow the power law distribution, in the sense that small sectors are many, while large sectors are few. For example, in 2010 (Figure B.2(b)), nearly 60% sectors have less than 0.5% national output share., while over 75% sectors' national output shares are less than 2%. On the other hand, only less than 8% of the sectors' shares of output in the national economy are higher than 4%. Sector share distribution suggests that the national economic output structure has been rather stable during the studied period.

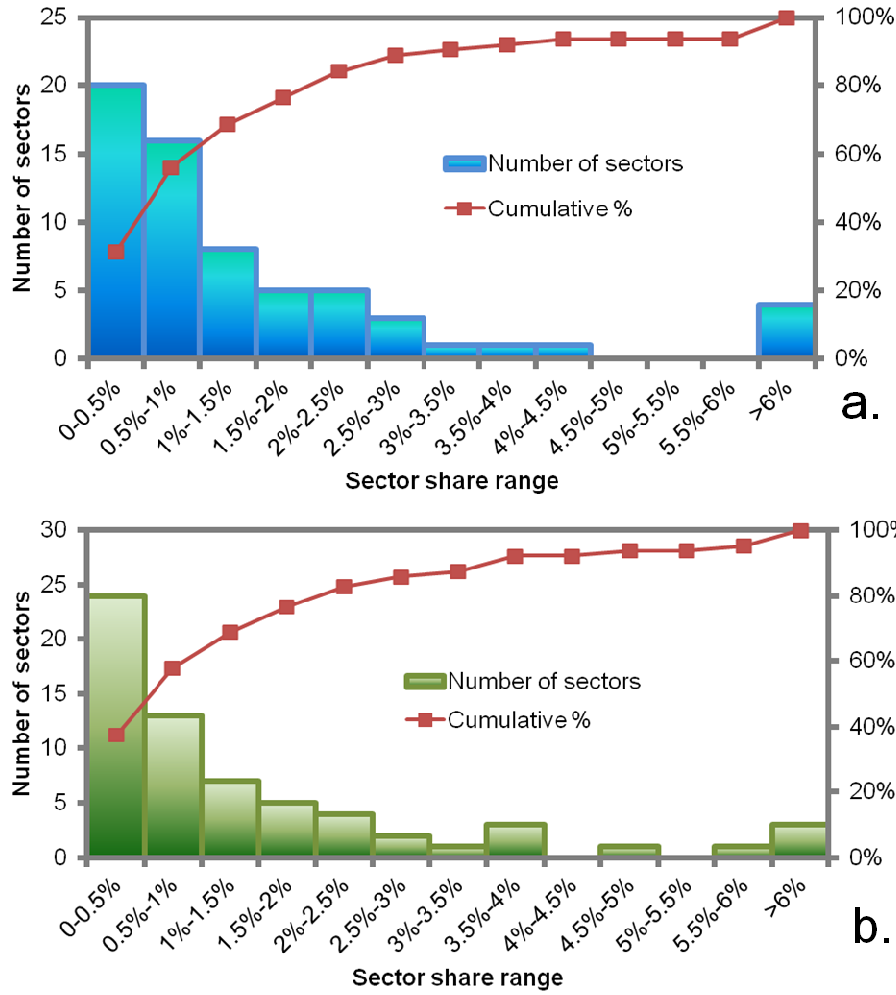


Figure B.2. Sector share distribution. (a) For the year 1997; (b) For the year 2010.

APPENDIX C

INDUSTRIAL ENERGY USE IDA RESULTS FOR U.S. STATES

(1997-2010)

We list the complete IDA results for 50 U.S. states and Washington D.C. in both multiplicative and additive forms. Table C.1 uses breaks down the energy use trend into three factors, economic growth, energy intensity change and industrial structural shift; Table C.2 further splits the industrial structural shift into region-specific dependence change and national output composition change. Variables have the same meaning as in Figure 1 in the main text.

Table C.1. Three-factor IDA for energy use from 1997 to 2010

State	Multiplicative IDA				Additive IDA (Unit: TJ)			
	Dtot	Dact	Dstr	Dint	ΔEtot	ΔEact	ΔEstr	ΔEint
Alabama	1.219	1.308	1.097	0.849	296373	402020	139214	-244861
Alaska	1.097	1.464	0.978	0.766	33954	139810	-8060	-97797
Arizona	1.303	1.489	1.007	0.869	392307	589877	10148	-207718
Arkansas	1.060	1.325	0.933	0.857	46692	227369	-56347	-124330
California	1.124	1.368	1.097	0.749	1146691	3079083	910614	-2843006
Colorado	1.328	1.476	1.081	0.833	312092	427832	85520	-201260
Connecticut	1.024	1.247	0.962	0.854	28457	265349	-46986	-189907
Delaware	0.977	1.424	0.862	0.796	-7348	110838	-46518	-71669
District of Columbia	1.510	1.592	1.129	0.840	135126	152460	39820	-57155
Florida	1.211	1.422	0.995	0.856	806649	1482365	-22942	-652774
Georgia	1.136	1.307	1.003	0.867	315352	661565	6751	-352964
Hawaii	1.226	1.363	1.112	0.809	90967	138098	47370	-94502
Idaho	1.303	1.516	0.971	0.884	74892	117907	-8255	-34760
Illinois	0.903	1.212	0.903	0.825	-409956	775376	-409691	-775640
Indiana	1.068	1.241	1.051	0.818	138013	455786	105627	-423400
Iowa	1.022	1.303	0.895	0.876	17711	214868	-89676	-107481
Kansas	1.134	1.327	1.019	0.838	106065	239189	16187	-149311
Kentucky	0.996	1.201	0.993	0.835	-4414	197581	-7424	-194571

Louisiana	1.171	1.509	1.254	0.619	427758	1112438	613412	-1298092
Maine	0.903	1.302	0.806	0.861	-32988	85752	-70024	-48716
Maryland	1.264	1.492	0.993	0.853	404131	691000	-11314	-275556
Massachusetts	1.145	1.299	1.031	0.855	205605	398631	46099	-239126
Michigan	0.935	0.971	1.097	0.878	-180353	-79057	249980	-351277
Minnesota	1.109	1.345	1.013	0.814	149408	426613	18701	-295906
Mississippi	1.127	1.274	1.138	0.777	106468	215541	114996	-224069
Missouri	1.075	1.194	1.038	0.867	104408	255469	54139	-205200
Montana	1.042	1.460	0.901	0.793	14158	130656	-36180	-80319
Nebraska	1.615	1.369	1.194	0.988	224769	147384	83104	-5719
Nevada	1.385	1.639	0.975	0.866	185789	281951	-14248	-81913
New Hampshire	1.002	1.299	0.899	0.859	951	100173	-40879	-58343
New Jersey	0.901	1.235	0.892	0.818	-325300	659899	-357603	-627597
New Mexico	0.926	1.249	0.895	0.828	-37032	106283	-52994	-90321
New York	1.035	1.326	0.917	0.851	203301	1648407	-504598	-940509
North Carolina	0.940	1.439	0.765	0.854	-145806	858188	-630894	-373099
North Dakota	1.187	1.697	0.804	0.870	43360	133512	-54961	-35191
Ohio	0.925	1.078	1.032	0.832	-269277	259357	107597	-636231
Oklahoma	1.233	1.445	1.083	0.788	243597	428202	92678	-277283
Oregon	1.087	1.442	0.857	0.879	62856	276216	-115962	-97398
Pennsylvania	0.965	1.251	0.922	0.836	-131935	819159	-296048	-655045
Rhode Island	1.000	1.328	0.875	0.861	119	67946	-31893	-35934
South Carolina	1.151	1.288	1.027	0.870	188172	339722	35635	-187185
South Dakota	1.245	1.502	0.953	0.869	41070	76397	-9057	-26270
Tennessee	1.070	1.276	0.974	0.861	49533	177901	-19468	-108901
Texas	1.162	1.570	1.022	0.724	1469602	4413749	215041	-3159188
Utah	1.223	1.611	0.948	0.801	108924	257963	-28795	-120244
Vermont	1.132	1.309	0.997	0.867	22376	48577	-452	-25749
Virginia	1.163	1.544	0.881	0.855	294738	847107	-247539	-304830
Washington	1.187	1.428	1.069	0.778	232945	484031	90326	-341412
West Virginia	0.933	1.280	0.851	0.856	-43452	153973	-100555	-96869
Wisconsin	1.164	1.251	1.060	0.877	215316	317759	83110	-185553
Wyoming	1.554	1.912	1.029	0.790	137254	201966	8754	-73467

Table C.2. Four-factor IDA for energy use from 1997 to 2010

State	Multiplicative IDA					Additive IDA (Unit: TJ)				
	Dtot	**Dact**	**Drcd**	**Dnst**	**Dint**	**ΔEtot**	**ΔEact**	**ΔErcd**	**ΔEnst**	**ΔEint**
Alabama	1.219	1.308	1.135	0.967	0.849	296373	402020	189983	-50769	-244861
Alaska	1.097	1.464	0.805	1.215	0.766	33954	139810	-79499	71440	-97797
Arizona	1.303	1.489	1.049	0.960	0.869	392307	589877	70670	-60522	-207718
Arkansas	1.060	1.325	0.965	0.967	0.857	46692	227369	-28903	-27444	-124330
California	1.124	1.368	1.033	1.063	0.749	1146691	3079083	314062	596551	-2843006
Colorado	1.328	1.476	1.088	0.994	0.833	312092	427832	92607	-7087	-201260
Connecticut	1.024	1.247	1.002	0.960	0.854	28457	265349	2547	-49532	-189907
Delaware	0.977	1.424	0.849	1.016	0.796	-7348	110838	-51346	4828	-71669
District of Columbia	1.510	1.592	1.152	0.980	0.840	135126	152460	46535	-6714	-57155
Florida	1.211	1.422	1.030	0.966	0.856	806649	1482365	123895	-146836	-652774
Georgia	1.136	1.307	1.052	0.953	0.867	315352	661565	125617	-118866	-352964
Hawaii	1.226	1.363	1.101	1.010	0.809	90967	138098	42804	4566	-94502
Idaho	1.303	1.516	1.017	0.955	0.884	74892	117907	4647	-12902	-34760
Illinois	0.903	1.212	0.912	0.990	0.825	-409956	775376	-369855	-39836	-775640
Indiana	1.068	1.241	1.085	0.969	0.818	138013	455786	172184	-66557	-423400
Iowa	1.022	1.303	0.944	0.949	0.876	17711	214868	-47235	-42441	-107481
Kansas	1.134	1.327	1.017	1.003	0.838	106065	239189	14026	2161	-149311
Kentucky	0.996	1.201	1.027	0.967	0.835	-4414	197581	28949	-36373	-194571
Louisiana	1.171	1.509	1.025	1.223	0.619	427758	1112438	67768	545645	-1298092
Maine	0.903	1.302	0.841	0.958	0.861	-32988	85752	-56047	-13977	-48716
Maryland	1.264	1.492	1.028	0.967	0.853	404131	691000	46937	-58251	-275556
Massachusetts	1.145	1.299	1.072	0.961	0.855	205605	398631	106327	-60227	-239126
Michigan	0.935	0.971	1.189	0.922	0.878	-180353	-79057	467908	-217928	-351277

Minnesota	1.109	1.345	1.012	1.001	0.814	149408	426613	17687	1013	-295906
Mississippi	1.127	1.274	1.099	1.035	0.777	106468	215541	83960	31036	-224069
Missouri	1.075	1.194	1.089	0.953	0.867	104408	255469	123484	-69345	-205200
Montana	1.042	1.460	0.851	1.058	0.793	14158	130656	-55728	19548	-80319
Nebraska	1.615	1.369	1.249	0.956	0.988	224769	147384	104213	-21109	-5719
Nevada	1.385	1.639	1.014	0.961	0.866	185789	281951	8178	-22426	-81913
New Hampshire	1.002	1.299	0.935	0.961	0.859	951	100173	-25606	-15272	-58343
New Jersey	0.901	1.235	0.903	0.988	0.818	-325300	659899	-320032	-37572	-627597
New Mexico	0.926	1.249	0.879	1.018	0.828	-37032	106283	-61597	8603	-90321
New York	1.035	1.326	0.953	0.962	0.851	203301	1648407	-280666	-223931	-940509
North Carolina	0.940	1.439	0.803	0.952	0.854	-145806	858188	-515858	-115036	-373099
North Dakota	1.187	1.697	0.819	0.983	0.870	43360	133512	-50511	-4450	-35191
Ohio	0.925	1.078	1.064	0.970	0.832	-269277	259357	213992	-106395	-636231
Oklahoma	1.233	1.445	1.039	1.042	0.788	243597	428202	44648	48030	-277283
Oregon	1.087	1.442	0.905	0.948	0.879	62856	276216	-75677	-40285	-97398
Pennsylvania	0.965	1.251	0.946	0.975	0.836	-131935	819159	-201902	-94147	-655045
Rhode Island	1.000	1.328	0.913	0.958	0.861	119	67946	-21720	-10173	-35934
South Carolina	1.151	1.288	1.086	0.945	0.870	188172	339722	111115	-75480	-187185
South Dakota	1.245	1.502	0.990	0.962	0.869	41070	76397	-1822	-7235	-26270
Tennessee	1.070	1.276	1.050	0.927	0.861	49533	177901	35748	-55216	-108901
Texas	1.162	1.570	0.931	1.098	0.724	1469602	4413749	-703563	918604	-3159188
Utah	1.223	1.611	0.945	1.004	0.801	108924	257963	-30855	2059	-120244
Vermont	1.132	1.309	1.043	0.956	0.867	22376	48577	7647	-8099	-25749
Virginia	1.163	1.544	0.911	0.967	0.855	294738	847107	-182236	-65303	-304830
Washington	1.187	1.428	1.035	1.033	0.778	232945	484031	46487	43839	-341412
West Virginia	0.933	1.280	0.874	0.974	0.856	-43452	153973	-84401	-16155	-96869
Wisconsin	1.164	1.25	1.134	0.93	0.87	215316	317759	178688	-95578	-185553

		1		5	7					
Wyoming	1.554	1.912	0.942	1.091	0.790	137254	201966	-18453	27208	-73467

APPENDIX D

LOGARITHMIC MEAN DIVISIA INDEX (LMDI)

DECOMPOSITION METHOD

Detailed derivation of LMDI is beyond the scope of this paper. While a practical guide for using LMDI in IDA can be found in Ang (2005) [133], we briefly list the LMDI formulae for the general case with n factors.

Assume E to be a region's total industrial energy use. The general IDA identity is given by

$$E = \sum_s E_s = \sum_s x_{1,s}\, x_{2,s} \cdots x_{n,s} \tag{D.1}$$

where *s* represents sectors; $x_{1,s}$, $x_{2,s}$, $\cdots x_{n,s}$ represents *n* determinant variables for sector s.

Between period *0* and period *T*, industrial energy use changes from $E^0 = \sum_s E^0{}_s = \sum_s x^0{}_{1,s}\, x^0{}_{2,s} \cdots x^0{}_{n,s}$ to $E^T = \sum_s E^T{}_s = \sum_s x^T{}_{1,s}\, x^T{}_{2,s} \cdots x^T{}_{n,s}$. Multiplicative decomposition focuses on the ratio:

$$D_{tot} = \frac{E^T}{E^0} = D_{x_1} D_{x_2} \cdots D_{x_n} \tag{D.2}$$

where D_{x_i} is the multiplicative effect associated with factor *i*.

Additive decomposition focuses on the difference:

$$\Delta E_{tot} = E^T - E^0 = \Delta E_{x_1} + \Delta E_{x_2} + \cdots + \Delta E_{x_n} \tag{D.3}$$

where E_{x_i} is the additive effect associated with factor *i*.

Table D.1. LMDI formulae for n factors

IDA identity	$E = \sum_s E_s = \sum_s x_{1,s}\, x_{2,s} \cdots x_{n,s}$	
Type of decomposition	Multiplicative	Additive
Index for change	$D_{tot} = \frac{E^T}{E^0} = D_{x_1} D_{x_2} \cdots D_{x_n}$	$\Delta E_{tot} = E^T - E^0 = \Delta E_{x_1} + \Delta E_{x_2} + \cdots + \Delta E_{x_n}$
LMDI formulae	$D_{x_i} = \exp\left(\sum_s \frac{(E_s^T - E_s^0)/(lnE_s^T - lnE_s^0)}{(E^T - E^0)/(lnE^T - lnE^0)} ln\left(\frac{x^T{}_{i,s}}{x^0{}_{i,s}}\right)\right)$	$\Delta E_{x_i} = \sum_s \frac{E_s^T - E_s^0}{lnE_s^T - lnE_s^0} ln\left(\frac{x^T{}_{i,s}}{x^0{}_{i,s}}\right)$

Notes: (a) Where $x_{i,s} = 0$, replace zeros by a small positive constant, e.g. 10^{-20};

(b) $\ln(D_{tot}) = \ln(D_{x_1}) + \ln(D_{x_2}) + \cdots + \ln(D_{x_n})$;

(c) $\frac{\Delta E_{tot}}{\ln(D_{tot})} = \frac{\Delta E_{x_1}}{\ln(D_{x_1})} = \frac{\Delta E_{x_2}}{\ln(D_{x_2})} = \cdots = \frac{\Delta E_{x_n}}{\ln(D_{x_n})}$.

APPENDIX E

MATCHING BEA AND MRIO SECTOR PROFILES

The MRIO database for the U.S. employs a 6-digit NAICS code sector scheme, which is less aggregated than the state-level GDP dataset. Therefore, we aggregate energy use coefficients by

1) Combining MRIO sectors into the state-level economic sector scheme based on NAICS sector definitions;

2) Calculating national sectoral GDP by the state-level sector scheme from the 2010 national 6-digit NAICS sectoral GDP dataset;

3) Calculating the total national sectoral EI and aggregating by the state-level economic sector scheme;

4) Dividing total national sectoral EI by national sectoral GDP by the state-level economic sector scheme.

These four steps give sectoral energy use coefficient by the BEA state GDP sector profile from 1997 to 2010. We converted all monetary values to 2009 chained U.S. dollars.

APPENDIX F

CONSTRUCTING PRODUCT SPACE MAP

The product space map is a network that depicts the interaction between sectors. In the network, nodes represent sectors and links represent inter-sector proximity above a certain threshold. For U.S. state-level sectoral GDP broken down to 64 sectors, we construct the product space map with the 2010 cross section.

To construct the product space map, the first step is to extract the maximum spanning tree (MST). This means using the smallest number of links to connect all nodes while maximizing total proximity. In this case, we have 64 sectors, and therefore need 63 links in the MST. We first choose two sectors with the highest proximity value; we then choose another sector that has the highest proximity value to this dyad; the third step is to choose one more sector that has the highest proximity value to the above triad. This process repeats until all sectors are connected with 63 links in total (Figure F.1).

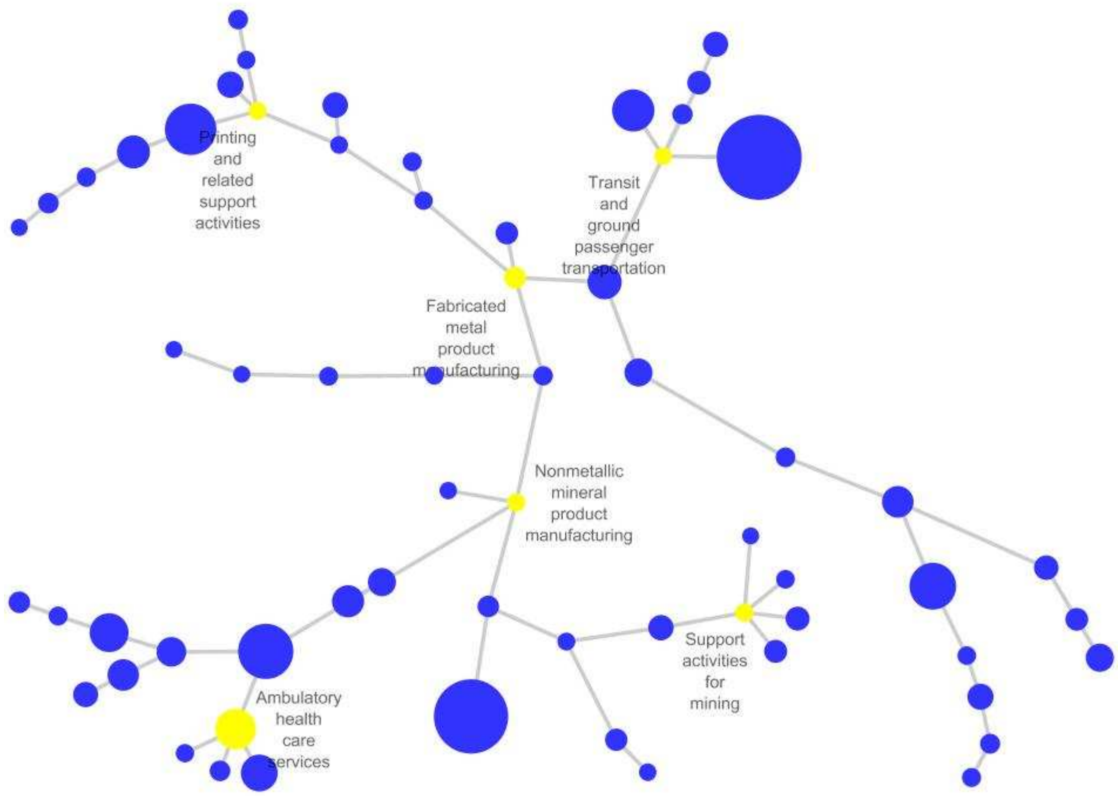


Figure F.1. The maximum spanning tree. Node size represents sectoral national GDP in 2010. Highlighted nodes have the highest betweeness (betweeness = 5 or 4).

We then add links to generate an informational yet clean topology. A general guideline is to choose the number of links so that the average degree of nodes in the network is 4. In this case, we need around 128 links. This requires keeping proximity links equal or above 0.59.

The network layout is generated through an edge-weighted spring-embedded algorithm, which treats nodes as equally charged particles and links as springs and manages to minimize the total force in the layout. Figure F.2 is the crude product space map, which shows significant heterogeneity in terms of the importance of nodes. We then slightly adjust the position of nodes to minimize stacking, followed by some final touches to achieve the final product space map in Figure 3.2.

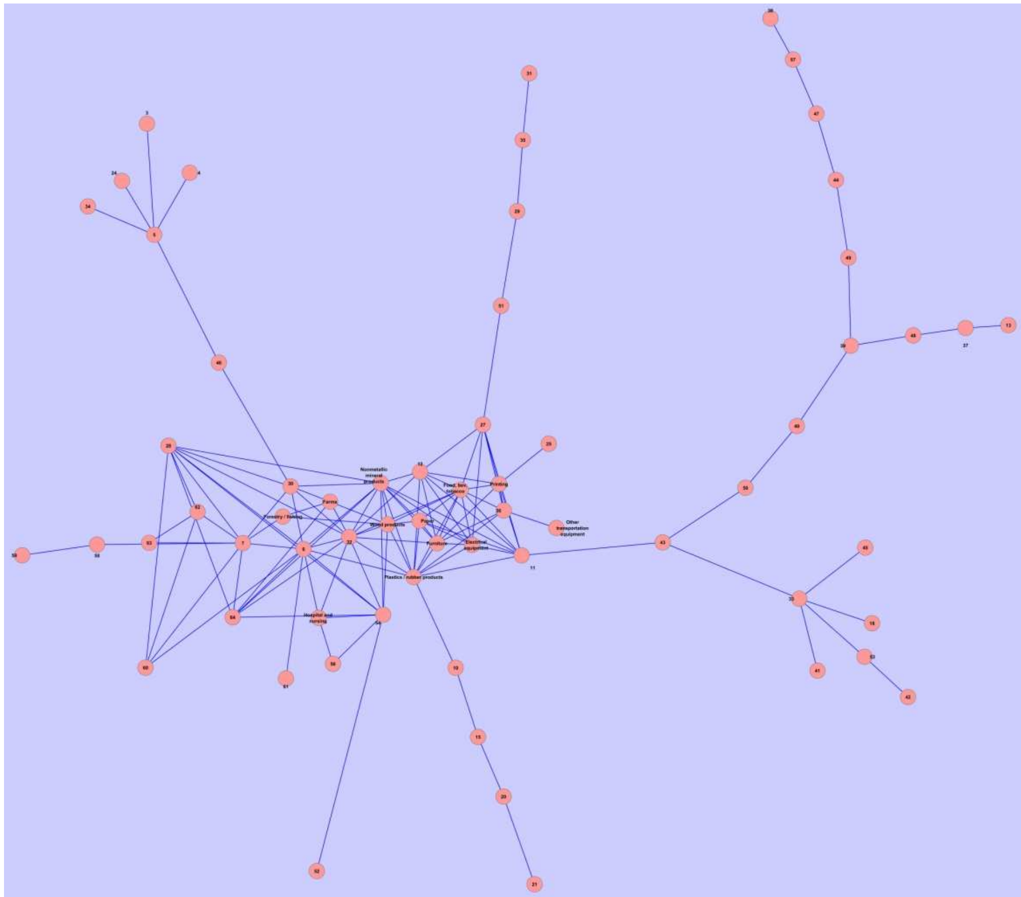


Figure F.2. Crude product space map generated with an edge-weighted spring-embedded algorithm

Keeping the product space map layout constant is based on the notion that the type and intensity of interaction between sectors has not changed dramatically during the period of study. Hidalgo et al. [129] adopted the same assumption in their original study of industrial network transition. Here we further justify this assumption by regressing proximity in 2010 against proximity in 1997 (Table F.1).

Table F.1. Comparison of proximity in 2010 and 1997

Dependent variable: proximity 2010 Independent variable: proximity 1997		
	With constant	Without constant
Coefficient	0.819 (62.01)	0.983 (147.06)
Intercept	0.062 (14.23)	-
R-squared	0.656	0.915
F statistics	3845.84	21626.42

Notes: t-statistics are in parentheses. Total number of observations is 2016 for both cases.

Regression without a constant term results in higher F value and higher R-squared value, which means better predicting power. For the case without a constant, the coefficient (0.983) is quite close to one, indicating that the relative "economic distance" between sectors has gone through only very slight changes.

Given the relative stability of proximity values, using the same product space map layout allows us to directly visualize how a region's industrial structure has evolved during the period of study.

APPENDIX G

COMPLETE PANEL REGRESSION ANALYSIS RESULTS

Table G.1. Effect of region-specific industrial structure change on regional energy use

	Dependent variable: logTE							
Regression Index / Regressor	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Number of key sectors in:								
-Total	-0.011 (-3.33)	_	-0.013 (-3.75)	_	_	_	_	0.042 (2.80)
-Energy	_	_	_	0.039 (2.63)	0.039 (2.64)	0.042 (2.77)	0.040 (2.68)	-0.032 (-7.04)
-Manufacturing	_	_	_	0.014 (1.91)	0.014 (1.93)	0.014 (1.98)	0.013 (1.81)	_
-Service	_	_	_	-0.031 (-7.01)	-0.308 (-6.76)	-0.032 (-7.13)	-0.031 (-7.10)	_
-Transportation	_	_	_	0.002 (0.15)	0.002 (0.15)	_	_	_
-Agriculture	_	_	_	-0.034 (-1.71)	_	-0.033 (-1.72)	_	_
-Trade	_	_	_	-0.039 (-1.96)	_	_	-0.039 (-1.89)	_
-Transportation and agriculture	_	_	_	_	_	_	-0.007 (-0.61)	_
-Transportation and trade	_	_	_	_	_	-0.004 (-0.43)	_	_
-Agriculture and trade	_	_	_	_	-0.035 (-3.12)	_	_	_
-Transportation, agriculture and trade	_	_	_	_	_	_	_	-0.010 (-1.10)
Number of key sectors that are hub sectors (key-hub) in:								
-Total	_	-0.0004 (-0.19)	0.004 (1.97)	_	_	_	_	0.013 (1.86)
-Energy	_	_	_	0.046 (4.20)	0.046 (4.32)	0.045 (4.15)	0.048 (4.36)	0.048 (4.37)
-Manufacturing	_	_	_	-0.006 (-1.38)	-0.006 (-1.42)	-0.005 (-1.36)	-0.005 (-1.19)	-0.004 (-1.15)
-Service	_	_	_	0.011 (3.29)	0.011 (3.26)	0.011 (3.37)	0.012 (3.30)	0.012 (3.41)
-Transportation	_	_	_	-0.010 (-1.43)	-0.010 (-1.51)	_	_	_
-Agriculture	_	_	_	0.019 (1.77)	_	0.019 (1.84)	_	_
-Trade	_	_	_	0.028 (2.40)	_	_	0.031 (2.60)	_
-Transportation and agriculture	_	_	_	_	_	_	-0.007 (-0.93)	_
-Transportation and trade	_	_	_	_	_	-0.009 (-1.30)	_	_
-Agriculture and trade	_	_	_	_	0.022 (2.49)	_	_	_
-Transportation, agriculture	_	_	_	_	_	_	_	-0.006

and trade								(-0.79)
log GSP	0.148	0.182	0.135	0.123	0.123	0.122	0.115	0.113
	(2.47)	(3.09)	(2.23)	(1.99)	(2.02)	(1.94)	(1.79)	(1.74)
Intercept	12.253	11.599	12.409	12.460	12.452	12.478	12.545	12.853
	(16.43)	(16.45)	(16.43)	(16.18)	(16.26)	(15.85)	(15.54)	(15.48)
Observations	714	714	714	714	714	714	714	714
R-squared (within)	0.047	0.025	0.050	0.164	0.164	0.157	0.157	0.151
R-squared (between)	0.778	0.920	0.757	0.571	0.576	0.573	0.495	0.496
R-squared (overall)	0.749	0.898	0.724	0.530	0.535	0.533	0.457	0.460
F statistics	13.12	4.90	9.41	22.72	24.91	22.45	21.24	18.20

Notes: Fixed-effect panel analysis. Regression results report coefficients for each regressor. t-statistics are in parentheses. Results are robust to heteroskedasticity. Dependent variable: natural log of yearly industrial total energy use (logTE) from 1997 to 2010. Sample size: 50 U.S. states and Washington D.C. over the 1997-2010 period, 714 observations in total. Regressors: loggsp – natural log of real gross state output (2009 price).

APPENDIX H

CONDENSED MATHEMATICAL FORMULATIONS FOR CGE MODEL

Table H.1. Condensed mathematical formulations for the CGE model

Equation	Mathematical formulation
Sectoral activity output price	$py_a = py_a(pi_a, w, rk)$
Sectoral intermediate composite price	$pi_a = pi_a(pa)$
Labor wage	$w = w(px, t_l)$
Labor force	$L = L^{ls} + L^x = \sum_a L_a$
Capital rental price	$rk = rk(\delta, \phi, px, t_k)$
Capital supply	$K = K^{ls} + K^x = \sum_a K_a$
Sectoral labor demand	$L_a = L_a(w, rk, INT_a, \sum_c Q_{a,c}^{ls})$
Sectoral capital demand	$K_a = K_a(w, rk, INT_a, \sum_c Q_{a,c}^{ls})$
Distribution of local production	$Q_{a,c}^{ls} + Q_c^{ins} = Q_c^{lsld} + X_c$
Local commodity market clear	$HD_c + GD_c + INVD_c + ID_c = Q_c^{lsld} + I_c = Q_c^{ld}$
Institutional supply	$Q_c^{ins} = Q_c^{ins}(\sum_a py_a Q_{a,c}^{ls}, pa_c, px,)$
Local supply used for local demand	$Q_c^{lsld} = Q_c^{lsld}(pa_c, px, Q_c^{ld})$
Household demand	$HD_c = HD_c(pa, Y)$
Government demand	$GD_c = HD_c(pa, GY)$
Commodity investment demand	$INVD_c = INVD_c(pa, INV)$
Commodity intermediate demand	$ID_c = \sum_a ID_{c,a}$ $ID_{c,a} = ID_{c,a}(pa, INT_a)$
Intermediate composite demand	$INT_a = INT_a(pi_a, w, rk, \sum_c Q_{a,c}^{ls})$
Capital updates between periods	$K_{t+1} = K_t - \delta K_t + INV_t^{net}$ $INV_t = INV_t^{net}(1 + \frac{1}{2}\phi \frac{INV_t^{net}}{K_t})$

Notation

Functions

$py_a(.)$	CES cost function for sectoral production activity
$pi_a(.)$	CES cost function for sectoral production intermediate composite
$w(.)$	Labor wage function
$rk(.)$	Capital rental price function
$L_a(.)$	Sectoral labor demand function
$K_a(.)$	Sectoral capital demand function
$Q_c^{ins}(.)$	Institutional supply function
$Q_c^{lsld}(.)$	Function for local supply used for local demand
$HD_c(.)$	Household demand function
$GD_c(.)$	Government demand function
$INVD_c(.)$	Commodity investment demand function
$ID_{c,a}(.)$	Commodity intermediate demand function
$INT_a(.)$	Intermediate composite demand function

Variables

a Sectoral activity

c Sectoral commodity

t Time period

$Q_{a,c}^{ls}$ Sectoral local supply from production (Conversion between activity and commodity)

Q_c^{ins} Institutional supply of sectoral commodity

Q_c^{lsld} Local supply used for local demand

Q_c^{ld} Total local commodity demand

X_c Commodity export

I_c Commodity import

HD_c Household commodity demand

GD_c Government commodity demand

$INVD_c$ Commodity for capital investment

ID_c Commodity demand as production intermediate

$ID_{c,a}$ Commodity c used as production intermediate for activity a

INT_a Intermediate composite output for activity a

Y Household income

GY Government income

INV Total capital investment

INV_t^{net} Net capital investment

L, L^{ls}, L^x Total, local and external labor supply

K, K^{ls}, K^x Total, local and external capital supply for production

py_a Sectoral activity output price level

pi_a Sectoral intermediate composite price level

pa_c Sectoral commodity Armington price

px Foreign exchange

w Labor wage

rk Capital rental price

Parameters

t_l Labor income tax

t_k Capital tax

δ Capital depreciation coefficient

ϕ Capital adjustment cost coefficient

APPENDIX I

SECTOR DISAGGREGATION PROFILE FOR CGE MODEL

Based on the NAICS sector classification, I break down the economy into 69 sectors. This sector disaggregation is similar to what I used in Chapter 2 and Chapter 3, except that energy production sectors are further separated from other sectors. Table I.1 lists our sector profile and the corresponding NAICS codes.

Table I.1. Sector disaggregation and corresponding NAICS codes in the CGE model

Sector description	NAICS 2007 code
Energy-coal	2121
Energy-oil	32411
Energy-gas	2212
Energy-electricity	2211
Crop and animal production (Farms)	111-112
Forestry fishing and related activities	113-115
Oil and gas extraction	211
Mining (except oil and gas)	2122-2123
Support activities for mining	213
Utilities	2213
Construction	23
Wood product manufacturing	321
Nonmetallic mineral product manufacturing	327
Primary metal manufacturing	331
Fabricated metal product manufacturing	332
Machinery manufacturing	333
Computer and electronic product manufacturing	334
Electrical equipment appliance and component manufacturing	335
Motor vehicle body trailer and parts manufacturing	3361-3363
Other transportation equipment manufacturing	3364-3369
Furniture and related product manufacturing	337
Miscellaneous manufacturing	339
Food and beverage and tobacco product manufacturing	311-312
Textile mills and textile product mills	313-314
Apparel and leather and allied product manufacturing	315-316
Paper manufacturing	322
Printing and related support activities	323
Petroleum and coal products manufacturing	32412-32419
Chemical manufacturing	325
Plastics and rubber products manufacturing	326
Wholesale trade	42

Retail trade	44-45
Air transportation	481
Rail transportation	482
Water transportation	483
Truck transportation	484
Transit and ground passenger transportation	485
Pipeline transportation	486
Other transportation and support activities	487-488, 492
Warehousing and storage	493
Publishing industries	511, 516
Motion picture and sound recording industries	512
Broadcasting and telecommunications	515, 517
Information and data processing services	518-519
Federal Reserve banks credit intermediation and related services	521-522
Securities commodity contracts investments	523
Insurance carriers and related activities	524
Funds trusts and other financial vehicles	525
Real estate	531
Rental and leasing services and lessors of intangible assets	532-533
Legal services	5411
Computer systems design and related services	5415
Other professional scientific and technical services	5412-5414, 5416-5419
Management of companies and enterprises	55
Administrative and support services	561
Waste management and remediation services	562
Educational services	61
Ambulatory health care services	621
Hospitals and nursing and residential care facilities	622-623
Social assistance	624
Performing arts spectator sports museums and related services	711-712
Amusement gambling and recreation	713
Accommodation	721
Food services and drinking places	722
Other services except government	81
Federal civilian	NA
Federal military	NA
State and local	NA
Miscellaneous	NA

APPENDIX J

DYNAMIC CAPITAL INVESTMENT IN CGE MODEL

Capital updates between periods according to the following equation (eq J.1):

$$K_{t+1} = K_t - \delta K_t + I_t \tag{J.1}$$

That is, capital depreciates at rate δ, and investment provides new capital for the next period.

However, there is always capital adjustment cost associated with capital investment. This means that gross investment (or total investment expenditure) is always higher than net investment which turns into capital for the next period. Gross investment in period t J_t and net investment I_t are linked together by the following function (eq J.2):

$$J_t = I_t(1 + \frac{1}{2}\phi \frac{I_t}{K_t}) \tag{J.2}$$

where ϕ is the adjustment coefficient. Using $\frac{I_t}{K_t}$ signifies the presence of adjustment costs in investment, and that adjustment cost increases as a function of the ratio $\frac{I_t}{K_t}$. The function implies that production does not adjust instantaneously to price changes and that desired capital stocks are only attained gradually over time.

In a dynamic model, because it is not possible to numerically solve for an infinite number of periods, we introduce the concept of terminal capital and add a constraint on the growth rate of investment in the terminal period (eq J.3):

$$\frac{I_T}{I_{T-1}} = \frac{Y_T}{Y_{T-1}} \tag{J.3}$$

where T is the terminal period and Y represents output (In model calibration, this can be output of any sector). The indication of the above equation is that investment in the terminal period grows at the same rate as output so that investment exactly counterbalances capital depreciation in future periods, yielding a constant capital growth rate for a balanced growth path.

For calibration, we need to introduce three prices for capital: a purchase price (*PK*)., a rental price (*RK*) and a price of capital adjustment premium for existing capital (*PKA*). The purchase price represents the cost of replacing lost capital, and can be used to model capital depreciation and investment between periods. The rental price represents the cost of using capital, and can be used to model production activities that utilize capital during a single period. The price of capital adjustment premium enters the model's investment block as an artificial input that represents the amount of capital that's lost during the investment process.

Next, we derive *PK*, *RK* and *PKA* based on the consumer's intertemporal utility maximization problem:

$$\max \sum_{t=0}^{\infty} (\frac{1}{1+r})^t U(C_t)$$

s.t. $C_t = F(K_t, L_t) - J_t$

$$K_{t+1} = (1-\delta)K_t + I_t$$

where $U(C_t)$ is utility in period t from consumption C_t (For simplicity, assume $U(C_t) = C_t$);

J_t is gross investment accounting for adjustment cost;

I_t is net investment excluding adjustment cost.

For first-order condition, consider two periods *t* and *t+1*, three decision variables C_t, J_t, I_t, and constraints for capital stock K in the two periods (K_t and K_{t+1})

Lagrangian:

$$L = (\frac{1}{1+r})^t U(C_t) + \lambda_1(F(K_t, L_t) - J_t - C_t) + \lambda_2((1-\delta)K_{t-1} + I_{t-1} - K_t) + \lambda_3((1-\delta)K_t + I_t - K_{t+1})$$

λ_1: consumption today constraint multiplier. $\lambda_1 = P_t$;

λ_2: capital today constraint multiplier. $\lambda_2 = PK_t$;

λ_3: capital tomorrow constraint multiplier. $\lambda_3 = PK_{t+1}$.

$$\frac{\partial L}{\partial C_t} = (\frac{1}{1+r})^t \frac{\partial U(C_t)}{\partial C_t} - \lambda_1 = 0 \qquad (1)$$

$$\frac{\partial L}{\partial K_t} = \lambda_1(\frac{\partial F}{\partial K_t} - \frac{\partial J_t}{\partial K_t}) - \lambda_2 + \lambda_3(1-\delta) = 0 \qquad (2)$$

$$\frac{\partial L}{\partial I_t} = -\lambda_1 \frac{\partial J_t}{\partial I_t} + \lambda_3 = 0 \qquad (3)$$

As $J_t = I_t + \frac{\phi}{2}(\frac{I_t}{K_t})I_t$

we have $\frac{\partial J_t}{\partial I_t} = 1 + \phi \frac{I_t}{K_t}$ (4)

and $\frac{\partial J_t}{\partial K_t} = -\frac{\phi}{2}(\frac{I_t}{K_t})^2$ (5)

From (1), $\lambda_1 = (\frac{1}{1+r})^t \frac{\partial U(C_t)}{\partial C_t} = P_t$

Assume $U(C_t) = C_t$, then $P_t = (\frac{1}{1+r})^t$

From (2) and (5), $PK_t = \lambda_2 = \lambda_1(\frac{\partial F}{\partial K_t} + \frac{\phi}{2}(\frac{I_t}{K_t})^2) + \lambda_3(1-\delta)$

From (3) and (4), $PK_{t+1} = \lambda_3 = \lambda_1 \frac{\partial J_t}{\partial I_t} = \lambda_1(1+\phi\frac{I_t}{K_t}) = P_t(1+\phi\frac{I_t}{K_t})$

Therefore,

$$PK_t = P_t(\frac{\partial F}{\partial K_t} + \frac{\phi}{2}(\frac{I_t}{K_t})^2) + (1-\delta)PK_{t+1} = P_t(\frac{\partial F}{\partial K_t} + \frac{\phi}{2}(\frac{I_t}{K_t})^2 + (1-\delta)(1+\phi\frac{I_t}{K_t})) \qquad (6)$$

At steady state, assuming no exogenous growth, $K_{t+1} = K_t$

Therefore $\frac{I_t}{K_t} = \delta$

$$PK_{t+1} = P_t(1+\phi\delta)$$

Given PK_{t+1}, we know that $PK_t = P_{t-1}(1+\phi\delta)$. In addition, $P_{t-1} = P_t(1+r)$.

Therefore, $PK_t = P_t(1+r)(1+\phi\delta)$

In (6), $\frac{\partial F}{\partial K_t} = RK_t$

$$PK_t = P_t(RK_t + \frac{\phi}{2}\delta^2 + (1-\delta)(1+\phi\delta))$$

$$RK_t = (1+\phi\delta)(r+\delta) - \frac{\phi}{2}\delta^2$$

For every period t, total adjustment cost $ADJ_t = \frac{\phi}{2}\frac{I_t}{K_t}I_t = \frac{\phi}{2}\delta^2 K_t$

Assume the adjustment premium $PKA = \frac{\phi}{2}\delta^2$

To summarize benchmark prices for calibration, assume $P_t = 1$

$$PK0 = (1+r)(1+\phi\delta)$$

$$PKA0 = \frac{\phi}{2}\delta^2$$

$$RK0 = (1+\phi\delta)(r+\delta) - \frac{\phi}{2}\delta^2$$

For calibration, we assume that capital stock remains the same between periods. We therefore have

$$I = \delta K_0 = \frac{\delta VK_0}{RK0}$$

where K_0 is base year capital stock, VK_0 is base year capital earnings (capital income of institutions).

It is noteworthy that I and VK_0 are both obtained from the SAM, and that interest rate r is exogenously set. Therefore, depreciation rate δ is calibrated endogenously given the mathematical formulation for *RK0*.

APPENDIX K

IMPORTANT PARAMETER CHOICES IN CGE MODEL

Production module:

Elasticity parameter between commodity and capital production: 0

Elasticity parameter between value-added and intermediates: 0.5

Elasticity parameter between capital and labor: 0.6 [169]

Elasticity parameter between energy and non-energy intermediates: 0.3 [65]

Elasticity parameter between non-energy intermediates: 0

Elasticity parameter between electricity and non-electricity: 1 [170]

Elasticity parameter between oil and non-oil: 2

Elasticity parameter between coal and gas: 2

Labor and capital supply:

Elasticity between labor import and local labor supply: 0.5

Elasticity between capital import and local capital supply: 1.5

Elasticity between domestic capital use and capital export: 1

Elasticity between domestic and foreign capital / labor import / export: 0

Market commodity supply:

Elasticity parameter between sectoral production activities and institutional make: 0.2

Elasticity parameter between domestic supply and export: 4

Elasticity parameter between export to RUS and ROW: 0

Armington elasticity parameter between domestic supply and import: 1.5 [171]

Armington elasticity parameter between import from RUS and ROW: 0

Household consumption:

Intertemporal elasticity: 0.5

Elasticity parameter between energy and non-energy goods: 0.5 [170]

Elasticity parameter between energy goods: 1 [170]

Elasticity parameter between non-energy goods: 1 [170]

Government consumption:

Elasticity parameter between energy and non-energy goods: 0.5 [170]

Elasticity parameter between energy goods: 1 [170]

Elasticity parameter between non-energy goods: 1 [170]

Investment:

Elasticity between capital directly for sale and capital used for investment: 0.2

Elasticity parameter between foreign investment and domestic Armington composite: 0.1

Elasticity parameter between commodities: 0

Elasticity parameter between RUS and ROW investment: 0

Elasticity parameter between net investment and adjustment premium: 0

Global variables:

Interest rate: 0.02

Population growth: 0

Depreciation rate: calibrated from base year investment, capital earning and interest rate

Capital adjustment cost coefficient: 0.2

APPENDIX L

GEORGIA'S ENERGY SPENDING STRUCTURE BY ENERGY SOURCES

Figure L.1 compares Georgia's spending in major energy production sectors in 2010 USD (Figure L.1(a)), as well as how individual energy sources are affected by 10% economy-wide energy efficiency improvement (Figure L.1(b)). Expenditure on coal is affected most heavily by increased energy efficiency on the production side. This is due to the fact that very little coal is directly consumed for end-use demand, which means that coal consumption is dominated by production activities. However, because coal accounts for such as small percentage (2.2%) in Georgia's benchmark energy spending structure, its impact on the state's total energy expenditure is predictably trivial. Oil has the largest share in Georgia's energy spending structure (54.3%). Therefore, how it responds to the energy efficiency shock has the largest impact on the economy-wide energy rebound effect. As it turns out, spending on oil shows 30.9% rebound, while the total non-electricity spending rebound is 24.8%.

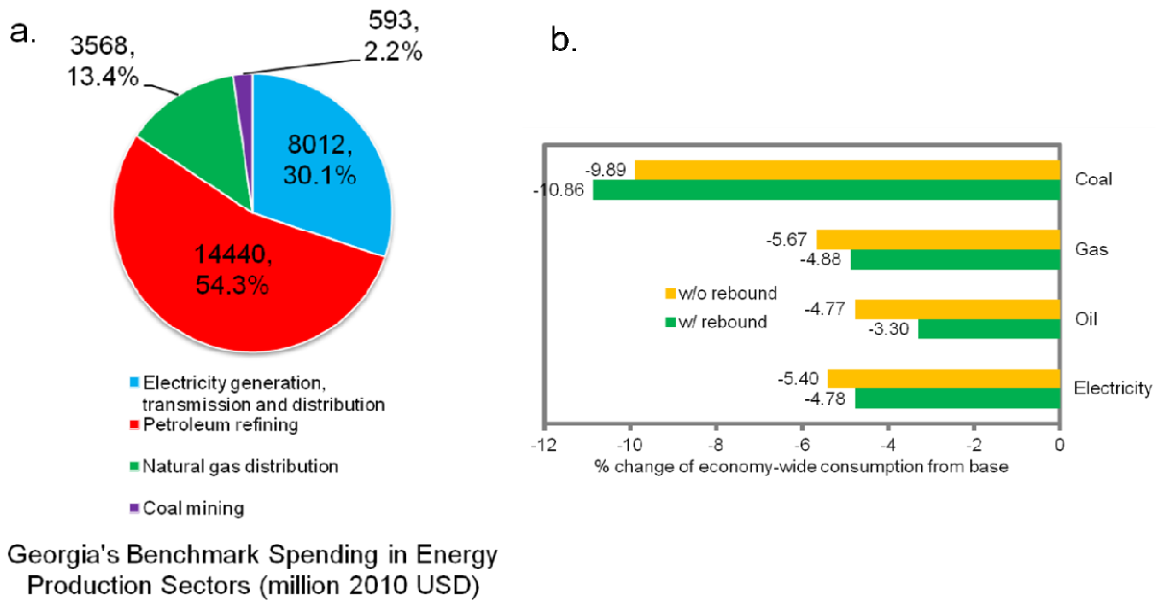


Figure L.1. Georgia's energy spending structure by energy sources. a) Georgia's benchmark spending in energy production sectors (million 2010 USD); b) Change in energy spending for the with rebound / without rebound scenarios after 10% economy-wide production energy efficiency improvement

APPENDIX M

COMPLETE CODES FOR CGE MODEL

```
$title A CGE model accounting for structural adjustment cost for Georgia 2010

*The purpose of this model is to evaluate energy rebound effects from exogenous energy
*efficiency improvement.

*Key features of the model:
*       A detailed description of energy substitution possibilities in the production structure
*       Highly disaggregated sector profile

$SETGLOBAL PROGPATH C:\CGE\GA2010\V9
$SETGLOBAL DATAPATH C:\CGE\GA2010\V9

*Declare "chk" so that check sums are displayed in the first column of output
set colorder /chk/;

*Define all social accounts, the subaccounts of which include activities, commodities,
*factors, institutions and trading regions

* Structure of the aggregated SAM

*           A     C     F     INST   T(FT)    T(DT)
*           1     2     3     4      5        6
* A    1          MAKE  FGEN
* C    2    USE               IUSE   CEXPRT   CEXPRT
* F    3    FD                       FEXPRT   FEXPRT
```

```
* INST  4           IMAKE   FS     TRNSFR  IEXPRT    IEXPRT
* T(FT) 5           CIMPRT   FIMPRT  IIMPRT  TRNSHP    TRNSHP
* T(DT) 6           CIMPRT   FIMPRT  IIMPRT  TRNSHP    TRNSHP

SET K  Aggregated Accounts /
*  Activities
 ECOAL-A       Energy-coal (2121)
 EOIL-A        Energy-oil (32411)
 EGAS-A        Energy-gas (2212)
 EELEC-A       Energy-electricity (2211)
 CROP-A        Crop and animal production (Farms)(111-112)
 FRST-A        Forestry fishing and related activities (113-115)
 OIL-A         Oil and gas extraction (211)
 MIN-A         Mining (except oil and gas) (2122-2123)
 MINSUP-A      Support activities for mining (213)
 UTIL-A        Utilities (2213)
 CONST-A       Construction (23)
 MANWOOD-A     Wood product manufacturing (321)
 MANNONM-A     Nonmetallic mineral product manufacturing (327)
 MANPRIM-A     Primary metal manufacturing (331)
 MANFBRM-A     Fabricated metal product manufacturing (332)
 MANMACH-A     Machinery manufacturing (333)
 MANCOMP-A     Computer and electronic product manufacturing (334)
 MANELEC-A     Electrical equipment appliance and component manufacturing (335)
 MANMTR-A      Motor vehicle body trailer and parts manufacturing (3361-3363)
 MANOTTRS-A    Other transportation equipment manufacturing (3364-3369)
 MANFURN-A     Furniture and related product manufacturing (337)
 MANMISC-A     Miscellaneous manufacturing (339)
 MANFOOD-A     Food and beverage and tobacco product manufacturing (311-312)
```

MANTXTL-A Textile mills and textile product mills (313-314)

MANAPRL-A Apparel and leather and allied product manufacturing (315-316)

MANPAPER-A Paper manufacturing (322)

MANPRT-A Printing and related support activities (323)

MANPTLM-A Petroleum and coal products manufacturing (32412-32419)

MANCMCL-A Chemical manufacturing (325)

MANPLST-A Plastics and rubber products manufacturing (326)

WHLTRAD-A Wholesale trade (42)

RTLTRAD-A Retail trade (44-45)

TRSAIR-A Air transportation (481)

TRSRL-A Rail transportation (482)

TRSWTR-A Water transportation (483)

TRSTRK-A Truck transportation (484)

TRSGRD-A Transit and ground passenger transportation (485)

TRSPIP-A Pipeline transportation (486)

TRSOTH-A Other transportation and support activities (487-488 492)

WRHS-A Warehousing and storage (493)

PBLS-A Publishing industries (511 516)

MTPC-A Motion picture and sound recording industries (512)

BRDCST-A Broadcasting and telecommunications (515 517)

IFMTPRS-A Information and data processing services (518-519)

BANK-A Federal Reserve banks credit intermediation and related services (521-522)

SCRT-A Securities commodity contracts investments (523)

INSUR-A Insurance carriers and related activities (524)

FUNDS-A Funds trusts and other financial vehicles (525)

REALEST-A Real estate (531)

RENTAL-A Rental and leasing services and lessors of intangible assets (532-533)

LEGAL-A Legal services (5411)

COMDESI-A Computer systems design and related services (5415)

OTPSERV-A Other professional scientific and technical services (5412-5414 5416-5419)

MANAGE-A Management of companies and enterprises (55)

ADMIN-A Administrative and support services (561)

WASTMANA-A Waste management and remediation services (562)

EDUCAT-A Educational services (61)

AMBUL-A Ambulatory health care services (621)

HOSPT-A Hospitals and nursing and residential care facilities (622-623)

SOCIAL-A Social assistance (624)

PERF-A Performing arts spectator sports museums and related services (711-712)

AMUSE-A Amusement gambling and recreation (713)

ACCOM-A Accommodation (721)

FOODSERV-A Food services and drinking places (722)

OTSERV-A Other services except government (81)

FDRCIV-A Federal civilian

FDRMIL-A Federal military

STATE-A State and local

MISC-A Miscellaneous

* Commodities

ECOAL-C Energy-coal (2121)

EOIL-C Energy-oil (32411)

EGAS-C Energy-gas (2212)

EELEC-C Energy-electricity (2211)

CROP-C Crop and animal production (Farms)(111-112)

FRST-C Forestry fishing and related activities (113-115)

OIL-C Oil and gas extraction (211)

MIN-C Mining (except oil and gas) (2122-2123)

MINSUP-C Support activities for mining (213)

UTIL-C Utilities (2213)

CONST-C Construction (23)

MANWOOD-C	Wood product manufacturing (321)
MANNONM-C	Nonmetallic mineral product manufacturing (327)
MANPRIM-C	Primary metal manufacturing (331)
MANFBRM-C	Fabricated metal product manufacturing (332)
MANMACH-C	Machinery manufacturing (333)
MANCOMP-C	Computer and electronic product manufacturing (334)
MANELEC-C	Electrical equipment appliance and component manufacturing (335)
MANMTR-C	Motor vehicle body trailer and parts manufacturing (3361-3363)
MANOTTRS-C	Other transportation equipment manufacturing (3364-3369)
MANFURN-C	Furniture and related product manufacturing (337)
MANMISC-C	Miscellaneous manufacturing (339)
MANFOOD-C	Food and beverage and tobacco product manufacturing (311-312)
MANTXTL-C	Textile mills and textile product mills (313-314)
MANAPRL-C	Apparel and leather and allied product manufacturing (315-316)
MANPAPER-C	Paper manufacturing (322)
MANPRT-C	Printing and related support activities (323)
MANPTLM-C	Petroleum and coal products manufacturing (32412-32419)
MANCMCL-C	Chemical manufacturing (325)
MANPLST-C	Plastics and rubber products manufacturing (326)
WHLTRAD-C	Wholesale trade (42)
RTLTRAD-C	Retail trade (44-45)
TRSAIR-C	Air transportation (481)
TRSRL-C	Rail transportation (482)
TRSWTR-C	Water transportation (483)
TRSTRK-C	Truck transportation (484)
TRSGRD-C	Transit and ground passenger transportation (485)
TRSPIP-C	Pipeline transportation (486)
TRSOTH-C	Other transportation and support activities (487-488 492)
WRHS-C	Warehousing and storage (493)

PBLS-C Publishing industries (511 516)

MTPC-C Motion picture and sound recording industries (512)

BRDCST-C Broadcasting and telecommunications (515 517)

IFMTPRS-C Information and data processing services (518-519)

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REALEST-C Real estate (531)

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WASTMANA-C Waste management and remediation services (562)

EDUCAT-C Educational services (61)

AMBUL-C Ambulatory health care services (621)

HOSPT-C Hospitals and nursing and residential care facilities (622-623)

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PERF-C Performing arts spectator sports museums and related services (711-712)

AMUSE-C Amusement gambling and recreation (713)

ACCOM-C Accommodation (721)

FOODSERV-C Food services and drinking places (722)

OTSERV-C Other services except government (81)

FDRCIV-C Federal civilian

FDRMIL-C Federal military

STATE-C State and local

MISC-C Miscellaneous

```
* Factors
  LAB          Employee Compensation
  CAP          Proprietary Income
  INDT         Indirect Business Taxes
* Institutions
  HHD          Household income
  FG           Federal government
  SG           State and local government
  CORP         Enterprise corporate profit
  CAPA         Capital account
* Trading Regions
  FT           Foreign Trade
  DT           Domestic Trade
* Total
  TOTAL        Total
* Difference of column total and row total
  DIFF         Difference
/;

alias(K,KK);
parameter sam(K,KK)      Base year social accounts;

*Load the SAM data
$gdxin 'GA2010.gdx'
$load sam

set negval(K,KK)  Flag for negative elements;
negval(K,KK)=yes$(sam(K,KK)<0);
display negval;
```

```
set empty(K,*)   Flag for empty rows and columns;
empty(K,"row")=1$(sum(KK,sam(K,KK))=0);
empty(KK,"col")=1$(sum(K,sam(K,KK))=0);
display empty;

SET A(K)   Activities /
  ECOAL-A       Energy-coal (2121)
  EOIL-A        Energy-oil (32411)
  EGAS-A        Energy-gas (2212)
  EELEC-A       Energy-electricity (2211)
  CROP-A        Crop and animal production (Farms)(111-112)
  FRST-A        Forestry fishing and related activities (113-115)
  OIL-A         Oil and gas extraction (211)
  MIN-A         Mining (except oil and gas) (2122-2123)
  MINSUP-A      Support activities for mining (213)
  UTIL-A        Utilities (2213)
  CONST-A       Construction (23)
  MANWOOD-A     Wood product manufacturing (321)
  MANNONM-A     Nonmetallic mineral product manufacturing (327)
  MANPRIM-A     Primary metal manufacturing (331)
  MANFBRM-A     Fabricated metal product manufacturing (332)
  MANMACH-A     Machinery manufacturing (333)
  MANCOMP-A     Computer and electronic product manufacturing (334)
  MANELEC-A     Electrical equipment appliance and component manufacturing (335)
  MANMTR-A      Motor vehicle body trailer and parts manufacturing (3361-3363)
  MANOTTRS-A    Other transportation equipment manufacturing (3364-3369)
  MANFURN-A     Furniture and related product manufacturing (337)
  MANMISC-A     Miscellaneous manufacturing (339)
```

MANFOOD-A	Food and beverage and tobacco product manufacturing (311-312)
MANTXTL-A	Textile mills and textile product mills (313-314)
MANAPRL-A	Apparel and leather and allied product manufacturing (315-316)
MANPAPER-A	Paper manufacturing (322)
MANPRT-A	Printing and related support activities (323)
MANPTLM-A	Petroleum and coal products manufacturing (32412-32419)
MANCMCL-A	Chemical manufacturing (325)
MANPLST-A	Plastics and rubber products manufacturing (326)
WHLTRAD-A	Wholesale trade (42)
RTLTRAD-A	Retail trade (44-45)
TRSAIR-A	Air transportation (481)
TRSRL-A	Rail transportation (482)
TRSWTR-A	Water transportation (483)
TRSTRK-A	Truck transportation (484)
TRSGRD-A	Transit and ground passenger transportation (485)
TRSPIP-A	Pipeline transportation (486)
TRSOTH-A	Other transportation and support activities (487-488 492)
WRHS-A	Warehousing and storage (493)
PBLS-A	Publishing industries (511 516)
MTPC-A	Motion picture and sound recording industries (512)
BRDCST-A	Broadcasting and telecommunications (515 517)
IFMTPRS-A	Information and data processing services (518-519)
BANK-A	Federal Reserve banks credit intermediation and related services (521-522)
SCRT-A	Securities commodity contracts investments (523)
INSUR-A	Insurance carriers and related activities (524)
FUNDS-A	Funds trusts and other financial vehicles (525)
REALEST-A	Real estate (531)
RENTAL-A	Rental and leasing services and lessors of intangible assets (532-533)
LEGAL-A	Legal services (5411)

```
 COMDESI-A      Computer systems design and related services (5415)
 OTPSERV-A      Other professional scientific and technical services (5412-5414 5416-5419)
 MANAGE-A       Management of companies and enterprises (55)
 ADMIN-A        Administrative and support services (561)
 WASTMANA-A     Waste management and remediation services (562)
 EDUCAT-A       Educational services (61)
 AMBUL-A        Ambulatory health care services (621)
 HOSPT-A        Hospitals and nursing and residential care facilities (622-623)
 SOCIAL-A       Social assistance (624)
 PERF-A         Performing arts spectator sports museums and related services (711-712)
 AMUSE-A        Amusement gambling and recreation (713)
 ACCOM-A        Accommodation (721)
 FOODSERV-A     Food services and drinking places (722)
 OTSERV-A       Other services except government (81)
 FDRCIV-A       Federal civilian
 FDRMIL-A       Federal military
 STATE-A        State and local
 MISC-A         Miscellaneous
/;

SET EA(A)  Energy activities /
 ECOAL-A        Energy-coal (2121)
 EOIL-A         Energy-oil (32411)
 EGAS-A         Energy-gas (2212)
 EELEC-A        Energy-electricity (2211)
/;

SET C(K)   Commodities /
 ECOAL-C        Energy-coal (2121)
```

EOIL-C Energy-oil (32411)

EGAS-C Energy-gas (2212)

EELEC-C Energy-electricity (2211)

CROP-C Crop and animal production (Farms)(111-112)

FRST-C Forestry fishing and related activities (113-115)

OIL-C Oil and gas extraction (211)

MIN-C Mining (except oil and gas) (2122-2123)

MINSUP-C Support activities for mining (213)

UTIL-C Utilities (2213)

CONST-C Construction (23)

MANWOOD-C Wood product manufacturing (321)

MANNONM-C Nonmetallic mineral product manufacturing (327)

MANPRIM-C Primary metal manufacturing (331)

MANFBRM-C Fabricated metal product manufacturing (332)

MANMACH-C Machinery manufacturing (333)

MANCOMP-C Computer and electronic product manufacturing (334)

MANELEC-C Electrical equipment appliance and component manufacturing (335)

MANMTR-C Motor vehicle body trailer and parts manufacturing (3361-3363)

MANOTTRS-C Other transportation equipment manufacturing (3364-3369)

MANFURN-C Furniture and related product manufacturing (337)

MANMISC-C Miscellaneous manufacturing (339)

MANFOOD-C Food and beverage and tobacco product manufacturing (311-312)

MANTXTL-C Textile mills and textile product mills (313-314)

MANAPRL-C Apparel and leather and allied product manufacturing (315-316)

MANPAPER-C Paper manufacturing (322)

MANPRT-C Printing and related support activities (323)

MANPTLM-C Petroleum and coal products manufacturing (32412-32419)

MANCMCL-C Chemical manufacturing (325)

MANPLST-C Plastics and rubber products manufacturing (326)

WHLTRAD-C Wholesale trade (42)

RTLTRAD-C Retail trade (44-45)

TRSAIR-C Air transportation (481)

TRSRL-C Rail transportation (482)

TRSWTR-C Water transportation (483)

TRSTRK-C Truck transportation (484)

TRSGRD-C Transit and ground passenger transportation (485)

TRSPIP-C Pipeline transportation (486)

TRSOTH-C Other transportation and support activities (487-488 492)

WRHS-C Warehousing and storage (493)

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MTPC-C Motion picture and sound recording industries (512)

BRDCST-C Broadcasting and telecommunications (515 517)

IFMTPRS-C Information and data processing services (518-519)

BANK-C Federal Reserve banks credit intermediation and related services (521-522)

SCRT-C Securities commodity contracts investments (523)

INSUR-C Insurance carriers and related activities (524)

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EDUCAT-C Educational services (61)

AMBUL-C Ambulatory health care services (621)

HOSPT-C Hospitals and nursing and residential care facilities (622-623)

```
  SOCIAL-C      Social assistance (624)
  PERF-C        Performing arts spectator sports museums and related services (711-712)
  AMUSE-C       Amusement gambling and recreation (713)
  ACCOM-C       Accommodation (721)
  FOODSERV-C    Food services and drinking places (722)
  OTSERV-C      Other services except government (81)
  FDRCIV-C      Federal civilian
  FDRMIL-C      Federal military
  STATE-C       State and local
  MISC-C        Miscellaneous
/;

SET EC(C)  Energy commodities /
  ECOAL-C       Energy-coal (2121)
  EOIL-C        Energy-oil (32411)
  EGAS-C        Energy-gas (2212)
  EELEC-C       Energy-electricity (2211)
/;

SET NEC(C) Non-energy commodities /
  CROP-C        Crop and animal production (Farms)(111-112)
  FRST-C        Forestry fishing and related activities (113-115)
  OIL-C         Oil and gas extraction (211)
  MIN-C         Mining (except oil and gas) (2122-2123)
  MINSUP-C      Support activities for mining (213)
  UTIL-C        Utilities (2213)
  CONST-C       Construction (23)
  MANWOOD-C     Wood product manufacturing (321)
  MANNONM-C     Nonmetallic mineral product manufacturing (327)
```

MANPRIM-C	Primary metal manufacturing (331)
MANFBRM-C	Fabricated metal product manufacturing (332)
MANMACH-C	Machinery manufacturing (333)
MANCOMP-C	Computer and electronic product manufacturing (334)
MANELEC-C	Electrical equipment appliance and component manufacturing (335)
MANMTR-C	Motor vehicle body trailer and parts manufacturing (3361-3363)
MANOTTRS-C	Other transportation equipment manufacturing (3364-3369)
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MANAPRL-C	Apparel and leather and allied product manufacturing (315-316)
MANPAPER-C	Paper manufacturing (322)
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WHLTRAD-C	Wholesale trade (42)
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TRSGRD-C	Transit and ground passenger transportation (485)
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WRHS-C	Warehousing and storage (493)
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OTSERV-C Other services except government (81)

FDRCIV-C Federal civilian

FDRMIL-C Federal military

STATE-C State and local

MISC-C Miscellaneous

/;

```
SET F(K)   Factors /
  LAB          Employee Compensation
  CAP          Proprietary Income
  INDT         Indirect Business Taxes
/;

SET I(K)   Institutions /
  HHD          Household income
  FG           Federal government
  SG           State and local government
  CORP         Enterprise corporate profit
  CAPA         Capital account
/;

SET GO(I)  Governments /
  FG           Federal government
  SG           State and local government
/;

SET T(K)   Trade /
  FT           Foreign Trade
  DT           Domestic Trade
/;

SET YR   Period /2010*2019/, YRFIRST(YR),YRLAST(YR);
YRFIRST(YR)=YES$(ORD(YR) EQ 1);
YRLAST(YR)=YES$(ORD(YR) EQ CARD(YR));
```

```
alias(A,AA),(C,CC),(F,FF),(I,II),(T,TT),(GO,GOGO)

*Generate a report of submatrix totals:
set ss   /A,C,F,INST,FT,DT/;
parameter totals(*,*)    SAM totals for reporting;
*Domestic industry make
totals("A","C")=sum((A,C),sam(A,C));

*Total foreign commodity exports
totals("C","FT")=sum(C,sam(C,'FT'));

*Total domestic commodity exports
totals("C","DT")=sum(C,sam(C,'DT'));

*Domestic use of commodities by industries or payments to commodities
totals("C","A")=sum((C,A),sam(C,A));

*Domestic institutional use or final demands by institution
totals("C","INST")=sum((C,I),sam(C,I));

*Factor incomes or value-added elements or payments to workers, interest, profit, etc
totals("F","A")=sum((F,A),sam(F,A));

*Total foreign factor export incomes
totals("F","FT")=sum(F,sam(F,'FT'));

*Total domestic factor export incomes
```

```
totals("F","DT")=sum(F,sam(F,'DT'));

*Total factor generation from sector activities from a few special sectors
totals("A","F")=sum((A,F),sam(A,F));

*Domestic institutional make (this is the same as institutional commodity sales)
totals("INST","C")=sum((I,C),sam(I,C));

*Employee compensation and factor tax
totals("INST","F")=sum((I,F),sam(I,F));

*Inter-institutional transfers
totals("INST","INST")=sum((I,II),sam(I,II));

*Foreign institutional commodity exports
totals("INST","FT")=sum(I,sam(I,'FT'));

*Domestic institutional commodity exports
totals("INST","DT")=sum(I,sam(I,'DT'));

*Total foreign imports to industry use or payments to imports
totals("FT","C")=sum(C,sam('FT',C));

*Foreign factor imports
totals("FT","F")=sum(F,sam('FT',F));

*Foreign institutional commodity imports or foreign imports to final demand
totals("FT","INST")=sum(I,sam('FT',I));
```

```
*Foreign trans-shipments or goods that are shipped into the US and backout again without further processing
totals("FT","FT")=sam('FT','FT');

*Also trans-shipment but not distinguished here in the SAM
totals("FT","DT")=sam('FT','DT');

*Total domestic imports for industry use
totals("DT","C")=sum(C,sam('FT',C));

*Domestic factor imports
totals("DT","F")=sum(F,sam('FT',F));

*Domestic institutional commodity imports or domestic imports to final demands
totals("DT","INST")=sum(I,sam('FT',I));

*Also trans-shipment but not distinguished here in the SAM
totals("DT","FT")=sam('DT','FT');

*Also trans-shipment but not distinguished here in the SAM
totals("DT","DT")=sam('DT','DT');

alias (ss,sss);
totals(ss,"total")=sum(sss,totals(ss,sss));
totals("total",ss)=sum(sss,totals(sss,ss));
option totals:1;
display totals;
```

```
*Extract submatrices from the SAM. When a submatrix is extracted, set the associated
*value to zero so that it is possible to verify at the end of the program that all
*the data has been extracted

*       1)Domestic production is associated with an exhaustion of product condition.
*       First extract all submatrices related to production

parameters
use(C,A)       Intermediate input demand,
fd(F,A)        Factor demand or value added,
make(A,C)      Domestic industry make-all goods marketed in this case,
fgen(A,F)      Factor generation from a few special sector activities;

loop((C,A),       use(C,A)=sam(C,A);sam(C,A)=0;);
loop((F,A),       fd(F,A)=sam(F,A);sam(F,A)=0;);
loop((A,C),       make(A,C)=sam(A,C);sam(A,C)=0;);
loop((A,F),       fgen(A,F)=sam(A,F);sam(A,F)=0;);

*Then check that the data balances. This check provides a clean representation
*of how the benchmark data is organized and how it balances.

parameter profit(A,*)    Zero profit checking for sector activities;
profit(A,"use")=sum(C,use(C,A));
profit(A,"fd")=sum(F,fd(F,A));
profit(A,"make")=sum(C,make(A,C));
profit(A,"fgen")=sum(F,fgen(A,F));

profit(A,"chk")=profit(A,"make")+profit(A,"fgen")-profit(A,"use")-profit(A,"fd");
display profit;
```

```
*       2)Commodity markets are associated with a supply-demand balance condition.
*       We extract the related submatrices and verify that market clearance
*       conditions are satisfied.

parameters
imake(I,C)      Domestic commodity payment to institutions which is institutional make or
negative institutional demand adding to total commodity supply,
cimprt(T,C)     Total imports to industry use or payments to imports,
iuse(C,I)       Domestic institutional use or final demands by institution,
cexprt(C,T)     Total commodity exports;


loop((I,C),         imake(I,C)=sam(I,C);sam(I,C)=0;);
loop((T,C),         cimprt(T,C)=sam(T,C);sam(T,C)=0;);
loop((C,I),         iuse(C,I)=sam(C,I);sam(C,I)=0;);
loop((C,T),         cexprt(C,T)=sam(C,T);sam(C,T)=0;);


parameter cmkt(C,*)     Commodity market clearance;
cmkt(C,"make")=sum(A,make(A,C));
cmkt(C,"imake")=sum(I,imake(I,C));
cmkt(C,"cimprt")=sum(T,cimprt(T,C));
cmkt(C,"use")=sum(A,use(C,A));
cmkt(C,"iuse")=sum(I,iuse(C,I));
cmkt(C,"cexprt")=sum(T,cexprt(C,T));

cmkt(C,"chk")=cmkt(C,"make")+cmkt(C,"imake")+cmkt(C,"cimprt")
        -cmkt(C,"use")-cmkt(C,"iuse")-cmkt(C,"cexprt");
```

```
display cmkt,imake;

*       3)Factor markets are similarly associated with a supply-demand balance
*       condition. We extract the related submatrices and verify that market
*       clearance conditions are satisfied.

parameters
fs(I,F)         Employee compensation (lab to household) enterprise capital dividend and capital
consumption allowance,
ftax(go,F)      Factor tax payment to federal and local government,
fimprt(T,F)     Total factor imports,
fexprt(F,T)     Total factor exports;

loop(F,         fs('HHD',F)=sam('HHD',F);sam('HHD',F)=0);
loop(F,         fs('CORP',F)=sam('CORP',F);sam('CORP',F)=0);
loop(F,         fs('CAPA',F)=sam('CAPA',F);sam('CAPA',F)=0);
loop(F,         ftax('FG',F)=sam('FG',F);sam('FG',F)=0);
loop(F,         ftax('SG',F)=sam('SG',F);sam('SG',F)=0);
loop((T,F),     fimprt(T,F)=sam(T,F);sam(T,F)=0;);
loop((F,T),     fexprt(F,T)=sam(F,T);sam(F,T)=0;);

parameter fmkt(F,*)     Factor market clearance;
fmkt(F,"fs")=sum(I,fs(I,F));
fmkt(F,"ftax")=sum(go,ftax(go,F));
fmkt(F,"fimprt")=sum(T,fimprt(T,F));
fmkt(F,"fd")=sum(A,fd(F,A));
fmkt(F,"fgen")=sum(A,fgen(A,F));
fmkt(F,"fexprt")=sum(T,fexprt(F,T));
```

```
fmkt(F,"chk")=fmkt(F,"fs")+fmkt(F,"ftax")+fmkt(F,"fimprt")+fmkt(F,"fgen")
        -fmkt(F,"fd")-fmkt(F,"fexprt");
display fmkt,ftax;


*       Before defining individual institutional imports and exports, assign two variables
*       to represent household / enterprise / government import and export not categorized by
commodities
parameters
insimprt(T,I)    Total institutional import of commodities,
insexprt(I,T)    Total institutional export of commodities;

loop((T,I),      insimprt(T,I)=sam(T,I));
loop((I,T),      insexprt(I,T)=sam(I,T));

*       4)Households are subject to budget constraints. Here we extract household
*       related data from the SAM and then verify that the budget constraint is
*       satisfied.

parameters
h2h             Household transfer to other households,
hsav            Household payment to capital account representing savings (There is no household
payment to CORP),
htax(go)        Household personal tax payment to federal and local government,
hexprt(T)       Total household export (not present in the SAM),
div             Household receipt of enterprise dividends,
hwtdr           Household dissaving or withdrawals from capital account to support consumption,
hg(go)          Government transfer to households,
himprt(T)       Total household import;
```

```
h2h=sam('HHD','HHD');sam('HHD','HHD')=0;
hsav=sam('CAPA','HHD');sam('CAPA','HHD')=0;
htax('FG')=sam('FG','HHD');sam('FG','HHD')=0;
htax('SG')=sam('SG','HHD');sam('SG','HHD')=0;
loop(T,        himprt(T)=sam(T,'HHD');sam(T,'HHD')=0);
div=sam('HHD','CORP');sam('HHD','CORP')=0;
hwtdr=sam('HHD','CAPA');sam('HHD','CAPA')=0;
hg('FG')=sam('HHD','FG');sam('HHD','FG')=0;
hg('SG')=sam('HHD','SG');sam('HHD','SG')=0;
loop(T,        hexprt(T)=sam('HHD',T);sam('HHD',T)=0);

parameter hbudget(*)    Household budget;
hbudget("huse")=sum(C,iuse(C,'HHD'));
hbudget("h2h")=h2h;
hbudget("hsav")=hsav;
hbudget("htax")=sum(go,htax(go));
hbudget("himprt")=sum(T,himprt(T));
hbudget("hmake")=sum(C,imake('HHD',C));
hbudget("hs")=sum(F,fs('HHD',F));
hbudget("div")=div;
hbudget("hwtdr")=hwtdr;
hbudget("hg")=sum(go,hg(go));
hbudget("hexprt")=sum(T,hexprt(T));

hbudget("chk")=hbudget("huse")+hbudget("h2h")+hbudget("hsav")+hbudget("htax")+hbudget("h
imprt")
        -hbudget("hmake")-hbudget("hs")-hbudget("h2h")-hbudget("div")-hbudget("hwtdr")-
hbudget("hg")-hbudget("hexprt");
```

display hbudget,htax;

*There is unbalanced inter-household transfer. Weird.

*	5)Corporate profit account needs to balance (No institutional import / export in this case)

parameters

cptax(go)	Corporate tax payment to federal and local government (corporate profit tax),

cpg(go)	Government transfer to enterprises,

cpinv	Corporate retained earnings for investment etc;

cptax('FG')=sam('FG','CORP');sam('FG','CORP')=0;

cptax('SG')=sam('SG','CORP');sam('SG','CORP')=0;

cpg('FG')=sam('CORP','FG');sam('CORP','FG')=0;

cpg('SG')=sam('CORP','SG');sam('CORP','SG')=0;

cpinv=sam('CAPA','CORP');sam('CAPA','CORP')=0;

parameter cpbudget(*)	Corporate profit budget;

cpbudget("div")=div;

cpbudget("cptax")=sum(go,cptax(go));

*Corporate profit with inventory valuation adjustment(IVA)

cpbudget("cppft")=fs('CORP','CAP');

cpbudget("cpg")=sum(go,cpg(go));

cpbudget("cpinv")=cpinv;

cpbudget("chk")=cpbudget("cppft")+cpbudget("cpg")-cpbudget("div")-cpbudget("cptax")-cpbudget("cpinv");

display cpbudget,cptax;

*	6)Capital account needs to balance, meaning that investment and savings need to balance as well.

```
parameters
capa2capa       Inventory change (insignificant),
gsav(go)        Government saving,
capaexprt(T)    Total capital sale to foreign regions,
capag(go)       Capital payment to government (government dissaving),
capaimprt(T)    Total capital purchase from foreign sources (Foreign source investment);

capa2capa=sam('CAPA','CAPA');sam('CAPA','CAPA')=0;
capag('FG')=sam('FG','CAPA');sam('FG','CAPA')=0;
capag('SG')=sam('SG','CAPA');sam('SG','CAPA')=0;
loop(T,         capaimprt(T)=sam(T,'CAPA');sam(T,'CAPA')=0);
gsav('FG')=sam('CAPA','FG');sam('CAPA','FG')=0;
gsav('SG')=sam('CAPA','SG');sam('CAPA','SG')=0;
loop(T,         capaexprt(T)=sam('CAPA',T);sam('CAPA',T)=0);

parameter capabudget(*)       Capital account budget;
*Capital investment by sector
capabudget("capainv")=sum(C,iuse(C,'CAPA'));
capabudget("hwtdr")=hwtdr;
capabudget("capag")=sum(go,capag(go));
capabudget("capaimprt")=sum(T,capaimprt(T));
capabudget("capamake")=sum(C,imake('CAPA',C));
*Capital consumption allowance, or tax-based depreciation costs of using capital
capabudget("capacons")=fs('CAPA','CAP');
capabudget("hsav")=hsav;
capabudget("cpinv")=cpinv;
capabudget("gsav")=sum(go,gsav(go));
capabudget("capaexprt")=sum(T,capaexprt(T));
```

```
capabudget("chk")=capabudget("capainv")+capabudget("hwtdr")+capabudget("capag")+capabud
get("capaimprt")
        -capabudget("capamake")-capabudget("capacons")-capabudget("hsav")-
capabudget("cpinv")-capabudget("gsav")-capabudget("capaexprt");
display capabudget;

*       7)The public sector is likewise subject to budget constraint.

parameters
g2g(go,gogo)     Federal and local government transfer,
fgexprt       Total federal government commodity export (not present in the SAM),
sgexprt       Total state government commodity export (not present in the SAM),
fgimprt(T)     Total federal government import of foreign commodities,
sgimprt(T)     Total state government import of foreign commodities;

g2g('FG','FG')=sam('FG','FG');sam('FG','FG')=0;
g2g('FG','SG')=sam('FG','SG');sam('FG','SG')=0;
g2g('SG','FG')=sam('SG','FG');sam('SG','FG')=0;
g2g('SG','SG')=sam('SG','SG');sam('SG','SG')=0;
loop(T,        fgexprt(T)=sam('FG',T);sam('FG',T)=0);
loop(T,        sgexprt(T)=sam('SG',T);sam('SG',T)=0);
loop(T,        fgimprt(T)=sam(T,'FG');sam(T,'FG')=0);
loop(T,        sgimprt(T)=sam(T,'SG');sam(T,'SG')=0);

parameters
fgbudget(*)      Federal government budget,
sgbudget(*)      State and local government budget;

fgbudget("fguse")=sum(C,iuse(C,'FG'));
```

```
fgbudget("hfg")=hg('FG');
fgbudget("cpfg")=cpg('FG');
fgbudget("fgsav")=gsav('FG');
fgbudget("fgout")=g2g('FG','FG')+g2g('SG','FG');
fgbudget("fgexprt")=sum(T,fgexprt(T));
fgbudget("fgimake")=sum(C,imake('FG',C));
fgbudget("fgftax")=sum(F,ftax('FG',F));
fgbudget("htax")=htax('FG');
fgbudget("cptax")=cptax('FG');
fgbudget("capag")=capag('FG');
fgbudget("fgin")=g2g('FG','FG')+g2g('FG','SG');
fgbudget("fgimprt")=sum(T,fgimprt(T));
fgbudget("chk")=fgbudget("fguse")+fgbudget("hfg")+fgbudget("cpfg")+fgbudget("fgsav")+fgbud
get("fgout")+fgbudget("fgexprt")
        -fgbudget("fgimake")-fgbudget("fgftax")-fgbudget("htax")-fgbudget("cptax")-
fgbudget("capag")-fgbudget("fgin")-fgbudget("fgimprt");
display fgbudget;

sgbudget("sguse")=sum(C,iuse(C,'SG'));
sgbudget("hsg")=hg('SG');
sgbudget("cpsg")=cpg('SG');
sgbudget("sgsav")=gsav('SG');
sgbudget("sgout")=g2g('SG','SG')+g2g('FG','SG');
sgbudget("sgexprt")=sum(T,sgexprt(T));
sgbudget("sgimake")=sum(C,imake('SG',C));
sgbudget("sgftax")=sum(F,ftax('SG',F));
sgbudget("htax")=htax('SG');
sgbudget("cptax")=cptax('SG');
sgbudget("capag")=capag('SG');
```

```
sgbudget("sgin")=g2g('SG','SG')+g2g('SG','FG');
sgbudget("sgimprt")=sum(T,sgimprt(T));
sgbudget("chk")=sgbudget("sguse")+sgbudget("hsg")+sgbudget("cpsg")+sgbudget("sgsav")+sgb
udget("sgout")+sgbudget("sgexprt")
        -sgbudget("sgimake")-sgbudget("sgftax")-sgbudget("htax")-sgbudget("cptax")-
sgbudget("capag")-sgbudget("sgin")-sgbudget("sgimprt");
display sgbudget;

*Verify that all data have been extracted

display "Only foreign tran-shipments, total and difference values should be shown if all account
data has been read:", sam;

*****************************************************************************
**
parameters
esub(a)       Elasticity of substitution (top level betwee value-added and intermediates),
delta         Capital depreciation rate (delta is endogenously calculated based on investment
capital earning  and interest rate),
ir            Interest rate,
phi           Capital adjustment coefficient between 0 and 1 depending on the speed of stock
adjustment,
enisub(a)     Elasticity of substitution between energy and non-energy intermediates,
lamda         A fixed proportionality coefficient for calculating structural adjustment cost,
phy(nec,a)    Proximity coefficient between non-energy intermediate nec and sector a,
esub_t        Intertemporal elasticity;


*Define some default elasticities
```

esub(a)=0.5;

*delta=0.04;

*delta=0.04 in iterations later;

ir=0.02;

*0.02 is U.S. annual interest rate

phi=0.2;

*phi=0.1,0.2,0.3 (Rutherford)

enisub(a)=0.1;

lamda=0;

*lamda=0.01 in iterations later;

phy(nec,a)=1;

*phy should be imported from the proximity coefficient later

*kforward=1;

*kforward should be smaller than 1 in later iterations

esub_t=0.5;

*Now we use the imported SAM in constructing the model

parameters

dod(c) Total domestic demand for commodity c (Institutional make is considered net addition to supply not reduced demand),

wl(yr) Wage level of the region in the yr th period yr=0 or 1,

u0 Benchmark employment rate,

*u(yr) Unemployment rate of the region in the yr th period,

ty0(a) Benchmark indirect business tax that increases output price,

ty(go,a,yr) Indirect business tax by federal or local government,

tva0(f) Benchmark total value-added tax (federal and local)on factor,

tva(go,f,yr) Value-added tax on factor by federal or local government,

ks(a) Capital's share of income in sector a,

ted(a) Total energy demand in sector a,

ileon(nec,a)   Inverse of Leontief coefficient for non-energy intermediate nec in the production of sector a,

trf(go,t)   Import tariff collected by local or federal government,

tld   Total labor demand for domestic production and labor export,

tkd   Total capital demand for domestic production,

pk0   Price of capital stock,

pka0   Shadow price of adjustment premium for existing capital (price of capital adjustment),

rk0   Benchmark capital rental rate,

kinc0   Benchmark capital income,

k0   Initial total capital stock,

khhd0   Initial household capital stock,

kent0   Initial enterprise capital stock,

ivst0   Benchmark initial total capital investment,

gis0   Benchmark gross investment spending (including adjustment cost),

thc   Total household consumption,

uhhd0   Baseline present value of household expenditure,

pgprov(go)   Total quantity of public good provision,

ugov0(go)   Baseline present value of government expenditure,

govdef(go,t)   Government export minus import,

pref(yr)   Reference price level in year yr,

kxt   Terminal capital stock;

dod(c)=sum(a,use(c,a))+sum(i,iuse(c,i));

*ty0(a) is indirect business tax on output which increases the price received by consumers. The net effect is that it reduces output price.

ty0(a)=fd("INDT",a)/sum(c,make(a,c));

*The distribution of indirect business tax between federal and local governments is determined by the ratio of there total INDT income

```
ty("FG",a,yr)=fd("INDT",a)/sum(c,make(a,c))*(ftax("FG","INDT")/(ftax("FG","INDT")+ftax("S
G","INDT")));
ty("SG",a,yr)=fd("INDT",a)/sum(c,make(a,c))*(ftax("SG","INDT")/(ftax("FG","INDT")+ftax("S
G","INDT")));
*Wage in the default year equals 1; Wage is inversely related to the current regional
*unemployment rate. It is positively related to last period's real wage.
wl('2010')=1;
u0=0.102;
*u('0')=0.102;
*log10(wl('1'))=0.539*log10(wl('1'))-0.0421*log10(u('0'))-0.0417;
*log10(wl(yr+1))=0.539*log10(wl(yr))-0.0421*log10(u(yr+1))-0.0417;
*Valued added tax on factor equals federal tax plus state and local tax
tva0("LAB")=(ftax('FG',"LAB")+ftax('SG',"LAB"))/(fs("HHD","LAB")+sum(t,fimprt(t,"LAB")));
tva(go,"LAB",yr)=ftax(go,"LAB")/(fs("HHD","LAB")+sum(t,fimprt(t,"LAB")));
tva0("CAP")=(ftax('FG',"CAP")+ftax('SG',"CAP"))/(fs("HHD","CAP")+fs("CORP","CAP")+fs("
CAPA","CAP")+sum(t,fimprt(t,"CAP"))-sum(t,fexprt("CAP",t)));
tva(go,"CAP",yr)=ftax(go,"CAP")/(fs("HHD","CAP")+fs("CORP","CAP")+fs("CAPA","CAP")+
sum(t,fimprt(t,"CAP")));
ks(a)=fd('CAP',a)/(sum(c,use(c,a))+sum(f,fd(f,a)));
ted(a)=sum(ec,use(ec,a));
ileon(nec,a)=use(nec,a)/(sum(c,use(c,a))+sum(f,fd(f,a)));
trf(go,t)=0;
tld=sum(a,fd('LAB',a))+sum(t,fexprt('LAB',t));
tkd=sum(a,fd('CAP',a))-sum(a,fgen(a,"CAP"));
*Investment includes sectoral commodity investment and foreign source investment, minus
insititutional sale from capital stock
ivst0=sum(c,iuse(c,"CAPA"))-sum(c,imake("CAPA",c))+sum(t,capaimprt(t))-sum(t,capaexprt(t));
kinc0=fs("HHD","CAP")+fs("CORP","CAP")+fs("CAPA","CAP");
```

```
*Benchmark initial total capital investment equals depreciation rate multiplied by total capital stock
*Total capital stock equals capital endowment (capital earning) divided by capital rental price
*When interest rate is exogenously specified, depreciation rate has to be calculated endogenousely
*delta = total investment / capital stock = total investment / (total capital income / rk0)
*rk0=pk0*(ir+delta)/(1+ir)-pka0
*pka0=1/2*phi*delta**2
*pk0=(1+ir)*(1+phi*delta)
*Use the functions above to derive delta, noting that delta needs to be smaller than 1.
*Therefore,  among the two solutions for delta, use the smaller one, with minus sign before sqrt
*delta=ivst0*ir/(fs("HHD","CAP")+fs("CORP","CAP")+fs("CAPA","CAP")-ivst0);
delta=(kinc0/ivst0-phi*ir-1-sqrt((kinc0/ivst0-phi*ir-1)**2-2*phi*ir))/phi;
pk0=(1+ir)*(1+phi*delta);
pka0=1/2*phi*delta**2;
rk0=pk0*(ir+delta)/(1+ir)-pka0;
k0=(fs("HHD","CAP")+fs("CORP","CAP")+fs("CAPA","CAP"))/rk0;
gis0=ivst0*(1+phi*ivst0/(2*k0));
khhd0=(fs("HHD","CAP")+fs("CAPA","CAP")*fs("HHD","CAP")/(fs("HHD","CAP")+fs("CORP","CAP")))/rk0;
kent0=(fs("CORP","CAP")+fs("CAPA","CAP")*fs("CORP","CAP")/(fs("HHD","CAP")+fs("CORP","CAP")))/rk0;


pref(yr)=(1/(1+ir))**(ord(yr)-1);
pgprov(go)=sum(ec,iuse(ec,go))+sum(nec,iuse(nec,go));
ugov0(go)=sum(yr,pref(yr)*pgprov(go));
*thc=sum(ec,iuse(ec,"HHD"))+sum(nec,iuse(nec,"HHD"))+sum(go,pgprov(go));
```

```
thc=sum(ec,(iuse(ec,"HHD")-(iuse(ec,"CAPA")-
imake("CAPA",ec))*phi*delta/2))+sum(nec,(iuse(nec,"HHD")-(iuse(nec,"CAPA")-
imake("CAPA",nec))*phi*delta/2));
uhhd0=sum(yr,pref(yr)*thc);
govdef("FG",t)=fgexprt(t)-fgimprt(t);
govdef("SG",t)=sgexprt(t)-sgimprt(t);

display thc,delta,pk0,pka0,rk0,k0,gis0;

*Define parameters for policy experiment
parameter
pen0        Price of energy composite (change to reflect energy efficiency increase),
eff(a)      Efficiency indicator (efficiency <1 means using less energy to produce the same output);
pen0=1;
eff(a)=1;

*****************************************************************************
***
*Within the MPSGE subsystem, always use "" to quote a specific element in a set, never '

$ONTEXT

$MODEL: Georgia_2010

$SECTORS:
*Sectors are represented by activity levels
x(c,yr)                       ! Allocation of domestic produced marketed coommodities
y(a,yr)                       ! Sectoral output (domestic production)
int(a,yr)$(sum(c,use(c,a)))         ! Intermediate supply
```

tec(a,yr)$(sum(ec,use(ec,a))) ! Total energy composite (modeled separately for different sectors)

noil(a,yr)$(use("ECOAL-C",a)+use("EGAS-C",a)) ! Non-oil energy composite including coal and gas (modeled separately for different sectors)

agi(c,yr) ! Aggregate supply of intermediate (Armington aggregate in the domestic market)

ls(yr) ! Labor supply

caps(yr) ! Capital supply

ka(yr) ! Capital accumulation

ivst(yr) ! Capital investment

uhhd ! Household intertemporal utility

hc(yr) ! Household consumption

*ugov(go) ! Government intertemporal utility

gc(go,yr) ! Government consumption

$COMMODITIES:

*Variables associated with commodities are prices, not quantities

pd(c,yr)$(sum(a,make(a,c))+sum(i,imake(i,c))-sum(t,cexprt(c,t))>0) ! Domestic market price, only applicable to commodities of which domestic sale is not zero. The exception is coal

pins(c,yr)$(sum(i,imake(i,c))) ! Demand price for institutional commodity make

py(a,yr) ! Demand price for domestic production activities by produced goods

pi(a,yr)$(sum(c,use(c,a))) ! Demand price for intermediate composite - energy and nonenergy. Only applies to sectors for which intermediate is not zero. The exception is federal military

pen(a,yr)$(sum(ec,use(ec,a))) ! Energy composite price (modeled separately for different sectors) pa(c,yr) ! Demand price for Armington composite which includes domestic (pd) and import (px)

pnoil(a,yr)$(use("ECOAL-C",a)+use("EGAS-C",a)) ! Demand price for non-oil composite (coal and gas) (modeled separately for different sectors)

px(t,yr) ! Domestic exchange for other states or foreign exchange

puhhd ! Household intertemporal utility price

phc(yr) ! Household welfare determined by household consumption

*pugov(go) ! Government intertemporal utility price

pgc(go,yr) ! Price of public goods (government consumption)

*vpg(go,yr) ! Consumer valuation of public good provided by the government

ptrans(go,yr) ! Price of artificially defined governmental transfer

pls(yr) ! Labor supply price faced by production sectors

pl(yr) ! Price for leisure

rks(yr) ! Capital supply price faced by production sectors

rk(yr) ! Rental price for capital

pk(yr) ! Purchase price for capital

pka(yr)$phi ! Price of capital adjustment premium

pkt ! Post-terminal capital constraint

pgsav(go,yr) !Government saving

$CONSUMERS:

*The variable associated with a consumer is an income level

rah ! Representative household (Combination of private households and enterprise)

gov(go) ! Government-Federal or state

pxy ! A hypothetical agent to collect structural equation cost in the form of a tax

$AUXILIARY:

*totabs(yr) !Total absorption

```
*dtax(go,yr)        !Direct tax
sac(nec,a)       ! Structural adjustment cost of changing the quantity of an non-energy intermediate
(nec) in the production of sector a (modeled as an endogenous tax levied on production input)
*u(yr)          ! Unemployment rate
*lgp(go,yr)      ! Level of government provision of public goods
tk             ! Terminal capital stock

*Commodity supply to domestic and export markets governed by a constant elasticity of
*transformation supply function. Sectoral production combines value-added factors
*(labor supply and capital) and immediate inputs to produce goods and services which
*are put to the market. A nested constant elasticity of substitution cost function
*characterizes the tradeoff between intermediate inputs and primary factor inputs.
*Indirect business tax and Labor / capital composite are Cobb-Douglas
*Labor and capital are also CES.

$PROD:x(c,yr)     t:4      tt:0      s:0.2
*t describes commodity sale aggregates between local sales and trade
*tt describes elasticity transformation between domestic trade with the rest of US and
international trade with the rest of the world
o:px(t,yr)$cexprt(c,t)                                   q:cexprt(c,t)      tt:
o:pd(c,yr)$(sum(a,make(a,c))+sum(i,imake(i,c))-sum(t,cexprt(c,t)))
q:(sum(a,make(a,c))+sum(i,imake(i,c))-sum(t,cexprt(c,t)))
i:pins(c,yr)$(sum(i,imake(i,c)))                                q:(sum(i,imake(i,c)))
i:py(a,yr)                                               q:make(a,c)

*Production activity produces output for sale as well as capital saved for investment used later.
Some sectors also produce capital directly
*The top-level production structure below applies only to sectors that use positive intermediate
values. The exception would be federal military activities.
```

```
*There are three sectors that actually generate capital. They are assumed to produce fixed
proportions of capital and final commodity
$PROD:y(a,yr)       t:0             s:esub(a)       va:0.6
*s describes top-level input aggregates. This is CES.
*va describes value-added aggregate in a lower nest, between capital and labor.
*Note that the initial price of labor and capital has to be declared before running the model.
o:rks(yr)$fgen(a,"CAP")            q:(fgen(a,"CAP")/(1+tva0("CAP")))
p:((1+tva0("CAP")))
o:py(a,yr)                    q:(sum(c,(make(a,c))))                    p:(1-ty0(a))       a:gov("FG")
t:ty("FG",a,yr)      a:gov("SG")     t:ty("SG",a,yr)
i:pi(a,yr)                    q:(sum(c,use(c,a)))
i:pls(yr)$fd("LAB",a)             q:(fd("LAB",a)/wl("2010")/(1+tva0("LAB")))
p:(wl("2010")*(1+tva0("LAB")))      va:               !wl("2010") should be wl(yr) later when it
comes to iterations
*p for labor is labor price faced by producer after tax. This is necessary for initial
*calibration. We must use tva0 here, not tva the parameter. This technology is
*assumed to be constant, and so price does not change when tax changes.
*The actual taxing behavior for labor is depicted in the labor supply module later
i:rks(yr)                     q:((fd("CAP",a)/(1+tva0("CAP"))))             p:((1+tva0("CAP")))
va:

*Intermediate composite is composed of non-energy and energy intermediates. Using non-energy
*intermediates also encounters structural adjustment cost, represented here as an endogenous
*tax collected by a hypothetical agent
*The intermediate production structure below applies only to sectors that use positive
intermediate values. The exception would be federal military activities.
*(This is mainly because the federal military activities defined here is only employment and
payroll for federal militaries)
```

*Sectors with zero intermediate usage is declared separately (in this case it is federal military specifically)

$PROD:int(a,yr)$(sum(c,use(c,a))) s:enisub(a) ne:0

*s describes elasticity of substitution between energy and non-energy intermediates. This should actually be FFF. LOOK INTO HOW TO MODEL LATER

*ne describes that non-energy intermediates satisfy Leontief condition

o:pi(a,yr) q:(sum(c,use(c,a)))

i:pa(nec,yr) q:use(nec,a) a:pxy n:sac(nec,a) ne:

*Structural adjustment cost is modeled here in the form of an endogenous tax collected by a hypothetical agent pxy

*The ad valorem tax rate is the product of the value of the endogenous tax (n) and the multiplier (m). By default m=1

i:pen(a,yr)$ted(a) q:(ted(a)*eff(a)) p:pen0

*pen is the energy composite including electricity (from both renewable and nonrenewable sources), oil, gas and coal

*Note: both non-energy and energy intermediates are modeled with the Armington composite price.

*Energy intermediate is a nested structure of electricity and non-electricity, which is in turn composed of oil and non-oil.

*Non oil is composed of gas and coal

$PROD:tec(a,yr)$(sum(ec,use(ec,a))) s:1 nel:2

*s describes the elasticity of substitution between electricity and non-electricity energy intermediates

*nel describes the elasticity of substitution between oil and non oil energy intermediates

o:pen(a,yr)$(sum(ec,use(ec,a))) q:(sum(ec,use(ec,a))) p:pen0

i:pa("EELEC-C",yr) q:use("EELEC-C",a)

i:pa("EOIL-C",yr) q:use("EOIL-C",a) nel:

```
i:pnoil(a,yr)$(use("ECOAL-C",a)+use("EGAS-C",a))        q:(use("ECOAL-C",a)+use("EGAS-C",a))      nel:

$PROD:noil(a,yr)$(use("ECOAL-C",a)+use("EGAS-C",a))      s:2
*s describes the elasticity of substitution between gas and coal
o:pnoil(a,yr)        q:(use("ECOAL-C",a)+use("EGAS-C",a))
i:pa("EGAS-C",yr)     q:use("EGAS-C",a)
i:pa("ECOAL-C",yr)    q:use("ECOAL-C",a)

*Domestic and imported goods are Armington substitutes
$PROD:agi(c,yr)    s:1.5     td:0
*s describes the elasticity of substitution between domestic production and imported goods
*td describes the elasticity of substitution between goods imported from other states and goods imported from other countries
o:pa(c,yr)                              q:dod(c)
i:pd(c,yr)$((dod(c)-sum(t,cimprt(t,c)))>1)        q:(dod(c)-sum(t,cimprt(t,c)))
i:px(t,yr)$(cimprt(t,c)>0.01)                q:cimprt(t,c)        a:gov("FG")     t:trf("FG",t)
a:gov("SG")     t:trf("SG",t)     td:

*Labor supply for domestic production comes from domestic and labor import.
$PROD:ls(yr)       s:0.5
o:pls(yr)                    q:(tld/(wl("2010")*(1+tva0("LAB"))))
p:(wl("2010")*(1+tva0("LAB")))         !wl("2010") should be wl(yr) in later iterations
i:pl(yr)                     q:fs("HHD","LAB")                 p:wl("2010")        a:gov("FG")
t:tva("FG","LAB",yr)   a:gov("SG")     t:tva("SG","LAB",yr)
i:px(t,yr)$fimprt(t,"LAB")        q:fimprt(t,"LAB")                 p:wl("2010")        a:gov("FG")
t:tva("FG","LAB",yr)   a:gov("SG")     t:tva("SG","LAB",yr)
```

*Capital supply from household, existing capital account, foreign region and some domestic production activities is up for domestic production and export in fixed proportions

```
$PROD:caps(yr)       t:1     s:1.5
o:px(t,yr)$fexprt("CAP",t)         q:fexprt("CAP",t)
o:rks(yr)                          q:(tkd/(1+tva0("CAP")))                p:((1+tva0("CAP")))
i:rk(yr)                          q:(fs("HHD","CAP")+fs("CORP","CAP")+fs("CAPA","CAP"))
a:gov("FG")       t:tva("FG","CAP",yr)          a:gov("SG")       t:tva("SG","CAP",yr)
i:px(t,yr)                         q:fimprt(t,"CAP")                                          a:gov("FG")
t:tva("FG","CAP",yr)          a:gov("SG")       t:tva("SG","CAP",yr)
```

*Capital accumulation

*Today's capital stock produces capital for today's production activities (capital rental) as well as capital used for tomorrow

*Capital used for tomorrow is calculated by subtracting the depreciated part of capital from today's stock

*The quantity of capital rental adds a coefficient rk0 because this is needed for correct calibration-now rk(yr) takes on the default value of 1 as every other price;

*otherwise we have to specify rk(yr) as delta and then change all the quantity of capital used for production

*Capital update between periods is never entirely at equilibrium. There is always a marginal of 0.001. Same case with capital purchase price.

*My suspicion is that this is because in the SAM the capital account is the least balanced of all, with total saving slightly lower than investment.

```
$PROD:ka(yr)
o:pk(yr+1)      q:(k0*(1-delta))
o:pkt$yrlast(yr) q:(k0*(1-delta))
o:rk(yr)        q:(k0*rk0)
o:pka(yr)       q:(k0*pka0)
```

```
i:pk(yr)        q:k0

*Capital investment comes from commodities sold in the domestic market (Armington
composite).
*Some of the capital investment is directly up for sale, turning into capital account institutional
income. The rest turns in to capital for next year
*Multi-layer nested structure requires clearly defining elasticities
*s: elasticity between net investment and adjustment cost. Should be set to zero
*ax1: elasticity between domestic and foreign investment
*adj: adjustment cost. We are putting two terms here, one is the actual adjustment input, the other
is the artificially defined adjustment premium.
*These two always equal each other, meaning that the elasticity should be 1
*ax2: the adjustment cost that arises from using foreign investment and local investment.
Elasticity should be the same as ax1
$PROD:ivst(yr)   s:0     ax1:0.1    adj:1        ax2(adj):0.1   t:0.2     capi:0      ncap:0
o:pk(yr+1)                        q:ivst0    capi:
o:pkt$yrlast(yr)                    q:ivst0    capi:
o:pins(c,yr)$(imake("CAPA",c))       q:imake("CAPA",c)  ncap:
o:px(t,yr)                         q:capaexprt(t)     ncap:
i:pa(c,yr)                         q:iuse(c,"CAPA")   ax1:
i:px(t,yr)                         q:capaimprt(t)     ax1:
i:pka(yr)                          q:(ivst0*phi*delta/2)      adj:
i:pa(c,yr)                         q:((iuse(c,"CAPA")-imake("CAPA",c))*phi*delta/2)      ax2:
i:px(t,yr)                         q:((capaimprt(t)-capaexprt(t))*phi*delta/2)          ax2:

*Household intertemporal utility
$PROD:uhhd       s:esub_t
o:puhhd                  q:uhhd0
i:phc(yr)              q:thc          p:pref(yr)
```

```
*Household consumption consists of energy and non-energy goods and services, and public
goods provided by the government
*Direct imports are considered a transfer in the demand module
*Capital adjustment cost needs to be subtracted from household consumption
$PROD:hc(yr)      s:0.5      en:1     nen:1
o:phc(yr)                    q:thc
i:pa(ec,yr)$(iuse(ec,"HHD")-((iuse(ec,"CAPA")-imake("CAPA",ec))*phi*delta/2))
q:(iuse(ec,"HHD")-((iuse(ec,"CAPA")-imake("CAPA",ec))*phi*delta/2))      en:
i:pa(nec,yr)$(iuse(nec,"HHD")-((iuse(nec,"CAPA")-imake("CAPA",nec))*phi*delta/2))
q:(iuse(nec,"HHD")-((iuse(nec,"CAPA")-imake("CAPA",nec))*phi*delta/2))      nen:
*i:vpg(go,yr)                  q:pgprov(go)

*Government intertemporal utility
*$PROD:ugov(go)     s:esub_t
*o:pugov(go)              q:ugov0(go)
*i:pgc(yr)              q:pgprov(go)       p:pref(yr)

*Government consumption consists of energy and non-energy goods and services
*Direct import from trading regions is considered a transfer in the demand module
$PROD:gc(go,yr)    s:0.5        en:1     nen:1
o:pgc(go,yr)              q:pgprov(go)
i:pa(ec,yr)               q:iuse(ec,go)        en:
i:pa(nec,yr)$iuse(nec,go)      q:iuse(nec,go)        nen:


*Household income and expenditure
*Public goods provided by the government is treated as an endowment
```

*Household is actually the combination of the household account and enterprise account from the SAM. Therefore, enterprise dividend does not have to be specified.
*Government transfer is the net transfer from government to household and enterprise in total.
*Saving is implicit through the household's intertemporal consumption choices.

```
$DEMAND:rah
d:puhhd        q:khhd0                          !Intertemporal utility from consumption
e:pk(yrfirst)  q:k0                             !Household initial endowment of capital
*e:pkt         q:(-1)     r:tk
e:pkt          q:(-(ivst0+(1-delta)*k0))   r:tk
e:pl(yr)       q:(fs("HHD","LAB")/(1-u0))
e:pl(yr)       q:((-fs("HHD","LAB")/(1-u0))*0.102)
*r:u("0")                                       !u("0") should be u(yr) in later iterations
e:pins(c,yr)$(sum(i,imake(i,c)))     q:imake("HHD",c)     !Institutioinal income
e:px(t,yr)     q:(hexprt(t)-himprt(t))          !Foreign transfer
e:px(t,yr)     q:((capaimprt(t)-capaexprt(t))*phi*delta/2)     !Need an endowment of foreign
*e:vpg(go,yr)    q:pgprov(go)     r:lgp(go,yr)      !Household valuation of public goods
e:pgc(go,yr)     q:(-htax(go)-cptax(go))
*r:dtax(go,yr)
e:ptrans(go,yr)    q:(hg(go)+cpg(go))
e:pgsav(go,yr)     q:(gsav(go)-capag(go))             !Government saving modeled as an
artificial endowment of household so that total saving will be implicit in the long run
```

*Government income and expenditure
*Factor tax is transferd to the government in the background, thus does not have to be specified in the government's demand function (MPSGE model M34)
*Government transfer is artificially defined as a good (ptrans) demanded by the government. The quantity is the total amount of transfer

```
$DEMAND:gov("FG")
```

*d:pugov("FG") q:ugov0("FG") !Demand for public goods and services

d:pgc("FG",yr) q:pgprov("FG") p:pref(yr)

d:ptrans("FG",yr) q:(hg("FG")+cpg("FG")+g2g("SG","FG"))

p:pref(yr) !Government net transfer to other institutions

d:pgsav("FG",yr) q:(gsav("FG")-capag("FG"))

p:pref(yr) !Government saving defined explicitly to balance account

e:pgc("FG",yr) q:(htax("FG")+cptax("FG"))

*r:dtax("FG",yr) !Direct tax

e:pins(c,yr)$(sum(i,imake(i,c)))

q:imake("FG",c) !Institutional commodity sale income

e:ptrans("SG",yr) q:g2g("FG","SG") !Transfer from local government to federal government

e:px(t,yr) q:(fgexprt(t)-fgimprt(t)) !Foreign transfer to government; Government deficit assumed fixed

*Assuming that the domestic government has a fixed endowment of foreign exchange is the way to model deficit.

*We can think of this as the foreign borrowing in the initial benchmark equilibrium. Government deficit is

*fixed here to produce more easily interpreted welfare results

$DEMAND:gov("SG")

*d:pugov("SG") q:ugov0("SG") !Demand for public goods and services

d:pgc("SG",yr) q:pgprov("SG") p:pref(yr)

d:ptrans("SG",yr) q:(hg("SG")+cpg("SG")+g2g("FG","SG"))

p:pref(yr) !Government net transfer to other institutions d:pgsav("SG",yr) q:(gsav("SG")-capag("SG"))

p:pref(yr) !Government saving defined explicitly to balance account

e:pgc("SG",yr) q:(htax("SG")+cptax("SG"))

*r:dtax("SG",yr) !Direct tax

e:pins(c,yr)$(sum(i,imake(i,c)))

q:imake("SG",c) !Institutional commodity sale income

e:ptrans("FG",yr) q:g2g("SG","FG") !Transfer from local government to federal government

e:px(t,yr) q:(sgexprt(t)-sgimprt(t)) !Foreign transfer to government; Government deficit assumed fixed

*pxy really is just a hypothetical agent to assign the additional structural adjustment cost. It does not interact with other agents in this model nor does its behavior

*affect anything. However, since it is declared, it has to be modeled. So we model it, but keeping basically everything as one so it does not affect anything.

$DEMAND:pxy

d:pa(nec,yr) q:1

e:pa(nec,yr) q:1

$Report:

v:localprod(a,yr) o:py(a,yr) prod:y(a,yr) !Local sectoral production

v:armq(c,yr) o:pa(c,yr) prod:agi(c,yr) !Armington quantity in the market

v:armlocal(c,yr) i:pd(c,yr) prod:agi(c,yr) !Domestic production as local supply

v:enforprod(a,yr) o:pen(a,yr) prod:tec(a,yr) !Total energy used for production activities

v:elec4p(a,yr) i:pa("EELEC-C",yr) prod:tec(a,yr) !Electricity used for production activities

v:oil4p(a,yr) i:pa("EOIL-C",yr) prod:tec(a,yr) !Oil used for production activities

v:gas4p(a,yr) i:pa("EGAS-C",yr) prod:noil(a,yr) !Gas used for production activities
v:coal4p(a,yr) i:pa("ECOAL-C",yr) prod:noil(a,yr) !Coal used for production activities
v:ne4hhd(nec,yr) i:pa(nec,yr) prod:hc(yr) !Household non-energy commodity consumption
v:e4hhd(ec,yr) i:pa(ec,yr) prod:hc(yr) !Household energy consumption

*Define an index of total absorption based on value of market supply at base year prices
*$CONSTRAINT:totabs(yr)
*totabs(yr)=e=sum(c,agi(c,yr)*dod(c))/sum(c,dod(c));

*Index of the level of direct tax
*Assume that government savings are fixed and direct tax rates adjust proportionally to total adsorption which reflects private saving and investment
*$CONSTRAINT:dtax(go,yr)
*gc(go,yr)=e=totabs(yr);

$CONSTRAINT:sac(nec,a)
sac(nec,a)=e=0;
*Later iterations: sac(nec,a)=e=(lamda*pa(nec)/phy(nec,a)*(y(a)*ileon(nec,a)-use(nec,a,yr-1))^2)/use(nec,a);
*Structural equation cost equals lamda * (price of nac) / proximity * (square of the change in intermediate use)
*ileon(nec,a) is the inverse of Leontief coefficient which equals quantity of nec divided by total production of sector a

*neuse(nec, a) should be the quantity used in the last period. Therefore there should be a time index

*y(a)*ileon(nec,a)-neuse(nec,a,yr-1) is the amount of change in intermediate use. Structural adjustment cost is proportional to the square of this change

*sac is only useful in re-establishing the equilibrium between periods

*$CONSTRAINT:u(yr)

*The function below should be the correct constraint. Use later.

*pl=g=phc;

*$CONSTRAINT:lgp(go,yr)

*lgp(go,yr)=e=gc(go,yr);

*Government provision of public good is considered a product demanded by the government (pgc).

*Consumer valuation of public good is declared a separate product (vpg) both consumed by and endowed to the consumer.

*Each consumer's endowment of public good is equal to the government's provision. This is achieved through using the constraint lgp.

*This way of modeling public good provision is especially helpful when there are multiple heterogeneous consumers. However, we still use it here for furture convenience.

$CONSTRAINT:tk

*sum(yr$yrlast(yr), ivst(yr)/ivst(yr-1)-y("CROP-A",yr)/y("CROP-A",yr-1))=e=0;

*Use multiplication instead of division to avoid the denominator being zero

sum(yr$yrlast(yr), ivst(yr)*y("CROP-A",yr-1)-ivst(yr-1)*y("CROP-A",yr))=e=0;

$OFFTEXT

$SYSINCLUDE mpsgeset Georgia_2010

```
*Use foreign currency as numeraire
*px.fx("FT",yr)=pref(yr);

*Benchmark replication
*Use consumer consumption as the numeraire
*phc.fx=1;

*Set bounds for auxiliary variables. Otherwise the model won't solve (infeasibility)
*totabs.lo(yr)=-inf;
*dtax.lo(go,yr)=-inf;
tk.lo=-inf;
*lgp.lo(go,yr)=-inf;
ivst.lo(yr)=-inf;

*Declare activity levels
*totabs.l(yr)=1;
*dtax.l(go,yr)=1;
*tk.l=k0*1** card(yr);
tk.l=1** card(yr);
*lgp.l(go,yr)=1;

*Declare price levels that are not initially 1. They don't need to be fixed, just an initial value
pls.l(yr)=wl("2010")*(1+tva0("LAB"))*pref(yr);
pl.l(yr)=wl("2010")*pref(yr);
rks.l(yr)=(1+tva0("CAP"))*pref(yr);
rk.l(yr)=pref(yr);
pk.l(yr)=pk0*pref(yr);
pkt.l=sum(yrlast,pk.l(yrlast)/(1+ir));
```

```
pd.l(c,yr)$(sum(a,make(a,c))+sum(i,imake(i,c))-sum(t,cexprt(c,t))>0)=pref(yr);

pd.l(c,yr)$(sum(a,make(a,c))+sum(i,imake(i,c))-sum(t,cexprt(c,t))<=0)=0;

pins.l(c,yr)$(sum(i,imake(i,c)))=pref(yr);

pins.l(c,yr)$(not sum(i,imake(i,c)))=0;

py.l(a,yr)=pref(yr);

pi.l(a,yr)$(sum(c,use(c,a)))=pref(yr);

pi.l(a,yr)$(not sum(c,use(c,a)))=0;

pen.l(a,yr)=pref(yr);

pa.l(c,yr)=pref(yr);

pnoil.l(a,yr)=pref(yr);

px.l(t,yr)=pref(yr);

phc.l(yr)=pref(yr);

pgc.l(go,yr)=pref(yr);

*vpg.l(go,yr)=pref(yr);

ptrans.l(go,yr)=pref(yr);

pgsav.l(go,yr)=pref(yr);

pkt.l=sum(yrlast,pk.l(yrlast)/(1+ir));

pka.l(yr)=pref(yr)$phi;



Georgia_2010.workfactor=50;


*Setting phi and xkshr to zero, and recalculating delta w/o phi would make the benchmark
scenario balanced. Otherwise it will not balance
*Benchmark replication
Georgia_2010.ITERLIM=0;


$INCLUDE Georgia_2010.gen
```

```
SOLVE Georgia_2010 USING MCP;
option decimals=5;


Georgia_2010.ITERLIM=1000000;
*Set time limit in seconds. Need to make it large enough.
Georgia_2010.reslim=1000000;


*Shock are applied here
*pen0=0.90;
*pen.l(yr)=0.90*pref(yr);

eff(a)=0.9;


$INCLUDE Georgia_2010.gen


SOLVE Georgia_2010 USING MCP;
option decimals=5;

*=========================
*REPORTING
*=========================

PARAMETERS
GDP0(yr)        Gross domestic product before shock
```

GDP(yr)   Gross domesitic product after shock

gGDP(yr)   Percentage GDP change induced by shock

ghhdc(yr)   Percentage change in household consumption induced by shock

ginv(yr)   Percentage change in capital investment

price(c,yr)   Local Armington price levels after shock

pchange(c,yr)   Percentage local Armington price change after shock

qlocal(a,yr)   Local production quantity after shock

gqlocal(a,yr)   Percentage local production quantity change after shock

qarm(c,yr)   Local Armington quantity after shock

gqarm(c,yr)   Percentage Armington quantity change after shock

sge4p(a,yr)   Percentage change in energy used for sectoral local production

ge4p(yr)   Percentage change in total energy use for local production

gearm(yr)   Percentage change in total local energy use

qenorb   Energy consumption quantity without rebound effect after shock

actenorb   Energy consumption activity level without rebound effect after shock

reboundq   Rebound effect in terms of energy quantity (%)

reboundsp   Rebound effect in terms of energy spending (%);

*To calculate GDP, assume price level for each product remains constant after shock. This is because GDP needs to be measured based on world market price

*which is unaffected by local changes.

GDP0(yr)=sum(a,(sum(c,pref(yr)*make(a,c))))+sum(a,(1+tva0("CAP"))*pref(yr)*fgen(a,"CAP")
);

GDP(yr)=sum(a,pref(yr)*(sum(c,(make(a,c))))*y.l(a,yr))+sum(a,(1+tva0("CAP"))*pref(yr)*fgen(
a,"CAP")*y.l(a,yr));

*Important price levels after shock

price(c,yr)=pa.l(c,yr);

pchange(c,yr)=(pa.l(c,yr)-pref(yr))/pref(yr)*100;

```
*Important quantity levels after shock
qlocal(a,yr)=(sum(c,(make(a,c))))*y.l(a,yr);
qarm(c,yr)=dod(c)*agi.l(c,yr);

*Important percentage changes after shock
gGDP(yr)=(GDP(yr)-GDP0(yr))/GDP0(yr)*100;
ghhdc(yr)=(hc.l(yr)-1)*100;
ginv(yr)=(ivst.l(yr)-1)*100;
gqlocal(a,yr)=(y.l(a,yr)-1)*100;
gqarm(c,yr)=(agi.l(c,yr)-1)*100;
sge4p(a,yr)=(tec.l(a,yr)-1)*100;
ge4p(yr)=(sum(a,tec.l(a,yr)*(sum(ec,use(ec,a))))/(sum((ec,a),use(ec,a)))-1)*100;
gearm(yr)=((sum(ec,agi.l(ec,yr)*dod(ec)))/(sum(ec,dod(ec)))-1)*100;

*Energy consumption quantity without rebound effect after shock
qenorb(ec)=sum(a,eff(a)*use(ec,a))+sum(i,iuse(ec,i));
qenorb("Total energy")=sum(ec,qenorb(ec));
actenorb(ec)=qenorb(ec)/dod(ec);
actenorb("Total energy")=qenorb("Total energy")/sum(ec,dod(ec));

*Important rebound percentages
reboundq(ec,yr)=((1-actenorb(ec))-(1-agi.l(ec,yr)))/(1-actenorb(ec))*100;
reboundsp(ec,yr)=((1-actenorb(ec))-(1-agi.l(ec,yr)*pa.l(ec,yr)/pref(yr)))/(1-actenorb(ec))*100;
reboundsp("Total energy",yr)=((1-actenorb("Total energy"))-(sum(ec,dod(ec))-
(sum(ec,agi.l(ec,yr)*pa.l(ec,yr)/pref(yr)*dod(ec))))/sum(ec,dod(ec)))/(1-actenorb("Total
energy"))*100;
```

```
display
GDP0,GDP,price,pchange,qlocal,qarm,gGDP,ghhdc,ginv,gqlocal,gqarm,sge4p,ge4p,gearm,qenor
b,actenorb,reboundq,reboundsp;

*parameter price  Capital price and wage rate;
*price(yr,"RK")=rk.l(yr)/phc.l(yr);
*price(yr,"PK")=pk.l(yr)/((1+ir)*phc.l(yr));
*price(yr,"PL")=pl.l(yr)/phc.l(yr);

*display price;
```

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