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Regional energy rebound effect: The impact of economy-wide and sector level energy efficiency improvement in Georgia, USA

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HIGHLIGHTS

- We developed a CGE model to investigate economy-wide energy rebound in Georgia, USA.
- The CGE model has detailed treatment for different energy inputs for production.
- The model has a highly disaggregated sector profile helpful for policy making.
- We compared the economy-wide impact shocks in different epicenter sectors.
- We analyzed why epicenters generate dramatically different economy-wide impacts.

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ABSTRACT

Rebound effect is defined as the lost part of *ceteris paribus* energy savings from improvements on energy efficiency. In this paper, we investigate economy-wide energy rebound effects by developing 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 us 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 economic structure to generate aggregate impacts. We find that with economy-wide energy efficiency improvement on the production side, economy-wide rebound is moderate. 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 particular sectors (epicenters) induce quite different economy-wide impacts. In general, we expect large 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. Our analysis offers valuable insights for policy makers aiming to achieve energy conservation through increasing energy efficiency.

1. Introduction

With the International Energy Agency (IEA) projecting global energy demand to grow by 37% by 2040 (International Energy Agency, 2014), energy conservation is more imperative than ever. While national and regional governments increasingly resort to energy efficiency improvement to save energy, their good intentions do not guarantee reductions in energy consumption. For example, the U.S. Department of Energy is actively promoting energy-efficient light bulbs (U.S. Department of Energy, 2013), yet historical studies show that energy use for lighting has increased with every lighting efficiency improvement (Tsao et al., 2010). 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 (Saunders, 2000a).

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

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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 not seem to align with each other.

In this study, we explore how sector-level energy efficiency improvement propagates its impact through the economic structure and generates economy-wide rebound. We develop a regional computable general equilibrium (CGE) model, with a detailed treatment of energy inputs in the production function, and a highly disaggregated sector profile incorporating 69 sectors. The first feature allows us to explore fuel substitution in detail as energy efficiency and sector price levels change. The second feature allows us to trace energy and economic changes to more micro scales. Applying the model to Georgia, USA, we 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. It is noteworthy that in reality, energy efficiency improvement does not happen instantaneously. The energy efficiency "shocks" we apply to the economy are indeed counterfactual scenarios of one-time external disturbance. These scenarios facilitate the investigation of the fundamental driving forces and mechanisms behind the rebound effect. Therefore, we follow the tradition in the CGE literature, and adopt the term "shock" in referring to these counterfactual simulation scenarios.

Our study builds upon existing theoretical literature on energy rebound effects. The notion of rebound started with Jevons (1906) in the discussion on UK's coal consumption. Yet complete rebound theories were established by modern economists including Khazzoom (1980), Brookes (1990) and Saunders (2000a, 2000b, 2008). Borenstein (2015) 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 (Berkhout et al., 2000). 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 (Frondel et al., 2012; Lin and Li, 2014; Su, 2012; Vivanco et al., 2014; Wang and Lu, 2014; Wolfe, 2012). At the higher macroeconomic level, Howells et al. (2010) 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. (2000) investigated multiple single-sector shock scenarios for the Netherlands' rebound effects, but only for a six-commodity case. Schipper and Grubb (2000) 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 (Allan et al., 2007; Hanley et al., 2009; Hanley et al., 2006; Turner and Hanley, 2011) did use a 25-sector industry profile, but the analysis was still based upon general technological change that increases economy-wide energy efficiency. Saunders (2013) 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. Our sector-level simulations 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. In addition, being conducted at the regional level, it can potentially highlight the different behavior of the same sector under the same shock for different regions. This would free policy makers from having to use national-level results for regional-level questions.

The rest of the paper is organized as follows. In section two, we introduce how we calculate economy-wide rebound effects. We 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 three, we analyze the impact of both economy-wide and sector-specific energy efficiency improvement on regional energy use and key economic indicators. We then focus on sectors with highly heterogeneous impacts, and explore how sector-level efficiency shocks propagate through the economic structure and generate aggregate impacts. We conclude and discuss policy implications in section four.

2. Methods

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, we 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 the price of energy services, 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.

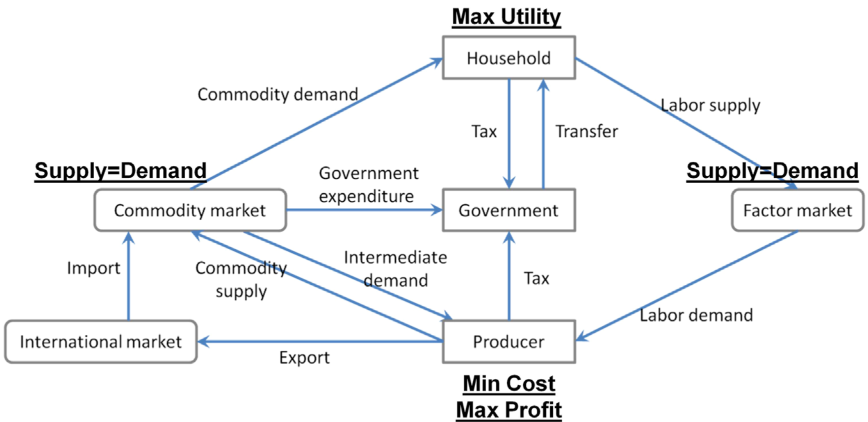

Fig. 1. Interactions between agents in a CGE model.

2.2. The computable general equilibrium (CGE) framework

Computable general equilibrium (CGE) modeling has proved suitable for economic and environmental policy appraisal because of its theoretical foundation and modeling structure (Böhringer and Löschel, 2006; Partridge and Rickman, 1998, 2008; Sjöström and Östblom, 2010). On the 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 (Sorrell, 2009; Sorrell et al., 2009) and should be able to indicate the approximate magnitude of regional-level rebound effects.

Fig. 1 displays 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 (supply equals demand), the model is said to have reached general equilibrium.

In building and working with a CGE model, we first choose agents' behavioral functions and market clearing criteria, 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.

2.3. Model description

Here we develop a regional CGE model (refer to Supplementary information A(S1) for condensed mathematical formulations) to systematically evaluate the impacts of technological change that increases energy efficiency at the sector level. Regarding the market structure, we 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. With our assumption of exogenous transactors, it is important to note that all the results regarding energy rebound effects and sectors' price elasticities are specific to Georgia, and that these numbers should not be directly applied to other regions, the national economy and the international economy. 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 (Armington, 2003). Locally produced goods are used for local consumption and export. We treat this choice as a production possibility frontier represented by a constant elasticity of transformation (CET) function. Relevant to our 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.

Production takes on a multi-level nested structure (Fig. 2). Since we are interested in how the industrial structure transforms under technological change that increases energy efficiency, we 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 (Truong, 2007). Other nested levels also adopt convenient functional forms such as CES and Leontief.

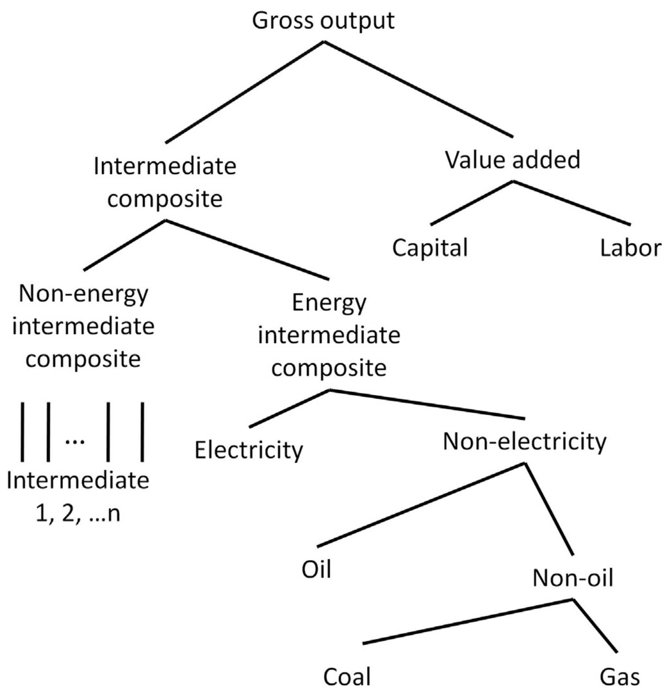

Fig. 2. Nested production structure with a detailed treatment of energy intermediate.

Understanding the way we introduce energy in the production structure is crucial for the evaluation of our results. We 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 (Lecca et al., 2011), we adopt the approach used by Hanley et al. (2009), 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 (Turner, 2009). We identify energy intermediates as the final product of the following sectors: electricity generation, transmission and distribution; petroleum refining (termed later in the text as oil production); coal mining; natural gas distribution. Similarly, non-energy intermediates always come from sector-level final products. For treatment of non-energy intermediates, we 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, we have chosen a highly disaggregated sector profile. While existing CGE studies hardly break down the economy into more than 20 sectors, we run the model with 69 sectors (refer to Supplementary information A (S2) for the list of sectors and corresponding NAICS codes). We design the sector profile at such a disaggregated level to ensure enough detail in the industrial network structure. This in turn allows us 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. We 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 Supplementary information A (S3) 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, we 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) (Inc., 2012) 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, we have chosen important elasticity parameters either based on econometric studies or existing CGE models. A complete list of parameter choices is available in Supplementary information A(S4).

2.4. Simulation scenarios

For the numerical simulations, we assume an exogenous energy efficiency improvement occurs either 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.

We consider two simulation scenarios. First, we 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, we consider energy efficiency improvement in individual sectors (epicenters). This allows us to compare the impacts of different sectors on aggregate economic outcome as well as on other sectors. We then identify relevant sectors that we can use to explore how epicenters' activity propagates through the economic structure.

These simulations, along with the design of the model structure, can potentially help researchers observe how the same sector behaves differently in different regions, and how different regions respond differently to the same shock. Above all, we would expect that the same sector should behave differently between a regional and a national context. Simulating energy efficiency improvement in individual epicenters provides information on the magnitude of this difference and how it arises. Moreover, the CGE model is designed in a way that facilitates region-wise comparison. If a researcher is interested in a region other than Georgia, she can easily calibrate the model to the other region without having to modify the model structure. This allows the comparison of the behavior of the same sector between the other region and Georgia, as well as between the other region and the national economy.

3. Results and discussion

We 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) (2015). 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.

We 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 we disaggregate the economy into 69 sectors (refer to Supplementary information A (S2) for sector profile), we run 69 simulations for the second type, improving energy efficiency in only 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 us to investigate how the impact of small idiosyncratic shocks propagates through the economic structure.

We run the simulation over 10 periods, with each period representing one year. In the discussions below, we 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 and that product quantities and prices no longer change between two consecutive years. 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.

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 (Fig. 3). Given a 10% economy-wide shock in energy efficiency for production activities, total energy used for production reduces by 8.51%, which is less than 10%. This indicates that energy rebound does exist on the order of 15% for production, and it is much less than 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.

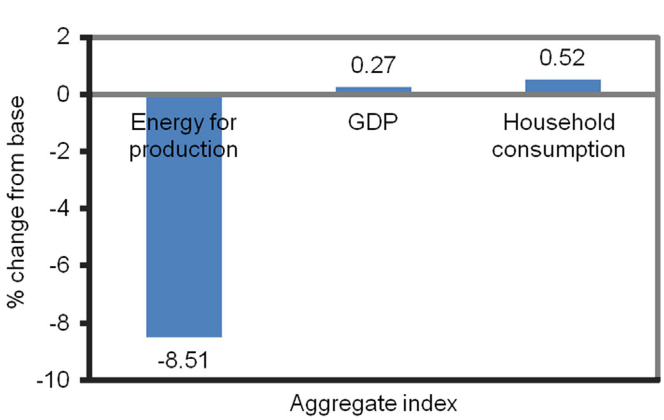

Fig. 3. Aggregate economic changes induced by 10% economy-wide increased energy efficiency for production.

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.

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 Supplementary information A (S5) for Georgia's energy spending composition). Therefore, we have found energy product cost data from other sources (refer to Supplementary information A (S6) for cost coefficient values and data sources), and have converted economy-wide spending on energy to energy quantity. Fig. 4 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.

We 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, our estimates are lower than a previous study on industrial energy use efficiency for the United Kingdom by Allan et al. (2007), who identify rebound effects of the order of 30% to 50%. Still, our results echo recent theoretical analysis in supporting low to moderate rebound (Borenstein, 2015; Sorrell and Dimitropoulos, 2008).

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 less than 0.77% and 0.75%, respectively. Fig. 5 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, Fig. 5). 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 (Path ACL). However, energy price reduction induces end-use consumers to increase energy consumption (Path LJ). It also causes producers to substitute energy for other production factors (Path LK). These effects drive up energy demand and keep energy prices from falling (Path JM, Path KJM). Another direct effect of increased energy efficiency is reduced final commodity prices from various sectors (Path AD). As locally produced commodities become cheaper, local demand (Path DFH, Path DGH) as well as export demand for these commodities increases (Path 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

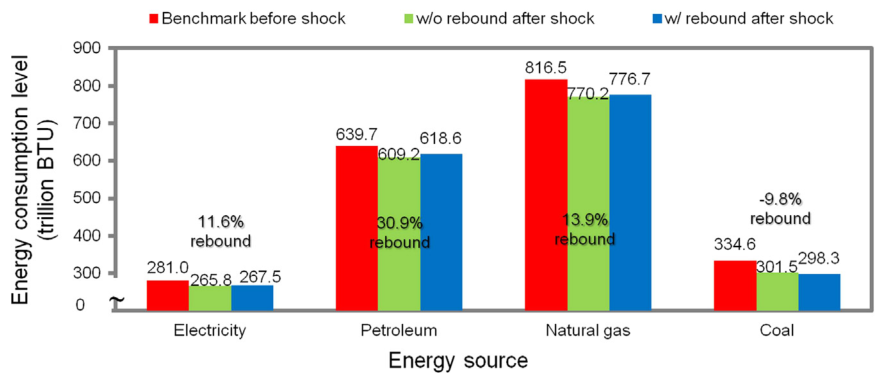

Fig. 4. Rebound effect by energy sources.

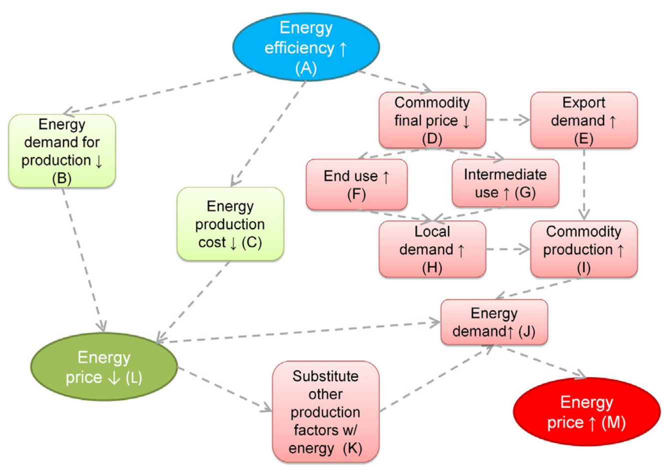

Fig. 5. Factors affecting local energy prices.

falling (Path IJM).

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 (Fig. 6(a)). As with local market prices, all commodity prices fall because of reduced production costs. Sectors affected most heavily are air transportation, further processing of petroleum product, pipeline transportation, paper manufacturing and nonmetallic mineral product manufacturing (Fig. 6(b)). Still, local production structure adjusts differently from local demand. Further processing of petroleum product grows by over 14%, far exceeding other sectors. Nevertheless, the sector's small size to begin with makes it quite trivial to the economy's production structure even after the considerable percentage growth. 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 (Fig. 6(c)).

We carried out sensitivity analysis by varying the values of several important parameters. 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. We find that simulation results do not change significantly when the above parameters vary, and the directions of these changes are consistent with our expectations. For example, as the elasticity between value-added and intermediate inputs increases from 0.5 in the central scenario to 0.7, the economy gains more structural flexibility. This is because it is easier to substitute between value-added and intermediate inputs 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 higher GDP and consumption growth, energy use must increase compared with the central scenario, thus the larger rebound effects. However, between low (0.3), central (0.5) and high (0.7) elasticity values, the change in key economic and energy indicators are not large. Specifically, regional GDP growth rate increases from 0.20% to 0.27% then to 0.34%; non-electricity rebound increases from 22.15% to 24.75% then to 27.35%; Electricity rebound increases from 10.01% to 11.58% then to 13.15%. The impact of elasticity is even further minimized at lower levels of the production structure, specifically between energy and non-energy intermediates, and between different energy inputs. 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. Detailed sensitivity analysis of model results from varying the above parameters is available in Supplementary information A (S7).

With the economy-wide efficiency shock on the production side, we 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, we compare the economy-wide impacts induced by energy efficiency improvement in individual sectors.

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, we 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 the shock at the epicenter, the CGE model calculates change in various indicators including regional GDP, household

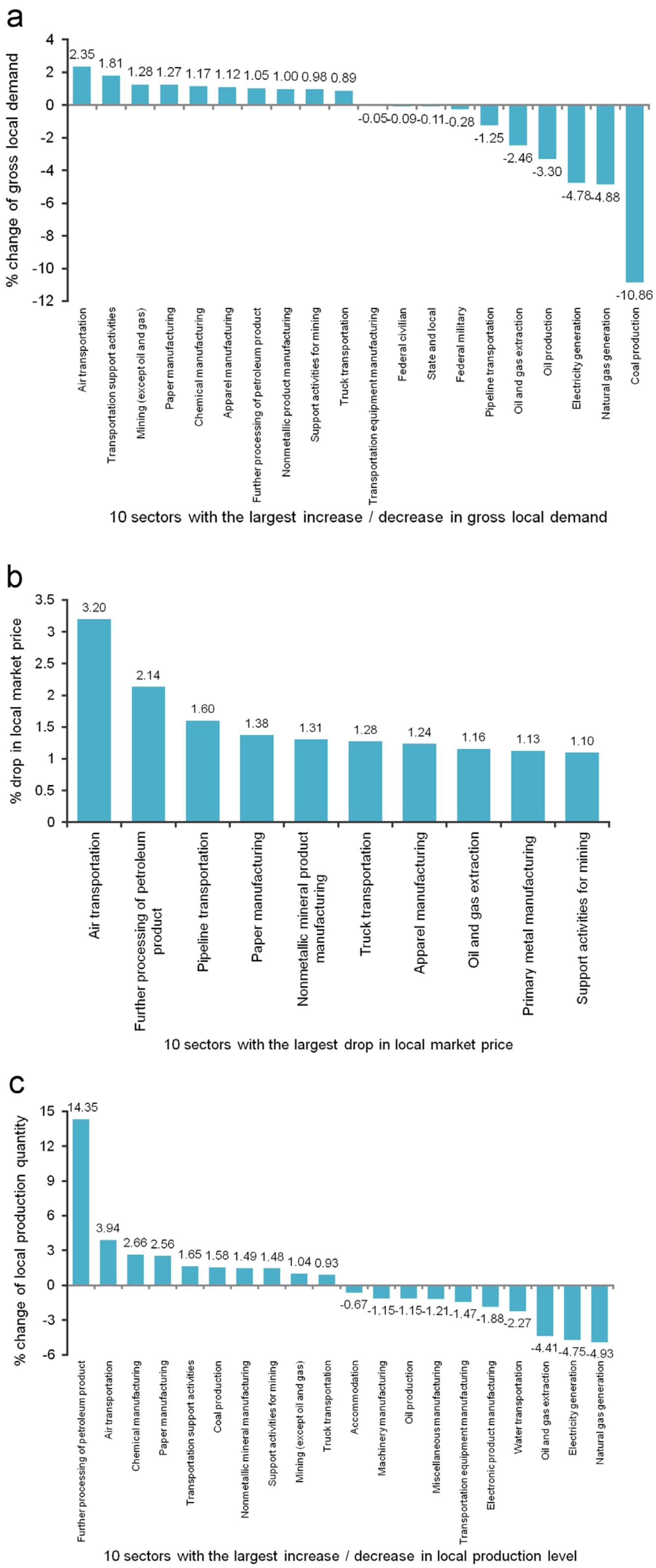

Fig. 6. Impact on local sectoral markets. (a) Sector with the largest increase/decrease in local demand; (b) Sectors with the largest drop in local market price; (c) Sectors with the largest increase/decrease in local production.

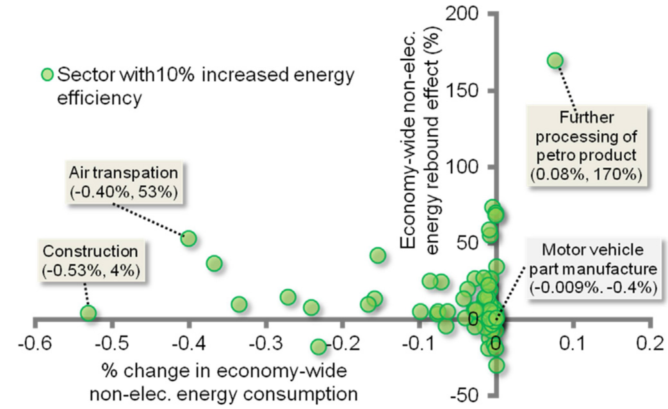

Fig. 7. Economy-wide non-electricity rebound and energy use reduction generated by 10% increased energy efficiency in individual sectors.

consumption, energy spending, as well as sector level price, local demand and local production level. We 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 us to single out the impact of every individual sector as the epicenter sector, and to identify sectors with large economy-wide implications (refer to Supplementary information B for complete data on sector economic output, energy consumption and impact on regional GDP, household consumption, economy-wide energy use and rebound effect). We 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. We plot economy-wide rebound effect against percentage change in economy-wide non-electricity energy use for all 69 epicenter sectors (Fig. 7). 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, we are most interested in those few very distinct sectors that are able to affect the whole economy. First, we 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, we 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.

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, we select three distinct sectors to analyze their impact on energy and economic indicators in greater detail.

3.3. Simulation scenario case studies

We choose three very 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 further processing of petroleum product (small reduction in energy use, large rebound). We 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 Fig. 7). We 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.

3.3.1. 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 (0.02%, Ranking No. 4) and household consumption (0.02%, 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 (Fig. 5, 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 (Fig. 5, Path ADG). In other words, the sector's structural influence is limited (Acemoglu et al., 2015). 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.

3.3.2. Air transportation

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 69 simulations with different epicenter sectors. 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 oil 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.

3.3.3. Further processing of petroleum product

Further processing of petroleum product 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 further processing of petroleum product 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 further processing of petroleum product is the most energy-intensive sector, thus more responsive to energy efficiency shocks.

Further processing of petroleum product is a manufacturing industry that further processes refined petroleum, such as the production of lubricating oils. Specific to Georgia's economy, the sector has the following key features: 1) it has very high own price elasticity; 2) it is a direct downstream sector of petroleum refining (this is our defined oil production sector); and 3) it is one of the smallest sectors in Georgia's economy. Regarding the first feature, 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. It also forms a sharp contrast with the elasticity of the petroleum refining sector, which is our defined oil production sector. Indeed, elasticity for oil production in Georgia stands at 0.73. Regarding the second feature, further processing of petroleum product 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.

Regarding the third feature, further processing of petroleum product does not have a strong influence on other sectors because of its small size, 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 further processing of petroleum product induces a huge rebound effect, gross impact on economy-wide energy use remains relatively small.

3.3.4. Summary

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. Further processing of petroleum product takes a small share in Georgia's economic output. Yet due to its heavy interconnection with an energy production sector, further processing of petroleum product, as an epicenter, has the potential to induce backfire in energy use.

It is important to note again that these results are specific to Georgia's economy, and cannot be directly used to explain the behavior of the same sector in other regions or at the national level. Nevertheless, methodology can be easily replicated to investigate other regions of interest, and the analysis of the fundamental mechanism that results in these sectoral behaviors remains valid in a broader sense. For instance, if another region has a sector that is small in size but with intensive energy consumption or heavily interconnected with energy production sectors, it can behave quite similarly to the further processing of petroleum product sector in Georgia. This means that it would be potentially sensitive to increased energy efficiency, while still remaining small relative to the size of the regional economy.

4. Conclusions and policy implications

In this paper, we investigate energy rebound effects at the regional level. By looking into both economy-wide and sector-specific energy efficiency improvement, we 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 considered 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. Our 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.

The design of the CGE model and the simulation scenarios build a solid foundation for cross-region comparative studies. While it is widely recognized that regional economies behave differently from the national economy and from each other, our analysis further allows researchers and policy makers to identify the magnitude and the structural cause of these differences. First, region-specific energy rebound results and sectors' elasticity values can be compared to existing studies for the national economy level. Secondly, the model can be easily recalibrated to different regions to enable cross-region comparison, in terms of both energy use and sectoral behaviors. Nevertheless, we recognize the caveats in our work. First, we 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, our exercise could be easily modified to investigate changes in renewable energy consumption at both the aggregate and sector level. Second, our model has not considered population migration in the CGE model. Yet we are more interested in the economy's response in short-to-medium terms, during which population migration does not play an essential role. Still, our simulations 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, our model can also be applied to other regions and address a wide range of policy questions.

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Appendix A. Supplementary material

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