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Biomass to Electricity:
The Case of South Korea

Gal Hochman and Chrysostomos Tabakis

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Korea Development Institute
263, Namsejong-ro
Sejong-si, 30149, Korea

Contents

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Gal Hochman* and Chrysostomos Tabakis†

Abstract

In this report, we investigate the biomass-based electricity potential of South Korea and the ramifications of the introduction of biomass in electricity production for the Korean electricity market. The novelty of our study lies in that we consider a broad portfolio of biomass-energy technologies and carefully analyze their potential economic and environmental implications for South Korea given its biomass availability (which we actually estimate). To the best of our knowledge, this is the first study to attempt this in the context of South Korea. Our biomass assessment suggests that (theoretically) biomass can be used to produce a significant portion of the total electricity consumed annually in South Korea, with the most promising feedstock being forestry residues. And out of all the technologies considered, pyrolysis of forestry residues could potentially impact the electricity market the most.

*Rutgers University (gal.hochman@rutgers.edu)

†*Corresponding author:* KDI School of Public Policy and Management, 263 Namsejong-ro, Sejong-si 30149, Korea. Telephone: +82–44–550–1024. E-mail: ctabakis@kdischool.ac.kr.

1 Introduction

South Korea was the ninth-largest energy consumer in 2015 (BP, 2016). At the same time, it is also among the top energy importers in the world, importing about 98% of its fossil fuel consumption, and ranking among the top five countries globally in terms of imports of liquefied natural gas (LNG), coal, crude oil, and refined products. However, it does not have any international pipeline infrastructure and thereby imports of LNG and crude oil are exclusively delivered to the Korean market via tankers (U.S. Energy Information Administration, 2017).

South Korea has enjoyed remarkable economic growth and development during the past decades, which was fueled by rapidly increasing energy use (especially in the industrial and transportation sectors; Kim, Shin and Chung, 2011). In recent years, according to Kim, Shin and Chung (2011), a new energy policy paradigm has emerged in South Korea, mainly as a response to oil market instability, environmental concerns, as well as concerns about energy supply security. To better address these concerns, South Korea's energy policies have evolved, placing increased emphasis on energy efficiency, renewable energy, privatization of energy-sector activities, and the downscaling of greenhouse gas (GHG) emissions. Through much of its recent history though, its policies were supply-oriented, mainly aimed at safeguarding a stable energy supply at a low price level, while relying on central planning rather than on energy market forces. This high degree of intervention by the Korean government in the energy market can be contrasted with the U.S. experience in the electricity sector. As Ros (2015) argues, since the 1970s, one of the major developments in the electricity sector of the United States has been the development of wholesale and retail competition (along with substantial advances in generation technologies). Ros then examines the ramifications of retail competition for electricity prices, and finds—using panel data over the period 1972–2009—that retail electricity competition is associated with lower electricity prices for all customer classes (i.e., residential, commercial, and industrial customers).

Understanding energy systems and their complexity is of paramount importance for evidence-based energy policymaking. Jebaraj and Iniyan (2006) provide a thorough review of the different energy models and discuss the various emerging issues related to energy modeling. They argue that the econometric models reflect the aggregate characteristics of energy supply and consumption and their orientation is towards forecasting (being best suited to short- and medium-term forecasting). They also conclude that the energy–economy models can assist policymaking as they provide insights into the energy–economy interactions. On the other hand, Swan and Ugursal (2009) review a subset of these models. In particular, they restrict their attention to models on energy consumption in the residential sector, while distinguishing between two approaches: the top-down approach and the bottom-up approach. A major weakness of top-down models is that they provide a very coarse analysis. The bottom-up approach has weaknesses of its own: the bottom-up statistical models often encounter multicollinearity problems, while the bottom-up engineering models are computationally intensive and abstract from economic factors. Other authors focus on the crude oil and/or natural gas markets. For example, Krichene (2002) examines the world markets for crude oil and natural gas over the period 1918–1999. More specifically, Krichene analyzes a time series of crude oil and natural gas output and price data and estimates demand and supply elasticities during two periods: 1918–1973 and 1973–1999. The paper shows that following the oil shock in 1973, deep changes in the market structure took place, which can explain the oil and gas price volatility during 1973–1999 (in contrast to their relative stability over 1918–1973). Finally, in an interesting contribution to energy modeling, Canyurt, Ceylan, Ozturk and Hepbasli (2004) develop and employ two non-linear forms—exponential and quadratic—of the genetic algorithm energy demand model in order to estimate Turkey's future energy demand based on its gross domestic product (GDP), population, imports, and exports.

Given the large body of literature on energy supply and consumption, what can we say about the energy system in South Korea? As Kim, Shin and Chung (2011) argue, even though nuclear power will continue to play a crucial role in South Korea's energy mix, its aggressive expansion alone will not suffice for South Korea to achieve its "green economy" and GHG emission reduction goals. In fact, the Fukushima episode is likely to make such an expansion politically difficult. Hwang (2015) investigates the applicability of the Model for Analysis of Energy Demand (MAED)—created by the International Atomic Energy Agency—to energy demand forecasting by the local governments of South Korea. The MAED is a bottom-up, accounting model, which makes it less demanding than optimization-based or econometric models. Applying this model, Hwang makes projections for the energy demand of Seoul for the period 2015–2035. In addition, Hwang examines the sensitivity of energy demand in Seoul to various policy levers of the Seoul Metropolitan Government, such as the Building Retrofit Program and the plan for electric vehicles. On the other hand, using cointegration methods, Bae (2015) estimates the long-run energy demand function for the whole of South Korea, and then makes energy demand forecasts up to 2035. Bae finds that there is a cointegration relationship among per capita energy consumption, real GDP per capita, and the energy price index. Also, using dynamic ordinary least squares (DOLS), the elasticities with respect to real GDP per capita and the price of energy are estimated to be, respectively, 1.06 and –0.3. Moreover, demand forecasts based on the DOLS estimation are generally in line with the projections of South Korea's Second National Energy Plan. Lee and Shin (2011) focus on electricity demand. They present an electricity demand forecasting model that employs the variable selection or extraction methods of data mining to select relevant only input variables, and uses the support vector regression method for making accurate predictions. Using then monthly electricity demand data for South Korea over 2000–2008, they show that the prediction performance of their model is more promising as compared with that of other frequently used data-mining models. Finally, Shin, Jo and Kim (2015) analyze Korean final energy consumption volatility following an endogenous structural-break approach, and demonstrate that it fell by 50% after January 2002. In terms of energy consumption by sector, they find that the volatility of final energy consumption decreased for the transportation, commercial–household, and public sectors. On the other hand, in terms of energy consumption by source, the consumption volatility of petroleum declined, but the consumption volatility of coal and renewable energy increased. Regarding policy, an important implication that emerges from their results is that the enhancement of energy efficiency and the structural transition from an energy-intensive to an energy-efficient industry should be accelerated so that the stability of Korean energy consumption is preserved.

Other authors look at the Korean natural gas market. For instance, Lee, Euh and Yoo (2013) estimate—using ordinary least squares with lagged dependent variable—the city gas demand function for South Korea during the period 1981–2012. Its short-run own-price and income elasticities are estimated to be –0.522 and 0.874, respectively, implying that the demand for city gas is own-price and income inelastic in the short run. However, their findings reveal that in the long run, the city gas demand is both own-price and income elastic. Moreover, Kim, Yang and Park (2011) estimate the consumption function of natural gas for city gas employing a time-series model with time-varying coefficients. Interestingly, the estimated consumption function is both temperature and GDP elastic.

Last, Chung, Tohno and Shim (2009) follow an energy input–output (E-IO) approach to analyze energy consumption in South Korea. In particular, they construct a 96-by-96 hybrid E-IO table—consisting of 14 energy sectors and 82 non-energy sectors of the Korean economy—and use it to estimate the energy intensities and GHG emission intensities associated with energy use for each sector in the table. In terms of direct energy use, the average values of the direct energy intensity and GHG emission intensity of the 96 economic sectors are 0.186 ton of oil equivalent/million Korean Won and 0.315 t-CO_2-eq./million Korean Won, respectively. On the other hand, in terms of total energy use, the average values of the total (or embodied) energy intensity and GHG emission intensity of these sectors are estimated to be, respectively, 0.640 ton of oil equivalent/million Korean Won and 1.534 t-CO_2-eq./million Korean Won. An important lesson that arises for their work is the need to take into account simultaneously the energy intensity and GHG emission intensity of the different sectors in order to design better energy and environmental policies.

In this report, we investigate the biomass-based electricity potential of South Korea and the ramifications of the introduction of biomass in electricity production for the Korean electricity market. This is an important endeavor given the environmental and energy security concerns discussed above. The novelty of our study lies in that we consider a broad portfolio of biomass-energy technologies and carefully analyze their potential economic and environmental implications for South Korea given its biomass availability (which we actually estimate). To the best of our knowledge, this is the first study to attempt this in the context of South Korea. Furthermore, past literature on biomass-based electricity generation typically focuses on a narrower range of technologies and mostly provides an engineering perspective.

We first use data from the Korean Statistical Information Service (supplemented with data from other sources where necessary) to offer a preliminary assessment of the theoretical (i.e., upper-bound) biomass potential (from forestry residues, livestock manure, and staple crops) and of the amount of electricity that could be generated using different domestic biomass feedstocks. Our biomass assessment suggests that (theoretically) biomass can be used to produce a significant portion of the total electricity consumed annually in South Korea, with the most promising feedstock being forestry residues. And out of all the technologies considered, pyrolysis of forestry residues could potentially impact the electricity market the most.

Next, to address the uncertainty regarding our model's parameters, we resort to a Monte Carlo simulation. More specifically, we simulate different biomass-based electricity supply shocks, while randomly perturbing the demand and supply elasticities (separately). Our analysis illustrates that the introduction of biomass feedstock in electricity production leads to an increase in the total amount of electricity consumed and a decrease in the market price of electricity. As a result, an environmentally detrimental rebound effect arises, whereby fossil-based electricity generation declines by less than the biomass-based electricity supply shock simulated. For example, when perturbing the demand elasticity and under an ambitious scenario of a 25% biomass-based electricity supply shock, fossil-based electricity generation declines by only 10.6% on average, implying a 57.6% rebound effect. Still, though, CO_2 emissions could be mitigated by up to 94 million tonnes in the most favorable (environmentally) biomass-technology scenario considered. And aggregate welfare in the economy does rise.

The next section presents a simple conceptual framework for our study. Section 3 offers a biomass assessment for biomass-based electricity production and describes the model calibration. Section 4 presents our analysis and results. Finally, Section 5 discusses the policy implications of our study and concludes.

2 Conceptual framework

When modeling the domestic electricity market of South Korea, we employ a partial equilibrium analysis. We elect to use partial equilibrium analysis because of its simplicity and clarity.

Let p_e denote the price of electricity in Won per kWh. For simplicity and brevity, let us assume that electricity demand, $D(p_e)$, is a linear downward-sloping function, while the supply of electricity from fossil fuels (i.e., coal, natural gas, and crude oil), $S(p_e)$, is a linear upward-sloping function. Note here that in 2015, 65% of the installed electricity generating capacity was fossil-based (U.S. Energy Information Administration, 2017):

- Coal — 28%
- Natural gas — 33%
- Crude oil — 4%

Figure 1 depicts the initial equilibrium, which is the point where demand intersects supply and marginal cost equals price (point A in Figure 1). The initial equilibrium quantity is q_e^0, while the corresponding equilibrium price is p_e^0.

The introduction of biomass feedstock in electricity generation results in a shift of the aggregate supply curve. In our analysis, we assume that it induces the aggregate supply of electricity to shift down and to the right.[1] More specifically, given the electricity price p_e^0, assume that the introduction of the biomass feedstock expressed in the same energy units (i.e., kWh) results in the supply curve shifting down and to the right by $B = \frac{X}{100} \cdot q_e^0$ units of kWh, where B is the amount of biomass-based electricity (see Figure 2).

Holding the amount of biomass in electricity production constant, we next describe the convergence to the new equilibrium—point C in Figure 2. At point C, the price has decreased to p_e^1, while the aggregate amount of electricity generated has increased to q_e^1. In other words, the introduction of biomass in electricity generation leads to lower prices to end users and more electricity consumed.

However, as the price of electricity decreases, an environmentally detrimental rebound effect arises. That is, the decline in the price of electricity results in fossil-based electricity generation declining by less than the biomass-based electricity supply shock B. In terms of Figure 2, point C is down and to the right of point A, and the new amount of fossil-based electricity consumed is $q_e^1 - B > q_e^0 - B$. The rebound effect, then, equals to:

$$\frac{q_e^1 - q_e^0}{B} \ . \tag{1}$$

The implication of the rebound effect is that the impact of biomass-energy introduction on CO_2 emissions is smaller than that implied by a life-cycle analysis, since although biomass-based electricity might be cleaner than fossil-based electricity (e.g., coal-based electricity), aggregate electricity consumption increases, and thus, total CO_2 emissions do not decline as much.

[1] We discuss this assumption in detail in Section 4.

3 Setting up the model

In this section, we first offer an assessment of the theoretical biomass potential and of the amount of electricity that could be generated using different domestic biomass feedstocks. We then describe our calibration methodology. We begin with the biomass assessment in Section 3.1.

3.1 Biomass assessment

The forestry data is taken from the Korean Statistical Information Service.[2] Although our focus is on the year 2013, data on forestry is collected in 5-year intervals—that is, data for either 2010 or 2015 can be used in our case. When approximating the amount of theoretical biomass potential, we use the 2015 data. To calculate the potential amount of biomass from forestry residues (in cubic meters), we use the data on forest area and volume. However, because the data only supplies information on the types of trees in South Korea and the aggregate area covered by forest, but not on the area covered per tree type, we cannot calculate the biomass potential from forestry residues directly from the data. Nevertheless, to obtain a preliminary assessment of it, we assume a density of 380 kg per cubic meter of solid volume.[3] Following Shelly (2007), we also assume that 1 Bone Dry Ton (BDT) is equivalent to 1 MWh.

Next, we calculate livestock manure. The number of heads of beef cattle, dairy cows and heifers, pigs, and chickens (layers and broilers) is taken again from the Korean Statistical Information Service.[4] Note here that the data on chickens includes information only on broilers and layers; it does not include information on breeding chickens. Furthermore, only chickens in farms that have more than 3,000 heads are counted (by complete enumeration). Therefore, the number of chicken heads is underestimated in the data. To get the amount of

[2] See http://kosis.kr/statisticsList/statisticsList_01List.jsp?vwcd=MT_ZTITLE&parentId=F (viewed: April 27, 2017).

[3] Similar numbers have been used in the literature (e.g., Kofman, 2010).

[4] See http://kosis.kr/statisticsList/statisticsList_01List.jsp?vwcd=MT_ZTITLE&parentId=F (viewed: May 14, 2017).

volatile solids (VS) that each type of livestock produces, the following equation and values are used:

$$VS = AP \cdot TAM \cdot vs \ , \quad (2)$$

where:

- AP: Animal Population in number of heads (Korean Statistical Information Service)
- TAM: Typical livestock Average Mass (NJ, 2011)
- vs: average annual production of VS per unit of livestock mass (NJ, 2011)

Livestock waste is then converted into MMBtu (and then into MWh). Each VS amount of each livestock is converted into MMBtu using the coefficients reported in the NJ (2011).

The final group of feedstocks used includes staple crops: sweet corn and wheat. The data is taken from FAOSTAT.[5] The data is in metric tons (for the year 2013). We convert the values to MMBtu applying the net usable percentage and percent dry matter coefficients as obtained from NJ (2011).

The data in Table 1 was constructed following the methodology outlined above and presents an approximation of the theoretical (i.e., upper-bound) biomass-based electricity potential of South Korea. A more precise evaluation of this potential (and even more so in the case of the political-economic one) would require data that is not currently available. In particular, the biomass potential from forestry residues depends on the exact types of trees present and the area covered per tree type (since moisture and energy content vary among different tree types). However, the data collected has the names of the various tree types in South Korea but provides no information on their spatial distribution.

3.2 Calibration

In this section, we calibrate the electricity demand and supply functions for South Korea. Specifically, let us assume the following system of linear demand and supply equations:

[5]See http://www.fao.org/faostat/en/#data/QC (viewed: April 1, 2017).

$$p_e = \alpha_0 - \alpha_1 \cdot q_e \qquad \text{(the demand equation)} \tag{3a}$$

$$p_e = \gamma_0 + \gamma_1 \cdot q_e \qquad \text{(the supply equation)} \tag{3b}$$

Then, using the definition of the own-price demand and supply elasticities, we can solve for the slope of the respective equation as follows:

$$\alpha_1 = -\frac{1}{\eta_d} \cdot \frac{p_e^0}{q_e^0} \tag{4a}$$

$$\gamma_1 = \frac{1}{\eta_s} \cdot \frac{p_e^0}{q_e^0} \tag{4b}$$

where η_d denotes the own-price demand elasticity, and η_s denotes the own-price supply elasticity. Once calibrating the slopes of the demand and supply curves, we can readily calibrate the intercepts of the two equations in the following way:

$$\alpha_0 = q_e^0 - \alpha_1 \cdot p_e^0 \tag{5a}$$

$$\gamma_0 = q_e^0 - \gamma_1 \cdot p_e^0 \tag{5b}$$

The own-price demand elasticity used in the baseline scenario is taken from Table 1 of Cho, Kim, Kim, Park and Roberts (2015). Therein, they list estimates—from different countries—of the demand price elasticity for different usage categories as found in the past literature. For the baseline analysis, we use the average elasticity estimate of –0.425 for residential electricity demand in South Korea, originally reported in a study of the Korea Energy Economics Institute (2012).

We then perturb the demand elasticity through a Monte Carlo simulation to address any uncertainty over this parameter. More specifically, we perform 1,000 Monte Carlo trials for each of the different biomass-based electricity supply shocks we consider (to be discussed below). Each trial is performed by randomizing the demand elasticity and then introducing a predefined shock to the model. For the random sampling, we assume that the own-price demand elasticity of electricity follows a truncated normal distribution with mean of –0.425 and standard deviation of 0.1, with the demand elasticity always being negative.

We could not find information though on the supply elasticity of electricity in South Korea; thus, in the baseline scenario, we use the value of 0.3. Nevertheless, given the uncertainty regarding this parameter, we also perturb the supply elasticity through a Monte Carlo simulation, where we assume a truncated normal distribution with mean of 0.3 and a standard deviation of 0.1 (with the supply elasticity being always positive).

When calibrating our system of equations, we use 2013 data on electricity consumption and price as reported by the Korean Statistical Information Service.[6] The quantity (490 TWh) is taken directly from the site, while the price (90.48 Won per kWh) equals the ratio of total electricity sales to end consumers divided by the quantity of electricity consumed.

4 Analysis and results

The biomass assessment suggests that, theoretically, biomass can be used to generate a significant portion of the total electricity consumed in Korea (almost 500,000 GWh in 2014).[7] Although the political-economic potential for biomass-based electricity generation is probably much smaller than the theoretical one (Brennan-Tonetta, Hochman and Schilling, 2014), it is likely to still be substantial for the Korean electricity market.

Table 1 (see Section 3.1) presents the results of our biomass assessment by summarizing the potential for electricity production from various crops, livestock, and forestry residues. As the table clearly illustrates, the most promising feedstock is forestry residues, whereas the staple crop potential is minimal, which is in line with the fact that South Korea imports almost all of the wheat and sweet corn it consumes. Moreover, out of all the technologies

[6]See http://kosis.kr/statisticsList/statisticsList_01List.jsp?vwcd=MT_ZTITLE&parentId=G (viewed: April 28, 2017).

[7]See https://www.cia.gov/library/publications/resources/the-world-factbook/rankorder/2233rank.html (viewed: June 2, 2017).

considered, pyrolysis of forestry residues could potentially impact the electricity market the most. The theoretical amount of electricity that could be produced via pyrolysis of forestry residues is 1.9 Petawatt hour. In addition, our analysis shows that the introduction of biomass in electricity generation results in a decline of the price to end consumers and an increase in the total amount of electricity consumed. For example, in the scenario of the introduction of beef cattle manure and using the baseline parameters, we find that the electricity price may (in theory) decline by up to 5.7%, while if pig manure were introduced, the price of electricity may decline by 2.3%.[8] On the other hand, if forestry residues were introduced, the shock to the electricity market could be of such magnitude that the market price of electricity collapsed.

Overall, the biomass assessment suggests that South Korea can theoretically meet its bioenergy targets without problem, especially by utilizing forestry residues. More specifically, the Renewable Portfolio Standard (RPS) system introduced in 2012 mandates that power producers with installed capacity over 500 MW should produce a minimum portion of their power using renewable energy sources.[9] The yearly RPS target stands at 4% for 2017 and will rise to 10% by 2023. The power producers involved in the RPS system receive certain amount of Renewable Energy Certificates (RECs) annually, certifying that they produced and supplied power using renewable energy sources.[10] The number of RECs allocated though varies depending on the technology used, with the REC weighting scheme placing a relatively high weight on wood biomass as an energy source. Clearly, our biomass assessment demonstrates not only that South Korea can (theoretically) readily meet these renewable energy targets, but that there is room for implementing more ambitious ones in the future.

Before proceeding further, a few remarks are in order. When assessing the net benefits from the expansion of bioenergy, the direct (and indirect) costs associated with the use of

[8] As Table 1 reveals, in the former case, up to 20,202 GWh of electricity could be produced, while in the latter case, the corresponding figure is 8,328 GWh.

[9] See http://www.iea.org/policiesandmeasures/pams/korea/name-39025-en.php?s=dHlwZT1yZSZzdGF0dXM9T2s.

[10] Power generators have the option to meet their obligatory RPS target by purchasing RECs on the market. In case of non-compliance, there is a financial penalty of 150% of the average REC market price (for the year in question) on every REC missing.

biomass in electricity generation should be carefully accounted for. However, some of the technologies listed in Table 1 are only at the research and development stage and have not been commercialized yet. Others, which have been commercialized, are currently employed to some extent only and gradually becoming cost-competitive (e.g., biomass anaerobic digestion or biomass combined heat and power). But as past experience has shown, learning by doing and learning by researching can be very substantial in the renewable energy industry (Azevedo, Jaramillo, Rubin and Yeh, 2013; Rubin, Azevedo, Jaramillo and Yeh, 2015), which suggests that renewable technologies should be evaluated from a dynamic point of view. For instance, there was a sharp drop in solar and wind energy costs (i.e., cost per kWh) in the United States within the timespan of a few decades. Furthermore, focusing on biomass, co-firing wood biomass with coal in existing coal plants has much potential relative to other renewable technologies assuming that the wood biomass feedstock is sufficiently clean relative to coal (e.g., it is not the product of logging of natural forest).[11] The U.S. Energy Information Administration (2016a) derived and compared updated cost estimates for different generic utility-scale electricity generating technologies. These updated estimates reveal that for a pulverized coal plant retrofitted to operate with 10% wood biomass fuel and with capacity of 300 MW (and heat rate of 10,360 Btu/kWh), its overnight capital cost, fixed non-fuel operations and maintenance (O&M) costs, and variable O&M costs equal, respectively, \$537/kW, \$50.9/kW-yr, and \$5/MWh. On the other hand, for an onshore wind facility of 100 MW and a photovoltaic tracker facility of 150 MW, the overnight capital cost equals, respectively, \$1,877/kW and \$2,534/kW; these facilities though are characterized by lower fixed O&M costs (of, respectively, \$39.7/kW-yr and \$21.8/kW-yr) and by zero variable O&M costs.

A final remark relates to the cost of air pollution (e.g., health costs due to air pollution). The generation of electricity from fossil fuels results in significant GHG emissions, imposing a cost on society both locally and globally. And Pareto efficiency dictates that in policy

[11] Co-firing is the simultaneous combustion of different fuels in the same boiler.

design, we should not restrict our attention solely to the private cost of electricity production (i.e., the cost borne by the electricity producers). Rather, the (marginal) external cost that electricity production imposes on society via pollution should also be explicitly taken into account. Therefore, when the social cost of electricity production is considered—which equals the sum of the private cost and the external cost of production—the cost competitiveness of renewable electricity generation vis-à-vis fossil-fired electricity generation improves significantly (Trancik and McNerney, 2015), and (some) low-carbon electricity technologies can become competitive with the fossil ones (which is consistent with the downward shift of the supply curve in Figure 2).[12]

Because of the many unknown parameters, which depend as we just discussed, among others, on the research and development of biomass-energy technologies and their commercialization and adoption, we simulate various supply-shock scenarios arising from the introduction of biomass feedstock in electricity production. To this end, we employ the Monte Carlo simulation described in Section 3.2, and analyze different supply-shock scenarios perturbing first the demand elasticity. In Figure 3, we depict the distribution of the changes in the total quantity of electricity consumed arising from 1,000 Monte Carlo simulations for two alternative biomass-based electricity supply shocks: 5% and 25% of the total electricity consumed in South Korea in the year 2013.[13] The distribution of the price changes for these two shocks is depicted in Figure 4. When focusing on the 5% shock, the total amount of electricity consumed increases by 2.9% (see Figure 3), while the market price of electricity decreases by 7.1% (see Figure 4). Similar effects in terms of sign (but, as expected, of larger magnitude) are documented when applying the 25% shock. The main difference—which arises from the assumption of a linear demand function and because the amount of biomass-based electricity introduced in the second scenario (i.e., the 25%-shock scenario) is

[12]A negative production externality like pollution can be efficiently addressed by a Pigouvian tax. In our case, an optimal carbon tax could render low-carbon electricity technologies cost-competitive even on a private-cost basis.

[13]We present the simulation results for these two shocks as they can be reasonably viewed as a "modest" and an "ambitious" biomass-energy scenario for South Korea. The simulation results for other supply shocks are available from the authors upon request.

substantially larger—is that the distributions of quantity and price changes in the 25%-shock scenario are more variable.

In Figure 6, we depict the rebound effect (see Figure 2). The introduction of biomass feedstock in electricity production does not result in a crowding out of fossil-based electricity generation. For example, under the 5%-shock scenario, there is a decline of only 2.1% in the total amount of electricity consumed from non-biomass sources (i.e., fossil-based electricity generation declines, on average, by only 2.1%). In other words, the 5% shock results in a 57.6% rebound effect. Similarly, under the (more) ambitious 25%-shock scenario, fossil-based electricity generation declines by 10.6% on average.

The rebound effect does mitigate the environmental benefits of the introduction of biomass feedstock in electricity generation. To examine the ramifications of biomass-energy introduction for CO_2 emissions, we build upon Spath and Mann (2004) and investigate three alternative biomass-technology scenarios: (i) a coal system with biomass co-firing and 15% co-firing rate (scenario 1); (ii) a biomass residue direct-fired system (scenario 2); and (iii) a biomass dedicated feedstock integrated gasification combined cycle (IGCC) system (scenario 3). In all three scenarios, the baseline scenario is a pulverized-coal-fired system, while in the first two scenarios, the biomass is assumed to be produced by urban sources and diverted from normal landfilling and mulching operations. For the 5% shock, CO_2 emissions decline by 18.8 million tonnes in scenario 2 (see Figure 7c) and by 7.6 million tonnes in scenario 3 (see Figure 7b), but increase by 8 million tonnes in scenario 1 (see Figure 7a). The increase in CO_2 emissions in the latter case is due to the rebound effect and the fact that, on a life-cycle basis, CO_2 emissions per kWh of electricity produced only moderately decrease in scenario 1 in comparison with the baseline scenario. On the other hand, for the 25% biomass-based electricity supply shock, CO_2 emissions are reduced by 94 million tonnes in scenario 2 and by 38.1 million tonnes in scenario 3, but are higher by 39.9 million tonnes in scenario 1.

Next, to further address the uncertainty regarding the parameters used to calibrate the model, we also perturb the supply elasticity, sampling 1,000 times from a truncated normal distribution with mean of 0.3 and standard deviation of 0.1. The results of these simulations are presented in Figures 8–10. Similar to the demand-elasticity Monte Carlo simulations, the 5% shock results in the electricity price declining and total electricity production increasing by 7.1% and 3%, respectively, while the 25% shock has (as expected) more pronounced effects on the electricity market. The amount of fossil-based electricity generation declines by 2% in the 5%-shock scenario and by 9.8% in the 25%-shock one. The rebound effect is thereby somewhat larger than that reported when randomly perturbing the demand elasticity and equals (in both scenarios) 60.6% (see Figure 10). Again, the effect on CO_2 emissions depends on the biomass-technology scenario considered. For the 5% shock, CO_2 emissions decrease by 18.4 million tonnes in scenario 2 (i.e., a biomass residue direct-fired system; see Figure 9c) and by 7 million tonnes in scenario 3 (i.e., a biomass dedicated feedstock IGCC system; see Figure 9b), but increase by 8.4 million tonnes in scenario 1 (i.e., a coal system with biomass co-firing; see Figure 9a). The corresponding figures for the 25% biomass-based electricity supply shock are, respectively, 92.2, 34.9, and 42 million tonnes.

Finally, we look at the ramifications of the introduction of different amounts of biomass in electricity production for consumer surplus, the surplus of fossil-based electricity producers, and revenues from biomass-based electricity production (using the baseline parameters). The change in surpluses/revenues over different biomass-based electricity supply shocks is depicted in Figure 11, where the sum of the three (i.e., welfare change) is positive and increasing over the range of shocks considered. Clearly, the total gain for the Korean economy is lower than the welfare gain reported in Figure 11 because the cost of producing biomass-based electricity needs to be taken into account. Nevertheless, we do not have reliable cost estimates to use for calculating the surplus of biomass-based electricity producers as, for instance, some of the technologies included in our analysis are—as we already discussed above—at the research and development stage and have not been commercialized yet. Having said that, the effect on consumer surplus is large and more than likely to compensate for the cost of utilizing biomass in electricity generation.

5 Policy discussion and concluding remarks

Fossil fuel use and especially the burning of coal are major contributors to GHG emissions. In South Korea, coal-fired electricity generation is the most economic form of fossil-based electricity production—as is the case in many other countries—but there are mounting environmental concerns associated with it.[14] According to the U.S. Energy Information Administration (2016b), South Korea's fleet of coal-fired power plants had an average annual capacity factor (i.e., ratio of generation to capacity) of 82% during 2008–2012 , with the average for natural-gas-fired and petroleum-fired plants standing at about 40% over the same period.[15] This vast difference in annual capacity factors across plants using different energy sources can be attributed to the significant improvements in the efficiency of coal-fired generation in South Korea—in 2010, 70% of South Korea's total coal-fired generation came from highly efficient supercritical units—and to the fact that the coal price in South Korea is much lower than the price of imported LNG.

Against this backdrop, the introduction of biomass-based electricity generation can yield substantial benefits to South Korea, especially on the environmental front. Before demonstrating (some of) these benefits, we approximated the theoretical (i.e., upper-bound) biomass potential from forestry residues, livestock manure, and staple crops, and used the existing literature to calculate the theoretical amount of electricity that could be generated using different domestic biomass feedstocks. Our preliminary analysis suggests that (theoretically) the biomass-based electricity potential of South Korea is very substantial. Future work, we believe, should offer a more comprehensive assessment of this potential along several dimensions. In particular, the analysis should take into account the spatial distribution of the domestic biomass resources—which is not feasible, to the best of our knowledge, with the data currently available—thus identifying regional low-carbon energy pathways and plausible

[14] Note that 39% of the electricity generated in 2015 was coal-based (U.S. Energy Information Administration, 2017).

[15] In comparison, the coal-fired power plants in the United States, Japan, and China recorded over the period 2008–2012 an average annual capacity factor of, respectively, 66%, 62%, and 54%.

supply chain structures that could become economically viable (in the future). Moreover, the analysis should explicitly consider political-economic and logistical constraints, such as policy and institutional barriers, political constraints, and infrastructure constraints. Such a comprehensive assessment will more accurately evaluate the economic viability and the environmental ramifications of biomass-based electricity generation in South Korea.

Furthermore, in this work, we calibrated a linear demand and supply system for the Korean electricity market, and subsequently, used the calibrated functions to compute the social benefits from the introduction of biomass feedstock in electricity production. In practice, though, these benefits depend both on the successful research and development of biomass-energy technologies and, afterwards, on their successful commercialization and adoption. It is true that some of the technologies considered in our analysis are only at the research and development stage and have not been commercialized yet, while others, which have been commercialized, are currently employed to some extent only and gradually becoming cost-competitive. But if past experience is any guide, learning by doing and learning by researching can be very substantial in the renewable energy industry, suggesting that renewable technologies should be evaluated from a dynamic point of view. In addition, from a Pareto efficiency perspective, the external cost that electricity production imposes on society via pollution should be explicitly taken into account in policy design. If so, the competitiveness—in terms of social cost of production—of renewable electricity generation vis-à-vis fossil-fired electricity generation improves significantly, and (some) clean technologies can become competitive with the fossil ones. This might be even more the case in countries like South Korea where the fossil feedstocks are delivered to the domestic market via expensive means such as tanker or bulk carrier shipments. However, before moving to large-scale deployment of biomass-based electricity, its land-use implications should be better understood. This is an important issue, but we leave it for future research.

On a different note, our analysis highlights that the rebound effect has important implications for the impact of biomass-energy introduction on CO_2 emissions (assuming that the introduction of biomass in electricity generation does shift the aggregate electricity supply curve downward). More specifically, we show that the biomass-technology employed has to be sufficiently clean on a life-cycle basis relative to the fossil ones so that biomass-energy introduction leads to a mitigation of CO_2 emissions. Otherwise, even though biomass-based electricity is cleaner than fossil-based electricity (in terms of CO_2 emissions per kWh of electricity produced), total CO_2 emissions might even rise as aggregate electricity consumption increases due to the rebound effect.

Regarding policy, the utilization of biomass for producing renewable electricity (or heat)—a major part of the bioeconomy—has important implications for the sustainable development of the agricultural and natural resource sectors. But the development of this industry requires significant investment in research and infrastructure, as well as policies for efficient and equitable transfer of technologies from the public to the private sector. It is likely that we will observe in the (near) future the emergence of multiple recommendations for policy and institutional designs conducive to the development and deployment of biomass-energy technologies. We are also likely to observe demand for tools to assess biomass-energy policies' economic and environmental impacts—the creation of such tools should be a major priority. To this end, it is important to understand the bioenergy industry as a whole and identify plausible supply chain structures that could secure the level of production of biomass-based electricity required to achieve the various policy goals.

Careful consideration needs also to be given to the benefits of biomass-based electricity generation vis-à-vis the benefits of possible alternative uses of the biomass resource. For example, biomass can be used to produce renewable electricity (like in this report), and the technologies therein can become carbon negative. Alternatively, biomass can be used in producing biofuels for the transportation sector. At the same time, biomass-based electricity can be utilized as a transportation fuel itself, especially in areas with relatively short commuting distance (e.g., ports or public transportation in cities). Another possible use of biomass is in producing hydrogen and/or ammonia, and even though the relevant technologies are very far from commercialization, their long-run potential is enormous.

Last, many countries, particularly among the developed OECD nations, are pursuing policies and implementing regulations so as to increase the pressure on electricity generators to reduce their GHG emissions by decreasing fossil fuel use. As a result, the renewable share of total world electricity generation is rising. According to recent projections by the U.S. Energy Information Administration (2016b), total electricity generation from renewable resources will increase on average by 2.9%/year over the period 2012–2040, with electricity generation from non-hydropower renewables being the predominant source of this increase, projected to grow annually by 5.7%—in comparison, the corresponding figure for coal-based generation is 0.8%/year. And of the 5.9 trillion kWh of new renewable electricity that will be added to world supply over 2012–2040, biomass- and waste-based electricity generation will contribute close to 856 billion kWh (i.e., 14% of the total).[16]

Focusing on South Korea, the introduction of the RPS system in 2012 has boosted interest in using biomass and wood pellets for energy generation. Wood pellets in particular are primarily used with coal in South Korea in co-firing applications, and their growing demand is met by imports coming mainly from Canada, Southeast Asia, and the United States. According to Bloomberg New Energy Finance, South Korea's demand for wood pellets in 2014 was estimated at 2.2 million short tons, being roughly equal to 40% of the United Kingdom's one (U.S. Energy Information Administration, 2016b).

In general, co-firing coal with biomass, especially when coupled with carbon capture and storage technologies, can produce substantial economic and environmental benefits (Spath and Mann, 2004; Gopalakrishnan, Liao, Norton and Hochman, 2017). A promising alternative for South Korea to co-firing is bioenergy generation along with carbon capture and storage (i.e., BECCS). BECCS refers to the production of energy using biomass, coupled with the capturing and subsequent storing of the resulting CO_2 emissions (e.g., underground geological storage or ocean storage), leading to negative overall emissions. Of course, besides

[16] A small part of the 856 billion kWh will come from tidal/wave/ocean energy.

its obvious environmental benefits, BECCS can greatly contribute to rural development, as forestry and agricultural residues can be utilized as biomass feedstocks for energy production. We believe this is an important research avenue to pursue, but we leave it for the future.

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Table 1: Biomass assessment

	Feedstock Technology	Quantity
Crop		
Wheat		
	Direct combustion—stand-alone for solid biomass	71 GWh
	Direct combustion—co-firing	54 GWh
	Gasification—stand-alone for BIGCC	46 GWh
	Pyrolysis	95 GWh
Sweet Corn		
	Direct combustion—stand-alone for solid biomass	302 GWh
	Direct combustion—co-firing	229 GWh
	Gasification—stand-alone for BIGCC	193 GWh
	Pyrolysis	400 GWh
Livestock		
Beef Cattle		
	Direct combustion—ADG/Landfill gas	12,881 GWh
	Direct combustion—stand-alone for solid biomass	12,928 GWh
	Direct combustion—small-scale CHP for solid biomass	20,202 GWh
	Gasification—stand-alone for BIGCC	8,287 GWh
	Gasification—small-scale CHP	15,343 GWh
Dairy Cows and Heifers		
	Direct combustion—ADG/Landfill gas	3,466 GWh
Pigs		
	Direct combustion—ADG/Landfill gas	8,328 GWh
Chicken		
	Direct combustion—ADG/Landfill gas	3,808 GWh
	Direct combustion—stand-alone for solid biomass	3,822 GWh
	Direct combustion—small-scale CHP for solid biomass	5,973 GWh
	Gasification—stand-alone for BIGCC	2,450 GWh
	Gasification—small-scale CHP	4,536 GWh
Forestry Residues		
	Direct combustion—stand-alone for solid biomass	1,405,858 GWh
	Direct combustion—co-firing	1,068,040 GWh
	Gasification—stand-alone for BIGCC	901,191 GWh
	Pyrolysis	1,864,178 GWh

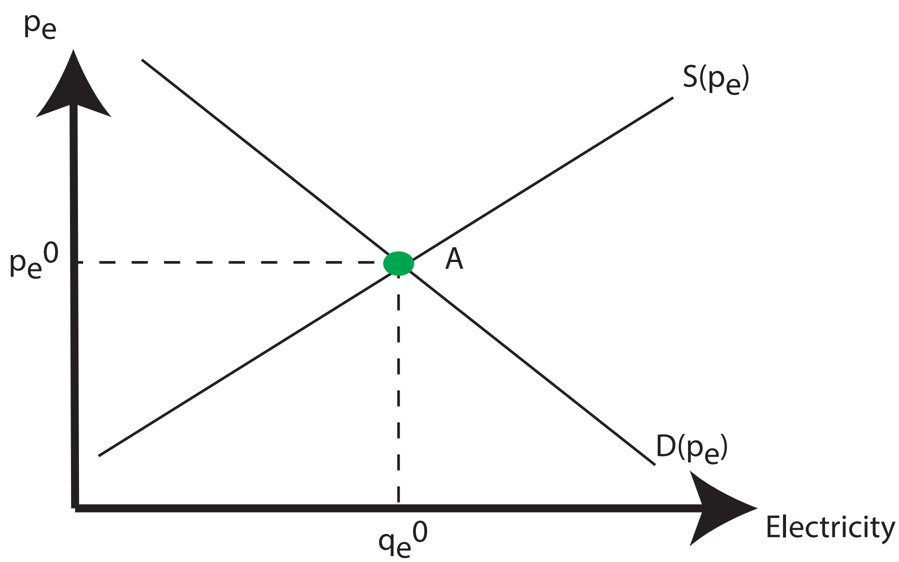


Figure 1: The fossil equilibrium

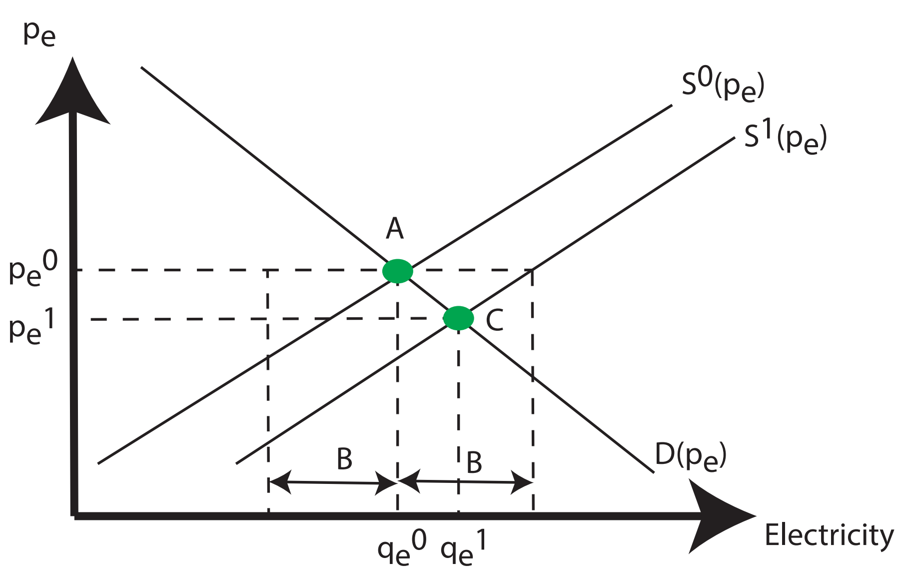


Figure 2: The biomass equilibrium

Figure 3: Change in electricity consumption after supply shock (demand simulations)

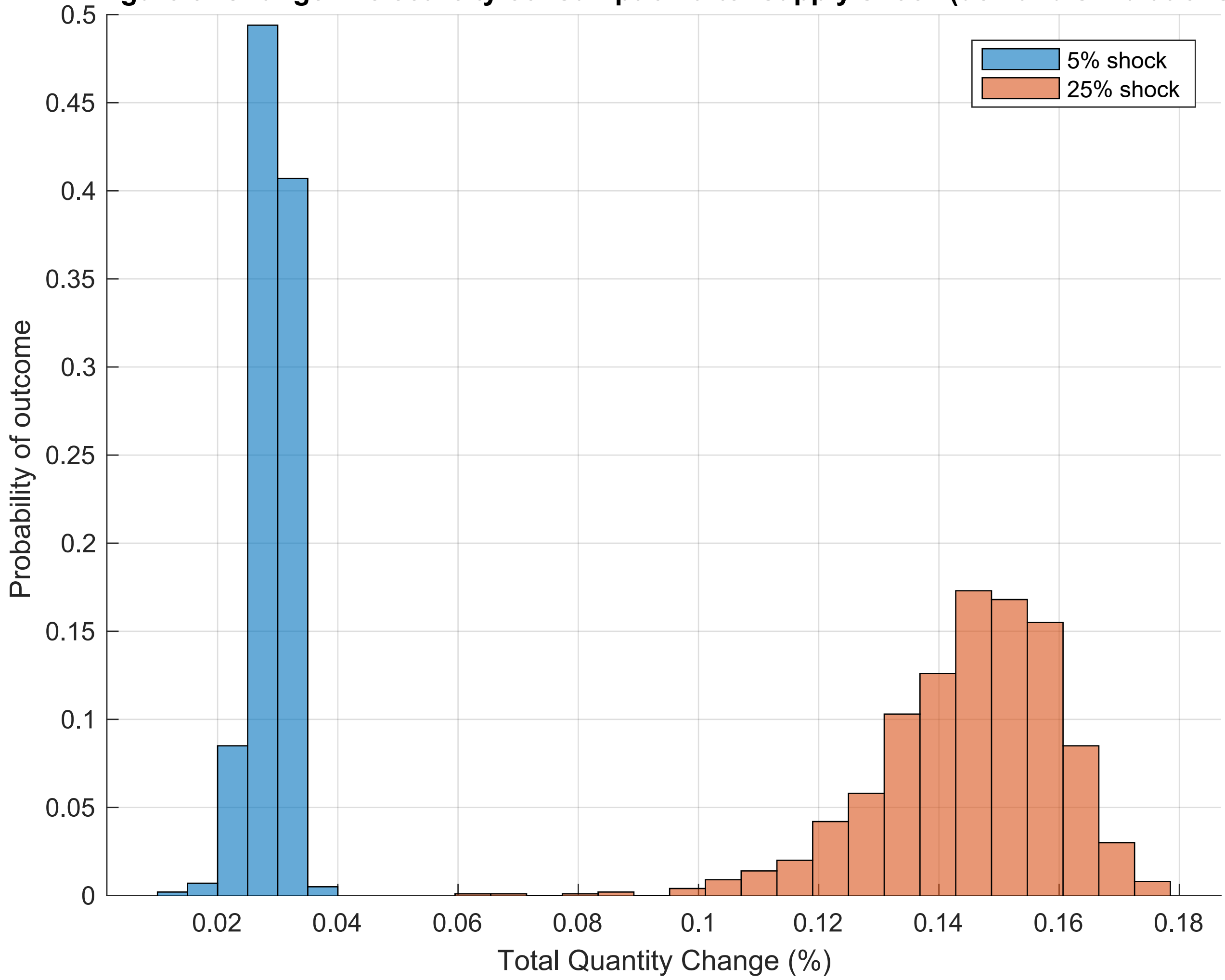


Figure 4: Change in electricity price after supply shock (demand simulations)

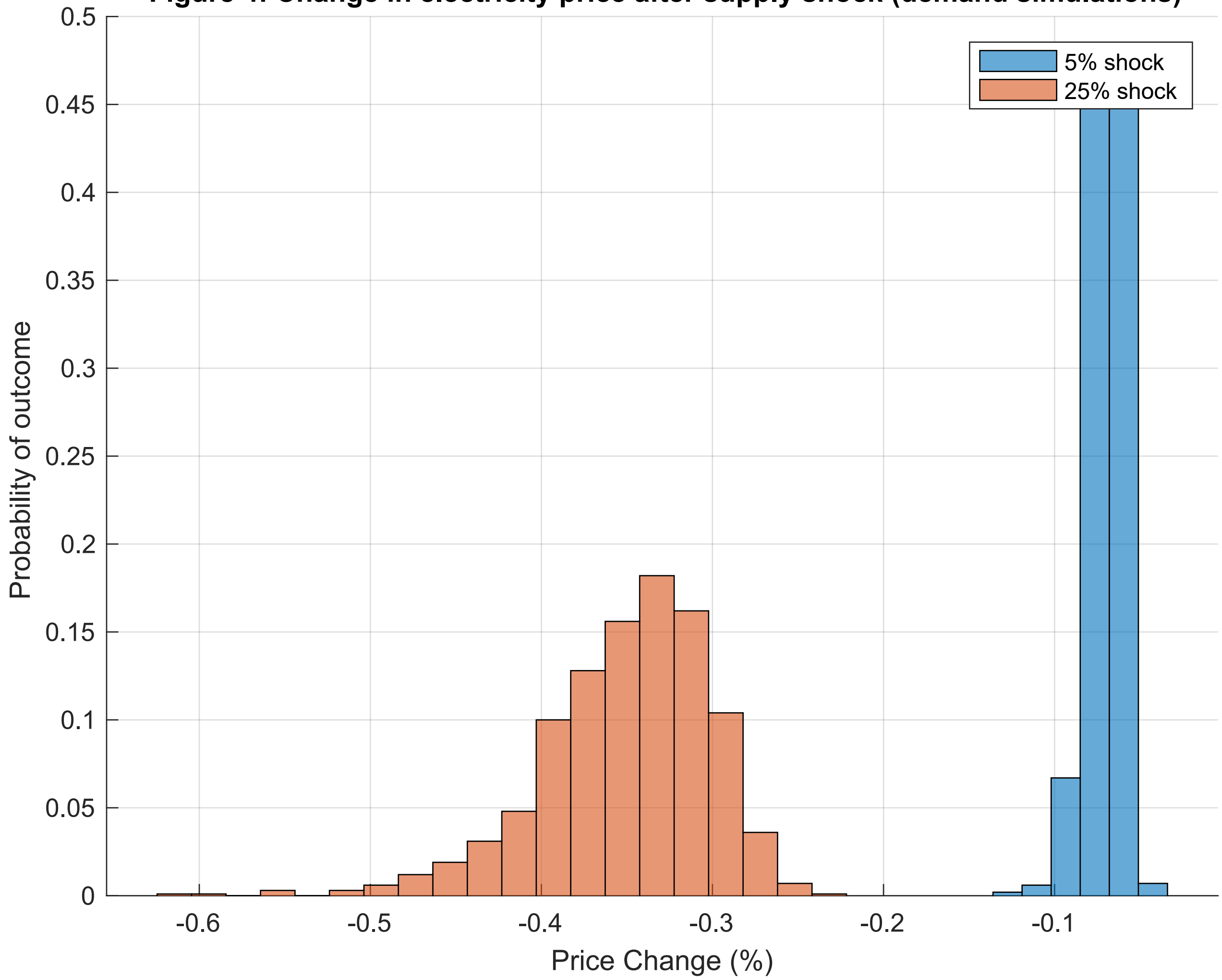


Figure 5: Change in fossil-based electricity consumption after supply shock (demand simulations)

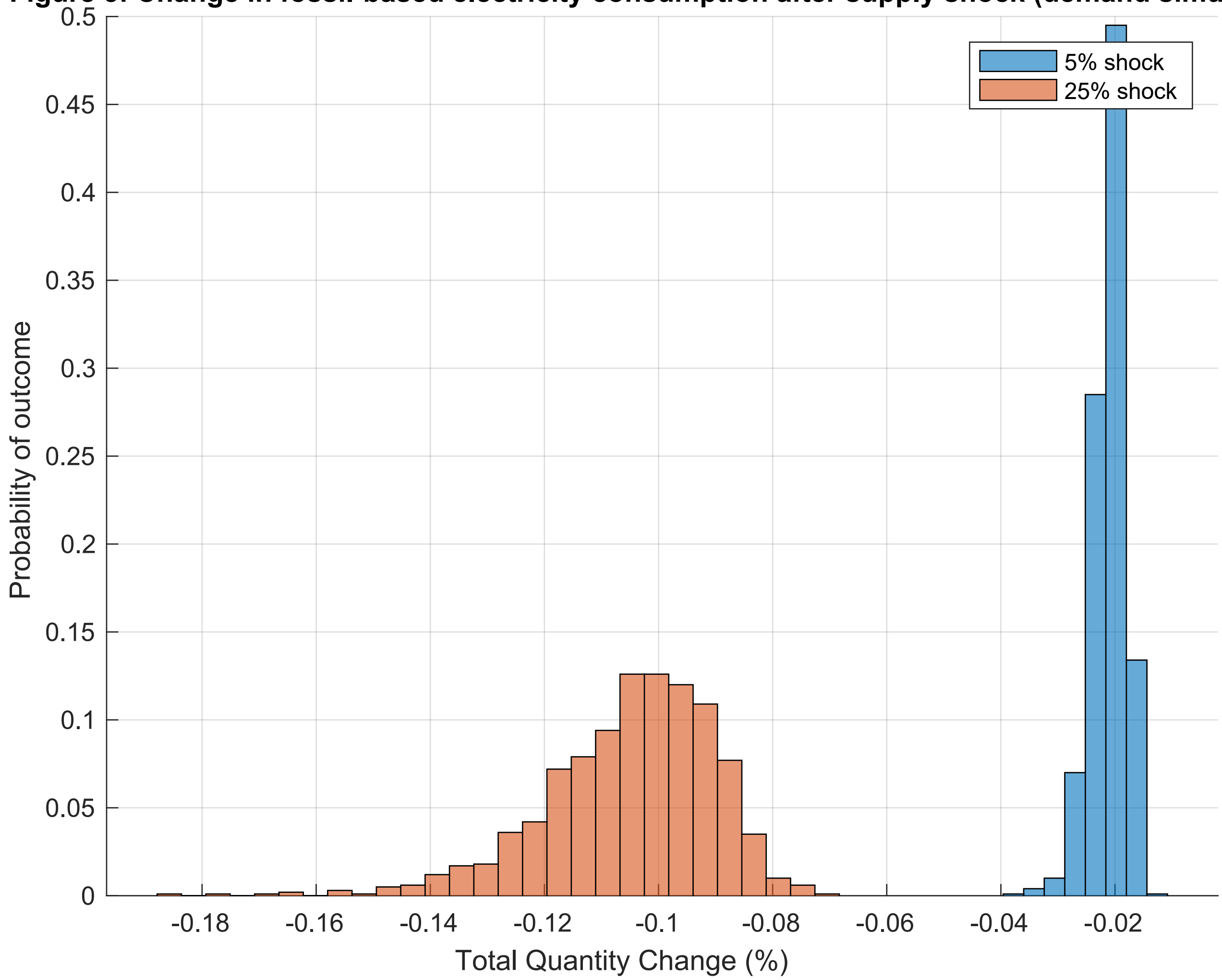


Figure 6: Rebound effect after supply shock (demand simulations)

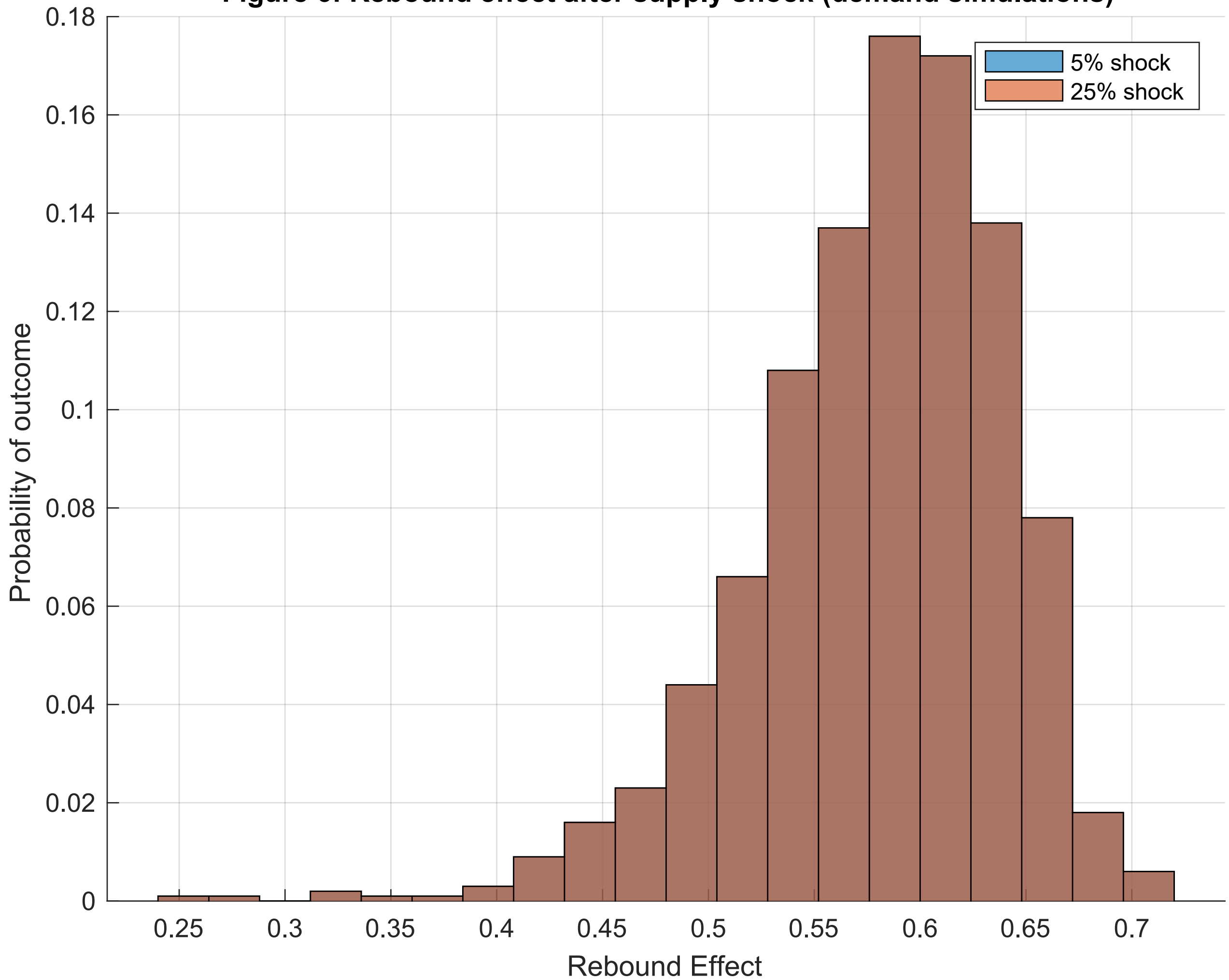
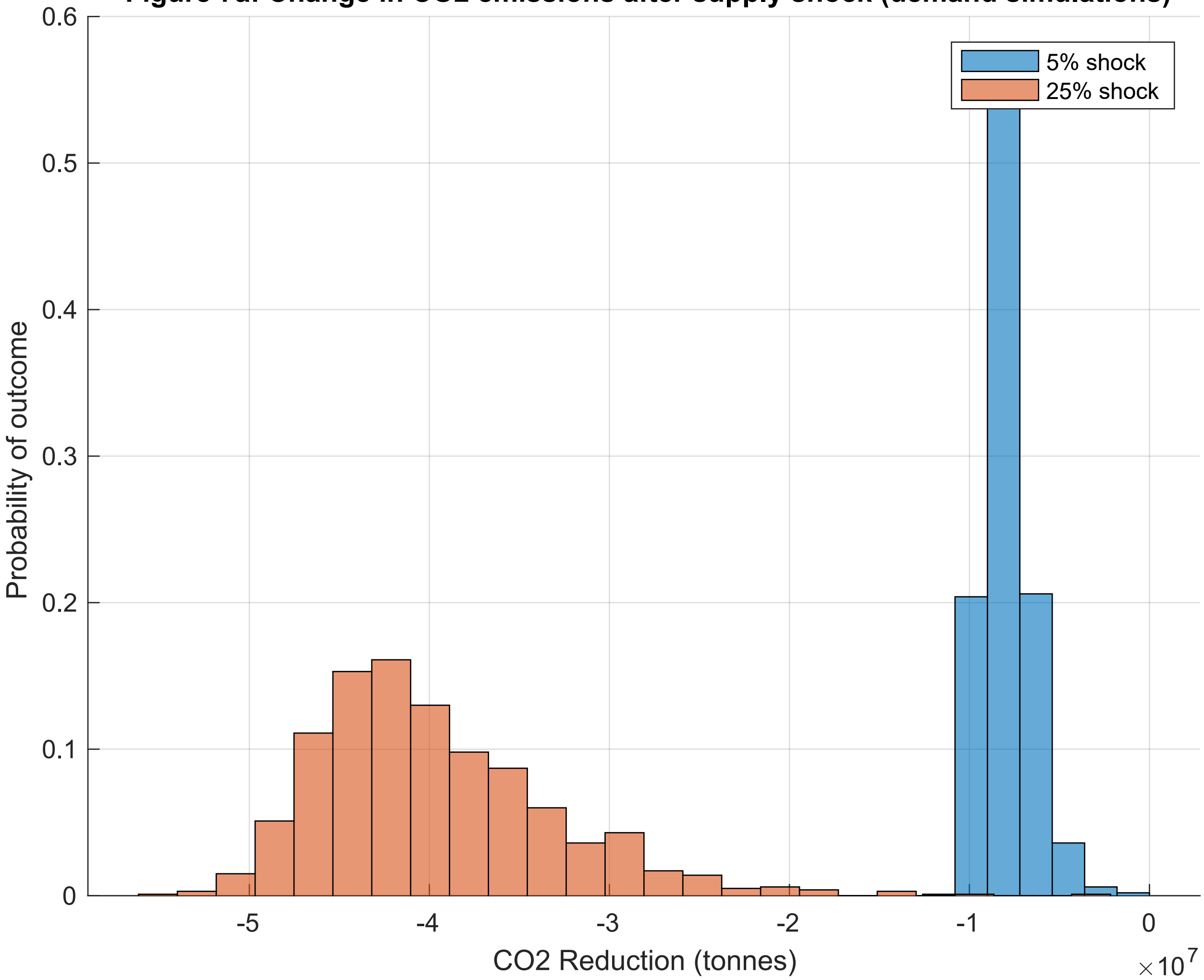


Figure 7a: Change in CO2 emissions after supply shock (demand simulations)



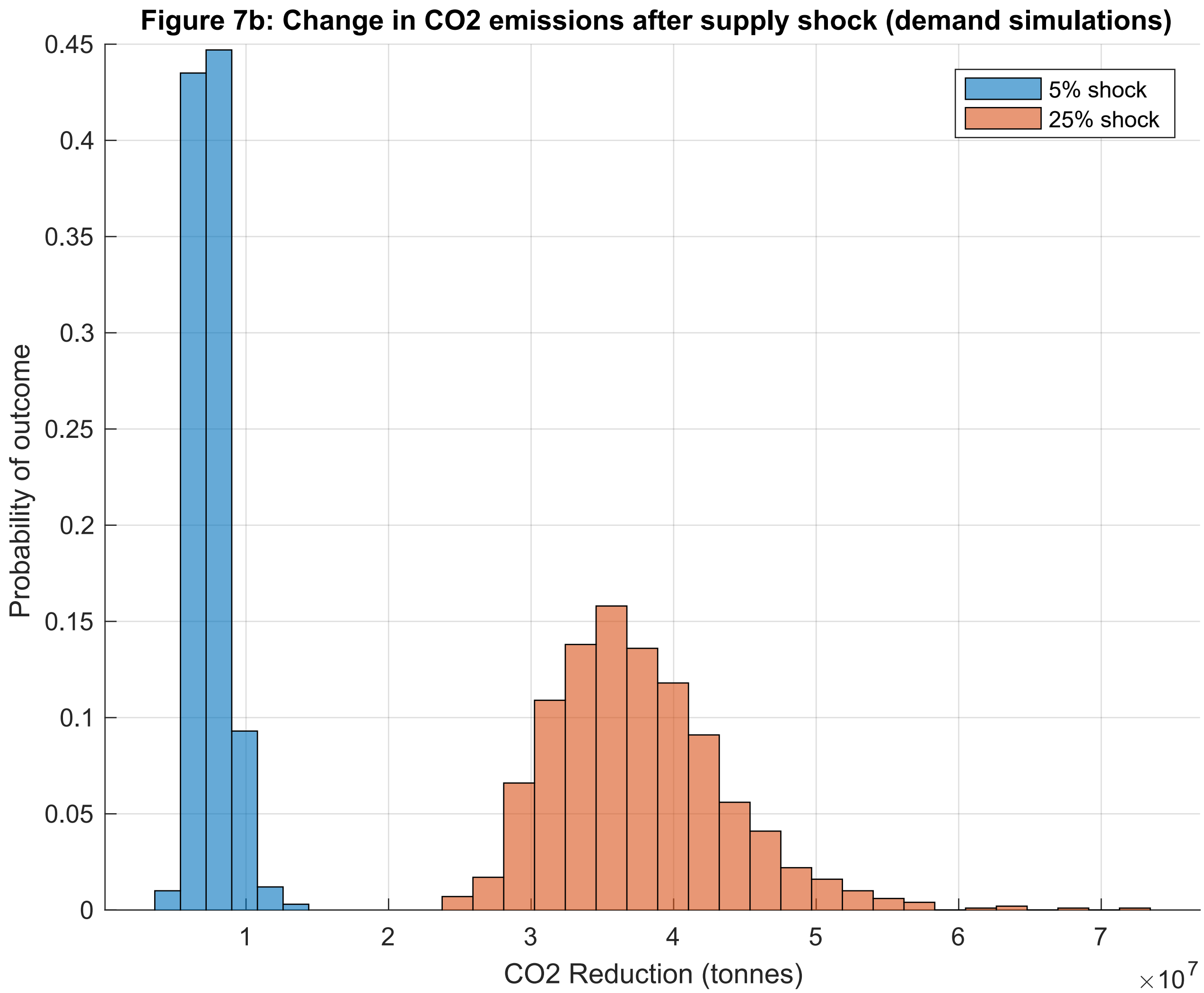


Figure 7b: Change in CO2 emissions after supply shock (demand simulations)
Probability of outcome
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1
2
3
4
5
6
7
CO2 Reduction (tonnes)
×10^7
5% shock
25% shock

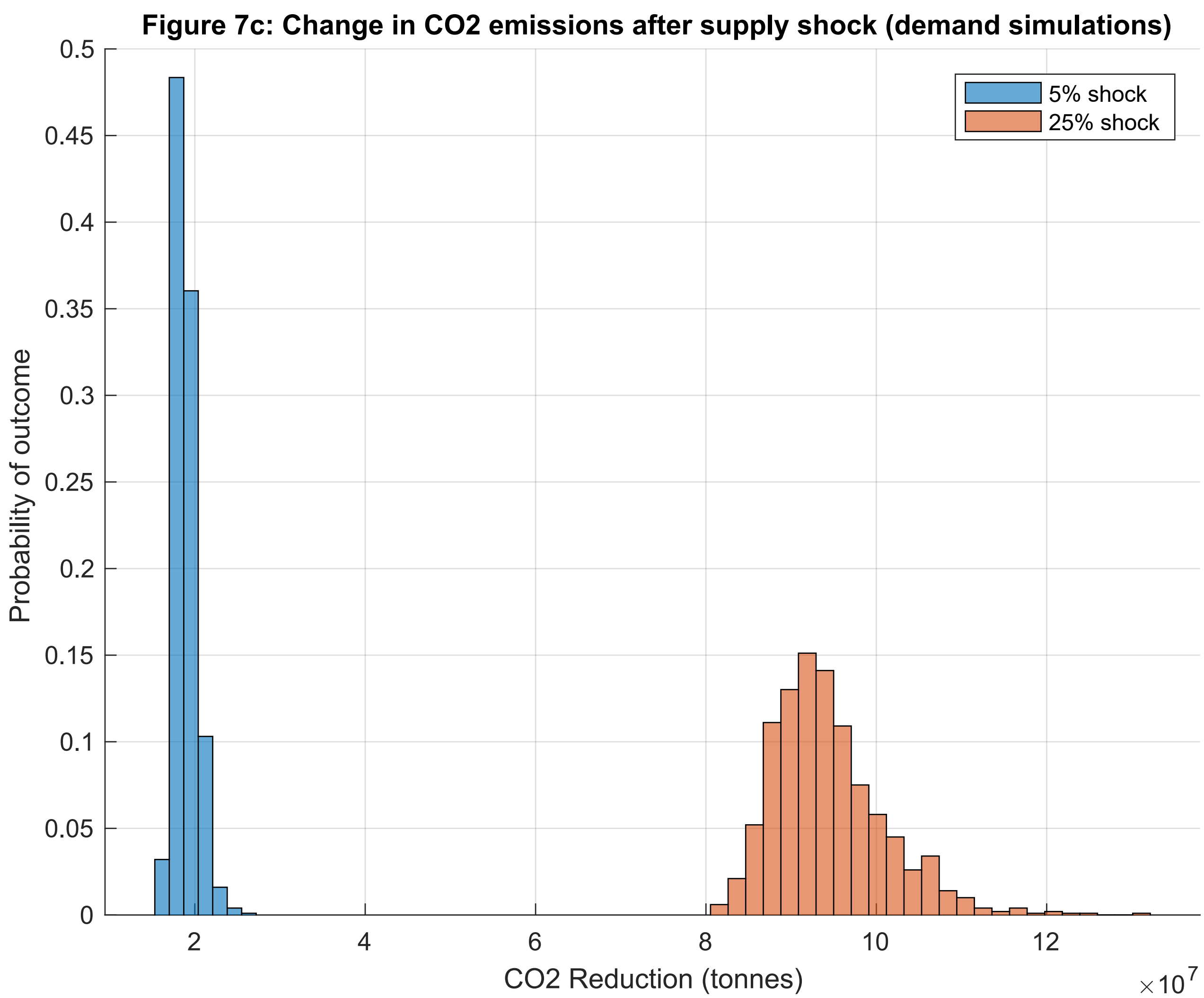


Figure 7c: Change in CO2 emissions after supply shock (demand simulations)
5% shock
25% shock
Probability of outcome
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2
4
6
8
10
12
CO2 Reduction (tonnes)
×10^7

Figure 8: Change in electricity consumption after supply shock (supply simulations)

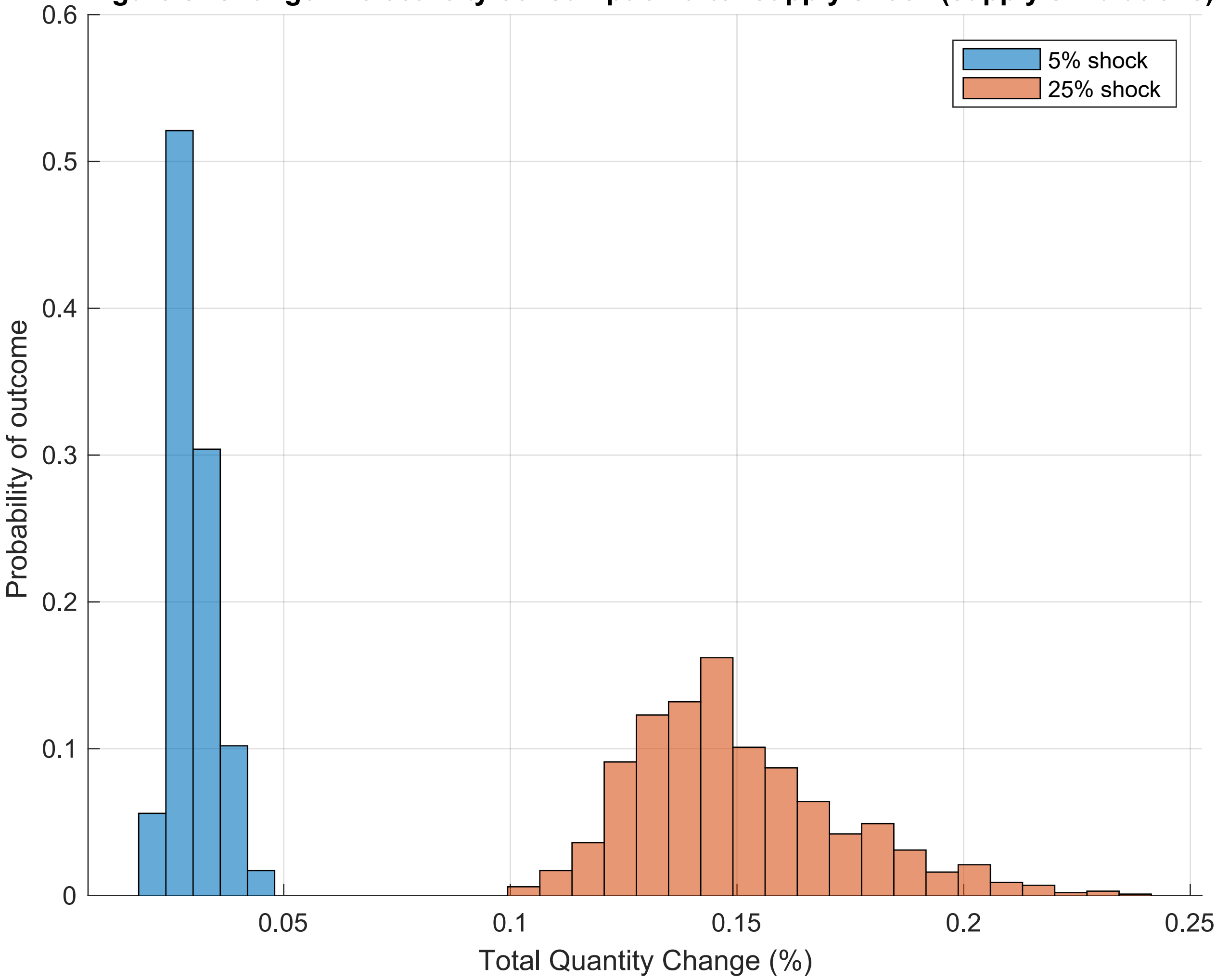


Figure 9a: Change in CO2 emissions after supply shock (supply simulations)

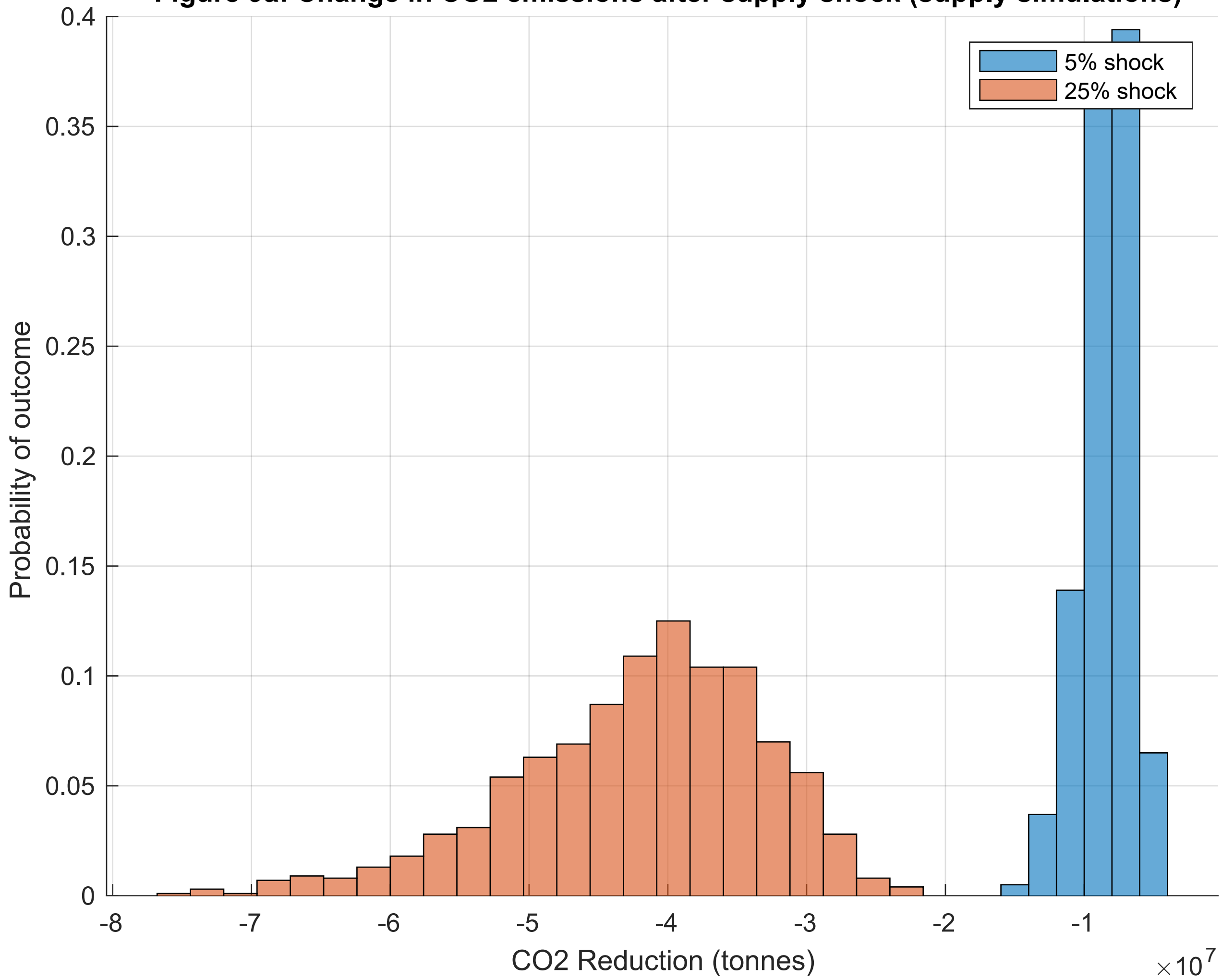


Figure 9b: Change in CO2 emissions after supply shock (supply simulations)

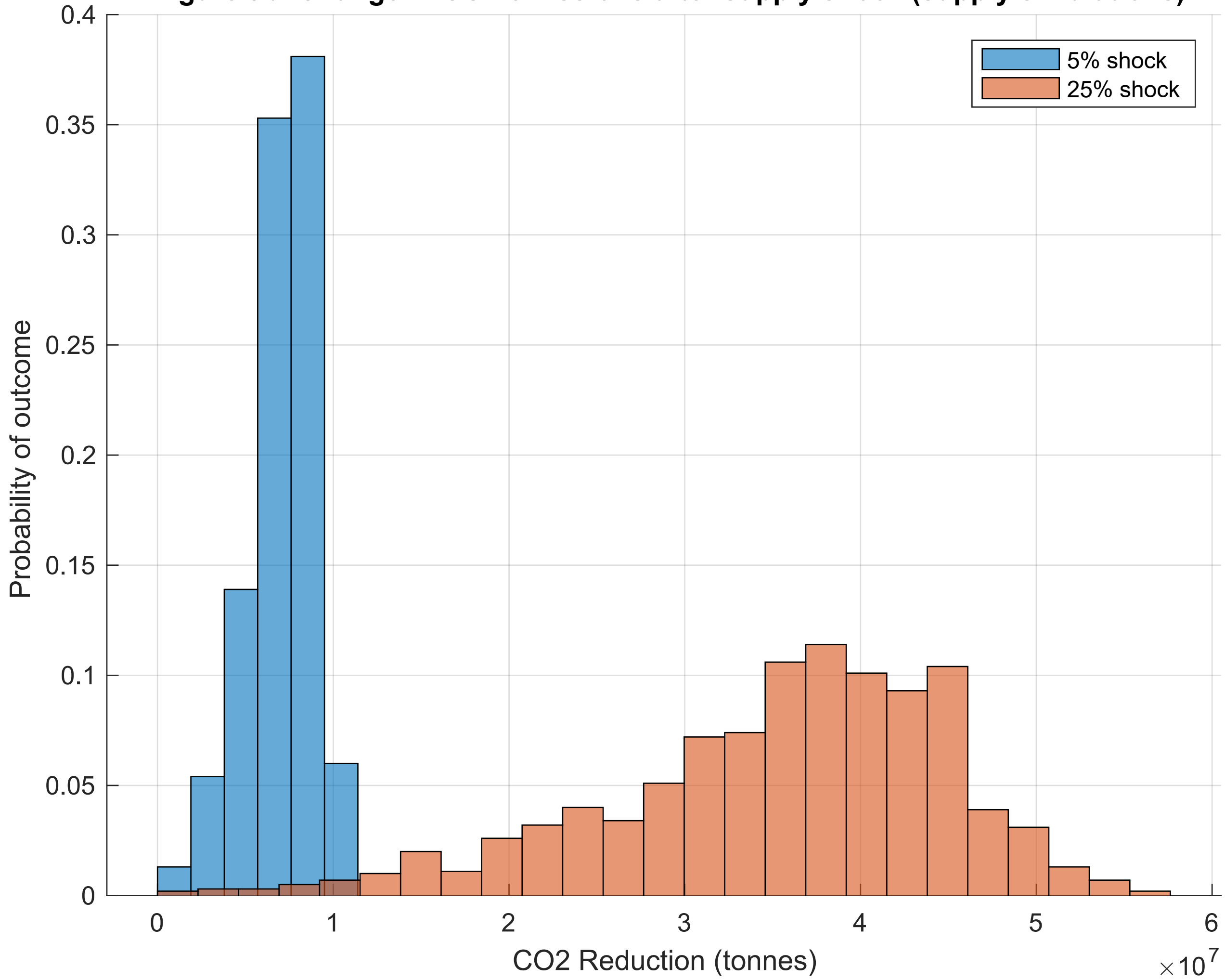
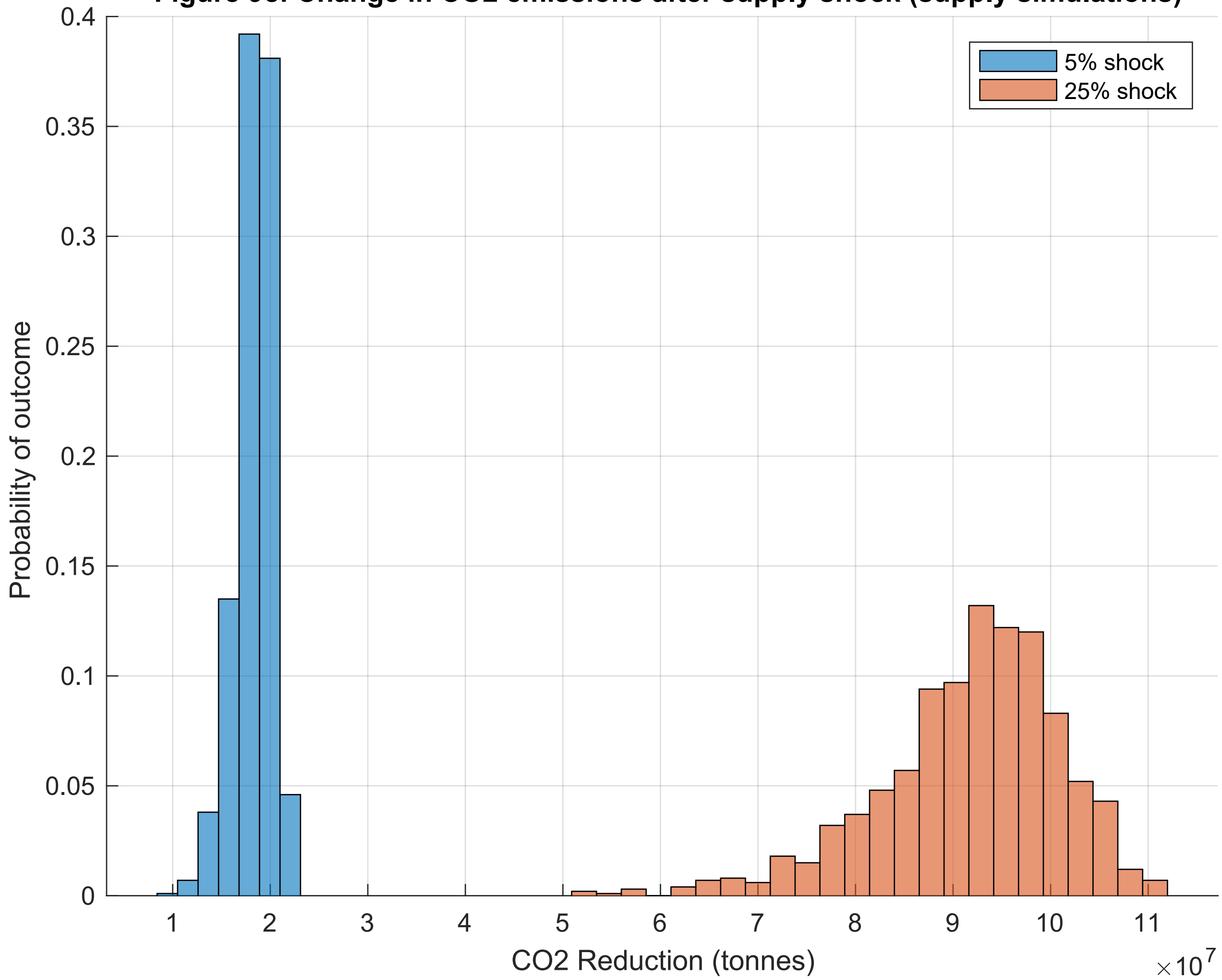


Figure 9c: Change in CO2 emissions after supply shock (supply simulations)



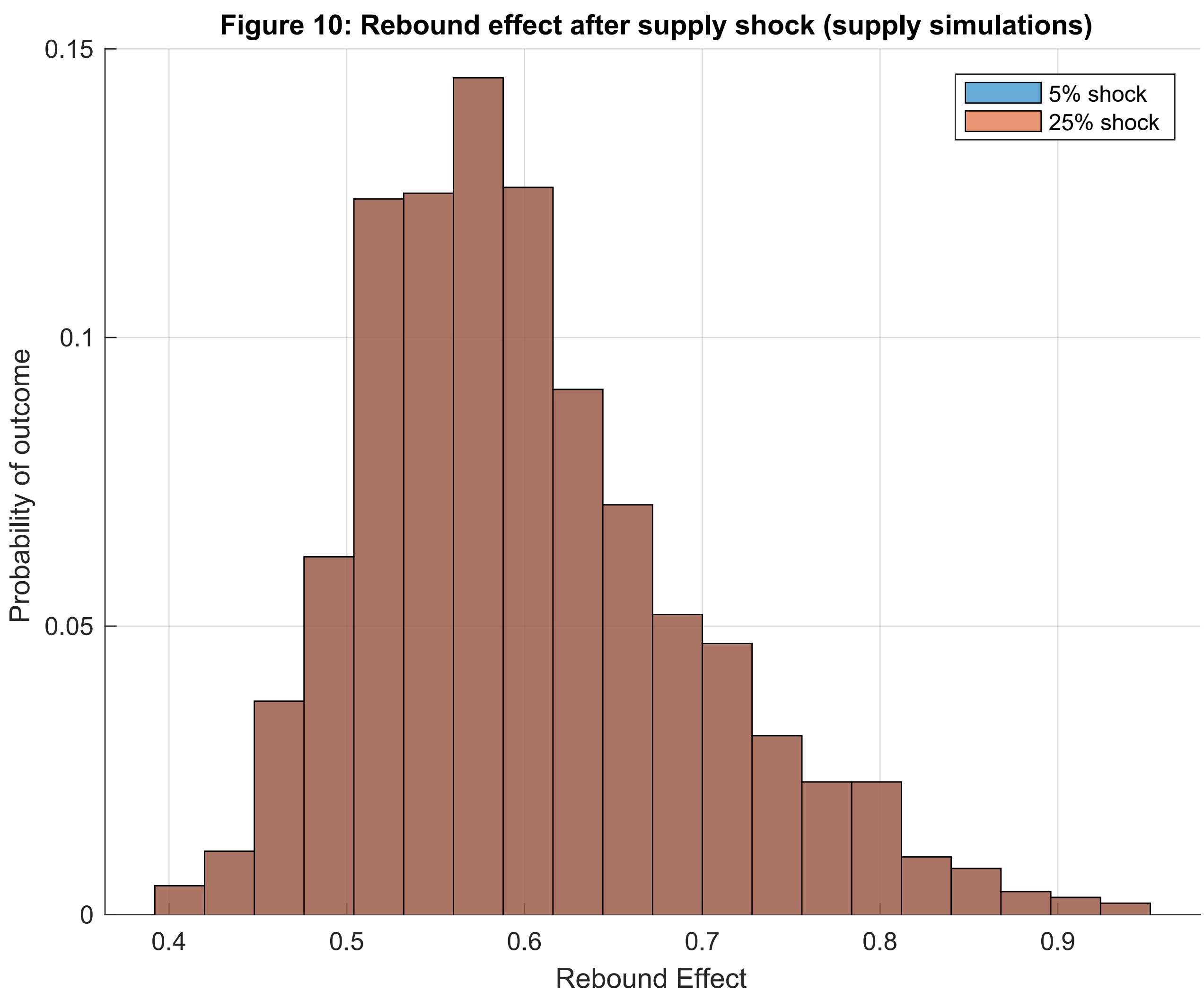


Figure 10: Rebound effect after supply shock (supply simulations)
5% shock
25% shock
Probability of outcome
Rebound Effect
0.15
0.1
0.05
0
0.4
0.5
0.6
0.7
0.8
0.9

Figure 11: Welfare change (baseline parameters)