Working Paper 2017-01

Biomass to Fuel:
The Case of South Korea

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Contents

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Abstract

In this report, we investigate the biofuel potential of South Korea and the implications of the introduction of biofuels for the Korean fuel market. Our biomass assessment suggests that (theoretically) biomass can be used to produce a significant portion of the fuel consumed annually in South Korea, with the most promising feedstock being forestry residues. And out of all the technologies considered, the production of cellulosic ethanol from forestry residues could potentially impact the fuel market the most. The key novelty of our study lies in that we consider a broad portfolio of biofuel technologies and carefully examine 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.

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1 Introduction

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

The motivation for the introduction of biofuels in South Korea is, in part, based on the costly means currently employed to deliver transportation fuels to its fuel consumers. Energy security—i.e., the uninterrupted availability of natural resources for fuel consumption at an affordable price—is thus an important component of the motivation to incentivize the use of biofuels. Moreover, the penetration of renewable energy technologies in South Korea's fuel market, albeit limited so far, has also been driven by its strategic goal to downscale greenhouse gas (GHG) emissions by 37% by 2030 as compared with the business-as-usual scenario (Kafle et al., 2017). This has led to, among other policies, government-funded research and development (R&D) activities regarding non-food feedstocks that could be used in the production of fuel for transportation. Still, at this point, there is urgent need for South Korea to efficiently manage its available natural resources in order to effectively support the growth of its bioeconomy (Kafle et al., 2017).

In the past, biofuels were (almost) exclusively produced from food commodities such as corn (in the United States) and sugarcane (in Brazil), and this led to a heated food-versus-fuel debate (Chakravorty et al., 2009; Hochman et al., 2014). Even though the effect of first-generation (i.e., conventional) biofuels on food commodity prices in the short run might be large, in the long run, a different picture seems to emerge. For instance, Hochman and Zilberman (2017) demonstrate that the effect of the introduction of corn-ethanol on corn prices in the medium to long run is moderate at most. However, the perceived impact of first-generation biofuels on food (commodity) prices and their substantial potential short-run price effects resulted in a strong push for the use of non-food feedstocks in the production of biofuels.

With respect to the environment, the environmental benefits of first-generation biofuels are minimal, if any (Hochman and Zilberman, 2017). Nevertheless, it should be noted here that the estimates of the indirect land use change (ILUC) impact of biofuels as reported in the literature have significantly declined since the concept of ILUC was first introduced back in 2008 (Searchinger et al., 2008), and are currently severalfold smaller than that original figure (Hertel et al., 2010; Hochman and Zilberman, 2017). On the other hand, advanced (i.e., second- and third-generation) biofuels have great(er) potential for mitigating GHG emissions (International Energy Agency, 2008).

South Korea is not a big user of biofuels and waste (in terms of their share in Total Primary Energy Supply), but it is a relatively large consumer of biodiesel (Kang et al., 2015). In addition, Lim et al. (2017) have shown that the gasoline consumers in South Korea are willing to pay a significant premium for the consumption of E5 gasohol (i.e., 5% bioethanol and 95% gasoline). On the other hand, Lee et al. (2011) argue that South Korea's limited biomass resources along with the high production costs of biofuels present significant barriers to the widespread adoption of biofuels and the achievement of the 2030 implementation targets. However, learning by doing can significantly reduce the biofuel production costs, as demonstrated by Goldemberg et al. (2004) and Chen and Khanna (2012). In a recent paper, Lee and Huh (2017) make projections for South Korea employing the forecasting model for new and renewable energy supply used in the 2014 Fourth Basic Plan for New and Renewable Energy of the Korean government—with the government target for 2035 for the deployment rate of new and renewable energy standing at 11%. Their projections show that Korean new and renewable energy production will reach approximately 37 million tonnes of oil equivalent by 2035, with part of this production coming from biofuels (bioethanol and biodiesel).

Focusing on advanced biofuels, with the development and commercialization of the relevant technologies, the numerous rice-growing areas in South Korea can use the rice straw to produce liquid fuels. Rice straw is an abundant and therefore attractive lignocellulosic material for biofuel production. It has high cellulose and hemicellulose content that can be readily hydrolyzed into fermentable sugars, although challenges do exist (Binod et al., 2010). Another promising advanced biofuel feedstock is microalgae, albeit high production costs—partly due to the challenge of harvesting these photoautotrophic microorganisms—are proving to be a major barrier to microalgae-based biofuel production (Lee et al., 2015). Microalgae have been researched in the context of biofuels in South Korea. In particular, as South Korea's energy policies over the past decade have placed increased weight on the development of green energies, the government has funded several R&D projects related to algal biofuel production. The underlying reason is straightforward. The Korean government has been gradually implementing higher biodiesel blending mandates, aiming to raise the portion of biodiesel to 5–7% in the blends by 2023. However, significant amounts of the feedstocks used in the production of biodiesel are currently imported by South Korea—mainly from Argentina, Brazil, Indonesia, and Malaysia. The Korean government is thus incentivizing the development of non-food biodiesel farms in order to reduce the reliance on foreign sources for biodiesel production (Hong et al., 2015). Finally, miscanthus is another advanced biofuel feedstock that has drawn considerable interest. This interest stems from its high productivity, low input requirements (N_2 fertilizer and herbicides), and high content of polysaccharides (Kim et al., 2012).

The potential of biofuels (especially of the advanced ones) for mitigating GHG emissions has led several countries to promote their production and consumption. The European Union, for example, is adopting policies to incentivize the use of advanced biofuels for transportation produced from agricultural and forestry residues and biogenic wastes (Searle and Malins, 2016). Nonetheless, numerous challenges do exist. For instance, Börjesson Hagberg et al. (2016) have used the MARKAL_Sweden model—a dynamic, bottom-up, cost-optimization model covering the energy system in Sweden—to show that although system integration of biofuel production could have noteworthy effects on the overall energy system of Sweden, in the long run and under stringent CO_2 constraints, it will have limited impact on total biofuel use in the transportation sector. Furthermore, in the United States, the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 ushered into the energy markets the Renewable Fuel Standard, which resulted in significant economic gains for its agricultural sector and improved substantially its balance of trade, but had relatively minor implications for GHG emissions (Hochman and Zilberman, 2017).[1]

In this report, we investigate the biofuel potential of South Korea and the implications of the introduction of biofuels for the Korean fuel market. A partial-equilibrium numerical model is employed in our analysis. 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 fuel 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 fuel consumed annually in South Korea, with the most promising feedstock being forestry residues. And out of all the technologies considered, the production of cellulosic ethanol from forestry residues could potentially impact the fuel 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 biofuel supply-shock scenarios, while randomly perturbing the demand and supply elasticities (separately). Our analysis illustrates that the introduction of biofuels leads to an increase in the total amount of fuel consumed and a decrease in the market price of fuel. As a result, an environmentally detrimental rebound effect arises, whereby gasoline consumption declines by less than the amount of the biofuels introduced. For example, when perturbing the demand elasticity and under an ambitious scenario of a 25% biofuel supply shock, the total quantity of gasoline

[1]See also Rajagopal et al. (2015) for a comparison of the costs and benefits of the Renewable Fuel Standard against those of the Low Carbon Fuel Standard introduced by California.

consumed decreases (on average) by only 8.7%, implying a 65.2% rebound effect. Still, though, CO_2 emissions are mitigated by 0.27 million tonnes. And aggregate welfare in the economy does rise.

A vast body of literature has investigated the economic and environmental ramifications of biofuels, with many of these papers focusing on corn-ethanol (see Hochman and Zilberman, 2017, and references therein). Regarding the analytical methods used, a large number of papers employ numerical methods in their analysis like in this report. Moreover, some papers resort to a partial-equilibrium analysis like here (e.g., Stoft, 2010; Hochman et al., 2011), while others use a computable general equilibrium model (e.g., Hertel et al., 2010; Tyner et al., 2010). The key novelty of our study lies in that we consider a broad portfolio of biofuel technologies and carefully examine 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.

The next section presents a simple conceptual framework for our study. Section 3 offers a biomass assessment for biofuel 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 fuel market of South Korea, we employ a partial equilibrium analysis. We have elected to use partial equilibrium analysis because it enables us to demonstrate our key results in a straightforward and clear manner.

Let p_g denote the price of gasoline in Won per gallon, and assume that demand, $D(p_g)$, is a linear downward-sloping function. For simplicity, let us assume that the supply of gasoline, denoted by $q_g = S(p_g)$, is a linear, upward-sloping function.

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_g^0, while the corresponding equilibrium price is p_g^0.

The energy content of ethyl alcohol (i.e., ethanol) per unit of volume is β percent that of gasoline (it is about 67% that of gasoline). We, therefore, assume that the price of ethanol is just:

$$p_e = \beta \cdot p_g \ . \tag{1}$$

For simplicity and brevity, we will henceforth focus on the price per gallon of gasoline equivalent (GGE), p_f, where $p_f = p_g = \frac{p_e}{\beta}$.

The introduction of biofuels results in a shift of the aggregate fuel supply curve. In our analysis, we assume that it shifts the aggregate fuel supply curve down and to the right. More specifically, given the fuel price p_f^0, we assume that the introduction of biofuels in GGE units results in the supply curve shifting down and to the right by $B = \frac{X}{100} \cdot q_f^0$, where B is the biofuel amount (in units of GGE; see Figure 2). Note that in the case of ethanol-blended gasoline, this is definitely a reasonable assumption. For instance, according to the July 2017 price report by Clean Cities (2017), in almost all regions of the United States, E85—which actually contains in the United States, on average, approximately 70% ethanol (and not 15%)—was cheaper than gasoline on a $/gallon basis during the period July 1–17, 2017.[2]

Holding the biofuel amount constant, we next describe the convergence to the new equilibrium—point C in Figure 2. At point C, the price has decreased to p_f^1, while the aggregate amount of fuel consumed has increased to q_f^1. Thus, the introduction of biofuels leads to lower fuel prices to end users and more fuel consumed.

Nevertheless, since the introduction of biofuels leads to the fuel price declining, it gives rise to an environmentally detrimental rebound effect. That is, the decline in the fuel price results in the demand for gasoline declining by less than the GGE amount of the biofuels

[2] The only exception was New England.

introduced. In terms of Figure 2, point C is down and to the right of point A, and the new amount of gasoline consumed is $q_f^1 - B > q_f^0 - B$. The rebound effect, then, equals:

$$\frac{q_f^1 - q_f^0}{B} \,. \tag{2}$$

The implication of the rebound effect is that the impact of the biofuel introduction on CO_2 emissions is smaller than that implied by a life-cycle analysis, since although biofuels might "burn" cleaner than gasoline, aggregate fuel consumption increases, and thus, total CO_2 emissions do not decline as much.

3 Setting up the model

In this section, we first offer an assessment of the theoretical biomass potential and of the amount of fuel 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 data on forestry residues that could be used for biofuel production (e.g., cellulosic biofuels) comes from the Korean Statistical Information Service.[3] 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 could be used in our case. When approximating the theoretical biomass potential, we use the data for 2015. To calculate the potential biomass from forestry residues (in cubic meters), we use the data on forest area and volume. Nevertheless, because the data only provides 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. However, to get some first insights into it, we

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

assume a density of 380 kg per cubic meter of solid volume.[4]

Next, we calculate livestock manure. The number of heads of beef cattle, dairy cows and heifers, pigs, and chicken (layers and broilers) is taken again from the Korean Statistical Information Service.[5] The data on chickens only includes information on broilers and layers; it does not include information on breeding chickens. Also, 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 volatile solids (VS) that each type of livestock produces, the following equation and values are used:

$$VS = AP \cdot TAM \cdot vs \ , \tag{3}$$

where:

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

The VS amount of each livestock is then converted into GGE using the parameters of the NJ (2011).

The final group of feedstocks that could be used for biofuel production includes staple crops: sorghum, sweet corn, and wheat. The data is taken from FAOSTAT.[6] The data is in metric tons (for the year 2013). We convert the values to GGE of biofuels, applying the net usable percentage and percent dry matter coefficients as obtained from NJ (2011).

The data in Table 1 was constructed following the above methodology and presents an approximation only of the theoretical (i.e., upper-bound) biofuel potential of South Korea.

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

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

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

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 various 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 fuel demand and supply functions for South Korea, assuming the following linear system of equations:

$$p_f = \alpha_0 - \alpha_1 \cdot q_f \qquad \text{(the demand equation)} \tag{4a}$$

$$p_f = \gamma_0 + \gamma_1 \cdot q_f \qquad \text{(the supply equation)} \tag{4b}$$

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

$$\alpha_1 = -\frac{1}{\eta_d} \cdot \frac{p_f^0}{q_f^0} \tag{5a}$$

$$\gamma_1 = \frac{1}{\eta_s} \cdot \frac{p_f^0}{q_f^0} \tag{5b}$$

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, it is straightforward to calibrate the intercepts of the two equations:

$$\alpha_0 = q_f^0 - \alpha_1 \cdot p_f^0 \tag{6a}$$

$$\gamma_0 = q_f^0 - \gamma_1 \cdot p_f^0 \tag{6b}$$

The elasticity of the Korean fuel demand used in the baseline scenario is taken from Hochman and Timilsina (2017) and equals –0.5755. By contrast, we could not find information on the elasticity of fuel supply for South Korea. Thus, in the baseline scenario, we use the value of 0.3, which is in line with the values used in the literature (Rajagopal et al., 2007; Hochman et al., 2008; de Gorter and Just, 2009). Nevertheless, given the uncertainty regarding these parameters, we then randomly perturb the demand and supply elasticities separately through a Monte Carlo simulation. More specifically, we perform 1,000 Monte Carlo trials for each of the different biofuel supply shocks we consider (to be discussed below). For the random sampling, we use a triangular distribution for the own-price demand elasticity (with parameters –1.05, –0.5755, and –0.16) and a truncated normal distribution for the own-price supply elasticity (with mean of 0.3 and standard deviation of 0.1), with the demand elasticity being always negative and the supply elasticity being always positive.

When calibrating the demand and supply curves, we use data on gasoline consumption and price for the year 2013 as reported by the Korean Statistical Information Service.[7] The quantity is taken directly from the site, while the price, in Won per gallon, equals the ratio of gasoline expenditure divided by the gallons of gasoline consumed.

4 Analysis and results

The biomass assessment suggests that, theoretically, biomass can be used to produce a significant portion of the fuel consumed annually in South Korea. Although the political-economic potential is probably much smaller than the theoretical one (Brennan-Tonetta et al., 2014), it is likely to still be substantial for the fuel market of South Korea—an economy that currently depends on imports of crude oil and which has no domestic oil reserves it can harness.

Table 1 (see Section 3.1) presents the results of our biomass assessment by summarizing

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

the potential for biofuel production from various crops, livestock, and forestry residues. In theory, the most promising feedstock is forestry residues, whereas the staple crop potential is minimal, which is consistent with the fact that South Korea imports almost all of the wheat and sweet corn it consumes. Furthermore, out of all the technologies considered, the production of cellulosic ethanol from forestry residues could potentially impact the fuel market the most. The theoretical amount of cellulosic ethanol that could be produced from forestry residues is 38.86 billion GGE, which equals 122.3 million tonnes of oil equivalent. Note here that in 2015, South Korea consumed 122.64 million tonnes of oil equivalent of petroleum and other liquids (U.S. Energy Information Administration, 2017). In addition, our analysis shows that the introduction of biofuels results in a decline of the fuel price to end consumers and an increase in the total amount of fuel consumed. For instance, if beef cattle manure were utilized for fuel production, the fuel price could (in theory) fall by 8.2% (using the baseline parameters), while if pig manure were used, the price of fuel may decline by 5.3%.[8] On the other hand, if forestry residues were utilized, the shock to the fuel market could be of such magnitude that the market price of fuel collapsed.

Before proceeding further, a few remarks are in order. When assessing the net benefits from the development and deployment of biofuels, the direct (and indirect) costs associated with their production 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, while some of the others which have been commercialized, are currently employed to a limited extent only and gradually becoming cost-competitive (e.g., production of landfill gas or production of biogas by anaerobic digestion). Nonetheless, learning by doing and learning by researching can be very substantial in the renewable energy industry, which suggests that renewable technologies should be evaluated from a dynamic point of view. In fact, this is definitely the case for advanced biofuels. For instance, according to the National Renewable Energy Laboratory (2013), the modeled cost of cellulosic ethanol production de-

[8] As Table 1 illustrates, 230,098,749 GGE of biofuel could be produced in the former case, while 148,772,707 GGE of biofuel could be produced in the latter one.

creased from \$9.00/gallon to \$2.15/gallon (i.e., a 76.1% drop in production cost) over the period 2002–2012. Last, it is important to remember that biofuels burn cleaner than fossil fuels, resulting in fewer GHG emissions. This implies that from a Pareto efficiency perspective, whether a biofuel can provide net benefits to the society (or not) depends not only on its cost competitiveness but also on its environmental benefits and costs vis-à-vis its fossil-based counterparts. Put differently, the cost advantage of fossil-based fuels vis-à-vis (most) biofuels in part stems from the fact that the high environmental (and health) costs associated with the former are not reflected in their market price (in the absence of government policy).

Because of the many unknown parameters, which depend as we just discussed, among others, on the research and development of biofuel technologies and their commercialization and adoption, we simulate various biofuel supply-shock scenarios. To this end, we employ the Monte Carlo simulation described in Section 3.2, and analyze different supply-shock scenarios randomly perturbing first the demand elasticity. In Figure 3, we depict the distribution of the changes in the total quantity of fuel consumed arising from the 1,000 Monte Carlo simulations for two alternative biofuel shocks: 5% and 25% of the total gasoline consumed in South Korea in the year 2013.[9] The distribution of the changes in the fuel price for these two shocks is depicted in Figure 4. When focusing on the 5% shock, the total amount of fuel consumption increases, on average, by 3.3% (see Figure 3), while the market price of fuel decreases by 5.8% (see Figure 4). The 25% shock yields similar effects in terms of sign, with the price declining (on average) by 29% and the total quantity of fuel consumed increasing by 16.3%. The main difference—which stems from the assumption of a linear demand function and the fact that the amount of biofuel introduced in the second scenario (i.e., the 25%-shock one) is substantially larger—is that the distributions of price and quantity changes in the 25%-shock scenario are more variable.

In Figure 7, we depict the rebound effect (see Figure 2). The introduction of biofuels

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

does not result in a crowding out of gasoline. For example, a 5% biofuel shock results in a decline of only 1.7% (on average) in the total amount of gasoline consumed. That is, it results in a 65.2% rebound effect. Similarly, the 25% biofuel shock leads to a decrease in the total quantity of gasoline consumed by 8.7%. Clearly, the rebound effect does mitigate the environmental benefits from the introduction of biofuels. In the 5%-shock scenario, CO_2 emissions decline by just 54,612 tonnes, whereas under the 25%-shock one, CO_2 emissions are mitigated by 0.27 million tonnes.

Our next step is to randomly perturb the supply elasticity, sampling 1,000 times—for each supply shock under consideration—from a truncated normal distribution with mean of 0.3 and standard deviation of 0.1. The results of these Monte Carlo simulations are displayed in Figures 8–11 and are very much in line with the predictions emerging from the demand-elasticity simulations. Under the 5%-shock scenario, the market price of fuel decreases, on average, by 5.8%, while total fuel consumption increases by 3.4%. As expected, the 25% biofuel shock has more pronounced effects on the fuel market, leading to a 29.1% drop in price and a 16.8% increase in the quantity of fuel consumed (see Figures 8 and 9). Regarding the environmental benefits from the introduction of biofuels, under the conservative 5%-shock scenario, there is a mere 1.6% drop in gasoline consumption (implying a 67.1% rebound effect), reducing CO_2 emissions by 51,665 tonnes. On the other hand, under the (more) ambitious 25%-shock scenario, gasoline consumption decreases by only 8.2%, mitigating CO_2 emissions by 0.26 million tonnes.

Overall, the introduction of biofuels produces a net welfare gain (see Figure 12). More specifically, we look at the ramifications of different biofuel supply shocks for consumer surplus, the surplus of gasoline producers, and revenues from biofuel production (using the baseline parameters). The change in surpluses/revenues over different biofuel supply shocks is depicted in Figure 12, where the sum of the three (i.e., welfare change) is positive and increasing over the range of shocks considered. Obviously, the total gain for the Korean economy is lower than the welfare gain illustrated in Figure 12 because the biofuel production costs need to be taken into account. Nevertheless, we do not have reliable cost estimates to use for calculating the surplus of biofuel 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 biofuel production costs.

5 Policy discussion and concluding remarks

Fossil fuel use is the primary anthropogenic source of GHG emissions, and the transportation sector (including aviation and marine transportation) contributes almost one-fourth of worldwide CO_2 emissions (International Energy Agency, 2009). Focusing on South Korea, according to the U.S. Energy Information Administration (2016), on-road transportation energy use accounts for the largest share of its transportation energy consumption (as in all regions in the world), while marine transportation accounts for one-fourth of its total transportation energy use. This latter figure highlights the importance of marine transportation for a country such as South Korea, with its economy relying heavily on exports and with major trading partners reached mostly by sea. Furthermore, the U.S. Energy Information Administration projects an average annual growth of 0.8% in delivered transportation energy consumption for South Korea over the period 2012–2040.

The introduction of biofuels into South Korea's transportation sector can be highly beneficial, mitigating the sector's contribution to GHG emissions, as well as creating economic value and improving South Korea's balance of trade. Before showing the benefits to the Korean economy from the introduction of biofuels, 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 fuel that could be generated using domestic biomass feedstocks. This preliminary analysis suggests that (theoretically) the biofuel potential of South Korea is very substantial, with the most promising feedstock being forestry residues. One gap we believe future work should address is a more detailed and thorough assessment of the biofuel potential of South Korea. This assessment 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 biofuel production pathways and plausible supply chain structures that could become economically viable (in the future). Moreover, this assessment should explicitly consider political-economic and logistical constraints, such as policy and institutional barriers, political constraints, and harvesting and transportation constraints (related to the infrastructure in place). Such a thorough assessment will more accurately evaluate the economic viability and the environmental ramifications of biofuel production in South Korea.

In addition, in this work, we used a linear demand and supply system for the fuel market and calibrated it taking the own-price demand and supply elasticities from the literature. We subsequently used these curves to compute the social benefits from the introduction of biofuels. However, given the experience with first-generation biofuels and the fact that the biofuel potential of staple crops is minimal in South Korea, these benefits depend in practice both on the success of R&D activities regarding advanced biofuels and, afterwards, on the successful commercialization and adoption of these biofuels. It is true that some of the advanced biofuel 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 a limited 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, whether a biofuel can provide (or not) net benefits to the society depends not only on its cost competitiveness but also on its environmental benefits and costs vis-à-vis its fossil-based counterparts. In any case, before moving to large-scale development and deployment of biofuels, the impact of their production on food prices should also be investigated, and their land-use implications should definitely be explored. We leave these important issues for future research. Overall, as past studies have shown for the United States and Brazil (Hochman and Zilberman, 2017; Khanna and Zilberman, 2017), biofuels result in net (economic) welfare gains for the country producing and exporting the biofuel commodity, while opening up new avenues for its rural communities to prosper.

Regarding policy, South Korea's light-duty vehicle manufacturers can choose to meet either a fuel economy or a GHG emissions standard. In practice, though, the different metrics are closely related: improvements in fuel economy reduce CO_2 emissions, while CO_2 emissions are a subset of GHG emissions (U.S. Energy Information Administration, 2016). At the same time, a Renewable Fuel Standard program is in place, which mandates oil refiners as well as oil importers and exporters to blend their transportation fuels with a certain amount of biofuels.[10] As of July 31, 2015, all diesel fuel must contain 2.5% biodiesel fuel, and this percentage is expected to increase to 3% by 2018 and 5–7% over 2020–2023.[11] Given the fact that significant amounts of the feedstocks used in the production of biodiesel are currently imported by South Korea—as we discussed in detail in the introduction—we believe that the Renewable Fuel Standard program should be supplemented by policy measures aimed at promoting the development and adoption of advanced biodiesel (and advanced biofuels in general) produced from domestically sourced feedstocks. For instance, researching and developing advanced biodiesel for marine vessels may result in very cost-efficient and clean alternatives to the conventional fossil fuels currently used in marine transportation. Of course, passenger vehicles should constitute the main focus of the Korean government's policies as they consume almost half of the total energy consumed by the transportation sector in South Korea (U.S. Energy Information Administration, 2016).

At a broader level, the development of biofuels—a major component of the bioeconomy—has important implications for the sustainable development of the agricultural and natural

[10] See http://iea-amf.org/content/publications/country_reports/korea.

[11] At present, there is no mandate in effect regarding ethanol use, but according to the Korean Renewable Fuel Standard program, a 3% ethanol blend mandate is expected to be implemented by 2018, with this percentage rising to 5–7% over 2020–2023.

resource sectors. However, 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 biofuels (in South Korea and elsewhere). We are also likely to observe demand for tools to assess biofuel policies' economic and environmental impacts—the creation of such tools should be a major priority. To this end, it is important to understand the biofuel industry as a whole and identify plausible supply chain structures that could secure the biofuel production levels required to achieve the policy goals set in the political arena.

Finally, much thought needs to be given to the benefits of biofuel production vis-à-vis the benefits of possible alternative uses of the biomass resource. In particular, biomass can be used to produce electricity, and the technologies therein can become carbon negative (i.e., bioenergy with carbon capture and storage). Biomass-based electricity can then be utilized as a transportation fuel, especially in areas where the commuting distance is not long (e.g., ports or public transportation in cities). Biomass can also be used to produce hydrogen and/or ammonia, and even though the relevant technologies are very far from commercialization, their long-run potential is enormous.

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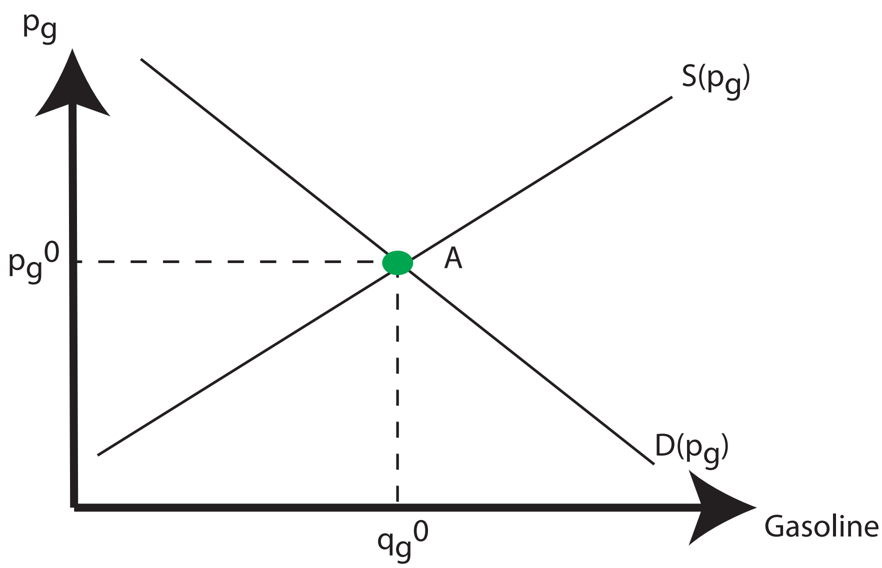


Figure 1: The gasoline market

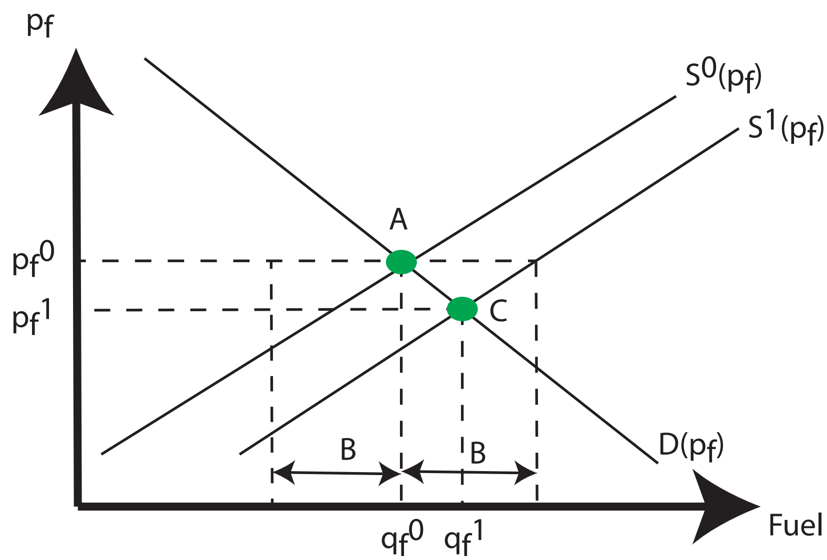


Figure 2: The fuel equilibrium

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

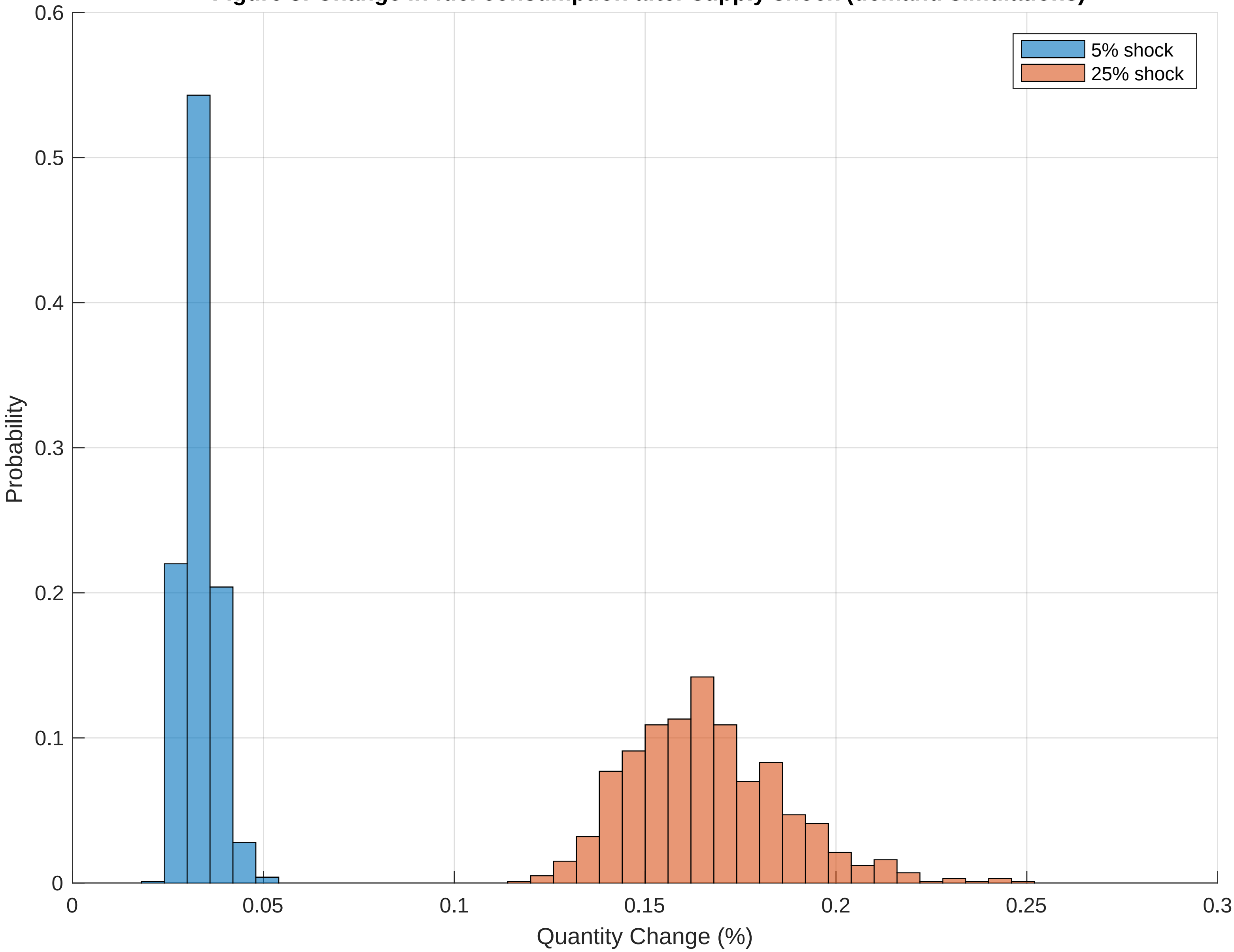


Figure 4: Change in fuel price after supply shock (demand simulations)

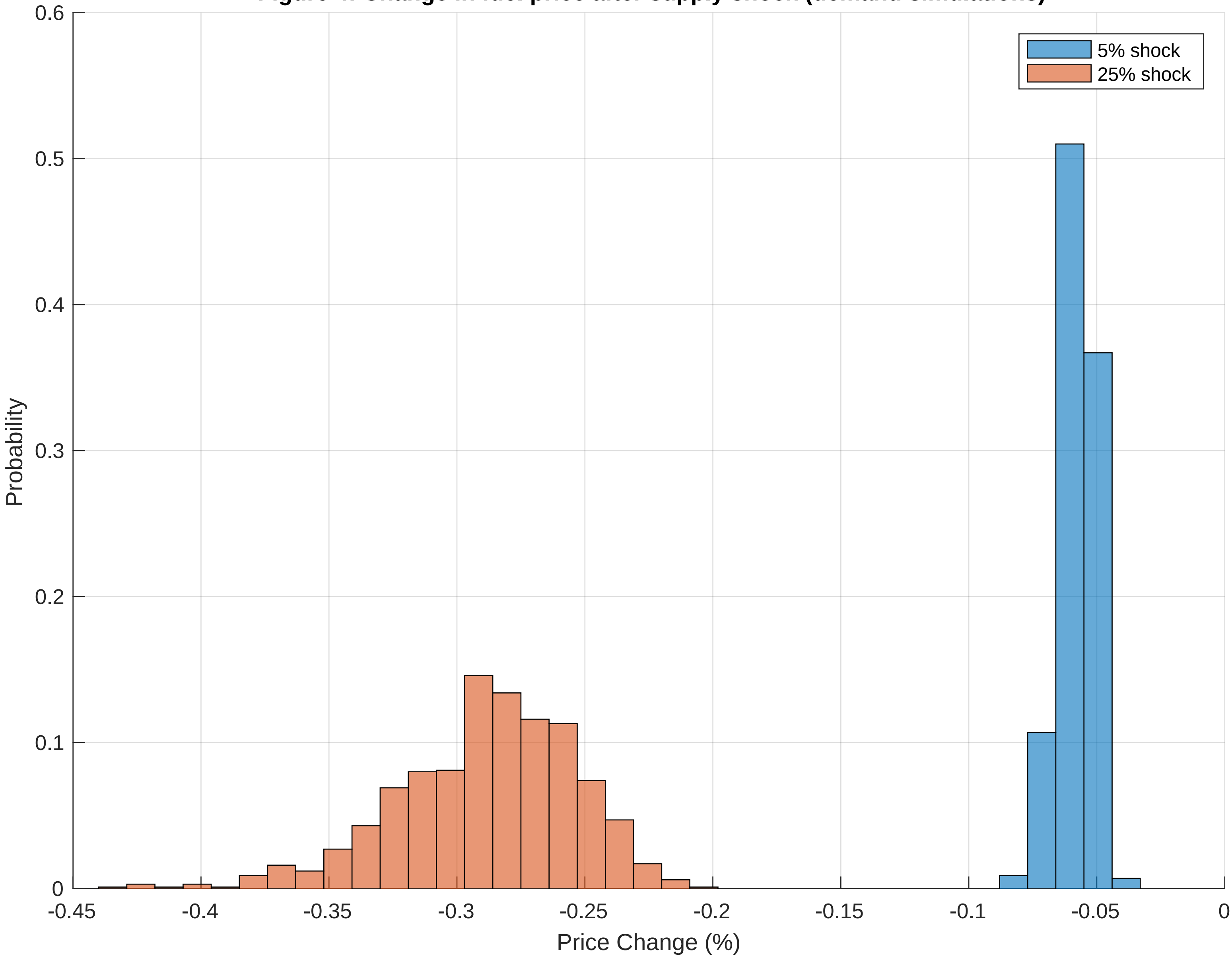


Figure 5: Change in gasoline consumption after supply shock (demand simulations)

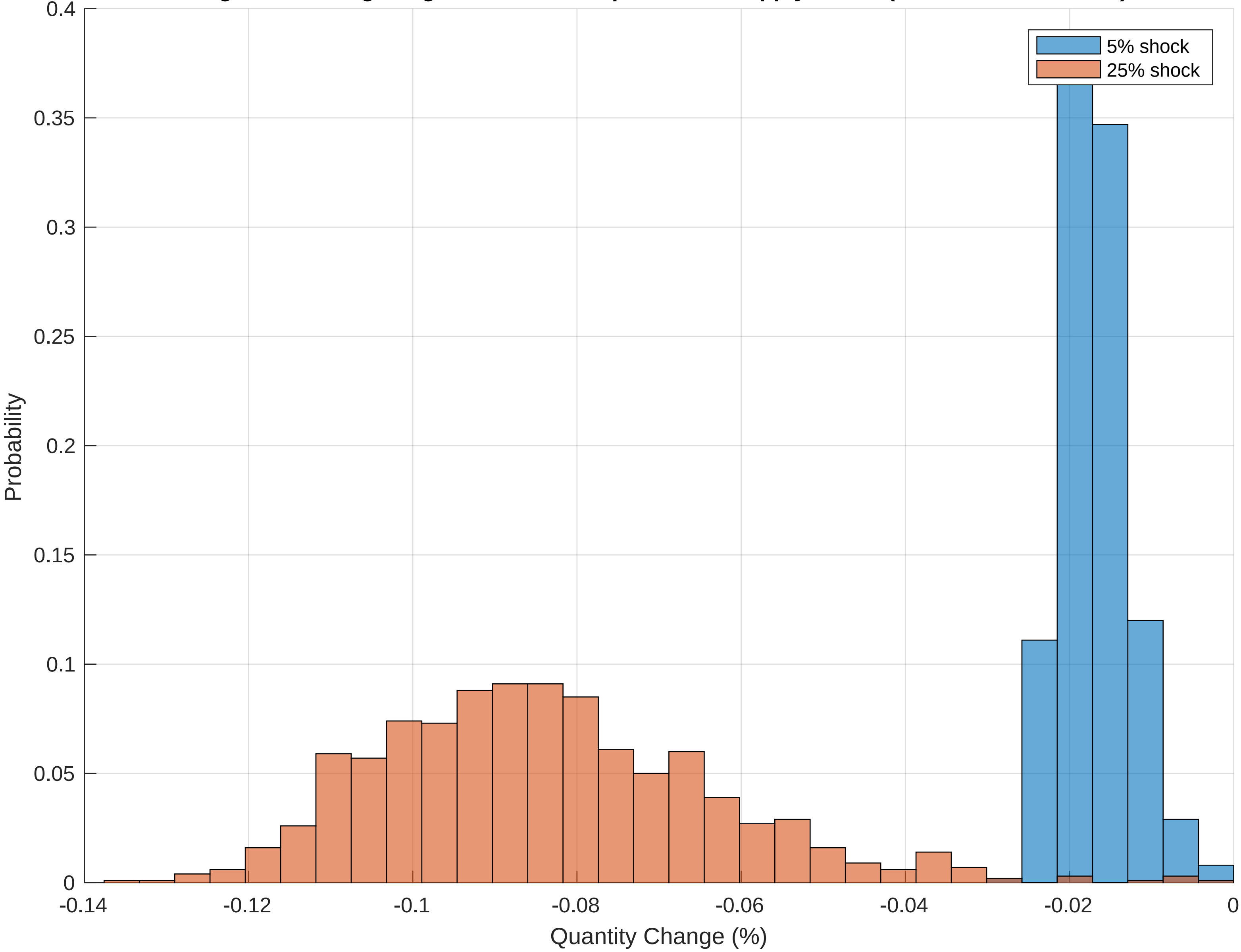


Figure 6: Change in CO2 emissions after supply shock (demand simulations)

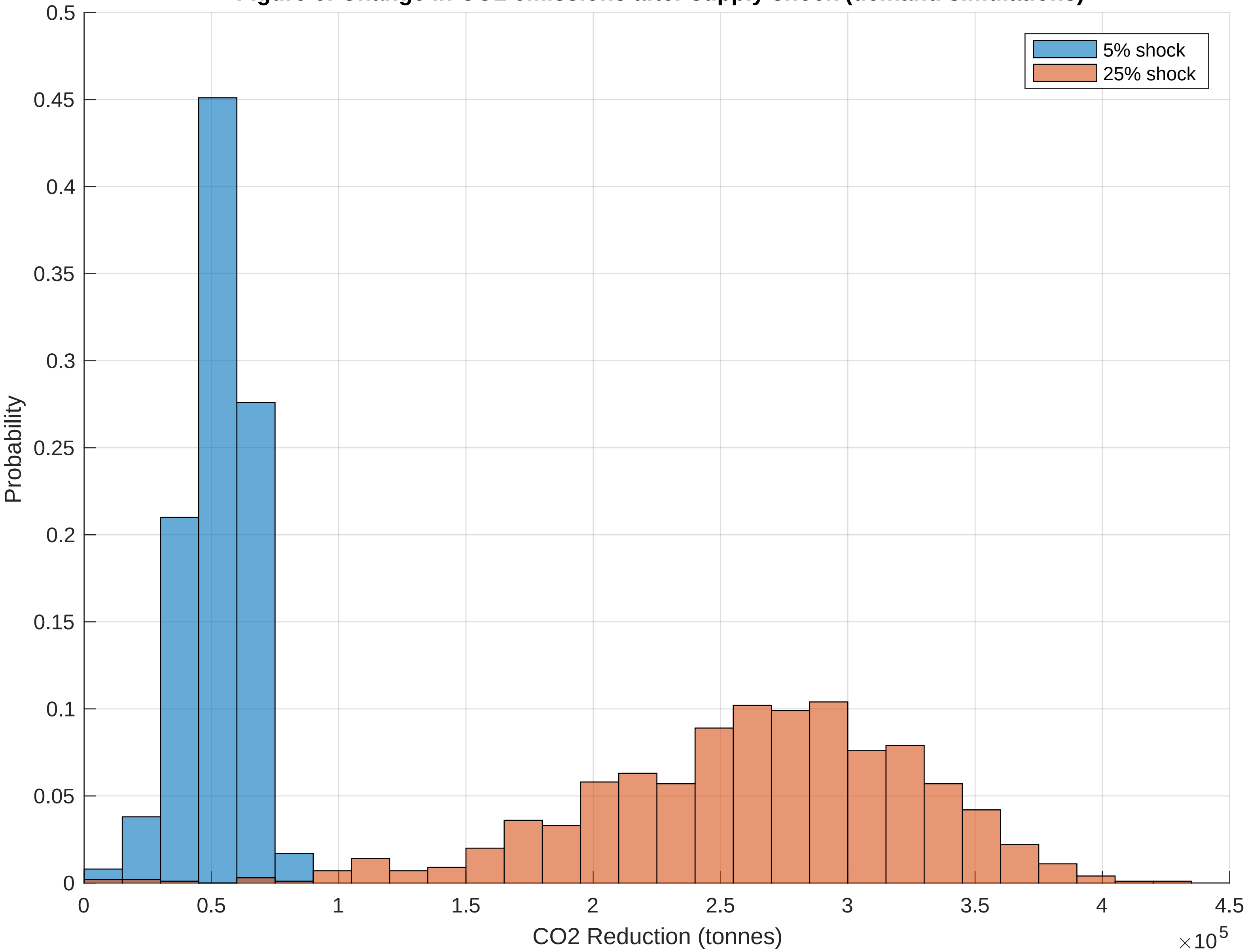


Figure 7: Rebound effect on gasoline consumption after supply shock (demand simulations)

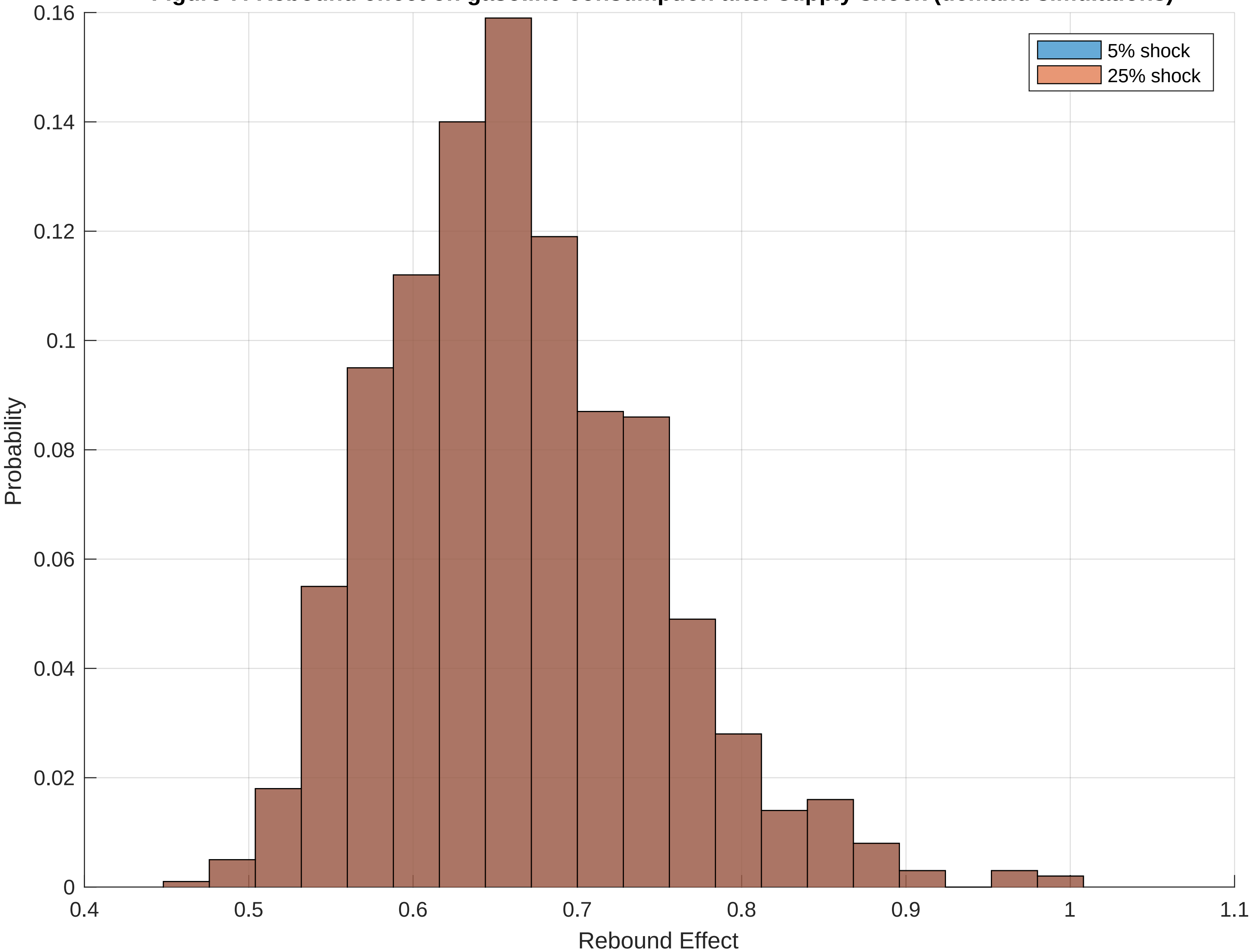


Figure 8: Change in fuel consumption after supply shock (supply simulations)

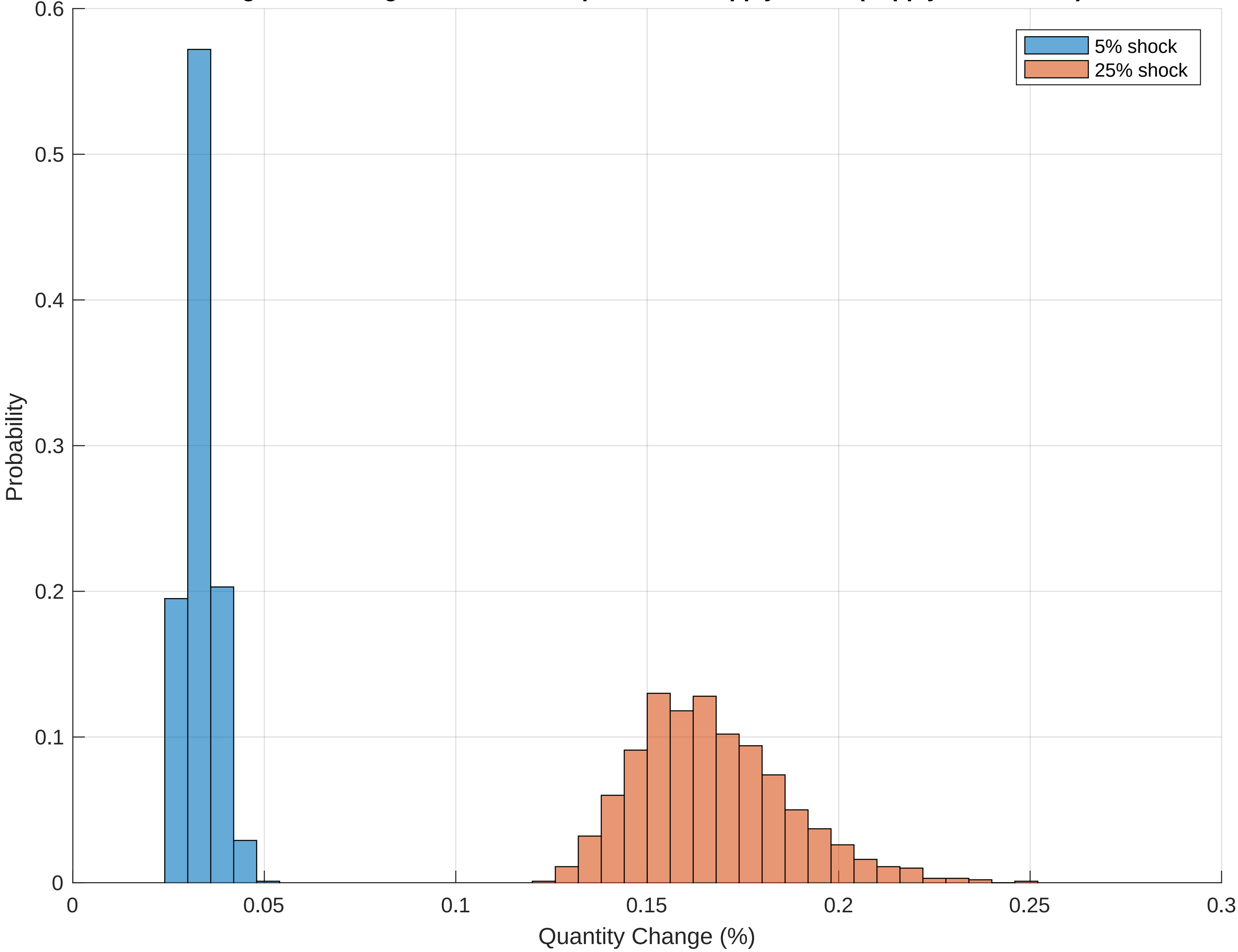
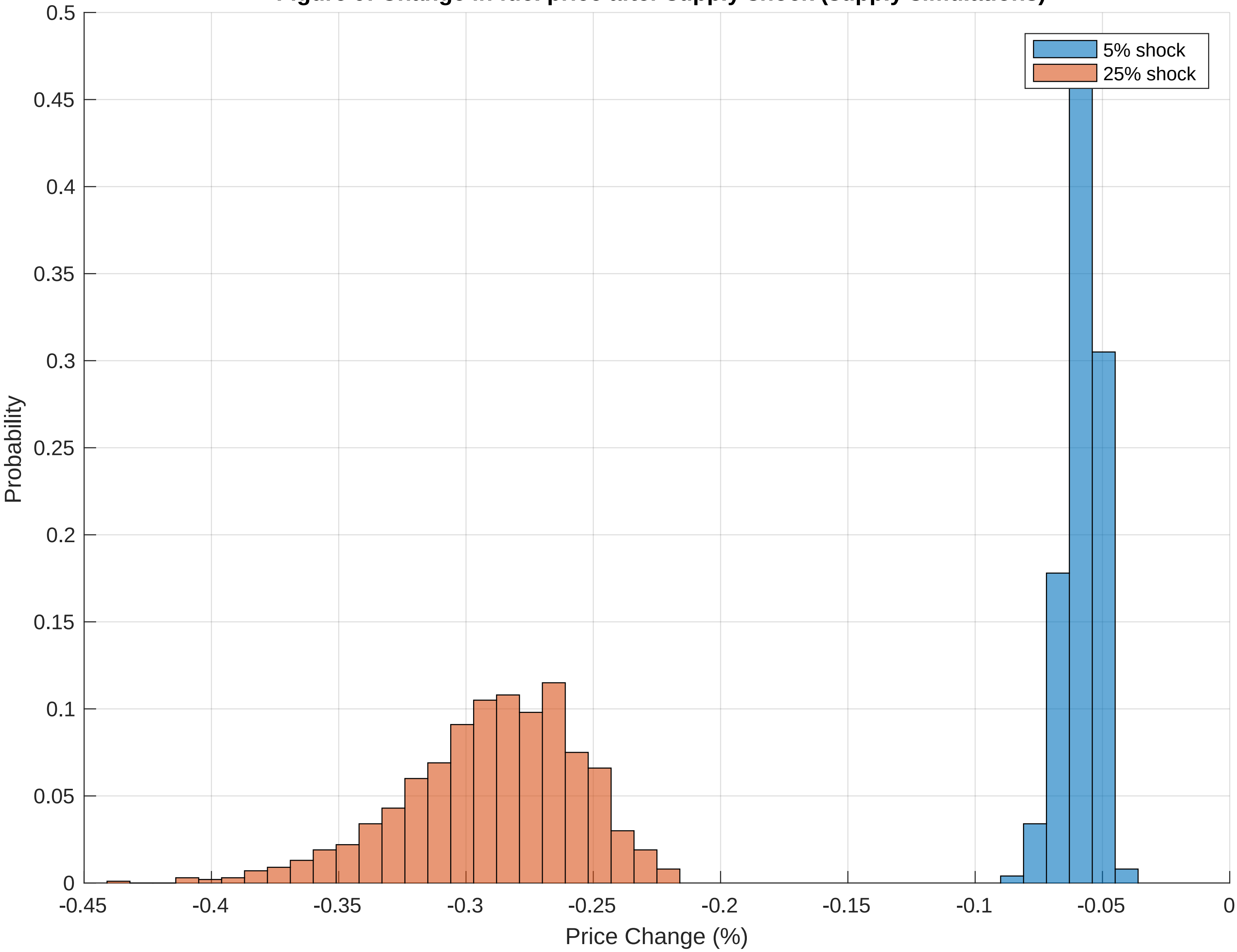


Figure 9: Change in fuel price after supply shock (supply simulations)



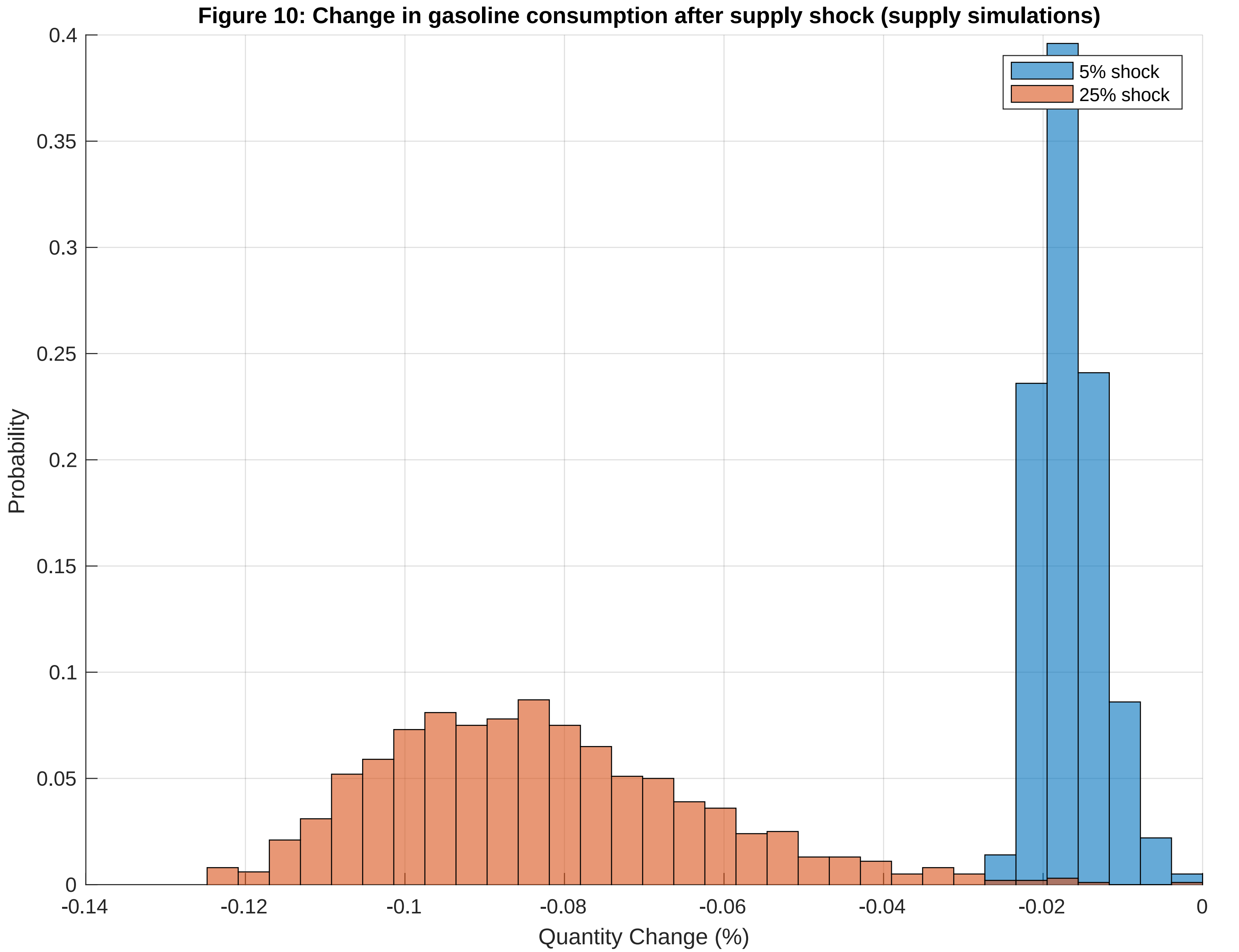
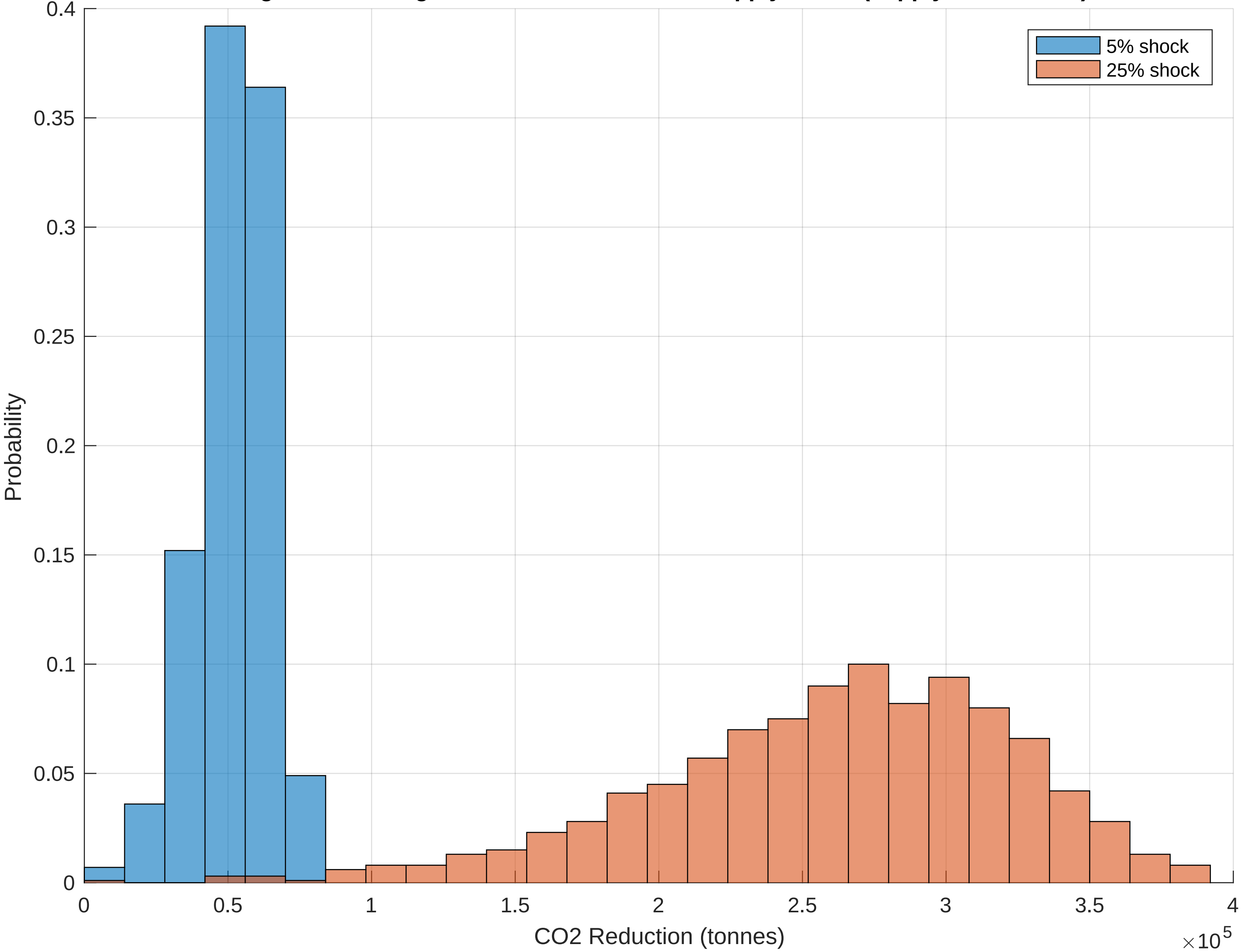


Figure 10: Change in gasoline consumption after supply shock (supply simulations)
5% shock
25% shock
Probability
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.14
-0.12
-0.1
-0.08
-0.06
-0.04
-0.02
0
Quantity Change (%)

Figure 11: Change in CO2 emissions after supply shock (supply simulations)



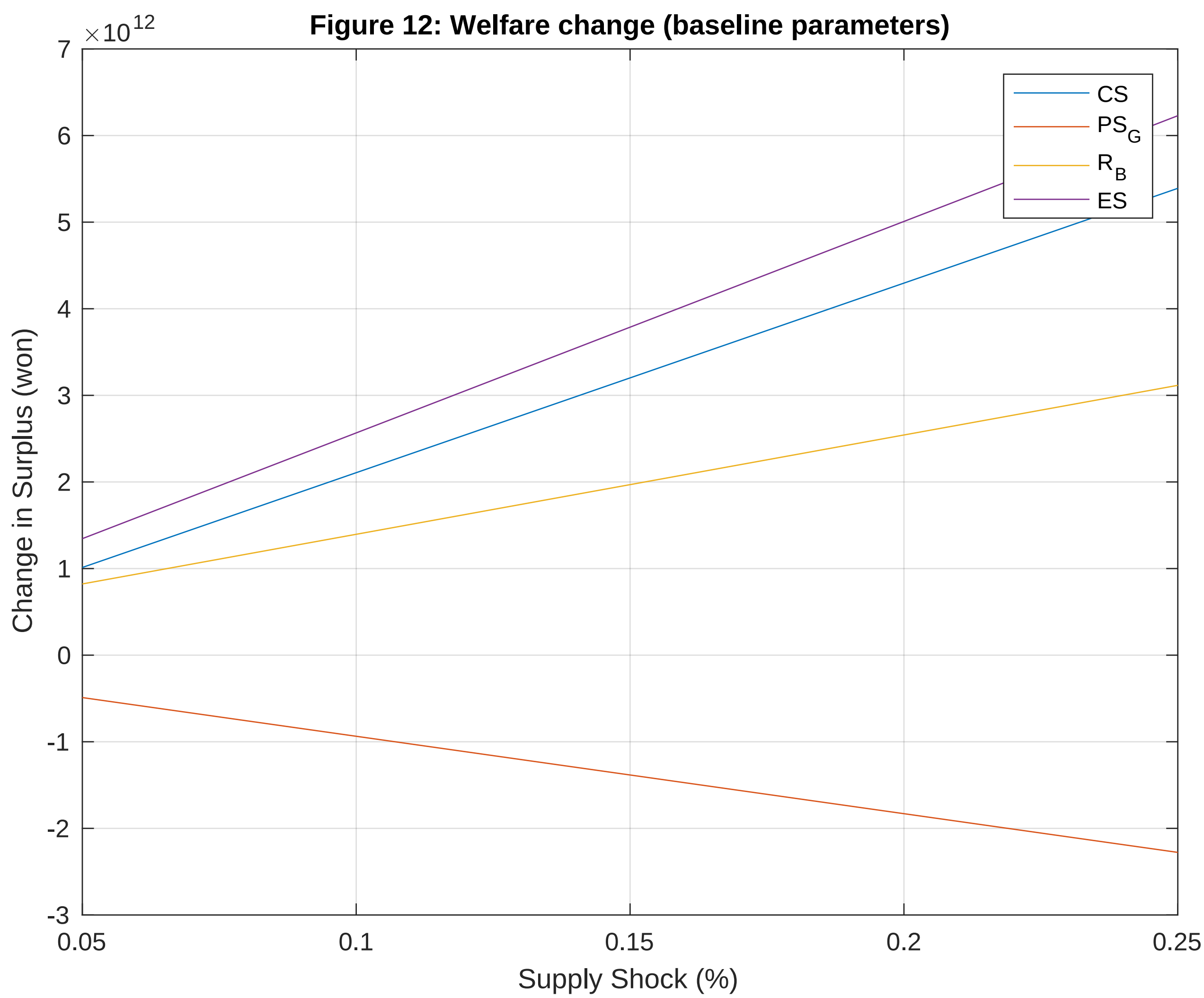


Figure 12: Welfare change (baseline parameters)
×10^12
7
6
5
4
3
2
1
0
-1
-2
-3
Change in Surplus (won)
0.05
0.1
0.15
0.2
0.25
Supply Shock (%)
CS
PS_G
R_B
ES

Table 1: Biomass assessment

	Feedstock Technology	Quantity	Unit
Crop			
Sorghum	Ethanol from starch	6,500	GGE
Wheat	Ethanol from starch	51,465	GGE
	Cellulosic ethanol	1,699,743	GGE
	Gasification-F–T	739,174	GGE
	Dilute acid hydrolysis	1,274,807	GGE
Sweet corn	Cellulosic ethanol	7,175,373	GGE
	Gasification-F–T	3,120,383	GGE
	Dilute acid hydrolysis	5,381,530	GGE
Livestock			
Beef Cattle	AD/Landfill gas to transportation fuel	230,098,749	GGE
Dairy Cows and Heifers	AD/Landfill gas to transportation fuel	61,923,062	GGE
Pigs	AD/Landfill gas to transportation fuel	148,772,707	GGE
Chicken	AD/Landfill gas to transportation fuel	55,319,876	GGE
Forestry Residues			
	Cellulosic ethanol	38,864,666,122	GGE
	Gasification-F–T	16,901,230,856	GGE
	Dilute acid hydrolysis	29,148,499,592	GGE