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Under What Conditions Does a Carbon Tax on Fossil Fuels Stimulate Biofuels?

Govinda R. Timilsina

Stefan Csordás

Simon Mevel

The World Bank
Development Research Group
Environment and Energy Team
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Abstract

A carbon tax is an efficient economic instrument to reduce emissions of carbon dioxide released from fossil fuel burning. Its impacts on production of renewable energy depend on how it is designed—particularly in the context of the penetration of biofuels into the energy supply mix for road transportation. Using a multi-sector, multi-country computable general equilibrium model, this study shows first that a carbon tax with the entire tax revenue recycled to households through a lump-sum transfer does not stimulate biofuel production significantly, even at relatively high tax rates. This reflects the high cost of carbon dioxide abatement through

biofuels substitution, relative to other energy substitution alternatives; in addition, the carbon tax will have negative economy-wide consequences that reduce total demand for all fuels. A combined carbon tax and biofuel subsidy policy, where part of the carbon tax revenue is used to finance a biofuel subsidy, would significantly stimulate market penetration of biofuels. Although the carbon tax and biofuel subsidy policy would cause higher loss in global economic output compared with the carbon tax with lump sum revenue redistribution, the incremental output loss is relatively small.

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Govinda R. Timilsina¹, Stefan Csordás and Simon Mevel

Key Words: Carbon tax, biofuels, climate change, CGE modeling, policy instruments

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¹ Corresponding author: Govinda R. Timilsina, Senior Research Economist, Development Research Group, The World Bank. 1818 H Street, NW. Washington, DC 20433, Tel: 1 202 473 2767. Fax: 1 202 522 1151. E-mail: gtimilsina@worldbank.org. We are grateful for insightful comments from three anonymous referees that have significantly helped improve the paper. We thank Mike Toman, Madhu Khanna, Luc Savard, Jian Xie, Ashish Shrestha and Henry Chen for their valuable comments; and participants of the 29th Conference of the North American Chapter of the International Association for Energy Economists for discussions. We acknowledge financial support from the Knowledge for Change Program (KCP) Trust Fund. The views and findings presented here should not be attributed to the World Bank, its management, or its member countries. Financial support from the Knowledge for Change program is gratefully acknowledged.

1. Introduction

Climate change is one of the greatest challenges the global community faces today.

Anthropogenic emissions of greenhouse gases (GHG) are the main culprit behind climate change (IPCC, 2007). One way of mitigating GHG emissions is to reduce the combustion of fossil fuels. This can be achieved in a number of ways such as by reducing end-use energy service (e.g., heat, light) demand through price increase, by reducing final energy (e.g., electricity, gasoline) without curtailing delivery of energy services through efficiency improvements and by substituting fossil fuels with non-fossil energy sources.

The transport sector is one of the main contributors to GHG emissions in many countries around the world (IEA, 2009). This sector does not offer many cost-effective alternatives to reduce GHG emissions. Biofuels is one of the options. While some life cycle analyses have cast doubt on the net GHG emission reduction potential of biofuels (Searchinger et al., 2008; Fargione et al., 2008), more than forty countries around the world have introduced mandates or set targets for biofuels (Timilsina and Shrestha, 2010). Several developed countries are continuing to push forward with policies that aim at increasing the share of biofuels in the transportation fuel mix (OECD, 2008).²

Long-term energy import substitution is another driving factor for biofuel promotion. For example, many Sub-Saharan African countries depend entirely on imports for meeting their transportation fuel demand and are thus exposed to the impacts of fuel price volatility on the cost of imports. These countries have abundant arable land resources that can be utilized to produce biofuel feedstock (Mitchell, 2010) in order to reduce their dependency on petroleum imports.

² The current policy instruments introduced in several countries to support biofuels include subsidies and mandates (Timilsina and Shrestha, 2010).

Despite recent efforts to promote biofuels, the current share of biofuels in the global energy mix for transportation is only around 2 percent on energy equivalence basis.³ One reason for this low market penetration⁴ is that the price of fossil fuels does not include its negative external costs (e.g., environmental damage) to society. Particularly in the context of climate change mitigation, this could be addressed by imposing a carbon tax on fossil fuels. However, how much a carbon tax would change the relative economics of biofuels and its penetration in the energy supply mix is an empirical question.

During the last two decades, a plethora of research both on carbon taxation and on biofuels has been produced. This literature spans a wide range of issues, methodologies and disciplines, and a detailed review is beyond the scope of this paper. A number of studies use either general equilibrium or partial equilibrium models that incorporate biofuels, to simulate climate change mitigation policies. For instance, Janssen and de Vries (2000) simulate different GHG mitigation policies, such as a carbon tax in the energy system model TIME that includes biofuels, to estimate the costs of stabilizing the CO₂ concentration in the atmosphere at 550 ppmv. However, the partial equilibrium approach employed in the TIME model does not account for economy-wide feedback effects of a carbon tax. Plevin and Mueller (2008) develop a bottom-up model to calculate the effects of a CO₂ tax and other emission policies on the costs of producing ethanol from corn, but also their model is partial equilibrium, and the study can therefore not account for the spill-over effects of carbon policies on other sectors of the economy. McCormick and Kåberger (2005) identify the Swedish carbon tax as a facilitating factor for the expansion of bioenergy in the town of Enköping, but such a case study does not

³ Authors' estimation for year 2008 based on data for global gasoline and diesel consumption in the transport sector from the International Energy Agency and ethanol and biodiesel production data from Timilsina and Shrestha (2010).

⁴ Biofuel penetration in this study is defined as the ratio of biofuels (ethanol and biodiesel) to the total liquid fuel consumption in the road transportation (i.e., biofuels, gasoline and diesel).

provide detailed aggregate quantitative results useful at the national or global levels. Schneider and McCarl (2005) show that a high level of carbon tax makes production of biofuel feedstocks profitable business and generates additional farm revenues. However, this would be true only in a partial equilibrium setting where negative impacts of a carbon tax on the other economic sectors and feedback to the agricultural sector is not accounted. This results would not necessarily hold true in a general equilibrium framework, the approach used in this analysis, as the contractual effects of a carbon tax on the economy could significantly erode the increased biofuel demand due to the substitution effect (i.e., substitution of fossil fuels with biofuels). In an earlier study by the same authors (Schneider and McCarl, 2003) reveal that a high level carbon tax causes biomass competitive in electricity production, however it does not help much stimulate ethanol production. However, the study focusses only on the US.

We developed a multi-country, multi-sector, recursive dynamic Computable General Equilibrium (CGE) model for the purpose of this study.⁵ We imposed a universal carbon tax on all fossil fuels, not just on gasoline and diesel as in a partial equilibrium approach.⁶ A carbon tax, if considered, would be introduced throughout the economy and applied to all fossil fuels because such a broad-based tax would be more effective than a narrowly based fuel tax to reduce GHG emissions. A sector specific carbon tax also would be difficult to implement as more than one sector uses the same fuel (e.g., use of diesel in the industry sector is almost at the same level or higher in some countries).

Accordingly, this study assumes a uniform carbon tax across the sectors, fuels and jurisdictions.

However, to understand the changes in biofuel penetration and overall economic impacts, we

⁵ A brief description of the model is provided in Section 2.

⁶ We note at the outset that the assumption of a global carbon-based tax on all fossil fuels is made only to facilitate the analysis of the issues mentioned above. There is no particular reason to suppose that international agreement on such a global carbon tax is likely.

also run a scenario in the sensitivity analysis where a carbon tax is imposed only on gasoline and diesel. The model produces a large number of results including impacts on GDP, sectoral outputs, household income and consumption, government revenue and expenditure, international trade of goods and services, demand for intermediate consumption and capital formation at country levels. However, for purpose of clarity and comprehensiveness, we present only key results, such as GDP, biofuel demand, agriculture outputs at the global and regional level.

Our study finds that such carbon tax, applied with lump-sum redistribution of revenues, does not in itself stimulate production of biofuels. This is because other opportunities for GHG mitigation, notably reduced coal use in the power sector, will be more cost-effective; in addition, the carbon tax will have negative economy-wide consequences (especially for fossil fuel producing and energy- and carbon-intensive manufacturing industries), and these effects in turn will reduce total demand for all fuels. However, if part of carbon tax revenue is used to subsidize biofuels, the combined effect of the carbon tax and biofuel subsidy would lead to a substantial increase in biofuel penetration. Although such a subsidy would cause further contraction of the economy by moving away from the cost-effective solution using the carbon tax alone, the additional output contraction is found to be small, in particular as compared to the negative aggregate output effect of a carbon tax alone. This finding is broadly similar to that of studies by Weber et al. (2005) and Barker et al. (2008), which find that if carbon tax revenue is used to finance GHG mitigation activities, such as improvement of energy efficiency, the environmental impacts of carbon tax is stronger as compared to a situation where carbon tax revenues are recycled for other purposes (e.g., lump-sum rebate to households).

The remainder of the paper is structured as follows. Section 2 provides a brief description of the CGE model developed for the study followed by presentation of key simulation results in Section

3. Section 4 highlights results of some sensitivity analysis followed by discussion on policy insight in Section 5. Finally, conclusions are presented in Section 6.

2. The Model and Data

We used a multi-regional, multi-sector, recursive dynamic CGE model⁷ for the purpose of this study. The basic data for the calibration of this model is derived from the GTAP 7.0 database with base year 2004. Although the GTAP database provides information for 113 countries and 57 production sectors/commodities, we disaggregated some sectors⁸ further and aggregated others and ultimately have 28 sectors and 25 countries/regions. The main reason of using the GTAP database is that there exists no other comprehensive global database required by this study. Moreover, most CGE models simulating biofuels are based on the GTAP database, and use of this database could help compare our results with those models where appropriate. The list of countries/regions and sectors/commodities considered in our model is provided in Table 1.

⁷ CGE models are based on disaggregated representations of various agents (households, firms, governments) exhibiting optimizing behavior and interacting via different markets (sectors, countries, regions). Underlying a CGE model are equations describing these variables and their interaction as well as the data needed to calibrate the model. Simple CGE models are comparative static, which means that they allow for comparison of the equilibrium state of the economy after a policy intervention has taken place with the situation in absence of the intervention. Dynamic models allow for tracing variables over the whole adjustment path. The advantage of CGE models over partial equilibrium analysis is that they account for interactive effects within and between sectors, agents and markets.

⁸ We disaggregated coarse grain to corn and other coarse grain as corn is the major biofuel feedstock. We also disaggregated petroleum products to gasoline, diesel and other petroleum products. We will briefly discuss the method of disaggregation later.

Table 1: Sector and Countries/Regions Considered in the Model

Sector/Commodity	Country/Region
1. Paddy rice	1. Australia and New Zealand
2. Wheat	2. Japan
3. Corn	3. Canada
4. Other cereal grains	4. United States
5. Vegetables, fruit	5. France
6. Oilseeds	6. Germany
7. Sugar (cane & beet)	7. Italy
8. Livestock	8. Spain
9. Forestry	9. UK
10. Processed food	10. Rest of EU & EFTA
11. Coal	11. China
12. Crude oil	12. Indonesia
13. Natural gas	13. Malaysia
14. Other mining	14. Thailand
15. Sugar ethanol	15. Rest of East Asia & Pacific (EAP)
16. Corn ethanol	16. India
17. Grains ethanol	17. Rest of South Asia
18. Biodiesel	18. Argentina
19. Gasoline	19. Brazil
20. Diesel	20. Rest of LAC
21. Refined oil	21. Russia
22. Chemicals	22. Rest of ECA
23. Other manufacturing	23. MENA
24. Electricity	24. South Africa
25. Gas distribution	25. Rest of Sub-Saharan Africa
26. Construction	
27. Transport services	
28. Other services	

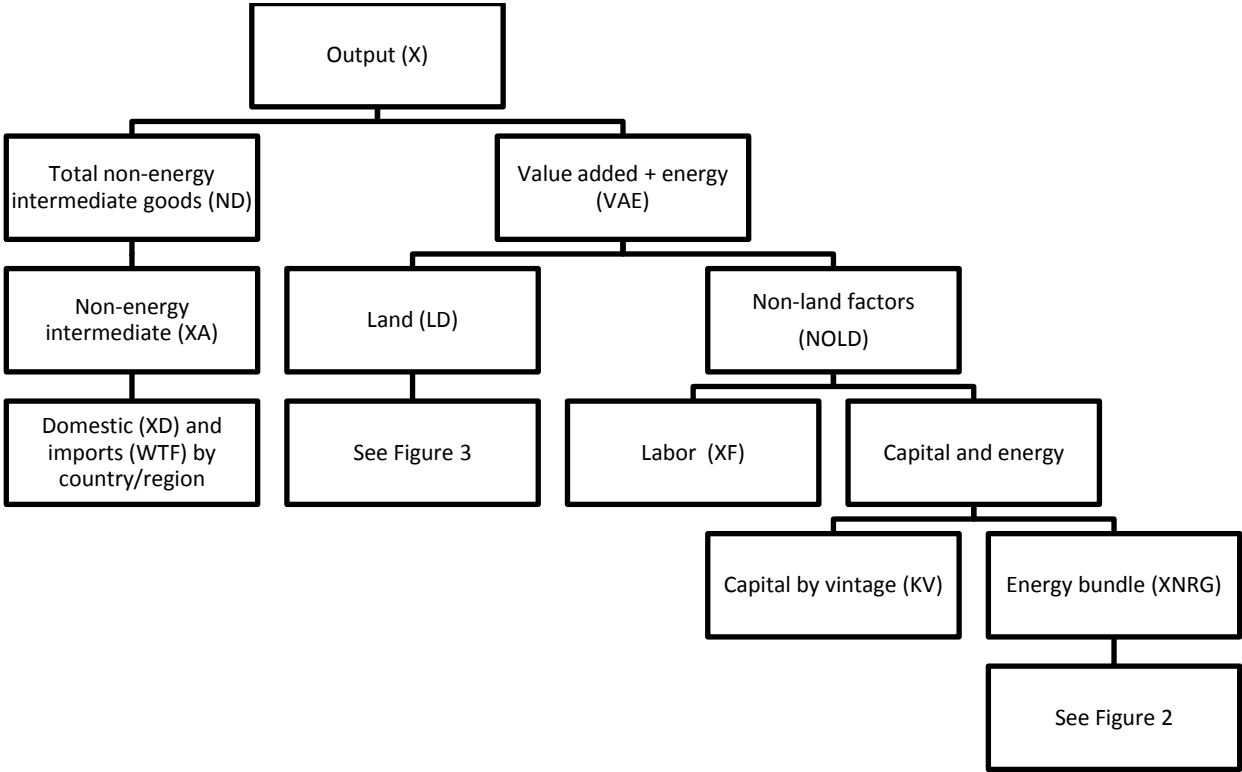
Note: EFTA includes Norway, Switzerland Iceland and Liechtenstein; MENA refers to Middle East and North Africa; ECA refers to Eastern Europe and Central Asia; LAC refers to Latin America and Caribbean.

Each of the 28 sectors is depicted by a set of nested constant elasticity of substitution (CES) production functions⁹ (see Figure 1). On the top level of the production structure firms in each

⁹ CES function is the most common functional form used in CGE modeling (please see e.g CGE models presented in Edenhofer et al., 2006 or Edenhofer et al., 2010). The main advantages of using CES functional form against other functional forms such as Cobb-Douglas and Leontief is that it allows to have nested production structure as well as

country/region minimize costs by choosing an optimal combination of the non-energy aggregate intermediate input (ND) and the composite of value added and energy input (VAE). On the left hand side of the second tier of the nested production structure, a non-energy commodity in a country or region is formed through a CES combination of that commodity produced in the country/region and imported from various countries/regions. Similarly, on the right-hand side of the same tier, the value added-energy composite is aggregated through a CES combination of the value added and the energy composite. The process continues as illustrated in Figure 1.

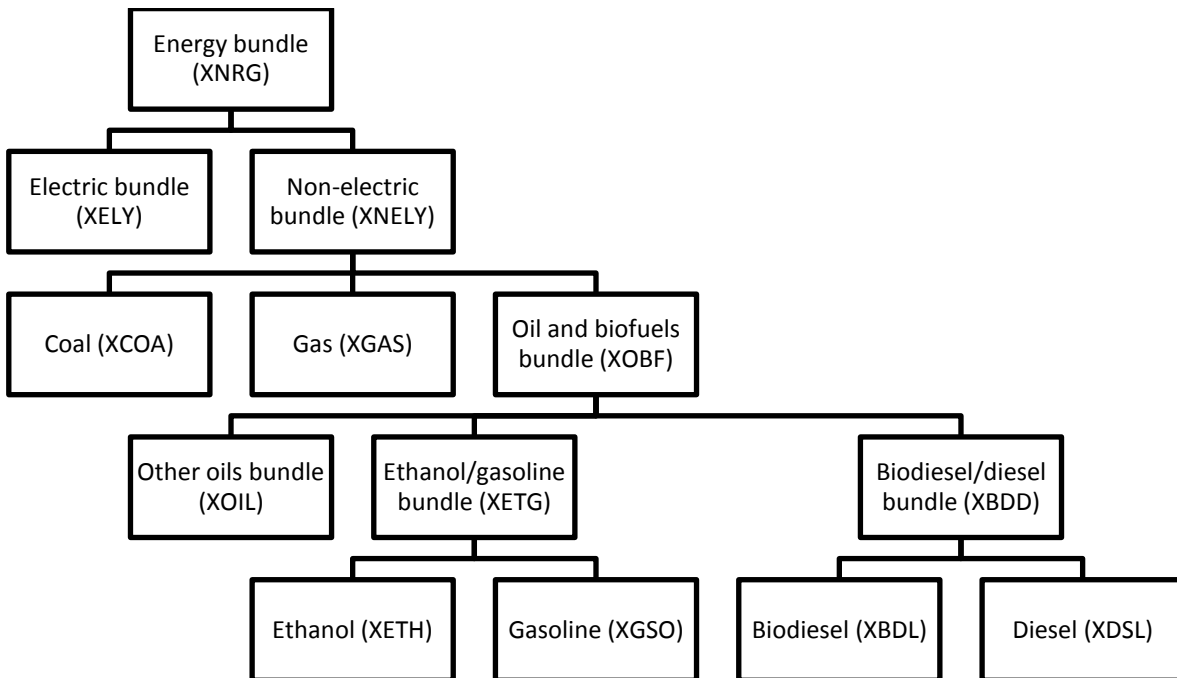
Figure 1: Structure of the CGE Model: Production Sectors



to have flexible substitution possibilities between factors of production; between aggregate factor of production and aggregate intermediate goods; and also between different types of intermediate goods. If necessary, the CES functional forms can be easily converted to Cobb-Douglas and Leontief functional forms by changing elasticity of substitution.

The study gives special attention to the energy sector modeling for two reasons. First, since a carbon tax is introduced to fossil fuels, we need an explicit representation of the fossil fuel sector including various petroleum products. Second, the study aims to assess the competitiveness of biofuels with fossil fuels when carbon tax is introduced into the latter; therefore, we also need an explicit representation of biofuels. As shown in Figure 2, the total demand for energy is a CES composite of electricity and an aggregate of non-electric energy commodities. One component of the latter is the liquid fuel, which is a CES composite of the ethanol-gasoline and diesel-biodiesel bundles. The model is structured in such a way that it allows direct substitution between gasoline and ethanol, and between diesel and biodiesel.

Figure 2: Module for the Energy Sector

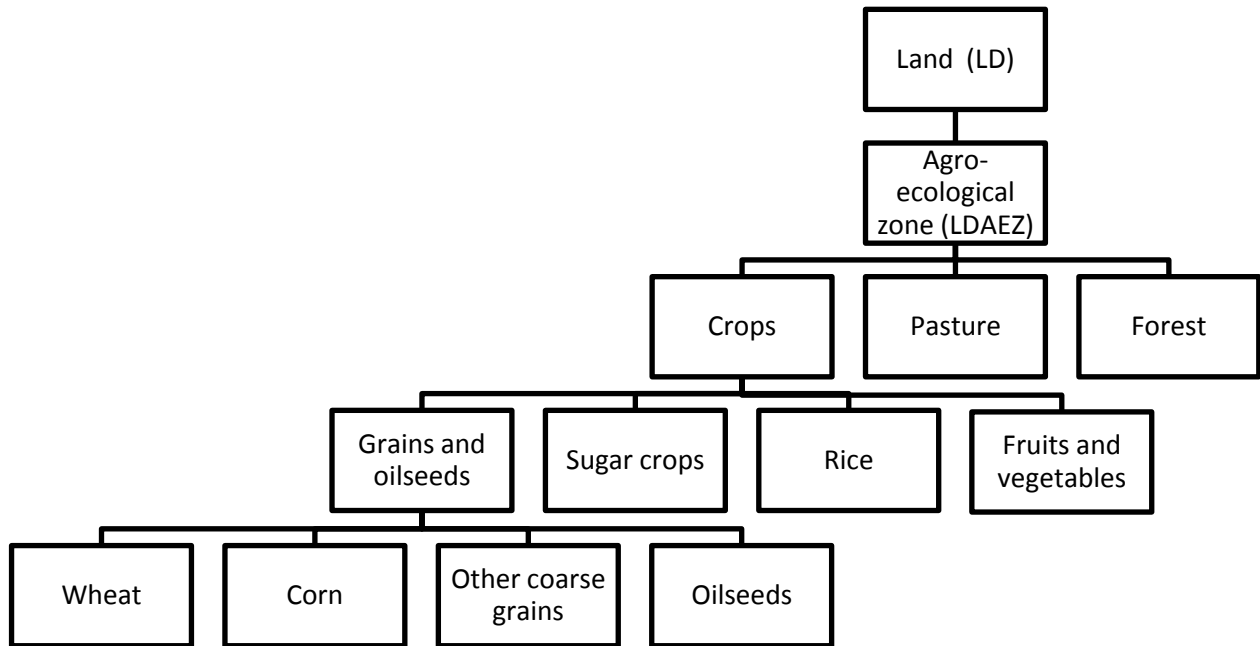


Land use changes are incorporated into the model via a constant elasticity of transformation (CET) representation of land supply for each country/region.¹⁰ Figure 3 presents structure of the land-use module incorporated in the CGE model. A similar approach can be found in existing literature, such as Huang et al. (2004) and Banse et al. (2008). Total land areas are first divided into 18 agro-ecological zones (AEZ) in every country/region. Under each AEZ in a country or region, total available land area is allocated to forest land, pasture and crop land.¹¹ On the second level, crops are further divided into the four different categories: rice, sugar-crops, grains and oilseeds, and fruits and vegetables. Finally, the grains and oilseeds category is partitioned into wheat, corn, other coarse grains, and oilseeds. Land use change is induced by changes in relative returns to land as in each of the CET nests of our land module, agents maximize payoffs by optimally allocating the fixed land area for this nest to the various competing uses.

¹⁰ Since a land can be utilized for different uses (e.g., crop production such as corn and wheat; livestock production). In the production context it represents a situation to allocate a single resource for the purpose of multiple outputs. Thus, a CET function is appropriate to represent land supply behavior (for more discussion please see Timilsina et al., 2010).

¹¹ A similar approach is also followed in Birur et al. (2008) and Hertel et al. (2010).

Figure 3: Structure of the Land-Use Module



While modeling the household sector, we assumed that a representative household maximizes its utility, using a non-homothetic Constant Difference of Elasticities (CDE) function,¹² subject to the budget constraint. The households' disposable income consists of the factor incomes (net of taxes) minus the direct tax. A household savings rate determines the fraction of disposable income that is saved, and thus available for investments. Hence, total national income accrues to government expenditures, household expenditures, and investments.

The government derives revenue from a number of indirect taxes, tariffs and a direct tax on households. Government expenditures are an exogenously determined share of nominal GDP. Government revenue equals the sum of government expenditures and government savings so

¹² See Surry (1993) for details on this functional specification .

that, in the model, the public sector always has a balanced budget. The direct tax on households is adjusted each period to ensure a balanced public budget.

International trade is modeled by a system of Armington demands that give rise to flows of goods and services between the regions. On the national/regional level, import demand is driven by CES functions of domestic and imported components of demand for Armington commodities. Export supply is depicted by a two tier constant elasticity of transformation (CET) function, where, on the first tier, the total output of a sector is designated either to total exports or to domestic supply, and, at the second tier, total exports are partitioned according to their destinations.

The capital stock is composed of old and new capital, where new corresponds to the capital investments at the beginning of the period and old corresponds to the capital installed in previous periods. The ratio of new to old capital is also a measure of the flexibility of the economy, as new capital is assumed to be perfectly mobile across sectors. Furthermore, each period, a fraction of the old capital depreciates.

Population and productivity growth are exogenous drivers of the model's dynamics. The former is taken from the projections of the United Nations Population Division, where labor force growth corresponds to growth of the population aged 15-64 years. Productivity growth is modeled as exogenous and factor neutral for agricultural sectors and labor augmenting for industrial and service sectors. Productivity of energy follows an autonomous energy efficiency improvement (AEEI) path so that there is no endogenous technological change in the model.¹³

¹³ This implies that potential improvement in efficiency of energy transformation and utilization has been already incorporated through the exogenously defined AEEI parameter. Note that the AEEI does not have significant influence on the results of the study as the results presented here are on difference between carbon tax policy

To ensure equilibrium in the model, three sets of market clearing conditions are met. First, total production of each commodity equals the sum of domestic consumption and export so that the goods and services markets clear. Second, total investment equals total saving, where savings are composed of private (household) savings, public (government) savings and exogenously fixed foreign savings. Third, factor markets clear, which implies full employment.

The model is calibrated with GTAP version 7.0 data. However, not all data needed for the model are available in the GTAP database. For example, biofuels are not a proper sector in the original GTAP 7.0; therefore, we modified the database in a way that allowed us to introduce biofuels sectors in our CGE model. For this purpose, we collected detailed information on production, consumption and trade, a total of seven new biofuel sectors, which have been created by splitting existing GTAP sectors. The Splitcom¹⁴ software was used to process the splits and keep the global social accounting matrix balanced. The land data are based on the GTAP 7.0 database and were derived analogously to Lee et al. (2008).

3. Simulation Results

We first consider a range of globally uniform carbon taxes on all fossil fuels, starting from US\$10/tCO₂ up to US\$100/tCO₂. The taxes are introduced in 2012 and kept fixed in nominal

scenarios and the baseline. Any value assumed for AEEI is common for both baseline and the carbon tax policy scenarios. Moreover, the role of AEEI would be significant only in the long-run; 50-100 years (e.g., models presented in Edenhofer et al. 2006,2010). The version of the model used in this analysis considers a short time horizon, 10 years (2010-2020). Interested readers are referred to existing literature such as Edenhofer et al. (2006,2010), Kaufmann (2004) and Edenhofer et al. (2005) for more discussion on AEEI.

¹⁴ This software and a detailed description can be freely downloaded at <http://www.monash.edu.au/policy/splitcom.htm>.

terms throughout the study horizon.¹⁵ The simulations are divided in two policy scenarios as follows:

- (i) Introduction of carbon tax to all fossil fuels and recycle surplus carbon tax revenue after keeping the government revenue neutral to households through a lump-sum rebate. We refer to this policy to as ‘carbon tax alone’ policy case.
- (ii) Introduction of carbon tax to all fossil fuels and use part of carbon tax revenue to finance subsidies to biofuels. Any surplus revenue after financing biofuel subsidies and keeping the government revenue neutral is transferred to households through a lump-sum rebate. We refer to this policy to as ‘carbon tax cum biofuel subsidy’ policy case.

To get a clear picture of carbon tax and biofuel subsidy impacts, we considered various rates for the carbon tax and also for the biofuel subsidy. The difference in impacts between the carbon tax cum subsidy case and carbon tax alone case are interpreted as impacts of biofuel subsidies.

Note that under both scenarios, surplus carbon tax revenue is recycled to households through a lump-sum rebate. Some studies use the surplus revenue to cut existing income taxes (see e.g., Goulder 1995; Goulder et al. 1999; Timilsina and Shrestha, 2007) and report cases of double dividends, i.e., reducing emissions as well as reducing some of the distortions due to existing taxes. Since our objective is to compare results between the carbon tax alone and carbon tax cum biofuel subsidy cases, the results do not significantly alter if other schemes are assumed to

¹⁵ We considered a range of tax rate instead of choosing a particular rate arbitrarily.

recycle surplus tax revenue (surplus after maintaining government revenue neutral under the carbon tax alone case and after financing biofuel subsidies and maintaining government revenue neutral under the carbon tax cum biofuel subsidy case).

3.1 Effect of carbon tax on biofuel penetration

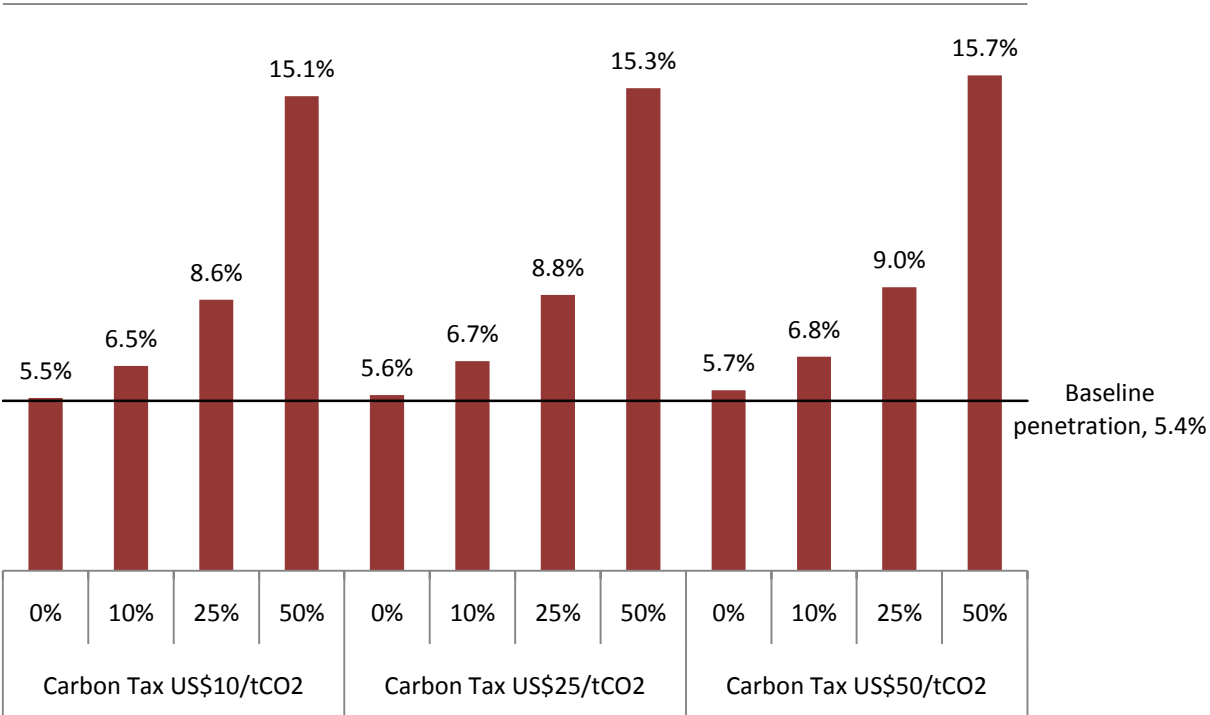
In our baseline simulation, where neither a carbon tax nor biofuel subsidies are considered, biofuels account for 5.5% of total liquid fuels used for road transportation in 2020 at the global level. This represents twice the current share of biofuels in total liquid fuels consumed for global road transportation (see Figure 4). The main reasons for the increase in biofuels in the baseline are existing policies to support biofuels (e.g., already implemented mandates). As illustrated in Figure 4, the impacts on global biofuel penetration is quite small under the carbon tax alone case (i.e., carbon tax with zero subsidy to biofuels). For instance, a carbon tax of US\$25/tCO₂ increases the market share of biofuels to 5.6% at the global level in 2020 compared to 5.5% in the baseline. Even a relatively high carbon tax rate of US\$100/tCO₂ increases this figure only to 6.1% (not shown in Figure 4).¹⁶

When part of the carbon tax revenue is used to finance biofuel subsidies, market penetration of biofuels increases substantially. For instance, a 25% subsidy would increase the global biofuel penetration to more than 8.5% in 2020. A 50% subsidy would lead to more than 15% global market share for biofuels. Note also that for a given rate of subsidy, the level of carbon tax does

¹⁶ We also estimated the share of biofuels in total consumption of biofuels, gasoline and diesel throughout the economy instead of the road transport sector only, although it is unlikely that other sectors such as industry or power generation would have noticeable use of biofuels in the near future. As expected, the new share is smaller as compared to that for the road transport sector only because of the larger base due to large-scale consumption of diesel in the industrial and power sectors in most countries.

not alter biofuel penetration significantly. For example, a US\$10/tCO₂ carbon tax with a 25% subsidy increases global biofuel penetration to 8.6%; if the carbon tax rate is raised to US\$25/tCO₂ with the same level of subsidy, the global penetration of biofuels increases to 8.8%, implying a mere 0.2 percentage point increase. The results clearly demonstrate that direct subsidies to biofuels would be much more powerful to stimulate market penetration of biofuels. Utilizing carbon tax revenue to finance subsidies to clean and renewable energy sources would further help mitigate climate change by stimulating production of clean and renewable energy services although such a policy would further contract the economy.¹⁷ Existing studies such as, Weber et al. 2005 and Barker et al. (2008), also reach similar conclusions.

Figure 4: Biofuels penetration at global level (2020)



¹⁷ Note that environmental policy instruments such as carbon tax and subsidies to clean energy technologies can be justified based on their environmental benefits, which are frequently not quantified and not included into the current practice of economic accounting. If the positive environmental benefits of these instruments are accounted for household welfare, these instruments are found to increase economic welfare (e.g. Parry et al., 1999).

It is also interesting to note the substantial change in biofuel penetration when biofuel subsidies are increased to 50% from 25%. This result indicates that not only a subsidy but also a high level of subsidy would be required to trigger a large increase in biofuel penetration. Another interesting finding is that the fraction of carbon tax revenue required to provide a high subsidy (e.g., 50%) would be relatively small particularly in countries with carbon intensive energy supply system (e.g., China, India, South Africa). An economy-wide carbon tax even at the small level (e.g., US\$10/tCO₂) would produce large revenue which would be much higher than needed to subsidize the biofuels. Therefore, we did not consider biofuel subsidy rate above 50%.

Although the carbon tax cum biofuel subsidy policy is helpful for strong penetration of biofuels, the study does not advocate carbon tax revenue to finance biofuels subsidies. This is because other fiscal measures, such as a fuel tax on gasoline and diesel, the fossil fuel counterparts of biofuels, could be more efficient if the policy objective is to stimulate biofuels. Timilsina et al. (2010) find that a small tax on gasoline and diesel would be enough to subsidize biofuels at the level necessary to meet the biofuel targets announced by various countries around the world.

Table 2 presents the penetration of biofuels at country/regional level under different levels of carbon tax and biofuels subsidies. Like in the global results, the carbon tax alone policy would not significantly stimulate penetration of biofuels. Under this policy, a relatively high carbon tax of US\$50/tCO₂ would increase biofuel penetration by maximum 2 percentage points in China and Russia where the economy is more carbon intensive. Less carbon intensive countries, such as Brazil and France would not experience any change in their biofuel penetration from the baseline due to the carbon tax alone policy. In fact a high carbon tax would even decrease biofuel

penetration in these countries as such a high carbon tax depress the economy and ultimately demand for fuels.

The carbon tax cum biofuel subsidy policy on the other hand, would cause a substantial increase in biofuel penetration in all countries. A 25% subsidy, for example, would increase biofuel penetration more than 60% from the scenarios with no subsidies in most countries.

The principal reason for the small impact on biofuel penetration under the carbon tax alone case is that a carbon tax causes a contraction of economic activities across the board, and leads to reduction of total energy demand. Although the carbon tax causes substitution of fossil fuels with biofuels on the supply side (i.e., substitution effect), the increase in biofuels demand would be partially offset by the overall demand cut resulted from the carbon tax (i.e., pricing effect).

Under carbon tax cum biofuel subsidy case, biofuels become more attractive as compared to their fossil fuel counterparts (i.e., gasoline and diesel). Although these subsidies also produce some negative feedback to the overall economy, the scale of the feedback would be much smaller as compared to that of the carbon tax. Thus, the subsidy would trigger substantial substitution of gasoline and diesel with ethanol and biodiesel, respectively.

It would also relevant to see the impacts of carbon tax and subsidies on biofuel demands in addition to biofuel penetration to draw further clarity to readers. Table 3 presents the impacts on biofuels demand under the different carbon tax with varying rates of subsidy for biofuels. As can be seen from the table, the patterns of impacts of carbon tax and subsidies on biofuels demand are similar to that on biofuel penetration. The increased biofuel demands due to subsidies are

many times higher as compared to corresponding values under the carbon tax alone.¹⁸ Moreover, the increases in demand for biofuels are much higher than the increases in subsidy rate. Under US\$10/tCO₂ carbon tax rate, for example, the global demand for biofuels in 2020 increases from 74% to 268% from the baseline when biofuel subsidy rates are increased from 25% to 50%. On the other hand, an increase in the carbon tax rate from US\$10/tCO₂ to US\$50/tCO₂ causes the global demand for biofuels in 2020 to increase by 2.2 percentage points from 0.5% under the US\$10/tCO₂ case to 2.7% under the US\$50/tCO₂ case.

Although subsidy is found to be much more effective than carbon tax to stimulate biofuels, impacts of carbon tax are also significant in some countries, such as China, where the energy supply system is highly carbon intensive. Moreover, the increase on biofuel demand along with a carbon tax rate is relatively higher in those countries compared to countries with carbon intensive energy supply system. In countries like Japan, France and Italy a carbon tax would cause a reduction in biofuel demand as the reduction in total fuel demand due to pricing effect would be higher than increase in biofuel demands due to substitution effect.

¹⁸ Impacts of a given level of subsidy can be derived by subtracting impacts of carbon tax with zero subsidy from impacts of carbon tax with the given level of subsidy.

Table 2: Biofuels penetration at country/regional level (2020)

Carbon tax	Biofuels subsidy	Baseline	US\$10/tCO ₂				US\$25/tCO ₂				US\$50/tCO ₂			
			0%	10%	25%	50%	0%	10%	25%	50%	0%	10%	25%	50%
Aus-NZ		0.9%	0.9%	1.1%	1.5%	3.3%	0.9%	0.6%	1.5%	3.3%	0.9%	1.1%	1.5%	3.3%
Japan		1.1%	1.1%	1.4%	1.9%	4.0%	1.1%	1.3%	1.9%	4.0%	1.1%	1.3%	1.9%	3.9%
Canada		2.7%	2.7%	3.3%	4.6%	9.0%	2.8%	3.4%	4.7%	9.2%	2.9%	3.5%	4.9%	9.6%
United States		7.7%	7.9%	9.4%	12.4%	21.3%	8.1%	9.6%	12.8%	21.9%	8.5%	10.1%	13.4%	22.7%
France		4.4%	4.3%	5.3%	7.4%	14.7%	4.3%	6.4%	7.3%	14.5%	4.2%	5.1%	7.2%	14.2%
Germany		5.8%	5.8%	7.0%	9.7%	18.8%	5.8%	7.2%	9.7%	18.7%	5.7%	7.0%	9.7%	18.7%
Italy		2.7%	2.7%	3.3%	4.7%	9.9%	2.6%	2.9%	4.6%	9.8%	2.6%	3.2%	4.5%	9.6%
Spain		2.3%	2.2%	2.8%	3.9%	8.4%	2.2%	2.5%	3.9%	8.3%	2.2%	2.7%	3.9%	8.3%
UK		0.9%	0.9%	1.1%	1.5%	3.3%	0.9%	1.3%	1.5%	3.3%	0.8%	1.0%	1.5%	3.2%
Rest of EU & EFTA		1.6%	1.6%	2.0%	2.8%	6.1%	1.6%	3.3%	2.8%	6.1%	1.6%	2.0%	2.8%	6.1%
China		5.0%	5.6%	6.7%	9.0%	16.0%	6.2%	7.4%	9.9%	17.5%	7.0%	8.3%	11.1%	19.4%
Indonesia		4.2%	4.4%	5.2%	6.9%	12.3%	4.6%	5.5%	7.2%	12.8%	5.0%	5.9%	7.8%	13.7%
Malaysia		6.1%	6.2%	7.6%	10.5%	20.1%	6.4%	7.7%	10.7%	20.5%	6.7%	8.1%	11.1%	21.3%
Thailand		3.3%	3.3%	3.9%	5.1%	8.7%	3.3%	3.9%	5.1%	8.7%	3.3%	3.9%	5.1%	8.7%
Rest of EAP		1.0%	1.0%	1.2%	1.7%	3.5%	1.0%	1.8%	1.7%	3.5%	1.0%	1.3%	1.8%	3.6%
India		6.3%	6.3%	7.5%	10.0%	17.3%	6.3%	7.5%	10.0%	17.3%	6.3%	7.5%	10.0%	17.4%
Rest of SA		0.9%	0.9%	1.1%	1.6%	3.4%	1.0%	0.3%	1.7%	3.7%	1.1%	1.4%	1.9%	4.1%
Argentina		3.8%	3.9%	4.7%	6.6%	13.0%	3.9%	8.5%	6.6%	13.1%	3.9%	4.8%	6.7%	13.2%
Brazil		43.0%	42.9%	46.8%	53.4%	65.8%	42.7%	57.1%	53.3%	65.8%	42.5%	46.6%	53.3%	65.9%
Rest of LAC		2.3%	2.3%	2.8%	4.0%	7.9%	2.4%	2.0%	4.1%	8.1%	2.5%	3.0%	4.2%	8.4%
Russia		7.1%	7.6%	9.1%	12.5%	23.0%	8.2%	6.9%	13.4%	24.5%	9.1%	11.0%	14.8%	26.6%
Rest of ECA		2.3%	2.3%	2.9%	4.1%	8.6%	2.4%	4.8%	4.3%	8.9%	2.6%	3.2%	4.5%	9.3%
MENA		0.2%	0.2%	0.2%	0.3%	0.7%	0.2%	0.3%	0.4%	0.8%	0.2%	0.3%	0.4%	0.8%
South Africa		5.6%	5.8%	6.9%	9.1%	14.7%	6.1%	3.7%	9.4%	15.1%	6.6%	7.7%	10.0%	15.8%
Rest of SSA		3.5%	3.5%	4.3%	5.9%	11.4%	3.6%	2.3%	6.0%	11.6%	3.7%	4.5%	6.2%	11.9%

Table 3: Change in biofuels demand (%) relative to baseline in 2020

Carbon tax	US\$10/tCO ₂			US\$25/tCO ₂			US\$50/tCO ₂		
	Biofuels subsidy	0%	25%	50%	0%	25%	50%	0%	25%
World total	0.5	74.1	267.8	1.2	75.5	270.4	2.7	78.1	275.7
High-income	0.2	74.0	268.7	0.6	74.9	270.3	1.6	76.6	273.8
Aus-NZ	1.1	76.3	293.2	2.4	79.4	298.1	4.6	83.2	306.2
Japan	-0.7	74.9	284.4	-1.7	73.5	280.9	-2.6	71.9	277.3
Canada	2.1	71.6	266.1	5.2	78.9	277.1	10.3	87.7	295.3
United States	2.9	72.6	240.2	6.9	79.4	252.7	13.3	89.8	272.2
France	-0.6	72.7	266.9	-1.5	71.6	264.3	-2.3	70.2	261.5
Germany	0.3	73.5	263.6	0.9	74.7	265.9	2.2	76.9	270.7
Italy	-0.4	76.0	290.7	-0.8	75.5	289.2	-1.0	75.1	288.3
Spain	0.1	76.5	288.8	0.2	77.0	289.7	0.9	78.3	292.5
UK	0.3	77.1	287.0	0.4	77.5	287.7	0.5	77.5	287.8
Rest of EU & EFTA	0.7	77.9	290.9	1.7	80.0	295.0	3.7	83.5	302.6
Middle & Low-income	2.0	74.6	261.6	4.9	79.5	271.3	10.1	88.1	288.1
China	8.6	77.4	264.3	19.1	97.5	298.7	33.9	122.3	347.6
Indonesia	3.2	73.2	249.2	8.1	81.5	265.0	17.0	96.2	293.2
Malaysia	1.0	75.9	271.9	2.2	77.9	276.5	4.3	81.5	283.8
Thailand	0.4	62.0	236.3	1.0	66.6	238.6	2.4	68.9	243.3
Rest of EAP	1.2	72.3	270.6	2.9	77.0	276.9	5.8	82.0	287.4
India	1.2	70.2	242.5	2.4	72.6	247.3	4.7	76.4	255.2
Rest of SA	5.0	77.8	284.2	12.2	92.2	311.3	24.0	112.9	355.6
Argentina	3.5	73.7	262.0	7.4	81.1	275.3	12.5	89.6	292.5
Brazil	0.2	48.6	161.3	0.7	50.9	163.9	1.8	53.0	169.0
Rest of LAC	3.2	61.0	212.7	7.9	69.2	225.3	15.8	81.2	246.7
Russia	6.7	78.6	272.6	15.2	94.5	301.5	27.5	115.3	342.9
Rest of ECA	3.9	80.7	303.1	8.9	90.9	322.9	16.4	104.4	352.6
MENA	5.4	83.1	298.8	12.6	96.3	325.4	23.9	115.8	366.5
South Africa	5.1	74.0	247.8	11.5	85.3	267.3	21.4	101.2	296.9
Rest of SSA	1.5	75.5	271.0	2.5	77.6	275.3	4.6	81.1	282.5

3.2 Impacts on GDP

Table 4 presents the effect of a carbon tax on GDP with and without subsidies to biofuels. As expected, the carbon tax would reduce global GDP under the carbon tax alone case. For instance,

a US\$25/tCO₂ carbon tax without tax revenue recycled to finance biofuel subsidies leads to a loss of global real GDP of 0.43% as compared to the business as usual scenario. Almost the entire loss in real GDP will accrue to middle and low-income countries that will suffer a reduction of 1.08%, while the loss of GDP in high-income countries would be relatively small, 0.07%. Intuitively, high-income countries have relatively lower energy intensity as measured by energy consumption per unit GDP due the higher share of lower energy intensive service sectors in the economy. On the other hand, middle-income countries, such as China, India, Russia and Brazil, have energy-intensive manufacturing sectors as the main economic base. Among the group of middle and low-income countries, Russia, China, India and Argentina which are reliant on carbon-intensive industries, will be the hardest hit. Also the MENA region suffers high GDP loss due to reduction in oil and gas production as a result of carbon tax induced demand cuts. For a US\$25/tCO₂ tax without subsidies to biofuels, the global GDP loss would be 0.43% and, again, mainly accrues to low- and middle-income countries. Finally, a fairly high tax rate of US\$50/tCO₂ would lead to an even stronger result, with global GDP dipping to more than 0.85% below its baseline level.

Table 4: Percentage change in real GDP relative to baseline (2020)

Carbon tax	US\$10/tCO ₂				US\$25/tCO ₂				US\$50/tCO ₂			
Biofuels subsidy	0%	10%	25%	50%	0%	10%	25%	50%	0%	10%	25%	50%
World total	-0.16	-0.17	-0.18	-0.27	-0.43	-0.44	-0.45	-0.53	-0.85	-0.85	-0.87	-0.95
High-income	-0.02	-0.02	-0.03	-0.10	-0.07	-0.07	-0.08	-0.15	-0.15	-0.15	-0.16	-0.23
Aus-NZ	-0.13	-0.13	-0.14	-0.15	-0.30	-0.30	-0.30	-0.31	-0.52	-0.52	-0.52	-0.53
Japan	-0.01	0.00	0.00	-0.01	-0.02	-0.02	-0.02	-0.02	-0.06	-0.06	-0.06	-0.06
Canada	-0.08	-0.08	-0.09	-0.11	-0.22	-0.22	-0.23	-0.25	-0.45	-0.46	-0.46	-0.48
United States	-0.06	-0.06	-0.08	-0.25	-0.15	-0.15	-0.17	-0.34	-0.30	-0.30	-0.32	-0.50
France	0.03	0.03	0.04	0.06	0.06	0.07	0.07	0.10	0.10	0.10	0.11	0.14
Germany	0.03	0.03	0.02	0.00	0.07	0.06	0.06	0.03	0.09	0.09	0.08	0.06
Italy	-0.02	-0.02	-0.03	-0.04	-0.06	-0.06	-0.06	-0.07	-0.13	-0.13	-0.13	-0.15
Spain	0.01	0.01	0.00	-0.01	0.01	0.01	0.00	-0.02	-0.02	-0.02	-0.02	-0.04
UK	0.02	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05
Rest of EU & EFTA	0.00	-0.01	-0.01	-0.03	-0.03	-0.03	-0.03	-0.05	-0.10	-0.10	-0.10	-0.12
Middle & Low-income	-0.41	-0.42	-0.45	-0.56	-1.08	-1.09	-1.12	-1.21	-2.09	-2.11	-2.14	-2.24
China	-0.84	-0.85	-0.88	-1.02	-2.10	-2.11	-2.14	-2.25	-3.87	-3.88	-3.92	-4.04
Indonesia	-0.16	-0.16	-0.16	-0.16	-0.45	-0.45	-0.45	-0.45	-0.94	-0.95	-0.95	-0.95
Malaysia	-0.09	-0.10	-0.14	-0.25	-0.35	-0.37	-0.41	-0.51	-0.89	-0.91	-0.95	-1.06
Thailand	-0.01	-0.01	-0.01	-0.03	-0.08	-0.09	-0.09	-0.11	-0.30	-0.30	-0.30	-0.32
Rest of EAP	-0.01	-0.01	-0.01	-0.02	-0.06	-0.06	-0.06	-0.08	-0.21	-0.21	-0.21	-0.24
India	-0.34	-0.35	-0.38	-0.49	-0.86	-0.87	-0.91	-1.00	-1.65	-1.66	-1.69	-1.79
Rest of SA	-0.26	-0.26	-0.27	-0.30	-0.64	-0.64	-0.64	-0.67	-1.19	-1.20	-1.20	-1.23
Argentina	-0.35	-0.35	-0.35	-0.36	-0.91	-0.91	-0.91	-0.89	-1.74	-1.74	-1.75	-1.72
Brazil	-0.06	-0.13	-0.24	-0.49	-0.16	-0.24	-0.37	-0.59	-0.35	-0.43	-0.56	-0.78
Rest of LAC	-0.18	-0.20	-0.23	-0.35	-0.50	-0.51	-0.55	-0.66	-0.98	-1.00	-1.03	-1.14
Russia	-0.64	-0.66	-0.70	-0.84	-1.96	-1.98	-2.03	-2.10	-4.17	-4.20	-4.25	-4.33
Rest of ECA	-0.27	-0.26	-0.25	-0.24	-0.72	-0.71	-0.70	-0.67	-1.45	-1.44	-1.43	-1.40
MENA	-0.41	-0.44	-0.49	-0.72	-1.23	-1.27	-1.33	-1.50	-2.57	-2.61	-2.68	-2.86
South Africa	-0.34	-0.35	-0.38	-0.46	-0.87	-0.89	-0.92	-0.98	-1.59	-1.61	-1.64	-1.71
Rest of SSA	-0.29	-0.31	-0.34	-0.46	-0.79	-0.81	-0.84	-0.92	-1.52	-1.54	-1.58	-1.67

When part of the carbon tax revenue is used to subsidize biofuels in each country/region (i.e., carbon tax cum biofuel subsidy case), the global GDP loss is even bigger. This result is non-trivial. This is because subsidizing biofuels, which are relatively expensive as compared to their

fossil fuel counterparts, would change the relative prices and thus lead to a suboptimal factor allocation.¹⁹

Although the subsidy on top of the carbon tax would cause higher GDP loss as compared to the situation with a carbon tax and no subsidy, the negative GDP impacts per unit increase of biofuel penetration would be many-fold smaller in the former case as compared to the latter. For example, when no subsidy is provided to biofuels a carbon tax of US\$25/tCO₂ would increase global penetration of biofuels by 0.2 percentage points from the baseline level at 0.43% GDP cost. On the other hand, if a 25% subsidy is provided to biofuels, it would increase global biofuel penetration by 3.2 percentage points on top of the increment caused by the carbon tax; the incremental loss in GDP would be 0.02%. If we define the rate of change in GDP with respect to the rate of change in biofuel penetration as ‘GDP elasticity of biofuel penetration’, the globally aggregated value of such an elasticity would be greater than 2 for the carbon tax, whereas it would be less than 0.01 for the subsidy.

3.3 Impacts on sectoral outputs

A carbon tax would increase the relative output of the biofuel sector in comparison to outputs of most other sectors. However, the increase in the output of the biofuel sector is insignificant compared to the decrease in outputs from the other sectors. For example, while a US\$25/tCO₂ carbon tax would increase output of the biofuel sector by US\$2.2 billion in 2020, it would decrease US\$1,173 billion worth of outputs from the other sectors.

¹⁹ It has to be noted here that the benefits of climate change mitigation does not enter into the welfare function in our analysis.

The carbon tax would not only reduce output from energy/mining and manufacturing sectors but also from the agricultural sectors. As illustrated in Table 5, the percentage reductions of agriculture outputs are higher than that in the service and, in some cases, manufacturing sectors. The agricultural sector is also an energy-intensive sector in high-income countries. Note that not only the agricultural sub-sectors which are not used for biofuel feedstock, but also those used for biofuel feedstock experience an output decline due to the carbon tax (see Table 6). Moreover, a globally uniform carbon tax will not only cause a reallocation between the sectors, but also cause a geographical reallocation of output towards less energy-intensive producers.

Since the carbon tax reduces outputs, demand for goods and services, including energy would fall. The consequences due to the overall fall in economic output would partially offset the substitution effect between biofuels and its fossil counterparts in the aggregate fuel supply mix. Thus, the stronger negative economic effect of a carbon tax is the primary reason for a smaller penetration of biofuels. The effects of using parts of the carbon tax revenue to subsidize biofuels at 25% are also illustrated in Table 5. The biofuels subsidy leads to a huge expansion in the biofuels sector as compared to the carbon tax alone. Not surprisingly, also the agricultural sector benefits from a biofuels subsidy, as feedstock production increases. However, the overall effect of the policy mix on the agricultural sector is still negative, which again illustrates the generally output-depressing effect of the carbon tax.

Table 5: Percentage change in real GDP relative to baseline (2020) due to carbon tax of US\$25/tCO₂ without biofuels subsidy and with 25% biofuels subsidy

	Agriculture		Biofuels		Energy and utility		Manufacturing		Services	
	0%	25%	0%	25%	0%	25%	0%	25%	0%	25%
Biofuels subsidy										
World total	-0.8	-0.3	3.6	67.3	-8.0	-8.2	-0.8	-0.9	-0.4	-0.4
High-income	-1.3	-0.7	2.8	72.8	-5.9	-6.0	0.3	0.3	-0.1	-0.1
Aus-NZ	-0.4	0.0	1.1	79.7	-11.3	-11.4	1.0	0.9	-0.2	-0.2
Japan	-1.6	-1.2	-1.9	75.7	-1.7	-1.7	0.0	0.0	0.0	0.0
Canada	-1.0	-0.7	6.4	82.4	-5.1	-5.2	1.4	1.4	-0.3	-0.3
United States	-0.7	-0.2	4.2	71.1	-9.2	-9.4	-0.1	-0.1	-0.1	-0.1
France	-2.1	-0.5	-0.7	73.8	0.3	0.2	0.4	0.3	0.0	0.0
Germany	-1.9	-0.9	0.7	74.5	-3.2	-3.4	0.4	0.4	-0.1	-0.1
Italy	-1.7	-1.0	-0.8	75.6	-1.2	-1.2	0.2	0.2	-0.1	-0.1
Spain	-1.8	-0.9	-0.5	76.4	-2.7	-2.7	0.3	0.2	-0.1	-0.1
UK	-1.7	-1.1	0.5	77.3	-7.0	-7.0	0.6	0.7	0.0	0.0
Rest of EU & EFTA	-1.7	-1.2	1.4	80.1	-3.5	-3.5	0.7	0.7	-0.2	-0.2
Middle & Low-income	-0.3	-0.1	4.4	62.3	-9.4	-9.7	-2.1	-2.2	-1.0	-1.1
China	-0.5	-0.3	23.7	102.4	-20.0	-20.3	-4.0	-4.1	-1.7	-1.7
Indonesia	0.2	0.3	8.0	76.2	-7.3	-7.6	-1.2	-1.3	-0.4	-0.4
Malaysia	0.7	0.8	2.3	77.8	-9.2	-9.5	0.4	0.3	-1.6	-1.6
Thailand	-0.2	0.1	0.3	57.9	-3.6	-3.8	-0.1	-0.2	-0.2	-0.2
Rest of EAP	0.0	0.1	3.2	79.2	-3.5	-3.4	-0.4	-0.4	-0.2	-0.2
India	-0.4	-0.3	0.4	59.9	-9.3	-9.6	-2.1	-2.1	-0.8	-0.8
Rest of SA	-0.1	0.0	11.3	98.1	-10.0	-10.1	-1.8	-1.9	0.2	0.3
Argentina	-0.4	0.0	4.1	81.6	-7.5	-7.8	-0.5	-0.7	-0.8	-0.8
Brazil	-0.9	-0.4	-0.5	48.1	-1.4	-3.0	0.3	-0.7	-0.3	-0.6
Rest of LAC	-0.3	-0.1	6.1	89.8	-5.3	-5.5	0.1	0.1	-0.9	-0.9
Russia	1.2	1.9	17.7	100.6	-10.1	-10.3	-2.6	-2.5	-1.8	-2.0
Rest of ECA	-0.4	0.1	10.1	96.6	-7.1	-7.2	-2.2	-2.3	-0.4	-0.4
MENA	-0.2	0.0	9.7	101.3	-5.5	-5.6	1.1	1.5	-1.4	-1.5
South Africa	-1.1	0.0	10.9	73.4	-17.0	-17.4	0.0	-0.1	-0.4	-0.4
Rest of SSA	-0.1	0.1	5.3	88.9	-3.0	-3.3	1.0	1.0	-1.3	-1.4

Table 6: Percentage change in agricultural output relative to baseline (2020) due to carbon tax of US\$25/tCO₂ without biofuels subsidy and with 25% biofuels subsidy

Biofuels subsidy	Agriculture		Paddy rice		Sugar crops		Other crops		Wheat		Corn		Other coarse grains		Oilseeds		Livestock	
	0%	25%	0%	25%	0%	25%	0%	25%	0%	25%	0%	25%	0%	25%	0%	25%	0%	25%
World total	-0.8	-0.3	-0.3	-0.5	-0.3	5.5	-0.9	-0.9	-0.3	0.6	0.0	5.9	-0.7	0.2	-0.5	0.8	-0.9	-1.0
High-income	-1.3	-0.7	-0.5	-0.6	-1.1	2.2	-1.5	-1.4	-1.0	-0.2	-0.2	8.9	-1.5	0.6	-0.9	2.4	-1.4	-1.4
Aus-NZ	-0.4	0.0	-0.1	0.1	0.6	1.6	-0.8	-0.5	1.3	2.9	0.5	4.5	0.6	1.5	0.8	3.1	-0.5	-0.3
Japan	-1.6	-1.2	-0.3	-0.3	-0.5	8.0	-1.9	-1.5	-0.5	1.2	-2.1	1.5	-0.8	0.4	-0.6	1.5	-2.2	-2.0
Canada	-1.0	-0.7	0.0	0.0	-0.7	-0.5	-1.2	-1.5	0.6	0.9	-0.1	13.1	-1.3	-0.9	-0.9	0.6	-1.2	-1.3
United States	-0.7	-0.2	-1.0	-1.7	-0.4	-0.4	-0.6	-1.3	0.0	-1.9	0.2	12.2	-0.8	-3.0	-0.5	-1.3	-1.0	-1.3
France	-2.1	-0.5	-2.0	-2.3	-0.7	16.0	-1.9	-2.0	-3.3	-0.7	-2.8	0.9	-2.6	-0.9	-2.9	15.1	-1.8	-1.8
Germany	-1.9	-0.9	0.0	0.0	-0.5	0.1	-1.8	-1.5	-2.3	-0.3	-2.1	3.3	-1.7	0.0	-1.4	14.3	-2.1	-1.8
Italy	-1.7	-1.0	-2.9	-2.3	-0.3	-0.1	-1.8	-1.3	-1.7	-0.3	-1.7	-0.6	-1.8	-0.7	-0.9	3.3	-1.7	-1.3
Spain	-1.8	-0.9	-2.4	-2.0	-0.5	-0.3	-2.2	-1.6	-2.6	-0.8	-1.5	1.7	-0.7	7.3	-1.0	0.9	-1.2	-1.0
UK	-1.7	-1.1	0.0	0.0	-1.3	1.7	-2.0	-1.7	-0.6	-0.2	0.0	0.0	-0.6	10.8	-1.0	5.8	-1.7	-1.6
Rest of EU & EFTA	-1.7	-1.2	-2.3	-1.7	-2.6	-1.2	-1.9	-1.5	-0.5	0.3	0.4	1.5	-2.1	-0.3	-0.7	3.4	-1.7	-1.5
Middle & Low-income	-0.3	-0.1	-0.3	-0.5	0.0	6.6	-0.4	-0.5	0.2	1.1	0.1	3.6	-0.1	0.0	-0.3	-0.1	-0.4	-0.6
China	-0.5	-0.3	-1.1	-1.2	-0.6	-0.2	-0.7	-0.8	-2.9	-1.5	0.7	7.8	-1.6	-2.0	-0.7	-0.7	-0.3	-0.5
Indonesia	0.2	0.3	0.4	0.1	1.7	11.6	-0.1	-0.4	0.0	0.0	0.6	1.1	0.0	0.0	0.5	1.0	0.1	-0.1
Malaysia	0.7	0.8	-1.1	-0.9	-0.1	0.1	2.1	2.3	0.0	0.0	0.0	0.0	3.8	4.5	2.3	3.7	0.5	0.4
Thailand	-0.2	0.1	-0.1	-0.8	0.1	18.3	-0.3	-0.8	0.0	0.0	0.7	4.1	1.0	0.3	1.0	1.1	-0.3	-0.8
Rest of EAP	0.0	0.1	0.2	0.0	0.4	4.7	-0.2	-0.1	0.9	1.4	0.7	6.2	0.0	0.4	0.8	1.3	0.0	-0.1
India	-0.4	-0.3	0.0	-0.2	0.0	3.9	-0.8	-1.0	-0.4	-0.5	-0.1	-0.1	-0.1	-0.2	-0.1	-0.3	-0.1	-0.3
Rest of SA	-0.1	0.0	0.1	0.1	0.1	1.3	-0.1	0.0	-0.4	0.1	0.0	3.3	0.0	0.1	0.8	1.5	-0.2	-0.2
Argentina	-0.4	0.0	-1.8	-2.0	0.0	-0.6	-0.9	-1.3	0.2	-0.4	-0.5	5.2	0.0	0.2	-0.6	-0.4	0.0	-0.5
Brazil	-0.9	-0.4	-0.5	-2.1	-0.5	27.5	-1.0	-3.2	-0.9	-3.8	-0.1	2.7	0.0	-1.8	-1.2	-1.1	-0.7	-2.1
Rest of LAC	-0.3	-0.1	0.0	-0.1	-0.1	1.3	-0.6	-0.7	0.6	0.7	0.4	2.9	0.3	0.3	-0.4	1.1	-0.2	-0.4
Russia	1.2	1.9	0.8	0.9	1.7	1.9	4.2	4.3	5.8	16.2	2.7	3.0	1.4	1.3	5.5	5.7	-0.9	-1.0
Rest of ECA	-0.4	0.1	-1.2	-1.0	-0.1	3.2	-0.5	-0.2	-0.3	1.5	-0.8	0.8	-0.1	1.1	0.8	1.7	-0.3	-0.3
MENA	-0.2	0.0	-0.5	-0.6	0.1	0.9	-0.1	0.1	1.1	1.7	-1.1	4.9	-1.1	-0.9	0.8	1.9	-0.8	-1.0
South Africa	-1.1	0.0	0.0	0.0	2.6	25.8	-1.7	-1.9	-1.9	-1.4	-1.8	-0.7	-1.5	-1.6	-0.7	-1.0	-0.6	-0.8
Rest of SSA	-0.1	0.1	0.1	0.2	0.0	1.7	0.3	0.4	2.2	3.1	-0.2	0.4	-0.6	-0.6	0.3	0.5	-0.8	-1.0

Table 6 also indicates the reallocation in production of agricultural commodities, particularly in developing countries, despite the overwhelming reductions of sectoral outputs due to the carbon tax. The reallocation is mainly caused by substitution of gasoline and diesel with ethanol and biodiesel, respectively. If there were no substitution, these reallocations would not occur and reductions of agricultural outputs would be higher. The effect of a biofuels subsidy is intuitive; while the outputs of sugar crops, wheat, corn and oilseeds, which are used as feedstock in biofuels production, expand, the subsidy further depresses the production of other agricultural products such as paddy rice and livestock.

3.4 Impacts on CO₂ emissions

Table 7 presents impacts of carbon tax and biofuel subsidies on CO₂ emissions in various countries or regions. As expected, the carbon tax considered in the study has a large effect on CO₂ emission; even a moderate carbon tax of US\$10/tCO₂, leads to reduction of global CO₂ emissions by about 13% below the baseline case in 2020, while a relatively high tax of US\$50/tCO₂ reduces emission by almost 33% below the baseline case. As can be seen from Table 7, a carbon tax in low and middle-income reduces relatively higher CO₂ emissions as compared to that in high-income countries. For instance, a US\$25/tCO₂ leads to a decrease in CO₂ of about 14% in high-income countries, while emissions in low and middle-income countries go down by 28%. This reflects the fact the low and middle income economies are more carbon intensive in terms of economic output than high income countries. Countries with high carbon intensive energy supply system such as Argentina, China, India and South Africa exhibit relatively stronger reduction of CO₂ emissions. On the other hand, countries with low carbon intensive energy supply system, such as Brazil, France, Italy and Spain would realize relatively smaller reduction of their CO₂ emissions. In fact, the mix of energy sources used for power

generation is also a good predictor for CO₂ mitigation potential; for instance, in France where nuclear power accounts for almost 80% of power generation, an emission tax even at the relatively high level of US\$50/tCO₂ reduces emission by only 6.5%, while the same tax rate reduces emissions in the UK, where coal and gas account for the bulk of power generation, by about 28%.

Table 7: Change in CO₂ emissions (%) relative to baseline in 2020

Carbon tax	US\$10/tCO ₂			US\$25/tCO ₂			US\$50/tCO ₂		
	0%	25%	50%	0%	25%	50%	0%	25%	50%
World total	-12.9	-13.0	-13.7	-23.5	-23.7	-23.9	-32.8	-32.9	-33.1
High-income	-6.9	-7.0	-7.4	-13.7	-13.8	-14.0	-20.6	-20.7	-20.9
Aus-NZ	-10.9	-10.9	-11.4	-19.6	-19.6	-19.7	-27.2	-27.2	-27.2
Japan	-6.0	-5.9	-6.0	-9.1	-9.0	-8.9	-12.6	-12.5	-12.4
Canada	-6.7	-6.8	-7.1	-13.4	-13.5	-13.5	-20.0	-20.1	-20.1
United States	-7.8	-8.0	-8.7	-15.9	-16.1	-16.4	-23.8	-23.9	-24.2
France	-1.7	-1.8	-1.9	-3.8	-3.9	-4.0	-6.5	-6.6	-6.6
Germany	-4.2	-4.4	-4.9	-9.1	-9.3	-9.6	-14.4	-14.6	-14.9
Italy	-2.5	-2.5	-2.8	-5.7	-5.7	-5.9	-9.6	-9.6	-9.8
Spain	-2.6	-2.6	-2.7	-5.8	-5.8	-5.9	-9.9	-9.9	-9.9
UK	-9.7	-9.7	-9.9	-19.1	-19.1	-19.1	-28.0	-28.0	-28.0
Rest of EU & EFTA	-5.6	-5.6	-5.8	-11.8	-11.8	-11.7	-18.2	-18.2	-18.2
Middle & Low-income	-15.8	-15.9	-16.8	-28.2	-28.4	-28.6	-38.6	-38.8	-39.0
China	-22.2	-22.4	-23.5	-38.3	-38.5	-38.8	-50.3	-50.5	-50.7
Indonesia	-9.3	-9.5	-10.1	-18.1	-18.3	-18.6	-26.2	-26.4	-26.7
Malaysia	-8.6	-8.9	-9.6	-17.7	-17.8	-18.2	-26.6	-26.8	-27.1
Thailand	-4.5	-4.6	-4.8	-9.5	-9.6	-9.7	-15.0	-15.1	-15.2
Rest of EAP	-8.2	-8.1	-8.3	-16.3	-16.3	-16.2	-24.2	-24.1	-24.1
India	-17.0	-17.2	-18.0	-29.1	-29.2	-29.5	-38.5	-38.6	-38.9
Rest of SA	-11.4	-11.5	-11.9	-21.8	-21.8	-22.0	-31.9	-31.9	-32.1
Argentina	-15.9	-16.0	-16.5	-28.2	-28.3	-28.3	-38.2	-38.2	-38.2
Brazil	-2.9	-4.1	-6.0	-6.4	-7.6	-9.3	-10.5	-11.7	-13.3
Rest of LAC	-8.0	-8.1	-8.5	-13.5	-13.6	-13.8	-19.4	-19.5	-19.7
Russia	-12.6	-12.9	-13.9	-24.7	-25.0	-25.5	-36.1	-36.4	-36.8
Rest of ECA	-10.8	-10.8	-11.2	-21.1	-21.1	-21.2	-30.9	-31.0	-31.0
MENA	-8.0	-8.0	-8.3	-16.9	-17.0	-17.1	-26.7	-26.8	-26.9
South Africa	-21.4	-21.7	-22.7	-35.9	-36.1	-36.4	-46.3	-46.5	-46.7
Rest of SSA	-9.9	-10.2	-10.8	-15.5	-15.7	-16.2	-21.2	-21.4	-21.8

It is interesting to notice in Table 7 that the reduction of CO₂ emissions due to biofuel subsidies is much smaller as compared to that caused by carbon tax. For example, the US\$10/tCO₂ carbon tax with no subsidies to biofuels reduces global CO₂ emissions by 12.9% from the baseline in 2020. If part of the carbon tax revenue is used to finance biofuel subsidies by 50%, the incremental CO₂ reduction is only 0.8% (i.e., 13.7% CO₂ reduction under the US\$10/tCO₂ carbon tax with 50% biofuel subsidy case minus 12.9% CO₂ reduction under the US\$10/tCO₂ carbon tax with 0% biofuel subsidy case). The reason is intuitive. Under the carbon tax case, demand for entire fossil fuels decreases, under the subsidy case only the demand for gasoline and diesel is reduced. In countries with a large share of the transport sector in the national economy and relatively cleaner electricity supply system the effects of subsidies would be higher compared to those countries with smaller transportation share in the economy as well as “dirty” electricity supply systems.

4. Sensitivity Analysis

We address three dimensions in the sensitivity analysis. First, we increase rates of carbon tax above US\$100/tCO₂ to check whether or not a high carbon tax would cause significant impacts on biofuel penetration if carbon tax revenue is not used to subsidize biofuels. Secondly, we analyze the role of the elasticity of substitution between fossil fuels and biofuels assuming that a higher value would cause higher penetration of biofuels. Third, we check whether targeting the carbon tax to gasoline and diesel only, as opposed to all carbon sources, significantly affects our results.

In the first sensitivity analysis, raising the carbon tax level to US\$150/tCO₂ causes further increase in biofuel penetration, but only slightly to 6.4% as compared to 6.1% for carbon tax US\$100/tCO₂ and 5.5% in the baseline (i.e., zero carbon tax). On the other hand, the US\$150/tCO₂ tax causes global GDP loss more than 2%. This sensitivity analysis confirms that a higher carbon tax would increase the penetration of biofuels slightly, but it would cause a significant loss of economic outputs. Thus, results from this sensitivity analysis confirm that a carbon tax alone policy would not help increase biofuel penetration significantly no matter how high the carbon tax rate is. This is because the reduction of total energy demand caused by a high carbon tax is also reflected in demand for biofuels although biofuels substitutes part of fossil fuels.²⁰

The elasticity of substitution between biofuels and their fossil fuel counterparts influences the strength of the substitution effect due to changes in the relative prices of the two fuel types. We check the robustness of our results by running our scenarios after doubling the elasticity parameter.²¹ The model is indeed sensitive to this parameter. Doubling the value of the elasticity of substitution between biofuels and its fossil counterparts (i.e., gasoline and diesel) substantially increases (almost doubles) the penetration of biofuels. However, this happens not only under scenarios (i.e., carbon tax cases), but also in the baseline as the same elasticity of substitution is considered under both the baseline and the scenarios. Thus, the difference in biofuel penetration between the carbon tax case and the baseline under this sensitivity analysis does not get affected

²⁰ It could be further interesting to experiment with a very high carbon tax rate, say US\$500/tCO₂; however, our model is not capable to run a shock of this scale. Nevertheless, we do not expect a different finding as a huge carbon tax would also depress the economy severely thereby reducing the total energy demand and also curtail the demand for biofuels.

²¹ Based on literature (e.g. Birur et al., 2007), the model initially used values linearly increasing from 1.2 to 3.0 between 2004 and 2020 for all countries. In the sensitivity analysis, 1.2 in 2004 is replaced with 2.4 and 3.0 in 2020 is replaced with 6.0.

much although biofuel penetration under the sensitivity case is found slightly higher than that under the main case.

Finally, we run our scenarios with a carbon tax applied only to gasoline and diesel. The idea here is that as biofuels compete mainly with gasoline and diesel, a tax on only these fuels would be relevant if the purpose is to increase penetration of biofuels in and of itself.²² Table 8 shows the results of this sensitivity analysis with a US\$50/tCO₂ tax on gasoline and diesel, and a 50% biofuels subsidy (the results of all other combinations of carbon tax/biofuels subsidy are similar). We retain the formulation of the tax in terms of carbon, versus e.g. energy content, to facilitate comparison with other scenarios. The results of this sensitivity analysis show that the penetration of biofuels is not significantly different from that in the main case where carbon tax is imposed to all fossil fuels. This finding is also supported from the fact that the substitution possibility between other fossil fuels (e.g., coal, natural gas) and petroleum products for transportation (i.e., gasoline and diesel) is very small. On the other hand, targeting the tax to gasoline and diesel only leads to a much smaller loss in global GDP than an economy-wide carbon tax. This makes intuitive sense given that an introduction of carbon tax to all fossil fuels would have much higher impacts on other sectors, particularly in electricity generation and manufacturing sectors, where coal and natural gas are the main fuels.

²² This is rather an artificial case because a carbon tax if introduced in practice would be introduced to all fossil fuels instead of only to gasoline and diesel (see Introduction section). However, this sensitivity analysis would help to understand how the results would change if the carbon tax is applied in partial equilibrium approach.

Table 8: Biofuels penetration (2020) due to carbon tax of US\$50/tCO₂ with 50% biofuels subsidy

	Biofuels market share		Percentage change in GDP	
	Comprehensive carbon tax	Carbon tax on gasoline & diesel	Comprehensive carbon tax	Carbon tax on gasoline & diesel
World total	15.7%	15.8%	-1.0	-0.2
High-income	14.0%	14.4%	-0.2	-0.1
Aus-NZ	3.3%	3.4%	-0.5	0.0
Japan	3.9%	4.2%	-0.1	0.0
Canada	9.6%	9.7%	-0.5	-0.1
United States	22.7%	22.9%	-0.5	-0.2
France	14.2%	15.2%	0.1	0.0
Germany	18.7%	19.4%	0.1	0.0
Italy	9.6%	10.3%	-0.1	0.0
Spain	8.3%	8.9%	0.0	0.0
UK	3.2%	3.3%	0.1	0.0
Rest of EU & EFTA	6.1%	6.3%	-0.1	0.0
Middle & Low-income	18.2%	17.8%	-2.2	-0.3
China	19.4%	16.7%	-4.0	-0.2
Indonesia	13.7%	12.7%	-1.0	0.0
Malaysia	21.3%	20.8%	-1.1	-0.3
Thailand	8.7%	9.0%	-0.3	0.0
Rest of EAP	3.6%	3.6%	-0.2	0.1
India	17.4%	17.6%	-1.8	-0.2
Rest of SA	4.1%	3.5%	-1.2	-0.1
Argentina	13.2%	13.3%	-1.7	-0.2
Brazil	65.9%	66.6%	-0.8	-0.5
Rest of LAC	8.4%	8.4%	-1.1	-0.3
Russia	26.6%	23.5%	-4.3	-0.6
Rest of ECA	9.3%	8.8%	-1.4	0.0
MENA	0.8%	0.8%	-2.9	-0.8
South Africa	15.8%	15.1%	-1.7	-0.2
Rest of SSA	11.9%	12.0%	-1.7	-0.6

5. Policy Insights

Under a partial equilibrium setting, an introduction of a higher carbon-based tax to fossil fuels could make biofuels economically attractive, thereby causing significant substitution of fossil

fuels with biofuels depending upon the substitution of elasticity between them (Schneider and McCarl, 2003 and 2005; McCarl et al. 2010). Such a finding is intuitive as a partial equilibrium analysis assumes *ceteris paribus*. However, in a general equilibrium framework this is not necessarily true as a carbon tax would have economy-wide repercussions; it would target lower-cost GHG abatement options, slow down economic activities and reduce demand for energy. Despite the substitution possibility between the liquid fossil fuels and biofuels, the reduction in total energy demand is also reflected in biofuel demand because the increased demand for biofuels caused by the substitution effect would be partially offset by the reduction in demand due to pricing effect. Thus, the net increase in biofuel demand under a general equilibrium setting would be smaller as compared to that in a partial equilibrium setting.

A companion study (Timilsina et al., 2010) shows that direct subsidies to biofuels to meet national targets announced by forty plus countries around the world would increase biofuel penetration by 3.3 percentage points (from 5.5% in baseline to 8.8% in the scenario to meet the announced targets) in 2020 at a cost of 0.02% of global GDP. This study shows in contrast that an economy-wide carbon tax of US\$150/tCO₂ applied globally would increase the biofuel penetration by merely one percentage point (from 5.5% in baseline to 6.4% in the carbon tax case) at a global GDP loss of 2%, which is 100 times as high as that in the case of subsidy simulated in Timilsina et al (2010). This is intuitively reasonable, since the direct subsidy is targeted at only one small portion of the overall energy system, whereas the carbon tax reduces GHG emissions across all sectors and fuel sources in the global economy, with greater aggregate impact. By similar reasoning, an oil price increase or increase in tax on petroleum products would have a larger impact on biofuels penetration than a carbon tax, in particular since an increase in the petroleum price would focus directly on liquid fuels and would have smaller

negative impacts on the economy as compared to that of a carbon tax introduced to all fossil fuels.²³

The fundamental logic underlying is that a carbon tax is the most efficient economic instrument to reduce carbon emissions; whereas, if the objective of policy is to promote biofuels for other purposes (such as reduced fuel imports), a direct subsidy to biofuels would be much more efficient. If the policy objective is both climate change mitigation and promotion of biofuels, a carbon tax with part of tax revenue recycled to subsidize biofuels would be the most effective policy since it brings two distinct instruments to bear on two different objectives.

6. Conclusions

This study examines the conditions under which a carbon tax, an efficient economic instrument for climate change mitigation, also would stimulate biofuels. A number of simulations and sensitivity analyses were carried out using a multi-country, recursive dynamic CGE model to answer the research questions. The results of our simulations suggest that a carbon tax with tax revenue recycled to households in a lump-sum manner would have little impact toward increasing the market penetration of biofuels in the national as well as global energy supply mix. The carbon tax would cause significant losses in GDP and sectoral outputs. The negative output impacts of the carbon tax affect not only energy intensive energy producing and manufacturing sectors, but also agricultural sectors that produce feedstock for biofuels. These findings are

²³ A fuel tax on petroleum products or equivalent hike in crude oil price also would have less of a negative economic impact compared to a comprehensive carbon tax, unless the energy supply system of the economy is predominantly based on oil.

robust across a wide range of carbon tax rates, key elasticity parameters and coverage of fossil fuels subjected to a carbon tax (i.e., carbon tax to gasoline/diesel vs. all fossil fuels).

If a carbon tax were to be introduced to reduce CO₂ emissions in a country, and part of carbon tax revenue is used to subsidize biofuels, the combined policies could substantially promote biofuels. However, a carbon tax is not the best way to finance biofuels subsidies; any other taxes on fossil fuels or other government revenues could be used to finance those subsidies with the possibility of lower economic burden.

The carbon tax would cause loss in GDP no matter whether the tax revenue is recycled to households in a lump-sum manner or used to subsidize biofuels. The GDP loss would be even higher in the latter case. However, the negative GDP impacts per unit increase of biofuel penetration would be many-fold smaller in the carbon tax plus biofuel subsidy case as compared to the carbon tax alone case. Moreover, since the carbon tax has a huge base, as it is normally introduced to all fossil fuels in an economy, it produces large revenue. A small fraction of this revenue would be enough to provide a subsidy (more than 50%) required for a large expansion of biofuel penetration.

We have considered a carbon tax only on fossil fuels. Production of biofuels also causes emissions of GHG due to land-use change. If those emissions are also accounted for while designing a carbon tax, the ability of a carbon tax alone policy to enhance the penetration of biofuels may deteriorate further.

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