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Roy Boyd, Alejandra Elizondo,  
and María E. Ibararán

*"How Clean Can We Get?*

*Technological Change and*

*Renewable Energy Use in Mexico,*

*A General Equilibrium Perspective"*

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# HOW CLEAN CAN WE GET? TECHNOLOGICAL CHANGE AND RENEWABLE ENERGY USE IN MEXICO, A GENERAL EQUILIBRIUM PERSPECTIVE

*Roy Boyd, Alejandra Elizondo, and María E. Ibararán\**

## **1. Introduction**

The past 40 years have witnessed an ever-increasing level of concern about the detrimental impacts of climate change stemming from human activities. As average worldwide temperatures have risen, environmental activists as well as concerned scientists, economists, and well-known media figures have issued stark warnings about the social and economic costs of changing weather patterns, and they have called upon policymakers, consumers, and industry to all limit their use of fossil fuels. In doing this these advocates' goal has been to drastically reduce

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\*Roy Boyd earned his BA in Economics at the University of New Mexico. He received his MA and PhD degrees in Economics at Duke University, and he is an *Emeritus* Professor of Economics at Ohio University. His research interests include CGE modeling, natural resource economics, international trade, and public finance. Articles that he has written on those topics have appeared in *Energy Economics*, *Rand Journal of Economics*, *Canadian Journal of Economics*, and *Review of Economics and Statistics*.

Alejandra Elizondo holds a PhD in Public Policy from Centro de Investigación y Docencia Económicas (CIDE), a MsC in Economic Policy from Columbia University, a Master in Positive Psychology from Universidad Jaume I, and a BA in Economics from Instituto Tecnológico Autónomo de México. She is a researcher at the Economics Department of CIDE in Mexico, and her interests include designing and applying economic tools to assess the impacts of energy and climate policies on production, government indicators and wellbeing.

María Eugenia Ibararán earned a PhD in Geography, a MA in Energy and Environmental Studies from Boston University, and a Bachelor's degree in Economics from Instituto Tecnológico Autónomo de México. Dr. Ibararán is a researcher at the Xabier Gorostiaga Environmental Research Institute of the Universidad Iberoamericana Puebla. Her research interests include environmental economics, in particular the economics of climate change, energy, air and water pollution, and economic valuation of environmental quality.

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the level of carbon emissions produced globally, and to encourage both developed and developing countries and to adopt “cleaner” technologies.

Since fossil fuels are widely seen as fairly convenient sources of energy, any curbs on their usage will itself entail economic costs, and, it is feared, constrict the pace of economic growth in all sectors of a given nation’s economy. Consequently, economists and policymakers have found it useful to rely on large economy-wide Computable General Equilibrium (CGE) models to measure the costs of different carbon emission abatement strategies. Indeed, this type of analysis has been done for a number of countries in various stages of economic development. Typically, these models quantify a policy’s impacts by explicitly accounting for the linkages between the fossil fuel sectors and the various other sectors of that country’s economy. The increased costs entailed by higher price energy alternatives are measured by consumer indices (e.g., Equivalent Variation), and, depending on the policy, these costs can at times be significant. Frequently, simulations are conducted to study the ameliorating effect that technological change in renewable energy generation has on compliance cost. Such technological change, however, is most frequently modeled exogenously in an *ad-hoc* manner and relies on conjectures and assumptions outside the basic framework of the CGE model itself.

While existing CGE models of developing countries (including Mexico) yield similar results to those of G7 countries, there are several factors which could, in fact, bias their predictions, and lead these models to overestimate the losses caused by fossil fuel restrictions. First, as authors such as Posner<sup>1</sup> and Vernon<sup>2</sup> have forcefully argued, developing countries often adopt technological innovations first pioneered in developed countries. This, in turn, allows them to take advantage of technological advances without themselves having to contend with high front-end costs and risky R&D investments. Second, due to their bloated bureaucracies and aging infrastructure, the services provided by public utilities in many developing countries are frequently unreliable and highly inefficient. Thus, we see, for instance, that the introduction of cellular technology from advanced economies allowed many developing countries to, in effect, “leapfrog” the task of upgrading their antiquated land line systems, and to do so in a rapid and very cost-effective manner.

In the present analysis then, we modify the typical CGE modeling structure in such a way as to account for the diffusion of new renewable energy technology in a developing country and examine the degree to which this modification alters the estimated welfare changes resulting from more stringent carbon emission restrictions. More specifically, using a large CGE model which we have constructed for Mexico, we adjust the energy sector so as to explicitly incorporate increasing returns to scale and thereby allow for endogenous technological change in a manner consistent with the introduction of renewable energy technology. In doing this we build on earlier theoretical analyses by Romer<sup>3,4</sup> and Barro and Sala-i-Martin.<sup>5</sup> Our empirical results are then examined to see how easily they can be generalized and applied to other, similar developing economies.

After first reviewing the economic literature on the use of renewable energy in Mexico in Section 2, when then turn, in Section 3, to the presentation of our CGE model of Mexico. There, special emphasis is placed on the modifications made which allow us to model increasing returns and endogenous change in the production of renewable energy. In Section 4 we present the results of our model's simulations as well as a sensitivity analysis to check the robustness of our findings. Finally, in Section 5 we conclude and discuss the wider policy implications of our model's findings.

## ***2. Reform in Mexico's Energy Sector***

Due to inadequate investment and a lack of competition, Mexico's (primarily state-owned) fossil fuel and electricity sectors have, over the past two to three decades, become increasingly inefficient and outdated.<sup>6</sup> Following a strong push in Mexico to reform these sectors, and, after a long and controversial public debate, major energy reforms were finally enacted in the latter part of 2013.<sup>7</sup> Recognizing the need to both revitalize its stagnating energy sector and to boost aggregate economic growth, the Mexican government was obliged to make significant modifications to its existing Constitution. In doing this their aim was to promote competition and attract both domestic and foreign capital into Mexico's energy sector.

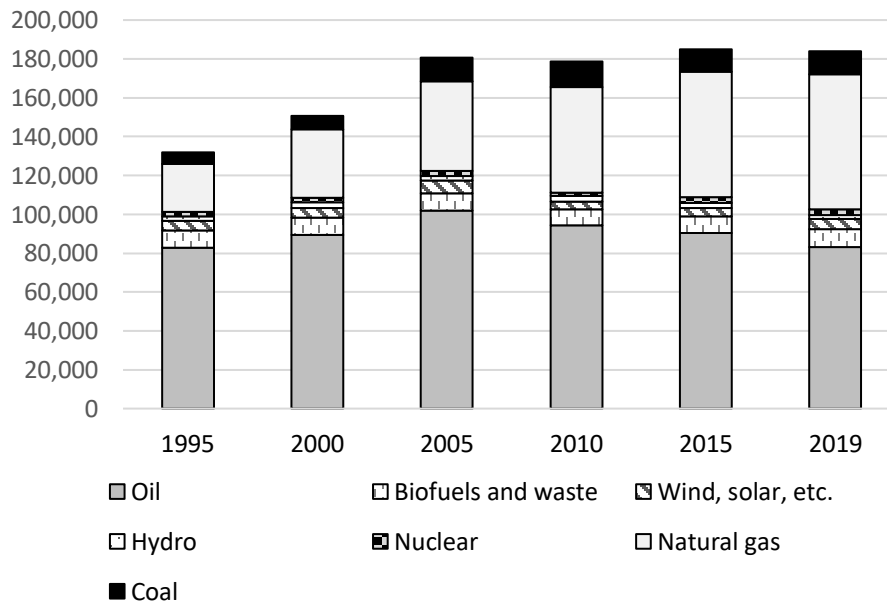
Mexico's state-run electric power utility, Comisión Federal de Electricidad (CFE) has been plagued by a host of inefficiencies including severe transmission losses, poorly directed subsidies, a lack of adequate investment in new transmission lines and dilapidated distribution systems. This has led to high consumer prices and a loss in Mexico's competitiveness vis-à-vis its main trading partner, the United States.<sup>8</sup> An important goal of the 2013 reforms was to leverage lower power costs into higher domestic growth. Such savings in power output costs, it was argued, would largely be the result of increased efficiency in the extraction of Mexico's large reserves of natural gas. The transmission and distribution of both electricity and natural gas would be kept under the control of CFE due to natural monopoly concerns, but pipelines could be built and operated by private investors (from both Mexico and abroad). Funding for renewable energy sources was also introduced into these reforms, but only as an afterthought, and primarily to placate political pressure from those directly affected by severe pollution as well as environmental activists. Auctions were to be held to award power generation project contracts with the winners subject to strict environmental standards.

Even though the auctions conducted by officials of Mexico's oil and power sectors were successful (as shown by the vast amount of committed investment resources<sup>9</sup>), and the bid prices were competitive by global standards<sup>10</sup> in 2018 the (newly installed) government of Andres Manuel López Obrador questioned the

wisdom of this ongoing energy reform. Charting a radically new direction, López Obrador proposed building a new refinery at Dos Bocas and advocated expanding the use of coal and fuel oil for power generation. Such actions have met resistance due to environmental concerns, and indeed increased activity initiated at existing refineries (in Salamanca and Tula) has already increased ambient effluent levels there. Additionally, it is feared that the use of high sulfur fuels from these refineries will lead to an uptick in air pollution in Mexico City and other large metropolitan areas<sup>11</sup>. Thus, far from being inconsequential, the actions of Mexico’s new government are likely to have significant implications for Mexico’s future energy use, its natural resource extraction, its environmental quality, and its commitments to international carbon emission reduction.

**Changing the Energy Matrix for Power Generation:** The energy mix in Mexico has traditionally relied heavily on fossil fuels, in general, and on petroleum, in particular. As of 2019 (the latest year where data were available) hydrocarbons provided 89% of Mexico’s total primary energy<sup>12</sup> with most of that fuel coming from reserves located in Mexico itself (see Figure 1).

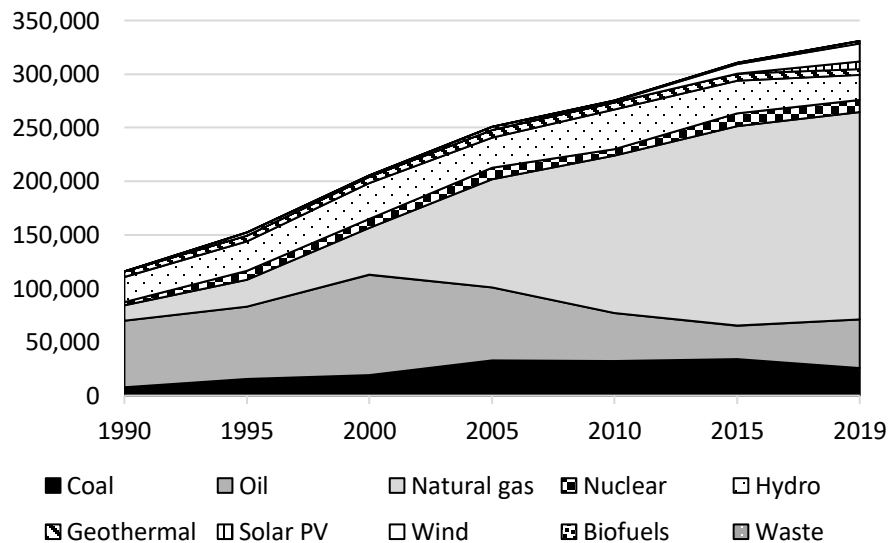
Figure 1  
MEXICO: TOTAL ENERGY USE BY SOURCE  
(in kilotons of oil equivalent – KTOE)



Source: International Energy Agency (IEA), *Mexico. Key Energy Statistics, 2020* (2020), also available at <https://www.iea.org/countries/mexico>.

Interestingly, however, the relative shares of the various fuels used for power generation have changed markedly over time. Whereas in 1990 30% of all electricity came from fuel oil, by 2019 that number had declined to 10%. This was largely replaced by natural gas, whose share had climbed to 60%. Coal use remained fairly steady and hovered between 7% and 9% (over that same period of time), but the share of energy from renewable sources continues to remain small, in spite of the best efforts of past governments to encourage the use of wind and solar. As of 2019, the share of energy produced by wind and solar sources only stood at 5% and 7%, respectively. This, combined with the fact that hydropower’s share shrank from 20% to 7% meant that Mexico has even become even more reliant on fossil fuels over the past 30 years.<sup>13</sup>

Figure 2  
 MEXICO: POWER GENERATION BY SOURCE  
 (in gigawatt-hours –GWh)



Source: International Energy Agency (IEA), *Mexico. Key Energy Statistics, 2021* (2021), also available at <https://www.iea.org/countries/mexico>.

Given its recent actions, it would seem that the López Obrador government has little interest in changing the status quo and promoting the use of renewable energy. Indeed, in December 2018 a fourth round of auctions for renewable energy contracts was abruptly cancelled by the government. During this same period of time, attempts were made by Mexico’s executive branch to roll back previous

reforms in the electric power industry, but these actions were vigorously challenged in the courts. López Obrador's ruling Morena party, and its allies have introduced a number of bills in the legislature designed to modify the 2013 reforms, but the fate of this legislation has yet to be resolved. The upshot of all this conflict, however, is to create a cloud of uncertainty and undermine the confidence of potential domestic and foreign investors in Mexican energy projects.

In spite of these obstacles there has been a sustained push from many quarters (both within and outside the country) to make investments in renewable energy in Mexico. Future policies in the energy sector could include Renewable Portfolio Standards either at a statewide or national level.<sup>14</sup> Proposed regulations to limit the extraction of fossil fuels or future surcharges on the extraction of fossil fuels may also constrain emissions.<sup>15</sup>

With this as background we now turn to addressing the methodology that we use here to model such policies, (i.e., computable general equilibrium (CGE) models) and describe how such models have been applied in various settings to assess energy policy changes in developing countries such as Mexico.

### ***3. The Role of CGE Models in Addressing Renewable Energy Policy***

As in most large developing countries there are a host of carbon abatement strategies available to policy makers in Mexico. These range from using taxes and subsidies to phase out fossil fuels (and promote the use of less polluting sources of energy) all the way to the introduction of marketable permits and quotas to explicitly discourage the use of fossil fuels. To determine the effects of these different policies, models that explicitly account for the linkages between a nation's economic sectors are needed. Computable general equilibrium models, or CGEs, such as ours are well suited to these kinds of analyses.<sup>16</sup> In the past, CGE models have frequently been used to analyze a variety of environmental and fiscal issues worldwide<sup>17</sup> as well as in Mexico.

**A Review of the Literature—General:** A methodology frequently employed by analysts involves the use of Computable General Equilibrium (CGE) models. Indeed, these types of models have become an indispensable tool in assessing the economic and environmental impacts of alternative carbon abatement strategies.<sup>18</sup> The advantage of using CGEs as a tool of analysis is that the energy sector is strongly linked to the rest of the economy. Thus, CGE models can address both the direction and magnitude of spillover effects on all the other sectors of a given nation's economy,<sup>19</sup> or, if necessary, calculate the sectoral impacts from climate change mitigation for an entire region such as the European Union. To date, most of these CGE analyses have been static in nature and, thus, fixed at one point in time. They can, however, be modified to be dynamic making them capable of

investigating the impacts of various environmental policy initiatives as they unfold over time.<sup>20</sup>

The popularity of CGE analysis as a tool to investigate climate change related issues cannot be overstated. CGE models are now widely used to simulate the effects of alternative carbon abatement strategies at the national, regional, and global levels.<sup>21</sup> To date, the largest number of such studies have looked at East Asia and the Pacific (36.4%), followed by Europe (31.8%) and North America (30.5%). The specific countries examined most frequently are China, Germany, Australia, India, and the United States. Perhaps, not surprisingly, these countries turn out to be the ones with the highest level of greenhouse gas emissions worldwide. Most of these studies focus on policies to mitigate emissions such as carbon taxes, emission reduction targets, emission trading, renewable energy, energy efficiency, and carbon capture and storage. Overall, their results show that the use of these policies and instruments leads to a cleaner and more efficient energy sector with lower GHG emissions, often with little negative macroeconomic impacts. The effect on the price of energy produced through renewable energy sources varies a bit however, with some countries facing significantly higher prices (e.g., Malaysia).<sup>22</sup>

Some of this literature looks at the macroeconomic effects of large-scale renewable energy deployment, as well as the overall costs of different technological options to attain such a transition.<sup>23</sup> Generally, it is found that the macroeconomic impacts of expanding the use of renewable energy sources is very low. Across this vast literature, some studies look at particular aspects of renewable energy such as its impact on employment.<sup>24</sup> They conclude that often such employment impacts are overestimated since more jobs are usually created during the construction phase of a given project (e.g., to build wind turbines or solar arrays) than during its operational phase. Another set of related papers is concerned with the financing of renewable energy projects. These include feed-in tariffs in Indonesia<sup>25</sup> as well as carbon taxes in Malaysia.<sup>26</sup> These studies find that such policy instruments increase the adoption of renewable energy sources and cut emissions without significant detrimental macroeconomic consequences.<sup>27</sup> Still other studies deal with the impact of renewable energy sources on environmental quality.<sup>28</sup> They find strong evidence that policies aimed at implementing renewable energy do, in fact, cut back on emissions and therefore have a positive impact on the environment, and that this effect is larger the more aggressive the policy. It is thus fair to say that CGE models have been used extensively to address policies in the energy sector including the impacts of increased use of renewable energy.

**CGE Analysis of Mexico:** In Mexico, CGE models have long been employed to examine a variety of energy-related issues. Initially, such studies were primarily

designed to estimate the effects of climate on the Mexican economy.<sup>29</sup> The findings of these studies suggested that such change would be detrimental to economic growth, particularly in sectors dependent on temperature and precipitation such as agriculture, livestock, forestry, and tourism. As a consequence of this, they calculated that the lower income groups in Mexico would be hurt (relatively) more by these changes.<sup>30</sup> Policies to mitigate GHG emissions, on the other hand, were found to increase growth in the long run and were shown to be quite progressive. In this vein, some studies using CGE models have focused on estimating economic double dividends from energy policy.<sup>31</sup> Double dividends, however, are difficult to attain if significant technological change does not simultaneously take place.<sup>32</sup>

Later CGE studies of Mexico deal with the 2013 energy market reforms,<sup>33</sup> and these studies find that energy prices would increase due to the elimination of subsidies under the reform. This, in turn, would negatively impact economic welfare if consumers were not compensated for their losses. Other studies look at the impact of syphoning off energy subsidies to finance health related policies.<sup>34</sup> They find that the effect of such reforms is to speed up economic growth. Furthermore, this growth is progressive and benefits the lower income groups in Mexico relatively more than the higher income groups. Interestingly then, the elimination of energy subsidies may have different effects depending on the nature of the policies it is combined with.

Finally, CGE models have been used to analyze the effectiveness of energy policy to reach climate and other environmental related goals.<sup>35</sup> These studies find that removing existing energy subsidies may provide up to 80% of the carbon reductions necessary for Mexico to comply with its international GHG reduction commitments, without even adding further climate change policies. In still another CGE study, H. Bravo Perez et al.<sup>36</sup> evaluated the effectiveness of an environmental policy to replace fossil fuels with renewable energy through a carbon tax policy. They found that the effectiveness of such a policy to promote renewables depends on the extent to which a clean energy sector can substitute for fossil fuels. Thus, they argue that there is a need to develop a viable renewable energy sector in order to create a robust, flexible, and effective energy policy.

**Endogenous Growth and the CGE Model:** The CGE model which we use here is national in scope, and Mexico's economic activity is disaggregated into 14 production sectors, 15 production goods, 4 household (income) categories, 10 consumption sectors, a foreign sector, and the government (see Table 1). The first column lists the production sectors and the second one the production goods produced by the sectors in the first column. The consumer goods are not necessarily related to those production goods.

The economic variables determined by the model are investment, production by each sector, household consumption by sector, input level, imports and exports,

relative prices, returns to primary factors, government budget expenditures and revenues, and the level of each consumers' economic welfare.

It is assumed that most of the sectors in our model exhibit constant returns to scale. In the case of the energy consumption sector, however, the market has an imperfectly competitive structure composed of R highly substitutable input varieties. This stands in marked contrast to previous CGE treatments of this sector, and, as explained below, allows us to endogenously model growth and technological change in this critical industry.<sup>37</sup>

Table 1  
CLASSIFICATION OF SECTORS AND GOODS

<b>Producing Sectors</b>	<b>Production Goods</b>	<b>Consumer Goods and Services</b>
Manufacturing	Manufacturing Goods	Food
Renewable Manufacturing	Renewable Energy Goods	Energy
Chemicals and Plastics	Chemicals and Plastics	Autos
Agriculture	Agricultural goods	Gasoline
Services	Producer Services	Consumer Transport
Transportation	Transportation for production	Consumer Services
Electricity	Electricity	Housing and Household goods
Oil and Gas	Crude Petroleum	Consumer Goods
	Natural Gas	Water
Refining output	Refined output	Medical Services
Livestock	Livestock	
Forestry	Wood and forest products	
Fisheries	Fish and fishery products	
Coal Mining	Coal	
Other Mining	Other mining Goods	

**Production:** The production portion of the model is built upon information from a balanced data set and is constructed so as to be flexible with regards to the substitution between both the primary factor inputs (capital, labor, and land), and the material (semi-finished) inputs from other production sectors.<sup>39</sup> The material inputs enter in a manner similar to that of an input-output model except that their substitutability can differ from zero. Technologies are represented by production functions which assume constant elasticities of substitution. More specifically, production in each sector is represented as a constant elasticity of substitution (CES) function of capital, labor, and material inputs where the elasticity of substitution can vary from zero to infinity.<sup>40</sup> Hence, we have, equation (1):

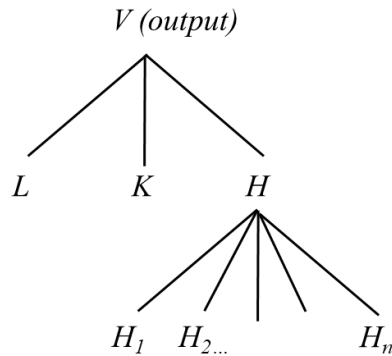
$$V = \Phi [\delta_L L^{(\sigma-1)/\sigma} + \delta_k k^{(\sigma-1)/\sigma} + \delta_H H^{(\sigma-1)/\sigma}]^{\sigma/(\sigma-1)} \quad (1)$$

where  $V$  is the value of the output in the sector and  $\sigma$  is the elasticity of substitution between inputs. The elasticity of substitution measures the degree to substitutability between two factors of production and it varies between 0 (no substitutability) and infinity (complete substitutability). The parameter  $\Phi$  is a scaling or efficiency parameter for the entire production function,  $L$  is labor,  $K$  is capital,  $H$  are materials, and the  $\delta$ 's are the share parameters. These share parameters give the relative importance of a given input in the production of a given sector's output and are defined so that:

$$\delta_L, \delta_K, \delta_H > 0 \text{ and } \delta_L + \delta_K + \delta_H = 1$$

The materials input,  $H$ , does not represent a single factor input but rather a host of inputs from the various production sectors. Hence, in our model  $H$  is a composite input produced by a nested CES production function whose arguments are the actual inputs from the model's production sectors. All of this is depicted in Figure 3. In the diagram the total output of a generic production good,  $V$ , is shown at the apex of the figure. The labor, capital, and composite materials inputs are placed at the second tier, and each of the individual materials inputs are placed at the third tier. Besides being more flexible, this setup has the distinct advantage of allowing the elasticity of substitution between materials inputs to differ from the elasticity of substitution between the primary inputs.<sup>41</sup>

Figure 3  
STRUCTURE OF NESTED PRODUCTION FUNCTIONS



It is important to note that the goods produced in the model's production sectors are not the same final goods consumed by consumers. In the case of energy, for example, electricity (from both renewable and non-renewable sources) and fuels must be combined with transportation services, manufacturing, and retail utility

services before they can be consumed at the household level. Following C. Ballard et al.<sup>42</sup> we then posit a 15 X 10 transformation matrix (which they denote as the  $Z$  matrix) to map the vector of production goods to the vector of consumption goods. This matrix assigns the output of each production good to the input of each consumption good in direct proportion to the share of total value added which they contribute to that good's assembly. Thus, each element of this matrix may be written as  $Z_{ij}$  where  $i$  is an index of the  $M = 15$  production goods and  $j$  is an index of the  $n = 10$  consumption goods. The output of each consumption sector  $X_j$ , then, can be expressed as a function of its  $Z_{ij}$  inputs. For 9 of these 10 consumption sectors, we assume (as we did for all 15 production sectors) that there are constant returns to scale.

The energy consumption sector  $X_{en}$ , however, is modeled differently. In this sector we assume that a subset of the  $Z_{ien}$  inputs (which we label as  $W_{ien}$ ) are not homogeneous in nature but instead consist of a large finite number of slightly differentiated, imperfectly substitutable input varieties. As it turns out, the proliferation of these distinct but highly substitutable inputs allows for increasing returns to scale and technological change to occur in our model. To see how this occurs mathematically, following Dixit and Stiglitz,<sup>43</sup> we write equation (2):

$$W_{iEN} = \sum_k^R w_k^\alpha \quad k = 1, 2, 3 \dots R. \quad (2)$$

Where  $W_{iEN}$  is a composite good made up of  $R$  varieties which are each denoted by a lower case  $w_k$  and indexed by  $k$ .<sup>44</sup> Technological progress here is manifested in the number of varieties of these inputs (i.e.,  $R$ ), and an increase in  $R$  can be thought of as a type of innovation just like the opening of a new industry. If we suppose that these  $R$  individual input varieties  $w$  can be expressed in a common physical unit, and that (as is the case in equilibrium) they are all used in the same quantity, then the total inputs to energy provided by each of these differentiated input categories is given by equation (3):

$$W_{iEN} = R * w_k. \quad (3)$$

The manner in which this formulation leads to increasing returns to scale is most easily shown by examining the simple two input Cobb-Douglas case. In this case we express output  $X$  as a function of a single composite input  $W$  and a single homogeneous input  $Z$  or equation (4):

$$X = \beta W^\gamma Z^{(1-\gamma)} \quad \text{where } 0 < \gamma < 1. \quad (4)$$

Using equation (3), this production function can then be equivalently expressed

as equation (5):

$$X = \beta R(w_k)^Y Z^{(1-Y)} \quad (5) \quad \text{or} \quad X = \beta (Rw_k)^Y R^{(1-Y)} Z^{(1-Y)} \quad (5a)$$

As can be seen from equation (5), production here exhibits constant returns to scale in  $Z$  and  $R^*w_k$ , the aggregate quantity of the differentiated input. For any given level of  $Z$  and  $R^*w_k$ , however, the term  $R^{(1-Y)}$  in expression (5a) indicates that the value of  $X$  increases with the total number of input varieties  $R$ . As noted by R. Barro and X. Sala-i-Martin, “This effect, which captures a form of technological progress, reflects the benefit from spreading a given total of intermediates [ $R^*w_k$ ] over a wider range [ $R$ ]. The benefit arises because of the diminishing returns to each of the [ $w_k$ ] individually.”<sup>45</sup>

**Aggregate Consumption:** In keeping with basic economic accounting, the income which individuals receive from their labor, along with the income from their capital receipts, is then either spent on consumption or invested through savings. Aggregate domestic consumers in this model are divided into four groups according to their level of income. Agent 1 consists of the lowest two deciles in terms of income. Agent 2 is made up of the next three deciles. Agent 3 consists of the following three deciles, and Agent 4 includes the top 2 deciles (see Table 2).

Table 2  
HOUSEHOLD CATEGORIES BASED ON INCOME

Category	Income
Agent 1	Bottom 2 deciles: 1-2
Agent 2	Deciles 3-5
Agent 3	Deciles 6-8
Agent 4	Top 2 deciles: 9-10

Consumers modify their choice of work, leisure, and consumption as result of the implementation of a given policy. Nonetheless, in this model they cannot migrate from one income group to another. Consumer utility is modeled according to nested CES functions for all consumption goods, where consumers are maximizing their utility subject to a budget constraint. Each agent  $a$  then selects their level of consumption as well as their amount of work, leisure, and savings to maximize equation (6):

$$\begin{aligned}
 &U_a = U_a(X_{ca}, LI_a), \\
 &s. t \\
 &TG_a + TF_a + (P_a * L_a) + (r * K * S_a) = (INV * S_a) + (P_{ax} * X_{ac}) + (P_L * LI_a)
 \end{aligned} \quad (6)$$

where  $U_a$  is the level of that household's utility,  $X_{ca}$  is a vector representing the amount of all goods consumed by each agent,  $LI_a$  is their leisure,  $TG_a$  and  $TG_a$  denote the level of government and foreign transfers that they receive,  $r$  is the rent from capital,  $K$  is capital,  $S_a$  is the share of capital for each household,  $INV$  is total investment, and  $P_{ax}$  is a vector of prices corresponding to the remainder of the final goods and services consumed.

**Government:** The government sector in our model is treated as a separate independent agent.<sup>46</sup> The government agent is modeled with an expenditure function similar to the household expenditure functions, based on a CES utility function. Revenues derived from all taxes and tariffs are spent according to this expenditure function. Within the expenditure function the government spends its revenues on goods and services from the various private production sectors discussed above. This structure assumes that the government faces a budget constraint and, hence, responds to price changes much as any utility maximizing agent would do. The government also spends its revenues on labor. Together these arguments represent the government purchases and payment of government employees necessary for it to carry on its work. The government also separately redistributes income through exogenously set subsidies and transfer payments, and all revenues are spent.<sup>47</sup> In connection with this last point, it should be pointed out, however, that the government sector does not save and there is a zero surplus in the government account. Hence, the government does not own capital, and the capital needed for government-provided goods such as education is rented from the private sector.

Taxes in the model are expressed *ad valorem* and include personal income taxes, labor taxes, capital taxes, property taxes, revenue taxes (such as payments from oil and gas activities), value added taxes, sales taxes, import tariffs and export taxes. As stated above, in the initial calibration of this model, taxes are calculated in such a way as to exactly reproduce the amount of revenue generated in Mexico in 2016. The taxes on final goods such as gasoline differ from those on other consumer goods because of special taxes levied on them by the government. By the same token final goods such as electricity differ in treatment due to the existing government subsidies which they receive. When applicable, taxation is based on marginal tax rates, and to capture the incentive effect of the tax system, the highest marginal rate is levied on the relevant revenue base. Since this procedure results in over-taxation, the difference between the revenue generated by the highest marginal tax rate and the average tax rate is rebated to consumers as a lump-sum transfer.

Subsidies in the model are essentially treated as negative taxes and in these cases the government transfers funds back to a sector in proportion to that sector's output. Thus, if these subsidies are abolished, the government will have more

revenue. To keep aggregate revenues equal to aggregate expenditures, the government will increase spending on all items in proportion to existing government expenditures on the different goods and services. This assumption may be relaxed later if desired.

**Trade:** International trade within the model is handled by means of a foreign agent. Output in each of the producing sectors is exported to the foreign agent in exchange for foreign-produced imports. Under this setup the aggregate level of imports is set, but the level of individual imports may change in response to changes in relative prices. Exports are constant as well. They are, however, responsive to changing prices, and can change in response to shocks in individual sectors. Transfer payments, on the other hand, are endogenous and act to clear the balance of payments in the model. Price-dependent import supply schedules are derived from elasticity estimates found in the literature.<sup>48</sup>

In specifying the substitutability between foreign and domestically produced goods we replace the classic Heckscher-Ohlin assumptions and rely instead on the Armington<sup>49</sup> assumptions. Under these assumptions, imports and domestically produced goods are imperfectly substitutable goods (as opposed to Heckscher-Ohlin where foreign and domestically produced goods are considered perfect substitutes). Armington postulates that domestic and foreign goods are both inputs in a CES production process, the output of which is a combination of the two. It is this combined good that is consumed domestically. The benefit of such a setup is that a country can both import and export goods from the same industrial sector. Furthermore, under these assumptions domestic prices can differ from world price levels, but the more closely substitutable the foreign and domestic goods, the closer the two prices are to each other. Under the Heckscher-Ohlin assumptions, by contrast, all goods are perfect substitutes and foreign and domestic prices must be equal.

The balance of trade relationship is given by equation (7):

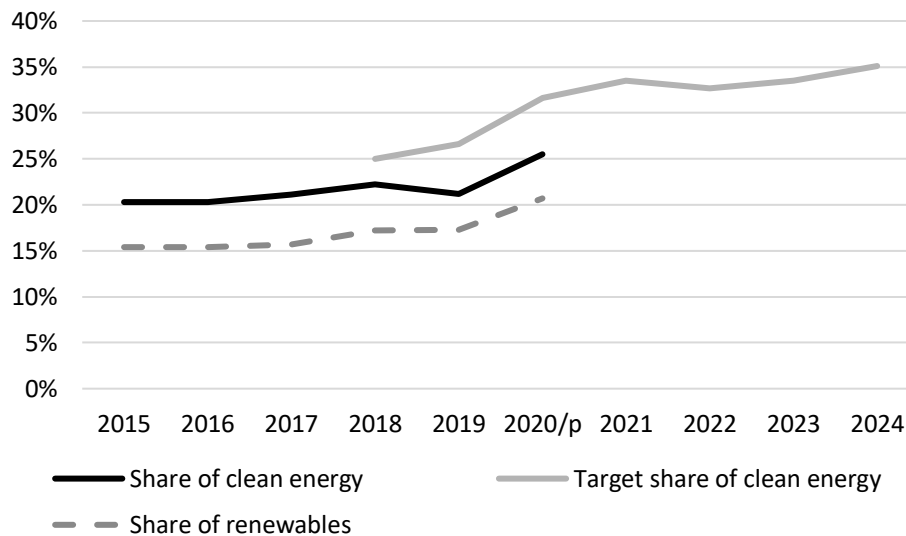
$$P_m * IM = P_{ex} * EX + TF \quad (7)$$

where  $IM$  is a vector representing the quantity of each of the producer goods imported,  $P_m$  is the vector of imported goods prices,  $EX$  is the vector of all producer goods exported,  $P_{ex}$  is the tariff inclusive vector of producer goods prices, and  $TF$  is the level of foreign transfers which can be positive, zero, or negative. Because of the Armington assumptions, as stated above, the import prices are not required to equal their domestic counterparts. The prices of exports are identical to their domestic price (adjusting, of course, for any export taxes). The value of total imports is equal to the total value of exports plus foreign transfers. Since these transfers are used to finance domestic investment this relation provides the

closure rule, namely, that investment is equated to domestic savings minus net exports. This, of course, includes balanced trade as a special case.<sup>50</sup>

**Scenarios:** The 2020 Energy Transition Strategy, published by the Mexican Government, mandates clean annual energy generation targets (Figure 4). These targets are aligned with previous commitments to increase the share of renewables (and other clean technologies) in the electricity matrix. According to these estimates, by 2024 Mexico should be generating 35% of its electricity using clean technologies, (i.e., that is renewables plus nuclear and efficient cogeneration). That target increases to 40% by 2035 and to 50% by 2050. As shown in the graph, however, Mexico has not been able to achieve the targets in previous years, and if it is going to achieve compliance new “tougher” policies would need to be enacted.

Figure 4  
TARGETS AND SHARE OF RENEWABLES AND CLEAN ENERGY IN MEXICO



Sources: Compiled by authors based upon the following: Secretaría de Energía (SENER), *Reporte de Avance de Energías Limpias* (México, 2016); Secretaría de Energía (SENER), *Reporte de Avance de Energías Limpias* (México, 2017); Secretaría de Energía (SENER), *Estrategia de Transición para Promover el Uso de Tecnologías y Combustibles más Limpios* (México, 2020); and Secretaría de Energía (SENER), *PRODESEN 2020-2034* (México, 2021).

Our business-as-usual (BAU) base setup mimics the current situation with respect to Mexico’s electricity fuel mix which relies almost exclusively on fossil fuels. We then compare this BAU case to three alternative scenarios where policies are enacted to encourage the adoption of energy from renewable sources. For

purposes of presentational clarity, the results of the alternative cases are listed as percentage changes from our original Business as Usual case. Each of these three policies, in turn, relies on two basic types of economic instruments. First, a carbon tax is implemented to disincentivize the use of fossil fuels in all relevant production and consumption sectors. Then, the resources generated by this policy are used by the government to foster power generation based on renewables.

The introduction of renewable technologies brings about two types of benefits. First, large scale projects contribute to the share of clean energy in the matrix, lowering GHG gases and helping to curb worldwide climate change. In Mexico, recent evidence suggests that wind and solar technologies have become more affordable and competitive in recent years. This experience is very much in line with development in other countries and is borne out by various analyses conducted by IEA, BP, and IPCC, among others (for a comprehensive analysis, see RFF.)<sup>51</sup> (Energy from nuclear and biomass also rise under these scenarios.)

The second type of benefit comes from small scale renewable technology projects. These projects help to significantly ease congestion on the transmission grid. The expansion and modernization of the Mexico's transmission network remains one of today's chief electricity policy challenges. Presently, in order to guarantee energy supply to households, businesses, and society in general, infrastructure projects must develop. However, new and more diverse technologies that expand the capacities for small scale projects also lower the pressure to expand the network, generating alternative solutions to satisfy energy needs locally.

In each of our three model simulations we assume that the Mexican government stimulates renewable energy production by means of a subsidy while simultaneously discouraging fossil fuel use via a carbon tax. More specifically, in each of our three simulations we subsidize the manufacturing, services, and transport inputs) to the renewable energy sector (by 40%, 20%, and 10%, respectively). This expense is then offset by a tax on coal, petroleum, and natural gas according to their carbon content so as to make the overall policy revenue neutral.<sup>52</sup> We first run the model without any counterfactual taxes or subsidies to confirm that it can accurately replicate the production and consumption figures in the 2016 "benchmark" year from which our data come. We then impose those taxes and subsidies to measure the changes they cause in production, consumption, imports and exports, prices, and welfare levels in all of the sectors of our model. This same procedure is followed in all three of our simulations.

In our first model simulation (Scenario 1) we modify the features of the economy so that new and diverse technologies used in electricity convey increasing returns to scale consistent with endogenous technological change as discussed in our modeling section above. We then examine the case where this policy is employed under the assumption of 20% inefficiency in the production of energy.

The costs of renewable energy have fallen sharply during the last decade and continue to fall. IRENA estimates that these costs dropped by between 30% to 80% during the period from 2010 until 2019, making these technologies not only available without financial support, but also more efficient options than fossil fuels generation. According to the U.S. Energy Information Administration,<sup>53</sup> levelized costs of electricity generated with wind and solar technologies are between 9% and 16% lower, respectively, than the most efficient fossil fuel technology (combined cycle). This gap in costs is probably an understatement of the Mexican situation since such comparisons consider new and, hence, more efficient plants. In Mexico, renewable energy would (by definition) be coming from new efficient sources. The power it would be replacing, however, would come from old inefficient fossil fuel plants. Indeed, I. Alpizar-Castro and C. Rodriguez-Monroy<sup>54</sup> explain that, due to aging infrastructure and bureaucratic inefficiency, Mexican electricity costs are currently about 25% higher than their U.S. counterparts.

The model is calibrated using the substitution and consumer demand elasticities listed in the appendix. Each of our three simulations are run several times using different energy demand elasticities as a sensitivity check. As with the initial run, in our sensitivity runs all taxes and subsidies are adjusted so as to make this policy mix revenue neutral for the government agent.

In our second simulation (Scenario 2) we again assume increasing returns to scale in energy production and subsidize the manufacturing, transportation, and service inputs to the energy sector in a manner similar to that employed in Scenario 1. Furthermore, as before, we levy a carbon tax on the production of fossil fuels so as to make the policy revenue neutral. Now, however, we assume that the inefficiency of the energy sector to be 30% rather than 20%, thereby increasing the potential gains due to the presence of technological change.

In our third and final scenario (Scenario 3) we drop our assumption of increasing returns to scale and assume that production in the energy sector exhibit constant returns to scale in a manner identical to each of our other consumption and production sectors. Under this assumption, the existing inefficiencies in the energy sector persist and there is no cost saving endogenous technological change from the adoption of new renewable energy sources. As with the two previous scenarios, we subsidize the manufacturing, transport, and service inputs to the energy consumption sector and counterbalance this with a carbon tax on fossil fuels.

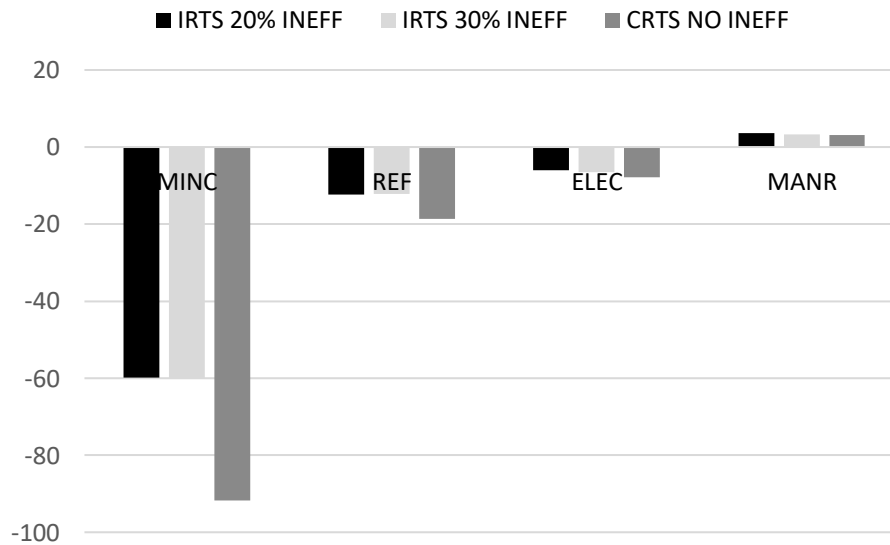
#### ***4. Results: Overview***

As stated at the outset, the justification for tax/subsidy schemes designed to encourage renewable energy at the expense of fossil fuels is based on their externality gains. Standard CGE analyses, however, show that, absent these gains, such policies lead to welfare losses using classic measures such as Equivalent

Variation (EV). As we have noted though, these CGE analyses (for both developing and developed countries) generally rely on the assumption of constant returns to scale (CRS) in the production of all goods and services in a given economy. The purpose of the present study then is to see if the presence of existing energy inefficiencies (as in Mexico) and the assumption of increasing returns to scale (IRS), as outlined above, can combine so as to avoid the EV losses associated with various fiscal policies designed to cut carbon emissions.

The effects of the carbon tax become evident when we examine the changes in the production sectors (Figure 5). There, in line with our expectations, the largest decline occurs in coal production, followed by those related to petroleum, natural gas and refined goods. Services and manufacturing (in general) see little change, but the manufacturing of those items used in the production of renewable energy goes up. Interestingly, our model results show the production of electricity going down. It must be remembered, however, that this number reflects the amount of electricity produced using fossil fuels and not that produced from renewable sources.

Figure 5  
PRODUCTION OF SELECTED GOODS <sup>a</sup>  
(% change with regards to benchmark)



<sup>a</sup> MINC = coal mining; REF = refining; ELEC = electricity; MANR = manufacturing for renewables; IRST 20% INEFF = 20% inefficiency and scale economies; IRST 30% INEFF = 30% inefficiency and scale economies; and CRTS NO INEFF = no inefficiency and no scale economies.

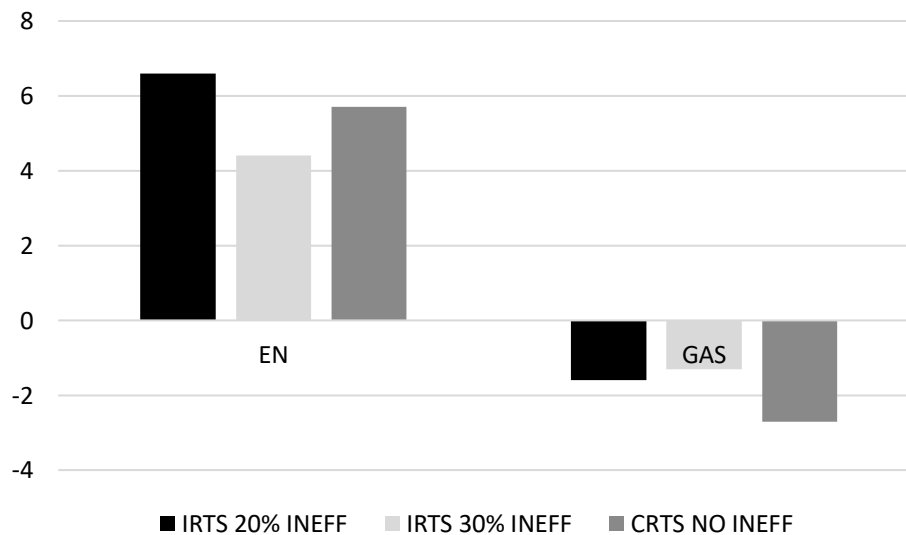
Consistent with what theory would predict, there is an increase in energy

production with respect to the benchmark case. The difference between energy production, however, is quite small suggesting that our results are not all that sensitive to changes in our assumptions about this efficiency parameter. Indeed, the output of most of the model’s production and consumption sectors are identical to what they were in the previous scenario.

Upon examination of scenario 3 we see that, qualitatively, the impacts of this policy on the model’s production and consumption sectors are similar to the two cases where we assumed increasing returns. Quantitatively, however, things change noticeably from Scenarios 1 and 2.

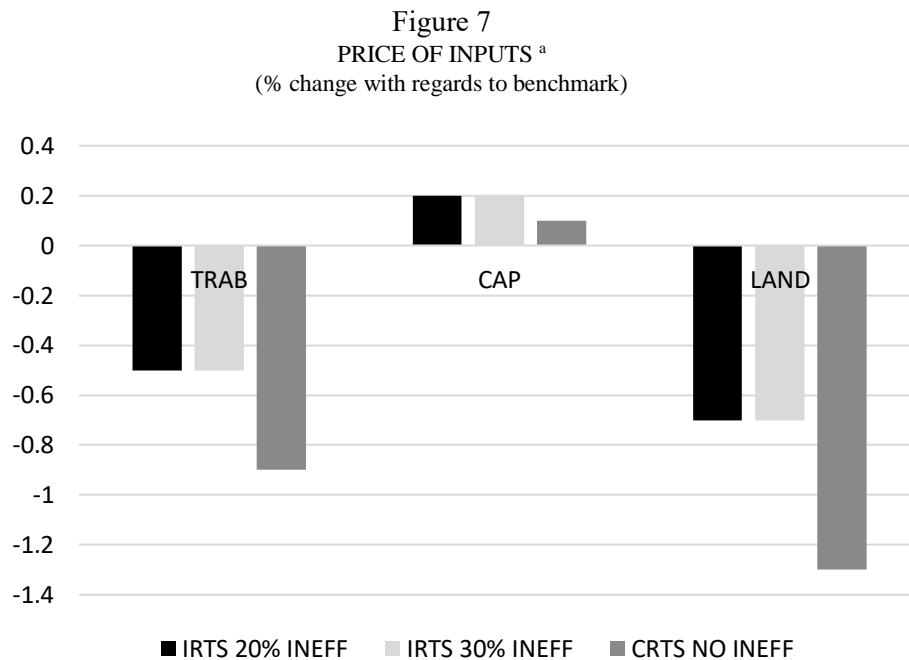
Turning to our model’s consumption sectors, we see that, as expected, the largest gains occur in the energy sector where increasing returns to scale occur due to the infusion of renewable technologies (Figure 6). Indeed, due to the presence of increasing returns to scale, the additional output in this sector outstrips the additional input resources used in its production. Consumption in most other sectors including services and consumer goods remains fairly stable. The sector here that experiences by far the largest decline is the consumption of gasoline (and other transportation fuels). This is largely due to the increase in fossil fuel prices brought about by the carbon tax.

Figure 6  
 CONSUMPTION OF SELECTED GOODS <sup>a</sup>  
 (% change with regards to benchmark)



<sup>a</sup> EN = energy; GAS = gasoline; IRST 20% INEFF = 20% inefficiency and scale economies; IRST 30% INEFF = 30% inefficiency and scale economies; and CRTS NO INEFF = no inefficiency and no scale economies.

Although not directly impacted by this policy, the factor market and foreign sectors are indirectly affected due to their CGE linkages to our model's energy and fossil fuel sectors. Thus, we see that, given the capital intensity of the fossil fuel sectors, a carbon tax has the effect of increasing the cost of capital relative to that of land and labor (Figure 7). Furthermore, the higher domestic price of carbon-based energy leads to a rise in the imports of refined petroleum, coal, and natural gas.<sup>55</sup>



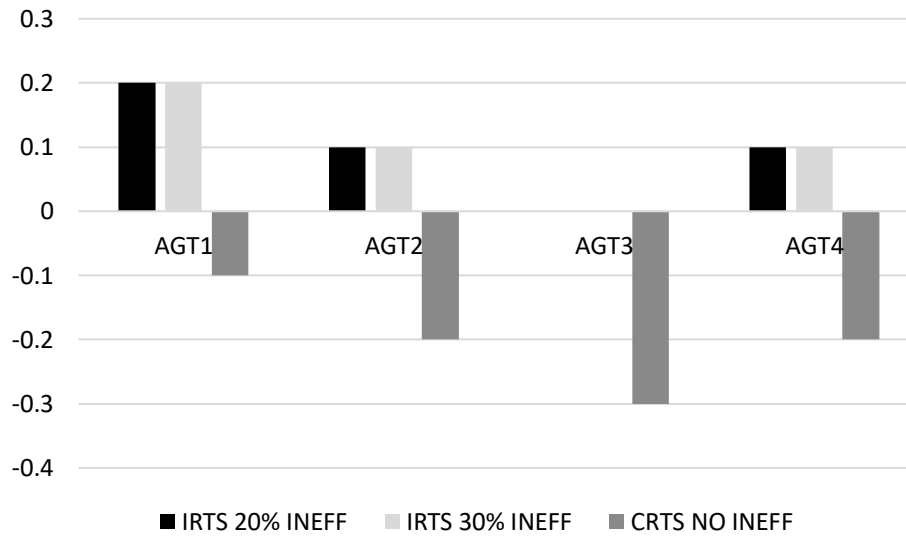
<sup>a</sup> TRAB = labor; CAP = capital; LAND = land; IRST 20% INEFF = 20% inefficiency and scale economies; IRST 30% INEFF = 30% inefficiency and scale economies; and CRTS NO INEFF = no inefficiency and no scale economies.

The incidence of this tax/subsidy case in scenario 3 remains the same with the price of capital rising relative to that of labor and land, but there is an important change in consumer welfare (Figure 8). Scenarios 1 and 2 show a slight uptick in overall consumer welfare reflecting the benefits that accrue to consumers from higher relative efficiency gains in the energy sector. In contrast to the initial two simulations, in the third scenario there is a slight decrease in the welfare of all four of our consuming agents.

The changes which we observe in consumer welfare can be directly attributed to the subsidies and the changes discussed above in our model's structure. As the proliferation of new inputs leads to technological change in the energy sector, the

efficiency of that sector increases as its output expands. Thus, rather than seeing a welfare loss we see a slight rise in the overall level of consumer welfare, except in Scenario 3, where no endogenous growth is happening. Furthermore, since energy expenditures account for a higher proportion of the total budget of lower income groups, we find that the impact of this policy is slightly progressive with the highest percentage gains accruing to agent 1.

Figure 8  
WELFARE BENEFIT OF DIFFERENT INCOME GROUPS <sup>a</sup>  
(% change with regards to benchmark)



<sup>a</sup> AGT1 = agent 1; AGT2 = agent 2; AGT3 = agent 3; AGT4 = agent 4; IRST 20% INEFF = 20% inefficiency and scale economies; IRST 30% INEFF = 30% inefficiency and scale economies; and CRTS NO INEFF = no inefficiency and no scale economies.

### 5. Conclusion and Policy Implications

As stated at the outset, while CGE analyses have often confirmed the effectiveness of initiatives like carbon taxes in achieving CO<sub>2</sub> reductions (in a given country), they have almost always indicated that those reductions would be somewhat costly in terms of traditional measures of economic welfare. Such results, however, are predicated on the assumption that, at least initially, renewable energy is more costly than energy from fossil fuels, and the assumption that the production and distribution of renewable energy exhibits constant returns to scale. This situation can be ameliorated by allowing for technological change. Most

commonly, though, this change is imposed on the renewable energy sector from outside the model in a fairly arbitrary and ad-hoc manner.

In our analysis here we have developed a CGE model of Mexico which allows for the existence of increasing returns in the production of renewable energy. Furthermore, by modeling sectoral growth in that sector via a proliferation of goods, we have been able to introduce technological change both endogenously and in a fashion that mimics the way that innovation has historically been transferred to developing nations' economies. Our results indicate that under such assumptions a policy that taxes carbon while, at the same time, subsidizing renewable energy can reduce carbon emissions without a loss in economic welfare. Furthermore, these results seem to be robust over a wide range of parameter values.

Although the results of our simulations are straightforward some caution should be taken when considering them as a basis for public policy. First of all, the overall changes in welfare remain somewhat small. The externality gains from this policy, however, are potentially quite large, and it is these gains that would constitute the primary justification of enacting such a tax/subsidy scheme in a country like Mexico. Indeed, the environmental gains from this type of policy would occur both in the short run (due to decreases in the emissions of particulates, SO<sub>2</sub>, NO<sub>x</sub>, etc.), and in the long run (due to the decrease in greenhouse gas emissions). Second, the potential exists for fossil fuel imports and exports to act in such a way as to dampen the effectiveness of this policy. Finally, as with any tax/subsidy plan, its efficiency in practice depends on the reliability of the governmental agencies actually collecting and dispersing the funds.

## APPENDIX

### *Modeling Sources*

Our model is built upon previous work on general equilibrium from Ballard, Fullerton, Shoven, and Whalley,<sup>56</sup> Shoven and Whalley,<sup>57</sup> Rutherford's work on nonlinear complementarity problems and MPSGE<sup>58</sup> integrated into GAMS, and Armington's<sup>59</sup> assumptions on imperfect substitutability between imports and domestically produced goods. We built our database from various information sources. Our social accounting matrix (SAM) relies heavily on the latest Input-Output Matrix.<sup>60</sup> We also use information from various Economic Census, the Mexican Household Expenditure Survey and fiscal data generated by the Ministry of Finance and the Central Bank.

In addition to the sources cited above, we looked at additional data from the International Financial Statistics, published by the International Monetary Fund (IMF), The Mexican Economy, published by Banco de México, and the Anuario Estadístico de los Estados Unidos Mexicanos. We also gathered information

published by the World Bank. Fossil fuel consumption, fuel prices, fuel imports and exports and consumption of various fuels were provided by the Ministry of Energy (SENER), PEMEX, and INEGI. Employment data and other information used for specific simulations were taken from the Mexican Survey on Employment (ENOE) and IMSS database.

The elasticity of substitution between capital and labor for production sectors is an important parameter in determining the distributional impacts of a policy. When feasible, we adopted elasticities estimates from literature specific to Mexico (Appendix Table 1). Other times, we made educated approaches according to the existing literature.

Table 1  
ELASTICITIES OF SUBSTITUTION BETWEEN LABOR AND CAPITAL <sup>a</sup>

Sector	Elasticity of substitution	Source
Agriculture	0.96	Hueter, 1997
Livestock	0.96	Hueter, 1997
Forestry	0.96	Hueter, 1997
Fisheries	0.96	Hueter, 1997
Mining <sup>a</sup>	0.8	Balistreri et al, 2003.
Electricity	0.45	Fragiadakis, 2012
Chemicals	0.8	Claro, 2003
Refining	1.08	Claro, 2003
Transport <sup>a</sup>	1.0	Balistreri et al, 2003.
Services <sup>a</sup>	1.0	Balistreri et al, 2003.
Manufacturing	1.0	Skuta, 1997

<sup>a</sup> According to Balistreri et al.'s analysis<sup>61</sup> the Cobb Douglas specification is a valid starting point in parameterizing models and working on simulations and sensitivity analysis. In his work analyzing 28 industries with a vast dataset from the Bureau of Economic Analysis, they supported a Cobb Douglas specification for 20 of them.

#### NOTES

<sup>1</sup> M. V. Posner, "International Trade and Technical Change," *Oxford Economic Papers*, vol. 13, no. 3 (1961), pp. 323–41, <https://doi.org/10.1093/oxfordjournals.oep.a040877>.

<sup>2</sup> R. Vernon, "The Product Cycle Hypothesis in a New International Environment," *Oxford Bulletin of Economics and Statistics*, vol. 41, no. 4 (1979), pp. 255–67, <https://doi.org/10.1111/j.1468-0084.1979.mp41004002.x>

<sup>3</sup> P. M. Romer, "Growth Based on Increasing Returns Due to Specialization," *The American Economic Review*, vol. 77, no. 2 (1987), pp. 56–62.

<sup>4</sup> P. M. Romer, "El cambio tecnológico endógeno," *El Trimestre Económico*, vol. 58, no. 231

(1991), pp. 441–80.

<sup>5</sup> R. J. Barro and X. Sala-i-Martin, *Economic Growth* (New York: McGraw-Hill, 1995).

<sup>6</sup> For a thorough review of the history of the energy sector in Mexico, see Roy Boyd, María E. Ibararán, and Roberto Vélez-Grajales, *Understanding the Mexican Economy: A Social, Cultural, and Political Overview* (Emerald Publishing, 2018), <https://doi.org/10.1108/978-1-78769-065-320181015>.

<sup>7</sup> I. Apizar-Castro and C. Rodríguez-Monroy, “Review of Mexico’s Energy Reform in 2013: Background, Analysis of the Reform and Reactions,” *Renewable and Sustainable Energy Reviews*, vol. 58, (2016), pp. 725–36, <https://doi.org/10.1016/j.rser.2015.12.291>.

<sup>8</sup> I. Rousseau, “Mexico’s Energy Reforms at Risk?” *Édito Énergie IFRI*, vol. 13, no. 3 (2018).

<sup>9</sup> Senado de la República, “Reforma Energética: balance de cierre a 2018,” *Notas Estratégicas*, no. 28 (2018), pp. 1–18.

<sup>10</sup> K. García, “Subastas tiran precios de energía renovable,” *El Economista*, November 23, 2017.

<sup>11</sup> A. Pradilla, “Respirando azufre: Profepa investiga termoeléctrica de Tula por alta emisión de contaminantes,” *Animal Político*, May 26, 2021.

<sup>12</sup> International Energy Agency (IEA), *Mexico. Key Energy Statistics, 2020* (2020), also available at <https://www.iea.org/countries/mexico>.

<sup>13</sup> K. Gillingham and P. Huang, “Is Abundant Natural Gas a Bridge to a Low-Carbon Future or a Dead-End?” *The Energy Journal*, vol. 40, no. 2 (2008), pp. 61–79, <https://doi.org/10.5547/01956574.40.2.kgil>.

<sup>14</sup> A. Hollingsworth and I. Rudik, “The Effect of Leaded Gasoline on Elderly Mortality: Evidence from Regulatory Exemptions,” *American Economic Journal: Economic Policy*, vol. 13, no. 3 (2021), pp. 345–73, DOI: 10.1257/pol.20190654.

<sup>15</sup> T. D. Gerarden, *Essays in Environmental Economics and Industrial Organization* (Cambridge, Massachusetts: Harvard University Dissertations, 2018).

<sup>16</sup> S. Jenniches, “Assessing the Regional Impacts of Renewable Energy Sources. A Literature Review,” *Renewable and Sustainable Energy Reviews*, vol. 93 (2018), pp. 35–51, <https://doi.org/10.1016/j.rser.2018.05.008>.

<sup>17</sup> P. Vikström, “Energy Efficiency and Energy Demand: A Historical CGE Investigation on the Rebound Effect in the Swedish Economy 1957,” *Ekonomisk Historia* (2008), pp. 1–27, and N. D. Hanley, P. G. McGregor, J. K. Swales, and K. Turner, “The Impact of a Stimulus to Energy Efficiency on the Economy and the Environment: A Regional Computable General Equilibrium Analysis,” *Renewable Energy*, vol. 31, no. 2 (2006), pp. 161–71, <https://doi.org/10.1016/j.renene.2005.08.023>.

<sup>18</sup> K. Babatunde, R. A. Begum, and F. F. Said, “Application of Computable General Equilibrium (CGE) to Climate Change Mitigation Policy: A Systematic Review,” *Renewable and Sustainable Energy Reviews*, vol. 78 (2017), pp. 61–71, <https://doi.org/10.1016/j.rser.2017.04.064>; A. Krook-Riekkola, C. Berg, E. O. Ahlgren, and P. Söderholm, “Challenges in Top-Down and Bottom-Up Soft-Linking: Lessons from Linking a Swedish Energy System Model with a CGE Model,” *Energy*, vol. 141 (2017), pp. 803–17, <https://doi.org/10.1016/j.energy.2017.09.107>; S. Fujimori, T. Masui, and Y. Matsuoka, “Development of a Global Computable General Equilibrium Model Coupled with Detailed Energy and End-Use Technology,” *Applied Energy*, vol. 128 (2014), pp. 296–306, <https://doi.org/10.1016/j.apenergy.2014.04.074>; and N. Bauer, O. Edenhofer, and S. Kypreos, “Linking Energy System and Macroeconomic Growth Models,” *Computational Management Science*, vol. 5 (2008), pp. 95–117, <https://doi.org/10.1007/s10287-007-0042-3>.

<sup>19</sup> K. Babatunde et al., op. cit.

<sup>20</sup> R. R. Palatnik, *Analysis of the Impact of Economic Incentives to Control Greenhouse Gas Emissions within the Framework of a General Equilibrium Model of the Israeli Economy* (Israel: University of Haifa, 2008).

<sup>21</sup> K. Babatunde et al., op. cit.

<sup>22</sup> F. Chatri, M. Yahoo, and J. Othman, “The Economic Effects of Renewable Energy Expansion in the Electricity Sector: A CGE Analysis for Malaysia,” *Renewable and Sustainable Energy Reviews*, vol. 95 (2018), pp. 203–16, <https://doi.org/10.1016/j.rser.2018.07.022>.

<sup>23</sup> Ibid; H. Dai, X. Xie, Y. Xie, J. Liu, and T. Masui, “Green Growth: The Economic Impacts of Large-Scale Renewable Energy Development in China,” *Applied Energy*, vol. 162 (2016), pp. 435–49, <https://doi.org/10.1016/j.apenergy.2015.10.049>; P. Thepkhun, B. Limmeechokchai, S. Fujimori, T. Masui, and R. M. Shrestha, “Thailand’s Low-Carbon Scenario 2050: The AIM/CGE Analyses of CO<sub>2</sub> Mitigation Measures,” *Energy Policy*, vol. 62 (2013), pp. 561–72, <https://doi.org/10.1016/j.enpol.2013.07.037>; and D’Artis Kancs, “Integrated Appraisal of Renewable Energy Strategies: A CGE Analysis,” *International Journal of Energy Technology and Policy*, vol. 1, no. 1–2 (2002), pp. 59–90, <https://doi.org/10.1504/IJETP.2002.000805>.

<sup>24</sup> Y. Mu, W. Cai, S. Evans, C. Wang, and D. Roland-Holst, “Employment Impacts of Renewable Energy Policies in China: A Decomposition Analysis Based on a CGE Modeling Framework,” *Applied Energy*, vol. 210 (2018), pp. 256–67, <https://doi.org/10.1016/j.apenergy.2017.10.086>; W. Blyth, R. Gross, J. Speirs, S. Sorell, J. Nicholls, A. Dorgan, and N. Hughes, “Low Carbon Jobs: The Evidence for Net Job Creation from Policy Support for Energy Efficiency and Renewable Energy,” *London: UK Energy Research Centre*, vol. 14 (2014); C. Böhringer, N. J. Rivers, T. F. Rutherford, and R. Wigle, “Green Jobs and Renewable Electricity Policies: Employment Impacts of Ontario’s Feed-in Tariff,” *The BE Journal of Economic Analysis & Policy*, vol. 12, no. 1 (2012), <https://doi.org/10.1515/1935-1682.3217>; and S. Fankhaeser, F. Sehlleier, and N. Stern, “Climate Change, Innovation and Jobs,” *Climate Policy*, vol. 8, no. 4 (2008), pp. 421–29, <https://doi.org/10.3763/cpol.2008.0513>.

<sup>25</sup> H. W. V. Hasudungan and S. S. Sabaruddin, “Financing Renewable Energy in Indonesia: A CGE Analysis of Feed-in Tariff Schemes,” *Bulletin of Indonesian Economic Studies*, vol. 54, no. 2 (2018), pp. 233–64, <https://doi.org/10.1080/00074918.2018.1450961>.

<sup>26</sup> F. Chatri et al., op. cit.

<sup>27</sup> J. Wu, Y. Fan, G. Timilsina, Y. Xia, and R. Guo, “Understanding the Economic Impact of Interacting Carbon Pricing and Renewable Energy Policy in China,” *Regional Environmental Change*, vol. 20 (2020), pp. 1–11, <https://doi.org/10.1007/s10113-020-01663-0>.

<sup>28</sup> W. Britz and T. W. Hertel, “Impacts of EU Biofuels Directives on Global Markets and EU Environmental Quality: An Integrated PE, Global CGE Analysis,” *Agriculture, Ecosystems & Environment*, vol. 142, no. 1–2 (2011), pp. 102–09, <https://doi.org/10.1016/j.agee.2009.11.003>.

<sup>29</sup> A. Hernández-Solano and A. Yúnez-Naude, *Impactos del cambio climático en la economía rural de México: un enfoque de equilibrio general* (Mexico: El Colegio de México, 2016); Y. Castillo and H. M. Bravo, *Incidencia económica de un impuesto a las emisiones de CO<sub>2</sub> en el sector energía en un modelo de equilibrio general computable para México* (Spain: Departamento de Economía Aplicada Universidad Autónoma de Barcelona, 2010); and R. Boyd and M. E. Ibararán, “Extreme Climate Events and Adaptation: An Exploratory Analysis of Drought in Mexico,” *Environment and Development Economics*, vol. 14, no. 3 (2009), pp. 371–95, <https://doi.org/10.1017/S1355770X08004956>.

<sup>30</sup> J. I. Rodríguez Sánchez, *El impacto de eliminar los subsidios a la electricidad en México: implicaciones económicas y ambientales mediante un modelo de equilibrio general computable* (Mexico: Repositorio Nacional CONACYT, 2003).

<sup>31</sup> G. Landa Rivera, F. Reynès, I. Islas Cortes, F. X. Bellocq, and F. Grazi, “Towards a Low Carbon Growth in Mexico: Is a Double Dividend Possible? A Dynamic General Equilibrium Assessment,” *Energy Policy*, vol. 96 (2016), pp. 314–27, <https://doi.org/10.1016/j.enpol.2016.06.012>.

<sup>32</sup> M. E. Ibararán, *Energy Taxation in Mexico: A Revenue Neutral Tax Reform*, Conference

Proceedings, GEE/IAEE European Conference on Energy Markets: What's New?, Berlin, Germany, September 9-10, 1998 available at <https://www.osti.gov/etdeweb/biblio/311855>.

<sup>33</sup> S. Moshiri and M. A. Martínez-Santillan, "The Welfare Effects of Energy Price Changes due to Energy Market Reform in Mexico," *Energy Policy*, vol. 113 (2018), pp. 663–72, <https://doi.org/10.1016/j.enpol.2017.11.035>.

<sup>34</sup> A. Antón, R. Boyd, A. Elizondo, and M. E. Ibararán, "Universal Social Insurance for Mexico: Modeling of a Financing Scheme," *Economic Modelling*, vol. 52, part B (2016), pp. 838–50, <https://doi.org/10.1016/j.econmod.2015.10.020>.

<sup>35</sup> A. Elizondo and R. Boyd, "Economic Impact of Ethanol Promotion in Mexico: A General Equilibrium Analysis," *Energy Policy*, vol. 101 (2017), pp. 293–301, <https://doi.org/10.1016/j.enpol.2016.11.017>, and R. Boyd and M. E. Ibararán, "El costo del cambio climático en México: análisis de equilibrio general de la vulnerabilidad intersectorial," *Gaceta de Economía*, vol. 16 (2011), pp. 115–33.

<sup>36</sup> H. Bravo Pérez, J. C. Castro Ramírez, M. Á. Gutiérrez Andrade, and E. P. Omaña Pulido, "Evaluación de una política de sustitución de energías fósiles para reducir las emisiones de carbono," *El Trimestre Económico*, vol. 84, no. 333 (2017), pp. 137–64, <https://doi.org/10.20430/ete.v84i333.265>.

<sup>37</sup> Dixit-Stiglitz type CGE models, i.e., with increasing returns to scale, have been used in various fields. Trade policy has been analyzed globally with these models (Zhai, 2008), as well as in specific countries (Das and Chakraborti, 2013; Movchan and Shportyuk, 2013; and Latorre, 2016 and 2014, for example). The Dixit-Stiglitz framework has also been used in spatial CGE models to address transport policy (Tavasszy et al., 2011, and Hansen, 2010). Additionally, these models have been used to analyze energy policy (Waschik, 2015; Bretschger et al., 2011; Otto et al., 2007; and Babiker, 2005). Increasing returns to scale models in the energy sector have not been applied to Mexico recently.

<sup>39</sup> The materials trade flows between the various production goods sectors as well as between the production and consumption sectors is based on the 2013 input-output table constructed by INEGI in 2013. It was updated using price and production data of 2020 provided by Banco de México.

<sup>40</sup> The demand elasticities for most goods were derived in accordance with our assumption of Cobb-Douglas utility for consumers. In the special cases of gasoline and energy, however, they were modified to fit the econometric estimates obtained by L. Galindo "Short-and Long-Run Demand for Energy in Mexico: A Cointegration Approach," *Energy Policy*, vol. 33, no. 9 (2005), pp. 1179–185, <https://doi.org/10.1016/j.enpol.2003.11.015>.

<sup>41</sup> It should also be pointed out that in the case of agriculture and livestock, land is also included as a primary input of production and for these sectors would be included on the second tier of our diagram.

<sup>42</sup> C. L. Ballard, J. B. Shoven, and J. Whalley, "General Equilibrium Computations of the Marginal Welfare Costs of Taxes in the United States," *The American Economic Review*, vol. 75, no. 1 (1985), pp. 128–38.

<sup>43</sup> A. K. Dixit and J. E. Stiglitz, "Monopolistic Competition and Optimum Product Diversity," *The American Economic Review*, vol. 67, no. 3 (1977), pp. 297–308.

<sup>44</sup> In this equation  $\alpha$  is a CES parameter associated with the elasticity of substitution between varieties.

<sup>45</sup> R. J. Barro and X. Sala-i-Martin, op. cit., p. 214.

<sup>46</sup> C. L. Ballard et al., op. cit.

<sup>47</sup> Hence, there is no elasticity of substitution between government expenditures and payroll expenses, on the one hand, and subsidies and transfer payments, on the other.

<sup>48</sup> J. Serra-Puche, H. E. Scarf, and J. B. Shoven, *A General Equilibrium Model for the Mexican Economy Applied General Equilibrium Analysis* (California, EUA: Conference on Applied General

Equilibrium Analysis, 1984); O. Fernández, “Efectos de la aplicación de un impuesto ecológico neutral en México: Análisis mediante un modelo de equilibrio general computable,” *Instrumentos económicos para un comportamiento empresarial favorable al ambiente en México* (1999), pp. 145–78; and P. J. Wylie, “Partial Equilibrium Estimates of Manufacturing Trade Creation and Diversion due to NAFTA,” *The North American Journal of Economics and Finance*, vol. 6, no. 1 (1995), pp. 65–84, [https://doi.org/10.1016/1062-9408\(95\)90006-3](https://doi.org/10.1016/1062-9408(95)90006-3).

<sup>49</sup> P. S. Armington, “A Theory of Demand for Products Distinguished by Place of Production,” *Staff Papers-International Monetary Fund*, vol. 16, no. 1 (1969), pp. 159–78.

<sup>50</sup> Capital flows are the remainder of the exports minus imports, or net exports since the deficit in the current account must be made up for by a surplus in the capital account.

<sup>51</sup> Resources for the Future (RFF), *Global Energy Outlook* (Washington, D.C.: RFF, 2021).

<sup>52</sup> Since coal has the highest content of any fossil fuel it receives the highest tax. Natural gas, containing the least amount of carbon per BTU has the lowest tax, and petroleum, whose carbon content lies between that of coal and natural gas, is taxed at an intermediate level.

<sup>53</sup> U.S. Department of Energy, Energy Information Administration (EIA), *Annual Energy Outlook* (Washington, D.C.: EIA, 2021).

<sup>54</sup> I. Apizar-Castro and C. Rodríguez-Monroy, op. cit.

<sup>55</sup> Since Mexico’s imports of crude petroleum are miniscule there would effectively be no increase in crude oil imports. Mexico does however presently import substantial quantities of refined petroleum products, principally from the United States.

<sup>56</sup> C. L. Ballard et al., op. cit.

<sup>57</sup> J. B. Shoven and J. Whalley, “Applied General-Equilibrium Models of Taxation and International Trade: An Introduction and Survey,” *Journal of Economic Literature*, vol. 22, no. 3 (1984), pp. 1007–051.

<sup>58</sup> T. Rutherford, “A Modeling System for Applied General Equilibrium Analysis,” *Cowles Foundation Discussion Papers* (1978), pp. 1–45; T. Rutherford, “Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem: An Overview of the Modeling Framework and Syntax,” *Computational economics*, vol. 14 (1999), pp. 1–46, <https://doi.org/10.1023/A:1008655831209>; and C. Böhringer, T. F. Rutherford, and W. Wiegard, “Computable General Equilibrium Analysis: Opening a Black Box,” *ZEW*, no. 03-56 (2011).

<sup>59</sup> P. S. Armington, op. cit.

<sup>60</sup> Instituto Nacional de Estadística y Geografía (INEGI), *Matriz de Insumo Producto Base 2013* (México, 2013).

<sup>61</sup> E. J. Balistreri, C. A. McDaniel, and E. V. Wong, “An Estimation of US Industry-Level Capital–Labor Substitution Elasticities: Support for Cobb–Douglas,” *The North American Journal of Economics and Finance*, vol. 14, no. 3 (2003), pp. 343–56, [https://doi.org/10.1016/S1062-9408\(03\)00024-X](https://doi.org/10.1016/S1062-9408(03)00024-X).