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The Economic, Energy, and Emissions Impacts of Climate Policy in South Korea

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This reprint is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn and John M. Reilly,
Joint Program Co-Directors

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GLOBAL CHANGE

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The Economic, Energy, and Emissions Impacts of Climate Policy in South Korea

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Abstract: Using an economy-wide model, we evaluate the impact of policies to meet South Korea's Paris pledge to reduce greenhouse gas (GHG) emissions by 37% relative those under business as usual (BAU) in 2030. Simulated BAU emissions in 2030 are 840.8 million metric tons (Mt) of carbon dioxide equivalent (CO_2e), indicating that economy-wide emissions should be constrained to 529.7 MtCO_2e. Under South Korea's Emissions Trading System (KETS) and fuel economy standards, a 2030 carbon price of \$89/tCO_2e is needed to meet this goal. Without considering benefits from avoided climate damages, these policies reduce 2030 GDP by \$20.6 billion (1.0%) and consumer welfare by 7.9 billion (0.7%). Comparing this scenario to one where South Korea's Paris pledge is met solely by an ETS, indicates that adding a fuel economy standard reduces GDP and welfare by, respectively, \$4.2 billion and \$1.1 billion. Declines in sectoral production are largest for fossil-based energy sectors and the chemical, rubber and plastic products, and iron and steel sectors.

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1. Introduction

At the 2015 Paris Climate Conference—the 21st Conference of the Parties (COP21) under the United Nations Framework Convention on Climate Change (UNFCC)—South Korea joined most other countries in signing an agreement to mitigate greenhouse gas (GHG) emissions, extending earlier commitments for reductions through 2020 to 2030. Nations that are parties to the Paris agreement are required to submit National Determined Contributions (NDCs) that outline future reductions in GHG emissions out to 2030.

South Korea has been actively developing a climate policy strategy since at least 2009 when it set a goal of reducing greenhouse gas (GHG) emissions by 30% below its business-as-usual (BAU) emissions level by 2020 as a part of its Nationally Appropriate Mitigation Action (NAMA). Based on its projected BAU level, that would leave emissions at 543 million tons of CO_2e, about 4½% below its 2005 emissions level of 569 million tons (Ministry of the Environment, 2017). In June 2015, South Korea replaced the NAMA with the new goal of reducing greenhouse gas (GHG) emissions by 37% below BAU emissions by 2030 as a part of its 2030 Intended Nationally Determined Contribution (INDC) target. An evaluation by Climate Action Tracker (2017) sees the replacement of the NAMA with the INDC as backsliding. While the INDC includes a slightly larger percentage reduction in emissions in 2030 from the BAU, the absolute level of emissions would be little different than the NAMA goal for 2020, emphasizing how interpretations of a target can vary depending on a focus on a reduction from BAU or an absolute reduction from an historic year. Climate Action Tracker (2017) also points out that 2030 emissions will be 81% above 1990 levels, reflecting very rapid growth between 1990 and 2012.

Projections given current policies indicate that South Korea's emissions will remain above the 2020 target, and additional new policies will be needed to achieve the 2030 goal. The Government indicated that a 25.7% reduction will be achieved domestically and a further 11.3% reduction will be achieved by international market mechanisms (Climate Action Tracker, 2017). To meet these goals, South Korea launched three major policies: a Target Management Scheme (TMS), an Emission Trading Scheme (ETS), and 2020 Corporate Average Fuel Economy (CAFE) Regulations. The TMS is a precursor to the ETS, with lower penalties for non-compliance. CAFE regulations were introduced in 2014, with targets to be fully phased in by 2020.

In this paper, we develop and deploy a custom-made economy wide model to evaluate the impacts of key climate policies in South Korea in 2030. Several studies focus on the global implications of the Paris agreement (Fawcett *et al.*, 2015; Aldy *et al.*, 2016; Vandyck *et al.*, 2016; and Jacoby *et al.*, 2017). While these studies provide regional details, they typically do not report results for South Korea or assume cost-minimizing attainment of the NDC emissions goals, rather than specific policy proposals.

Yongrok *et al.* (2017) use an economy-wide model to examine the economic and emissions impacts of the KETS, but their analysis differs from ours in several ways. First, Yongrok *et al.* (2017) evaluate outcomes in 2015 and our analysis considers 2030. Second, the authors simulate emission reductions in sectors covered by the KETS without imposing an economy-wide emissions target. Third, Yongrok *et al.* (2017) specify a single (aggregated) electricity technology while we explicitly represent eight different electricity generation technologies. Fourth, Yongrok *et al.* (2017) only consider CO_2 emissions from fossil fuel combustion, whereas our modelling framework includes all GHGs covered by the policy. Fifth, we evaluate the KETS accounting for the impact of South Korea's fuel economy standard, while Yongrok *et al.* (2017) do not consider complementary measures. To our knowledge, our study is the first detailed economy-wide analysis of South Korea's 2030 NDC emissions pledge.

This paper has four further sections. Section 2 provides a further overview of key climate policies in South Korea. Section 3 describes the structure and data sources for our economy-wide model and the scenarios implemented in our analysis. Our results are presented and discussed in Section 4. Section 5 concludes.

2. Climate policy in South Korea

Key climate policy legislation in South Korea includes the Korean Emissions Trading Scheme (KETS) and fuel economy standards. The long-term goal of the KETS is to reduce 2030 emissions by 37% relative to business as usual (BAU). The foundations for the cap-and-trade system were set by The Framework Act on Low Carbon, Green Growth (Framework Act) in May 2012. The KETS was launched in January 2015 and is divided into three phases: Phase I runs from 2015 to 2017, Phase II operates from 2018 to 2020, and Phase III covers the period 2021 to 2025. In each phase, the cap on GHG emissions and rules concerning the operation of the system (e.g., the allocation of emission allowances, and the use of offsets) can differ. In phase I, the cap on emissions is 573 $MtCO_2e$ in 2015, dropping to 562 in 2016 and to 551 in 2017. Emissions caps for subsequent phases have not yet been set.

Sectors covered by the KETS include (1) electricity, (2) industry (e.g., mining, oil refining, food and beverages, cement, steel, non-ferrous metals, automobiles, shipbuilding, electronic equipment), (3) building (including telecommunication), (4) domestic aviation, and (5) public waste treatment. GHGs included in the KETS include emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) from energy, industrial processes, product use and waste. Emissions from land use, land-use change and forestry (LULUCF) are not currently included in the KETS.

In Phase I, there will be 100% free allocation of allowances, with allocations based on firm activities in 2011–2013. In subsequent phases, a proportion of allowances will be auctioned, with at least 10% of allowances auctioned in Phase III. Energy-intensive, trade-exposed sectors will receive 100% of their allowances for free in all phases. Banking of emission permits is allowed without any restrictions. Borrowing permits is only allowed within each phase, with restrictions on the amount that can be borrowed. In all phases, up to 10% of emission rights can be sourced from outside the ETS in the form of offsets. In Phases I and II, only domestic offset credits can be used for ETS compliance. In Phase III, up to 50% of offsets can be sourced internationally (i.e., international offsets can contribute up 5% of the total number allowances submitted for compliance obligations).

In our analysis, we evaluate the KETS in 2030 under the stated objective of reducing business as usual emissions by 37% in this year. Our representation of the policy in 2030 is guided by legislation for Phase III of the KETS, or where specifics for Phase III are yet to be set, the latest year for which legislation has currently been set. We do not consider banking and borrowing of emission permits in our analysis as evaluating these mechanisms would require emissions caps for each year out to 2030. The representation of the KETS in our modeling framework is described in Section 2.

South Korea's Ministry of Environment introduced new fuel economy and GHG standards for passenger cars, buses with a maximum seating capacity of 15 or fewer persons, and trucks that weigh less than 3.5 tons (ICCT, 2015). The regulations will be phased-in from 2016 to 2020. They require a 30.7 percent reduction in the fleet average GHG emission for passenger vehicles from 2015 levels. Similar to regulations in the EU, some classes of very efficient vehicles are weighted more heavily. For example, zero emission vehicles get a weight of 3 and vehicles with less than 50 g/km of GHGs get a weight of 2. Light trucks and buses are required to reduce their GHG emissions by 15.2 percent from 2013 to 2020, with the actual standard varying by gross curb weight of the vehicle (i.e. each curb weight must meet the 15.2 percent improvement from 2013 levels, recognizing that heavier vehicles have higher emissions per km). The Korea Energy Management Corporation on behalf of the Ministry of Trade, Industry and Energy introduced a nearly equivalent set of fuel economy standards.

Vehicle manufacturers can select by the end of March each year whether to achieve the average fuel economy standard or the GHG emission standard. The manufacturer can also choose either a sales ratio target or a yearly target for passenger cars and light trucks (Ministry of Environment, 2014). The sales ratio target requires that 10 percent of vehicles sold in 2016 must meet the 2020 targets, with this percentage increasing to 20 percent by 2017, 30 percent by 2018, 60 percent by 2019 and 100 percent by 2020 (ICCT, 2015). If a manufacturer chooses the yearly target, the total manufactured cars in the corresponding year are required to produce 127 g/km or less GHG by 2016, 123 g/km or less GHG by 2017, 120 g/km or less GHG by 2018, 110 g/km or less GHG by 2019, and 97 g/km or less GHG by 2020 on average (Ministry of Environment, 2014).

South Korea's targets are among the most stringent in the world (**Figure 1**). The European Union (EU) at 95 gCO_2/km emission is nominally the most stringent, however, an important consideration is how the test standard for fuel economy. The EU tes standard produces significantly lower emissions than achieved under average actual driving conditions. South Korea uses the US test standards which are more closely calibrated to actual driving averages. Factoring in the test standard difference makes South Korea's standard more stringent than Europe's.

Climate Action Tracker (2017) concludes that current policies in South Korea will be insufficient to meet the INDC target, and hence further tightening of policies would be required to meet it. South Korea has not set fuel economy targets beyond 2020 at this point.

3. Methods

3.1 Modeling Framework

Our analysis develops a bespoke multisector applied general equilibrium model of economic activity, energy, and GHG emissions tailored to South Korea. The model links South Korea to the rest of the world via sectoral imports and exports and sectors are interconnected by purchases of intermediate inputs.

The model links sectoral production to emissions of CO_2, CH_4, N_2O, and aggregated fluorinated gases (F-gases: HFCs, PFCs, and SF_6) from the combustion of fossil fuels, industrial processes, agriculture and waste.[1] The 35 sectors represented in the model are listed in **Table 1**. The model represents 13 sectors related to energy extraction, production and distribution, including eight electricity generation technologies. Transportation is represented by separate commercial and household transportation (transportation in own-supplied vehicles and household purchases of commercial transportation). The model also represents 13 manufacturing sectors and five non-transportation service sectors.

In each sector, there is a representative firm that produces output by hiring primary factors and purchasing intermediate inputs from other firms. Production in each sector

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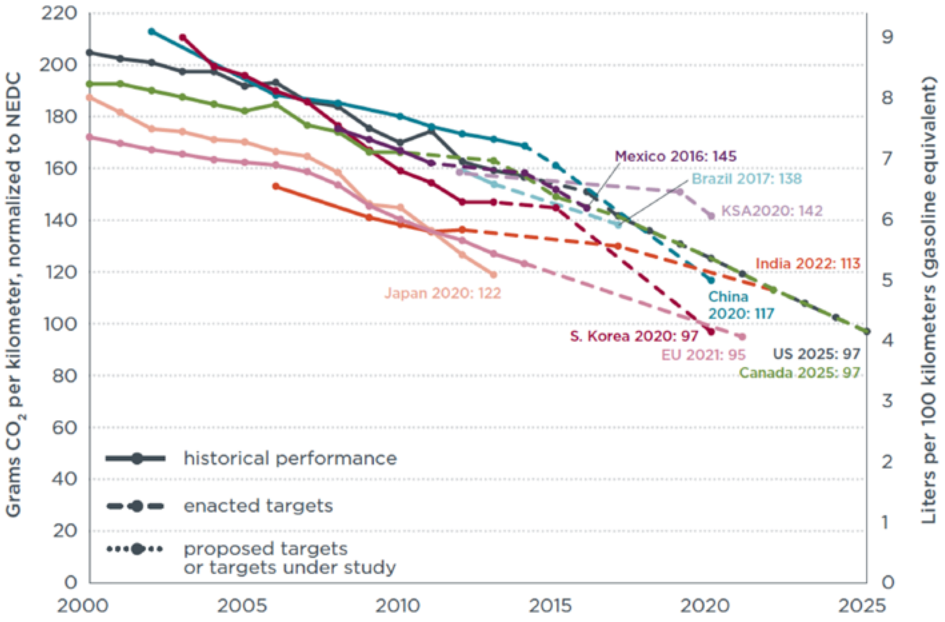
[1] The model does not include emissions from land use, land-use change and forestry (LULUCF).



** Note that Japan has already exceeded its 2020 statutory target, as of 2013.*

Figure 1. Global CO_2 emissions standards for passenger vehicles. (Source ICCT, 2015)

Table 1. Sectoral aggregation

Energy extraction, production & distribution		**Manufacturing**	
`cru`	Crude oil extraction	`crp`	Chemical, rubber & plastic products
`oil`	Refined oil products	`nmm`	Non-metallic minerals
`col`	Coal extraction	`i_s`	Iron and steel
`gas`	Natural gas extraction and distribution	`nfm`	Non-ferrous metals
`ecoa`	Coal electricity	`fmp`	Fabricated metals products
`egas`	Gas electricity	`fod`	Food processing
`eoil`	Oil electricity	`w_p`	Wood & paper products
`enuc`	Nuclear electricity	`tcf`	Textiles, clothing & footwear
`ehyd`	Hydroelectricity	`mvh`	Motor vehicles and parts
`ewin`	Wind electricity	`otn`	Other transportation equipment
`esol`	Solar electricity	`ele`	Electronic equipment
`eoth`	Other electricity	`ome`	Other machinery & equipment
`tnd`	Electricity transmission and distribution	`omf`	Other manufacturing
Other primary production		**Other services**	
`agr`	Agriculture, forestry & fishing*	`trd`	Wholesale & retail trade*
`omn`	Other mining	`wtr`	Water collection & distribution
		`cmn`	Communications
Transportation		`cns`	Construction
`hht`	Household transportation*	`ser`	Other Services*
`Trn`	Commercial transportation*		

* Model sectors not included in the Korean ETS.

is represented by a multi-level nest of constant elasticity of substitution (CES) functions. Nesting structures for sectoral groups are outlined in Figures 2 to 5. All sectors except fossil fuel extraction, electricity production and agriculture are built on the production structure described in **Figure 2**. A key feature of the production nest is substitution between aggregate energy and a capital-labor composite, which allows price-induced improvements in energy efficiency. Other opportunities to abate emissions are provided by the ability to substitute between electricity and (in aggregate) non-electricity energy, and among non-electricity energy inputs (coal, gas, and refined oil). The top-level nest combines non-energy intermediate inputs with the energy-value added composite using a Leontief aggregation. Mining activities, including fossil fuel extraction sectors, are produced by a CES aggregate of a sector-specific resource (e.g. coal resources for the coal sector) and a composite of capital, labor and intermediate inputs (**Figure 3**).

In fossil-based electricity sectors (**Figure 4a**), there is substitution between fuel inputs and a capital-labor aggregate to capture price-induced improvements in energy conversion efficiency. There is also the potential for fuel-switching within each fossil-fuel electricity sector, but substitution among fuels is limited by the small (or zero) share of other fossil fuels used in each fossil electricity sector.[2]

A key characteristic of non-fossil electricity sectors is the aggregation of a technology specific factor and (aggregat-

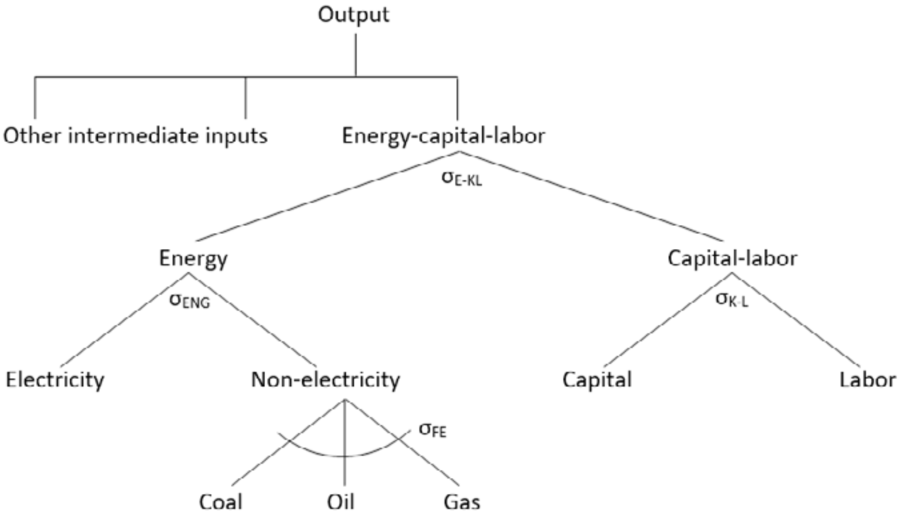


Figure 2. Production nest for all sectors except electricity, mining, and agriculture

Vertical lines in the input nest signify a Leontief or fixed coefficient production structure where the elasticity of substitution is zero.

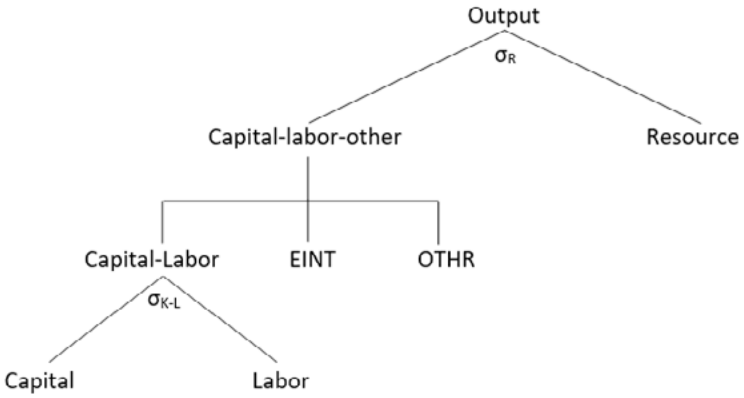


Figure 3. Production nest for mining sectors

See notes to Figure 2.

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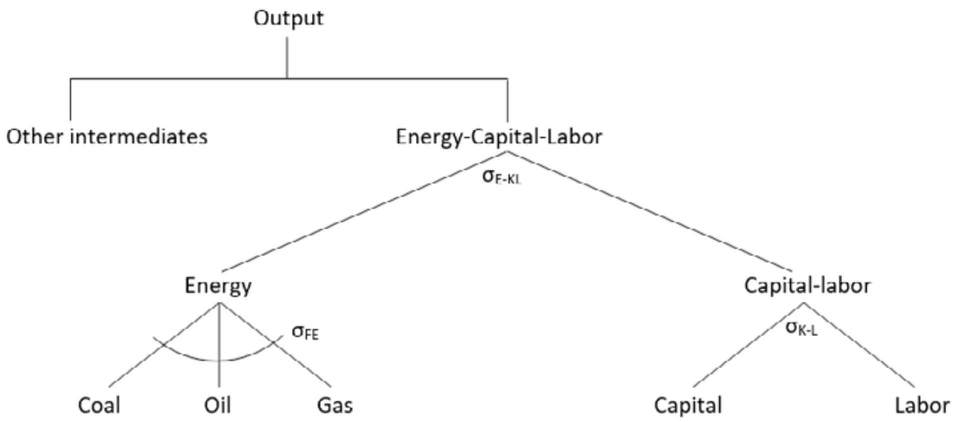
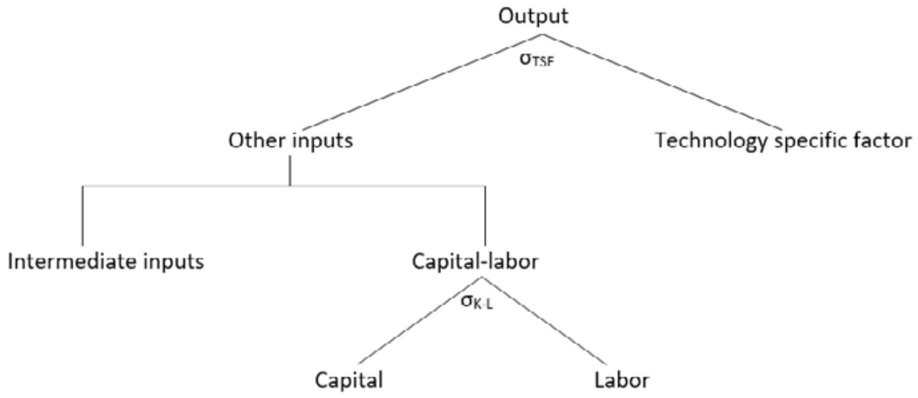
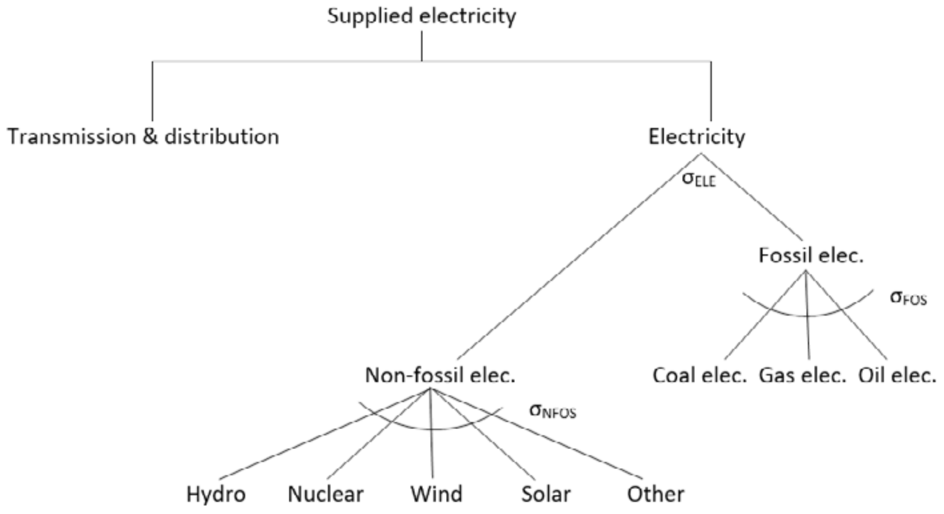
[2] In the base data, coal electricity and oil electricity are exclusively produced from, respectively, coal and refined oil. Gas electricity uses mostly gas and a small amount of refined oil.



(a) Fossil electricity



(b) Non-fossil electricity



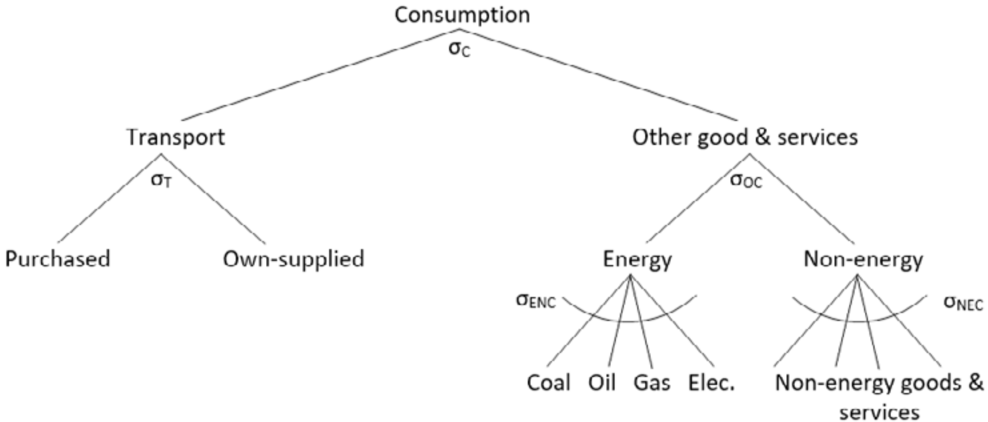
(c) Supplied electricity

Figure 4. Production nests for (a) fossil electricity, (b) non-fossil electricity, and (c) supplied electricity

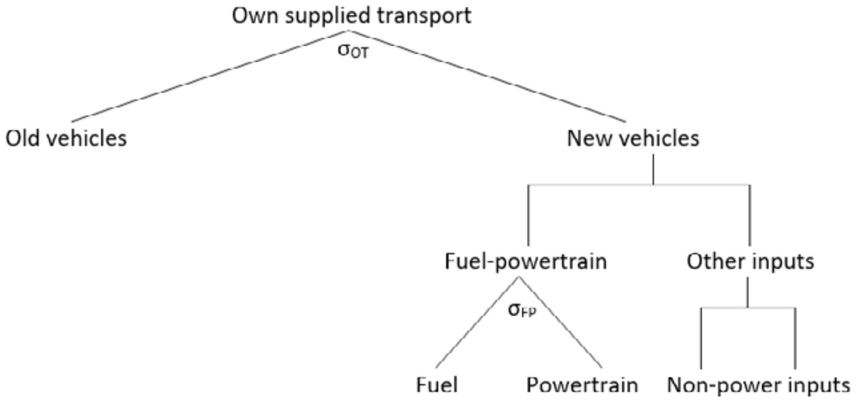
See notes to Figure 2.

ed) other inputs in the top level of each production nest (**Figure 4b**). For nuclear electricity and hydroelectricity, which are largely determined by regulations, the top-level elasticity is set equal to zero. This feature allows output for these sectors to be assigned exogenously using estimates from external sources. For other non-fossil electricity sectors (wind, solar, and other electricity), top-level elasticity values capture constraints due to intermittency and resource availability, while at the same time allowing production of these technologies to respond to price changes. To produce supplied electricity (which is purchased by firms and consumers), fossil electricity types and non-fossil electricity outputs are combined using separate CES functions, and the two aggregates are combined using a further CES function (**Figure 4c**). In this nesting structure, non-fossil electricity sources are perfect substitutes for each other, and aggregate fossil fuel electricity is a perfect substitute for non-fossil electricity ($\sigma_{ELE} = \sigma_{NFOS} = \infty$). Aggregate electricity is combined with transmission and distribution in a Leontief nest.

A representative agent derives income from selling factor services and allocates expenditure across private consumption, government consumption, and saving/investment. The nesting structure for final consumption is outlined in **Figure 5**. Important features of the specification include substitution among goods with different GHG intensities and a detailed representation of household transportation. The household transportation specification allows substitution between purchased transportation (supplied by the commercial transport sector) and own-supplied transportation. Building on Karplus *et al.* (2013), own-supplied transportation distinguishes old and new vehicles, and breaks down new vehicles into several components based on the services they provide. Importantly, substitution between powertrain capital and refined oil inputs used in new vehicles reflects the scope for consumers to purchase more fuel efficient cars, at a higher cost, in response to increases in the price of fuel and/or policies. A mandated maximum amount of fuel per kilometre of travel services (to represent a fuel economy standard) is specified using a powertrain certificate system. In this system, powertrain



(a) Consumption



(b) Own-supplied transport

Figure 5. Nesting structure for **(a)** consumption and **(b)** own-supplied transport

See notes to Figure 2.

capital used for the production of new cars is allocated one certificate per unit of output, and both powertrain capital and refined oil require φ certificates to be used in new car production. Under this system, the share of fuel inputs in transport services from new cars is $(1-\varphi)\gamma$, where γ is the share of the fuel-powertrain aggregate in transport services from new cars. As the fuel-powertrain aggregate is combined with other inputs using a Leontief function, γ is fixed and a fuel economy standard can be imposed by setting the value for φ. If a fuel economy standard is not simulated, the powertrain certificate system is turned off in the model.

A government sector collects taxes and provides subsidies, and purchases good and services. Net fiscal deficits and, where applicable, revenue from the sale of emission permits are passed to consumers as (implicit) lump sum transfers. Although the model is static, investment is included as a proxy for future consumption and is a fixed proportion of expenditure by each regional household.

CO_2 emissions from fossil fuels are included in the model in fixed proportion with the use of each fossil fuel. CO_2 emissions from industrial processes and non-CO_2 emissions (non-combustion GHGs) are linked to output in each sector. Non-combustion GHGs per unit of output decrease in future years according to assumed autonomous improvements in GHG intensities. When there is a carbon price, total inputs trade-off with non-combustion GHGs according to a CES function in each sector, allowing abatement of emissions by using more other inputs.

Elasticity values in production and consumption that, in tandem with input cost shares, govern substitution possibilities are guided by those used in the MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev *et al.*, 2005, Chen *et al.*, 2016).

International trade in goods and services follows the 'Armington approach' that assumes goods are differentiated by country of origin (Armington, 1969). Specifically, for each commodity, domestic production is differentiated from imports using a CES function. Values for elasticities of substitution in the trade specification are sourced from Hertel *et al.* (2007). Also for each commodity, production is allocated across the domestic market and exports using a constant elasticity of transformation function.

Turning to closure, factor prices are endogenous and there is full employment; capital and labor are mobile across sectors (and technology/sector specific resources are immobile); and the current account deficit is a fixed proportion of GDP.

The model is calibrated using the Global Trade Analysis Project (GTAP) Power Database (Peters, 2016). This database augments version 9 of the GTAP Database (Aguiar *et al.*, 2016) and includes economic data and CO_2 emissions from the combustion of fossil fuels for 140 regions and 68 sectors. We extract the data for South Korea and aggregate the sectors to those listed in Table 1 by extending tools provided by Lanz and Rutherford (2016). We also augment GTAP-Power with data on non-CO_2 emissions from Irfanoglu and van der Mensbrugghe (2015), and estimates of non-combustion CO_2 emissions from Greenhouse Gas Inventory & Research Center of Korea (2014). The base data for the model a snapshot of South Korea in 2011.

The model is formulated and solved as a mixed complementarity problem using the Mathematical Programming Subsystem for General Equilibrium (MPSGE) described by Rutherford (1995) and the Generalized Algebraic Modeling System (GAMS) mathematical modeling language (Rosenthal, 2012) with the PATH solver (Dirkse and Ferris, 1995).

3.2 Scenarios

Table 2 summarizes the five scenarios considered in our analysis. The first, *Benchmark*, requires no simulation and simply reports economic, energy and emission outcomes for South Korea in 2011, as measured by the database used to calibrate the model. Remaining scenarios simulate outcomes for 2030. Our *BAU* simulation creates projections for economic, energy and GHG emission outcomes in South Korea in 2030 under a hypothetical 'no climate policy' or 'business as usual' case. Key inputs for our BAU simulation include (1) the assignment of technology specific factor endowments for certain electricity sectors, (2) changes in fossil fuel prices, (3) autonomous energy efficiency improvements, (4) autonomous improvements in non-combustion GHG intensities, and (5) improvements in total factor productivity.

Table 2. Scenarios

Name	Description
Benchmark	South Korea economy as represented by the benchmark data in 2011
BAU	South Korea in 2030 under 'Business as usual' (no climate policies)
ETS	Implementation of the KETS (with offsets) to meet South Korea's 2030 NDC pledge
ETS-Vehicles	*ETS* with fuel economy standards for new vehicles
ETS-All	An all-sectors ETS (with offsets) to meet South Korea's 2030 NDC pledge

Our assignments for technology specific factors for electricity generation types, which drive output from these technologies, are informed by 'Reference case projections for electricity capacity and generation by fuel (2015–50)' from EIA (2017). Fossil fuel price forecasts are also guided by EIA (2017). We impose autonomous energy efficiency improvements of 1.5% per year in fossil fuel use, and a 0.3% annual efficiency improvement in electricity use. The BAU also simulates autonomous decreases in non-combustion GHG (both CO_2 and non-CO_2) emissions per unit of output of 1.5% per year. Total factor productivity improvements are determined endogenously in the model and target a 2030 GDP estimate from OECD (2017). Under this estimate, GDP in South Korea increases by 73.9% between 2011 and 2030, which implies a cumulative annual average growth rate of 2.95%. In the policy scenarios, total factor productivity is exogenous (and equal to values derived in the BAU scenario) and GDP is endogenous.

In the *ETS* scenario, we implement an emissions trading system across covered sectors that reduces economy-wide emissions in South Korea by 37% relative to those in the BAU scenario (i.e., meets South Korea's 2030 NDC pledge). The ETS includes 30 of the 35 sectors in the model (see Table 1), and covers all GHG emissions with trading across gases and sectors.[3] As the ETS targets a reduction in economy-wide emissions but does not cover all sectors, the emissions cap on covered sectors is chosen endogenously in the model to target a desired level of economy-wide emissions.

As noted above, up to 10% of emissions rights can be sourced from outside the ETS. We model the supply of domestic offsets using a (secondary) cap-and-trade program for all sectors not included in the ETS (except fossil fuels purchased by households) with a BAU emissions cap. Under this system, emissions reductions by non-KETS sectors below the BAU level create domestic offsets that can, up to a certain limit, be used for compliance with the KETS. We assume that international offsets are available at a fixed price of \$5/tCO_2e.

We model the use of total offsets and international offsets with two (pseudo) certificate schemes to ensure that the limits on offset use are enforced. Specifically, to use an (domestic or international) offset to meet ETS obligations for one ton of emissions, an entity must turn in an offset credit for one ton of emissions and one 'offset certificate'. To use an international offset, in addition to providing an offset credit for one ton of emissions and an 'offset certificate', an entity must hand over one 'international certificate'. On the supply side, certificates are 'produced' in fixed proportions with ETS permits: for each permit for one ton of emissions there are α 'offset certificates' and $\alpha\theta$ 'international certificates'. By setting $\alpha = 0.1$ and $\theta = 0.5$, we impose the upper limits on the use of total offsets and international offsets set out in the KETS (offsets can be used to meet up 10% of obligations to surrender emissions rights, and international offsets can contribute up 50% of the total amount of offsets). As the quantity of ETS emissions is endogenous, maximum limits on the supply of offsets (in tons) are also endogenous in the model.

In the *ETS-Vehicles* scenario, we impose a fuel economy standard for new vehicles in addition to the policies in the *ETS* scenario. Current legislation mandates fuel consumption per kilometer for cars of 31.1% by 2020 relative to a 2013 baseline. We assume the fuel economy standard continues to be tightened beyond the 2020 mandate by extending to 2030 the same annual rate of improvement between 2013 and 2020. This results in an estimated reduction in fuel consumption per kilometer of 59.5% relative to 2013.

The final scenario, *ETS-All*, simulates an ETS covering all sectors, including the household, to meet South Korea's 2030 NDC pledge without fuel economy standards. The scenario allows international offsets to account for up to 5% of domestic ETS permits and, as the ETS is economy-wide, there are no domestic offsets. This scenario provides an estimate of a first best/least cost policy to meet South Korea's stated emissions reduction.

4. Results

A summary of results for each scenario is presented in **Table 3**, with additional results reported in **Table 4** (GHG emissions by gas), **Table 5** (electricity generation by technology), **Table 6** (primary energy by fuel), and **Table 7** (sectoral output). Under BAU, the exogenously-imposed 73.9% increase in GDP between 2011 and 2030 drives an increase in GHG emissions of 24.2% (from 677.1 $MtCO_2e$ in 2011 to 840.8 in 2030)[4]. The proportional increase in emissions is significantly less than the proportional increase in GDP due to improvements in energy efficiency (both autonomous and price-induced), autonomous improvements in non-combustion GHG intensities, and expansion of non-fossil electricity generation (Table 5). Consistent with EIA (2017), total electricity production increases by 29.2% while non-fossil electricity generation increases by 87.7%. The largest absolute increase in electricity generation between 2011 and 2030 occurs for nuclear electricity (92.3 TWh). The decrease in the fuel economy index for new cars indicates that (in the absence of a fuel economy standard) the number of liters of fuel per kilometer trav-

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[3] The GTAP database does not differentiate domestic and international aviation, so a limitation of our work is that domestic aviation (included in the commercial transportation sector in the model) is not included in the ETS.

[4] Our simulated BAU emissions in 2030 are those estimated by estimated by Climate Action Tracker (2017) (850.6 $MtCO_2e$).

Table 3. Summary results

	2011	2030			
	Benchmark	**BAU**	**ETS**	**ETS-Vehicles**	**ETS-All**
GDP and welfare					
GDP *billion 2011$*	1202.3	2090.4	2074.0	2069.8	2070.0
GDP *% change relative to BAU*	-	-	-0.78	-0.99	-0.97
Welfare *billion 2011$*	634.1	1094.8	1088.0	1086.9	1089.2
Welfare *% change relative to BAU*	-	-	-0.63	-0.73	-0.52
CO2 prices, 2011$/tCO$_2$e					
ETS permits	-	-	90.1	88.6	62.9
Domestic offsets	-	-	5.0	5.0	-
GHG emissions, MtCO$_2$e					
ETS sectors	491.3	575.6	292.7	294.5	557.6
Other sectors	185.8	265.2	250.2	248.2	-
Gross emissions	677.1	840.8	542.8	542.7	557.6
International offsets	-	-	-13.1	-13.0	-27.9
Net emissions	677.1	840.8	529.7	529.7	529.7
Energy and vehicles					
Electricity production *TWh*	574.6	742.6	585.2	586.8	612.5
Primary energy *Mtoe**	296.4	411.5	350.4	349.8	351.2
New car fuel economy, index	1.00	0.80	0.80	0.40	0.78
New car sales	1,578,716	2,423,438	2,411,140	2,360,492	2,382,133

* Primary energy from nuclear is based on the amount of heat generated in reactors assuming a 33% conversion efficiency. For wind, solar and hydro, the primary energy equivalent is the physical energy content of electricity generated.

eled decrease by 20% in the *BAU* scenario relative to the *Benchmark* case. The number of new cars sales increases by 53.5% between 2011 and 2030 in the *BAU* simulation.

In the *ETS* scenario, constraining GHG emissions relative to *BAU* reduces GDP by $16.4 billion (0.78% of GDP) and welfare, measured as the equivalent variation in consumption expenditure, by $6.8 billion (0.63%). These estimates do not include any benefits from avoided climate damages. A carbon price, in 2011 dollars, of $90.1 per ton of CO$_2$e (tCO$_2$e) on emissions from covered sectors is needed to reduce national net GHG emissions by 37% relative to the *BAU* scenario.[5] This carbon price reduces emissions from ETS sectors by 49.2% (from 575.6 MtCO$_2$e to 292.7).

As noted above, several emissions sources not covered by the ETS are included in a secondary cap-and-trade program to approximate a domestic offset market (with a BAU emissions cap and a limit on the quantity of permits that can be sold to ETS sectors). This mechanism decreases emissions from sources not covered by the ETS by 5.7% relative to BAU. The price of domestic offsets in the *ETS* scenario is equal to the price of international offsets ($5/tCO$_2$e). This is because the use of international offsets (13.1 MtCO$_2$e or 44.8% of the total quantity of offsets) is less than the maximum amount allowed (50% of the quantity of offsets). That is, at a fixed price of $5/tCO$_2$, 55.2% of the total allowed offsets is sourced domestically.

Although private transportation is not included in either the ETS or the domestic offset cap-and-trade program, there is an improvement in the fuel economy of new cars in the *ETS* scenario. This is because the price of crude oil is fixed in the model and the inclusion of oil refining in the ETS increases the price of refined oil, causing a price-induced substitution toward more fuel-efficient vehicles. The ETS reduces the number of new car sales by 12,297 (0.5%) relative to BAU.

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[5] Comparable to our estimate, Vandyck *et al.* (2016) project that an emissions price, in 2015 dollars, of $119/tCO$_2$ is required to meet South Korea's 2030 NDC target.

Table 4. GHG emissions, $MtCO_2e$

	2011	2030			
	Benchmark	**BAU**	**ETS**	**ETS-Vehicles**	**ETS-All**
CO_2, combustion	582.4	725.8	469.6	469.5	486.7
CO_2, non-combustion	32.0	41.0	24.6	24.6	25.4
CH4	29.8	36.5	25.6	25.6	22.9
N2O	14.3	17.2	11.6	11.6	10.6
F-gases	18.7	20.4	11.4	11.4	11.9
Gross emissions	677.1	840.8	542.8	542.8	557.6
International offsets	-	-	-13.1	-13.0	-27.9
Net emissions	**677.1**	**840.8**	**529.7**	**529.7**	**529.7**

Table 5. Electricity production, TWh

	2011	2030			
	Benchmark	**BAU**	**ETS**	**ETS-Vehicles**	**ETS-All**
Coal	230.5	250.0	84.9	86.0	107.2
Gas	145.4	136.9	124.6	125.2	130.8
Oil	18.4	17.3	10.8	10.9	12.3
Nuclear	171.0	263.3	263.3	263.3	263.3
Hydro	5.1	22.0	22.0	22.0	22.0
Wind	1.0	27.9	43.6	43.5	41.9
Solar	1.0	13.6	21.1	21.1	20.3
Other	2.3	11.6	14.9	14.9	14.6
Total	**574.6**	**742.6**	**585.2**	**586.8**	**612.5**

Table 6. Primary energy, Mtoe*

	2011	2030			
	Benchmark	**BAU**	**ETS**	**ETS-Vehicles**	**ETS-All**
Coal	82.46	102.33	55.95	55.99	60.29
Gas	42.49	54.91	48.11	48.28	47.97
Oil	127.26	181.00	170.93	170.10	167.76
Nuclear	43.45	66.92	66.92	66.92	66.92
Hydro	0.43	1.85	1.85	1.85	1.85
Wind	0.08	2.34	3.66	3.65	3.51
Solar	0.08	1.14	1.77	1.77	1.70
Other	0.19	0.97	1.25	1.25	1.23
Total	**296.44**	**411.46**	**350.44**	**349.80**	**351.23**

* Primary energy from nuclear is based on the amount of heat generated in reactors assuming a 33% conversion efficiency. For wind, solar and hydro, the primary energy equivalent is the physical energy content of electricity generated.

Table 7. Output changes in 2030 relative to the BAU, 2001$ and %.

	ETS		ETS-Vehicles		ETS-All	
	$, m	**%**	**$, m**	**%**	**$, m**	**%**
Refined oil products	-12,770	-6.1	-14,132	-6.7	-16.1	-7.6
Coal extraction	-133	-46.4	-132	-46.2	-0.1	-37.0
Natural gas	-391	-69.2	-388	-68.6	-0.3	-58.2
Coal electricity	-10,862	-66.0	-10,788	-65.6	-9.4	-57.1
Gas electricity	-1,210	-9.0	-1,156	-8.6	-0.6	-4.4
Oil electricity	-1,270	-37.8	-1,252	-37.2	-1.0	-28.8
Nuclear electricity	0	0.0	0	0.0	0.0	0.0
Hydroelectricity	0	0.0	0	0.0	0.0	0.0
Wind electricity	1,220	56.3	1,213	56.0	1.1	50.1
Solar electricity	1,580	55.2	1,571	54.9	1.4	49.1
Other electricity	317	28.9	316	28.8	0.3	26.5
Electricity transmission & distrib.	-2,956	-23.9	-2,918	-23.6	-2.3	-18.9
Agriculture, forestry & fishing	-614	-0.8	-586	-0.7	-1.0	-1.2
Other mining	-307	-5.4	-305	-5.4	-0.2	-4.0
Chemical, rubber & plastic products	-22,361	-6.6	-21,800	-6.4	-16.8	-4.9
Non-metallic minerals	-3,303	-5.9	-3,303	-5.9	-2.4	-4.4
Iron and steel	-16,412	-5.7	-16,328	-5.7	-11.5	-4.0
Non-ferrous metals	-3,723	-5.0	-3,656	-4.9	-2.6	-3.5
Fabricated metals products	-2,737	-2.1	-2,618	-2.0	-1.8	-1.4
Food processing	-1,641	-1.1	-1,501	-1.0	-1.4	-1.0
Wood & paper products	-1,454	-2.0	-1,452	-2.0	-1.2	-1.7
Textiles, clothing & footwear	-3,967	-4.6	-3,928	-4.6	-2.9	-3.4
Motor vehicles and parts	-1,449	-0.6	5,244	2.3	-2.0	-0.9
Other transportation equipment	-3,575	-3.4	-4,610	-4.4	-1.5	-1.4
Electronic equipment	-7,700	-2.1	-8,138	-2.2	-3.5	-1.0
Other machinery & equipment	-1,851	-0.6	-2,993	-0.9	0.5	0.2
Other manufacturing	-1,286	-1.7	-1,162	-1.6	-0.8	-1.1
Commercial transportation	-916	-0.4	-1,696	-0.7	-13.8	-6.1
Wholesale & retail trade	-4,292	-1.0	-3,845	-0.9	-3.4	-0.8
Water collection & distribution	-319	-2.6	-311	-2.5	-0.2	-2.0
Communications	-588	-0.6	-537	-0.6	-0.4	-0.5
Construction	-2,040	-0.7	-2,346	-0.8	-1.6	-0.5
Other Services	-5,580	-0.5	-6,279	-0.5	-4.6	-0.4

Changes in output relative to BAU for the *ETS* and *ETS-Vehicles* scenarios are reported in Table 7. In the *ETS* scenario, output for all sectors decreases except for low-carbon electricity sectors without regulatory constraints (solar electricity, wind electricity, and other electricity). The largest proportional reductions in output occur in energy sectors (e.g., coal electricity generation). Among non-energy sectors, the chemical, rubber & plastic products sector experiences the largest proportional output decrease (6.6%). Absolute decreases in output are largest for chemical, rubber & plastic products; iron and steel; refined oil products; and coal electricity. The output decrease for motor vehicles and parts (0.6%) is small relative to those for other sectors, as the GHG intensity for this sector is relatively low. Consequently, the negative impact of rising energy costs is partially offset by reduced demand for capital and labor from most other sectors. Changes in exports relative to BAU (not reported) follow a similar pattern to changes in output. Proportional exports decreases are largest for chemical, rubber and plastic products (8.6%) and iron and steel (9.4%), and the decline in exports of motor vehicles and parts is 0.6%.

When vehicle fuel economy standards are added to the ETS policy (*ETS-Vehicles*), reduced emissions from own-supplied transportation allow more emissions from sectors covered by the ETS policy (294.5 $MtCO_2e$ in the *ETS-Vehicles* scenario compared to 292.7 $MtCO_2e$ in the *ETS* scenario). This results in a small reduction in the CO_2 price but increases the GDP cost (by $4.2 billion) and welfare cost (by $1.1 billion) of meeting the economy-wide reduction in emissions. By increasing the cost of motor vehicles, the fuel economy standard also decreases new car sales by 50,648 (2.1% of new car sales under BAU).

In the *ETS-Vehicles* scenario, output changes for all sectors except motor vehicles and refined oil are similar to those in the *ETS* scenario. The fuel economy standard has two opposing impacts on the output of the motor vehicles sector. First, by increasing the costs of new cars, the standard decreases the demand for motor vehicles (as illustrated by the decline in new car sales). Second, for each kilometer of travel, the standard forces consumers to spend more on powertrain capital and less on fuel, which increases demand for outputs from the motor vehicles sector. The 2.3% increase in motor vehicle output relative to BAU in the *ETS-Vehicles* (compared to a 0.6% decrease in the *ETS* scenario) indicates that the powertrain-share effect dominates the cost effect. The forced decrease in fuel expenditure per kilometer traveled in the *ETS-Vehicles* scenario leads to a larger decrease in output of refined oil products relative to BAU (6.7%) than in the *ETS* scenario (6.1%).

In the *ETS-All* scenario, as expected, the carbon price ($\$62.9/tCO_2$) and the welfare cost of meeting the NDC goal is lower than in other policy scenarios. Due to the lower carbon price, relative to other ETS scenarios, there is more electricity from coal and gas and less from wind and solar. There are smaller reductions in the output of energy-intensive sectors included in the KETS (e.g., relative to BAU, output of chemical, rubber and plastic products decreases by 4.9% in the *ETS-All* scenario and 6.6% in the *ETS* scenario). Conversely, there is a large reduction in the output of the commercial transportation sector, an energy-intensive sector that was excluded from carbon pricing in other ETS scenarios. Relative to the *ETS* scenario, output of motor vehicles and parts falls in the *ETS-All* scenario as the inclusion of household fuel purchases in the ETS reduces the demand for vehicles.

5. Conclusions

South Korea's NDC has been rated as "Inadequate" by the Climate Action Tracker (2017) on the basis that the proposed 2030 target would allow emissions to be more than double the 1990 level. In contrast, the EU is rated "Insufficient", a higher rating. These ratings are against what is required to achieve the 1.5 or 2.0 degrees C target of the Paris agreement. Essentially no country of any significance has sufficient objectives by this rating, hardly a surprise given that a variety of studies have shown that the Paris agreement is insufficient to achieve the 2-degree target. However, the comparison of South Korea and the EU illustrate the extra challenge of countries like South Korea that are in a rapid growth phase. The carbon price in the EU is currently about 7.6 Euro ($9) per ton (in current dollars), and its 2030 target can probably be achieved with only a modest increase. However, we estimate the South Korean carbon price would need to be nearly $90 (in 2011 dollars), making full use of offsets their legislation allows. From the perspective of the GHG price required, the South Korean INDC is among the more ambitious. Still the GDP and welfare costs remain less than 1%. That highlights an advantage of the country's recent rapid growth—its industrial base is relatively new and energy efficient, and so even with a higher carbon price the cost remains a small share of the economy.

The economic prescription for achieving emissions goals at least-cost is to allow the market to seek out the least cost abatement options by establishing a uniform carbon price, and avoiding duplicative policies. Most countries do not heed this advice, and choose a mix of policies. Very often countries regulate vehicle emissions through GHG or fuel standards for new vehicle sales, as South Korea is doing. There are a variety of economic arguments as to why these are less efficient than including vehicle fuel sales in a cap and trade system. For one, they provide incentives only for new vehicle sales, and so the effect of the policy is small in the short run until more of the fleet is replaced. A carbon pricing mechanisms affects use of existing vehicles as well as the choice of new vehicle purchase, and so works to reduce emissions through vehicle choice, miles driven, and vehicle maintenance. Then a second inefficiency is that once the more efficient vehicle is purchased under a fuel or GHG standard, the cost of driving is lower, and so it can lead to increases in miles traveled, offsetting some of the apparent gain from more efficient vehicles.

In some previous studies comparing vehicle standards and cap and trade, a quite large additional cost was incurred when vehicle standards were imposed (Paltsev, *et al.*, 2016; Rausch and Karplus, 2014). These studies focused on costs of standards in the EU and the US, generally for the period up to about 2030, similar to our South Korea study. However, in the case of South Korea, we see some additional cost but much less than in these previous studies even though the basic structure of the model applied here is similar. There are a few reasons for this difference. First, the scenario construction among these studies was different. Rausch and Karplus (2014) compared achieving a given reduction via technology standards for vehicles and power generation versus achieving the same emissions level with an economy wide cap. That both broadens the coverage from two sectors to the entire economy and substitutes a more efficient policy mechanism. Here we are comparing a cap and trade that does not include transportation with a policy that adds transportation via fuel standards. In principle by broadening the policy to include more sectors, it should reduce the cost, but instead the cost is increased—clear evidence of an inefficiency (partly because of the mechanism itself, and possibly also because the standard is more stringent than it should be). The Paltsev *et al.* (2016) study for the EU imposed the standards on top of a cap that included the transportation sector, a slightly different scenario design. In our comparable scenario, which imposed a cap on the transportation sector instead of the vehicle standards, we get a more similar result to the Paltsev *et al.* (2016) study, with the welfare cost lowered by about 30 percent compared with controlling emissions from vehicles with vehicle standards.

A second reason for the smaller cost add-on is due to the fact that the carbon price needed to meet the target for South Korea is much higher than the near-term carbon price in, for example, the EU. The South Korean carbon price level in 2030 would, by itself, create incentives to adopt more efficient vehicles, and so the fuel standard is pushing in the right direction, albeit inefficiently. Paltsev *et al.* (2015), using a recursive dynamic model, and comparing regulatory approaches to cap and trade demonstrated that as the GHG price rose, eventually the added cost of the fuel standards largely disappeared.

Of course, our estimates depend on the added vehicle costs related to improving efficiency, relative to the cost of abating elsewhere in the economy, but our formulation here is similar to that in the earlier cited studies.

Our results show impacts on sectors generally as expected: fossil fuel dependent electricity production drops substantially, especially coal, and non-fossil electricity expands. Production in nearly all other sectors declines. The decline is in the range of 4.5 to 6.5% for more energy intensive sectors such as iron & steel and chemicals, rubber & plastics. For other less energy intensive sectors the decline in production is on the order of 0.5 to 2.0%. The value of production of motor vehicles and parts is one sector that actually increases under the fuel standards scenario. While we estimate that the number of vehicles sold falls, the cost of vehicles rise and so the total value of sales actually increases by a bit over 2% whereas under the cap and trade the value of vehicle sales fall by about 0.6%. Vehicle sales and the value of sales falls when the sector's emissions are covered by the cap and trade measure instead of the vehicle standards.

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