THE ENERGY TRANSITION AND DECARBONIZATION: ESSAYS AT THE INTERSECTION OF POLICY AND TECHNOLOGY

by

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ABSTRACT

The chapters in this dissertation comprise three separate works exploring the economics of mineral, energy, and environmental policy. In the first chapter, I use analytical and computational methods to examine the output and welfare responses to a tradable performance standard (TPS) under price-responsive demand, long-lived investment, capacity constraints, and foresighted decision-making. The results validate much of the pre-existing work within the environmental economic policy literature, in that the TPS is more costly than a period-over-period emissions equivalent cap (CAP) when costs are summed across an infinite time horizon from start to finish. However, when discounting is present, after the costly transition to the steady-state has taken place and the steady-state is reached, the present value of the perpetual stream of net-benefits that defines the steady-state is greater under the TPS in most cases. This suggests that some classes of future generations — particularly those less-endowed with wealth — stand to benefit from a TPS as opposed to a CAP. The second chapter uses applied general equilibrium modeling to understand the effect on the U.S. consumer of a disruption to Chinese cobalt supply. The results suggest that a Chinese cobalt supply disruption is small and that electric vehicle adoption plays a key role in diversifying the channels for cost-reduction in the event of a Chinese export ban or other extreme supply disruption. This work can help policy-makers prioritize upstream and downstream mineral policy goals into the coming decade. The third chapter uses an applied general equilibrium model of North-South trade to explore the ability of regional climate policy to induce innovation in end-of-pipe carbon-saving technology at home and abroad. The results suggest that carbon-saving technologies such as carbon-capture and storage have unique benefits in terms of reducing carbon leakage and reducing costs associated with policy designed to curb global greenhouse gas emissions. This work highlights benefits associated with a specific class of technology that should be considered by policymakers at the forefront of the global climate policy debate.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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CHAPTER 1

TRADABLE PERFORMANCE STANDARDS IN A DYNAMIC CONTEXT

Many sectors of the economy that are targets of emissions reduction policy tend to be subject to price-responsive demand, long-lived capital, capacity constraints, and foresighted decision-making. I explore these features together, in conjunction with a sequence of tradable performance standards (TPS). First, I provide a complete characterization of the short-run and steady-state output responses analytically. Second, I validate the intermediate analytical results, explore the dynamics of the transition from pre- to post-policy steady-state, and discuss the welfare implications using a stylized numerical equilibrium model calibrated to a representative electricity sector. I show that the difference in social surplus gains between a TPS and a period-over-period sequence of damage equivalent emissions caps (CAP), summed over the infinite time horizon and discounted back to present, is always lower for a TPS, and is small relative to total social surplus gains from either policy. Most interestingly, under all but the smallest discount rates, the TPS can lead to a more cost-effective post-transition steady-state than a CAP.

1.1 Introduction

Rate-based standards come in many forms and are characterized by requiring the sum of emissions from all sources divided by total output to be less than some pre-specified intensity target. With a tradable performance standard (TPS), the average emissions rate is fixed. For production with emissions rates below the standard, operation creates permits which can be sold. For production with emissions rates above the standard, operation requires the purchase of permits to cover the difference. The equilibrium that arrives as a result of trading these permits determines the price of emissions and total amount of emissions, such that the average emissions intensity for the entire industry equals the TPS policy target (Fischer, 2001). A consequence of the TPS is that while the pre-specified intensity standard acts as an implicit tax on dirty or more emissions-intensive inputs to production of some good (e.g. electricity), it also provides an implicit subsidy to a producer's output where the less emissions-intensive inputs receive a net subsidy (Fischer, 2001; Helfand, 1991; Holland *et al.*, 2009). Generally, a TPS results in inefficient outcomes by encouraging abatement efforts via emission rate reduction as opposed to curbing demand.

The typical analysis of the efficiency of a TPS proceeds by characterizing the pollution externality and the ability of a TPS to internalize the marginal external cost of the externality. Substitution towards less emissions-intensive sources as a result of the subsidy endogenously adjusts the levels of the implicit tax and subsidy. Because an emissions intensity standard taxes only the portion of emissions that exceed the standard and subsidizes inputs with emissions below the standard, the policy is considered a second-best option - as opposed to a first-best option - as it fails to address the marginal external damage of the pollution externality. This issue creates a disconnect between the damages caused by emissions and the efficient level of emissions. Cost effectiveness of the policy requires that the marginal abatement cost be equalized across all sources of pollution. This cannot be the case if some polluters are receiving a net subsidy while others are being taxed.

In this paper I focus on better understanding the TPS within a dynamic context. Much of the literature exploring the TPS is static in nature, and does not consider dynamics or foresight. [1] The closest related work is Fischer & Newell (2008), where technical change and spillovers are explored in a two-stage stylized electricity model. While foresighted decision-making and discounting is represented in this work, the methods are specifically targeted to the research question and do not allow for a close examination of the initial short-run response, the steady-state policy response, and the transition from the first period through the steady-state.

It is important to analyze a TPS in a dynamic framework because many emissions intensive sectors (e.g. electricity) depend on long-lived capital (e.g. generation capacity) that needs to be replaced as it ages. Also, issues related to climate tend to be longer term problems where investment is likely to be an important margin of adjustment. Regarding foresight, agents make investment decisions regarding long-lived capacity that require some degree of foresight and have

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[1] Static analyses range from general policy comparisons to examination under imperfect competition, emissions leakage, pre-existing tax distortions, technical change, to energy efficiency implications in the following works: Burtraw *et al.* (2014); Bushnell *et al.* (2017); Fell *et al.* (2017); Fischer (2003, 2011); Fischer & Newell (2008); Holland (2012); Li & Shi (2017); Parry & Williams (2011); Paul *et al.* (2014)

implications for the future. Expectations about the future have implications for decision making today.

There are potential factors not captured in a static analysis that could provide new insight when considered in a dynamic context. Adjustment costs and their intersection with the foresighted decision-maker are one such factor. Amigues *et al.* (2013) consider the extraction of a renewable and non-renewable resource, taking into account that the extraction of the renewable source requires capital investment in renewable electricity generating units (EGUs) and payment for adjustment costs (Gould, 1968). Amigues *et al.* (2013) show that the best strategy is to start to build renewable power early and spread investment over time as optimal investment in renewables is independent from existing fossil sources. Coulomb *et al.* (2019) study the transition from a dirty fuel (e.g. coal) to a clean fuel (e.g. gas) and renewable source of power under infinite resource stocks, capacity constraints, a carbon budget, and adjustment costs. They confirm the findings of Amigues *et al.* (2013). In particular, they find that investment in gas can start before coal is phased out and that investment in renewables can start before gas or coal are phased out. The reason for this is that the foresighted planner smooths investment over time in order to reduce adjustment costs.

Additionally, consider that the implicit subsidy to low emitting sources of production under a TPS may incentivize firms to retire dirtier sources and invest in cleaner sources. Firms may even decide to retire dirtier sources early and replace the capacity with cleaner alternatives in order to capture the subsidy. With a TPS, as low emitters enter (and high emitters exit), the average baseline emissions rate falls, loosening the constraint on average emissions, causing the price of permits to fall (Fischer, 2001). These characteristics could have important implications for how decision makers deploy capital in a foresighted context compared to policies, such as a carbon tax or emissions cap, that prioritize output reduction as a form of abatement.

Another factor that could provide new insight is the incorporation of discount rates. Discounting is incorporated to represent the assumption that net benefit flows in the future are not as important to agents as net benefits in the present. Higher discount rates encourage agents to shift abatement efforts towards the present. The channel by which this abatement effort primarily occurs, whether by fuel switching or output reduction, could change the abatement cost and social surplus implications of comparative policies within particular regions of the time horizon, such as the steady-state.

In this paper, I explore a TPS under capacity constraints and investment using a stylized equilibrium model. In section 1.2, I define an analytical model that I use to provide a complete characterization of the initial period and steady-state output responses to the TPS policy. The existing literature compares the TPS in relation to a first-best outcome and acknowledges that output and emissions can increase or decrease, providing a proof that it can (Holland *et al.*, 2009). However, it is still unclear why this happens. Policymakers have expressed interest in output effects of rate-based policies. Specifically, if a policy designed to reduce emissions can't actually accomplish the goal under certain circumstances, then it should be understood why this occurs and what course of action policymakers should take to prevent this. Also, policymakers have expressed interest in whether a given policy increases or decreases the price of a good, as this has distributional and equity implications. Fischer (2010) explores the output response of a similar rate-based standard in a renewable portfolio standard, whereas I perform a similar analysis as it relates to a TPS.

I find that there exists a performance standard that leaves the price of output unchanged from the no-policy case in the post-policy, post-transition steady-state. Using this performance standard as a reference point, I find that if I set a new standard that is more (less) stringent than this reference point and the new standard binds, the price of output will be higher (lower) and quantity demanded will be lower (higher) in the post-policy steady-state. These intermediate results are important in understanding how the prices and quantities of the model respond to the TPS and should be used as an aide in understanding the output from the numerical model in section 1.3. Furthermore, these results highlight the fuel-switching nature of the TPS, as the slope of the demand curve has no bearing on the position of the standard that leaves prices and quantities unchanged. Additionally, the results show how certain conditions need to be met in order for prices to possibly decrease, and how any policy that is set with a realistic degree of stringency will be unlikely to cause emissions or output to increase. Knowing when these output responses occur and whether they are positive or negative can help determine whether emissions will decrease (Holland *et al.*, 2009).

In section 1.3, I use a numerical model to validate the analytical results and to place the model within the context of an electricity sector. The numerical model is also used to explore the costs and benefits of the TPS in comparison to a no-policy scenario as well as that of a period-over-period sequence of damage equivalent emissions caps (CAP). Analysis of the numerical output shows that steeper marginal investment cost curves cause investment to be spread further across the time horizon, as expected. I also find that my results agree with existing literature, as the present value of all social surplus that accumulates to the TPS over an infinite time horizon is always less than that of the CAP, except when there is a zero emitting fuel and the performance standard is set to zero (Fischer, 2001; Holland *et al.*, 2009). Additionally, the difference in present value of total social surplus changes that accumulate to the TPS and CAP over time are small relative to total social surplus changes associated with either policy. First, this suggests that dynamic considerations don't change the well-known results in the literature — that an emissions cap is more cost-effective than a TPS, except under special circumstances (Holland, 2012). Secondly, the result indicates that if the goal is to reach zero emissions in the future, either policy is suitable (Holland *et al.*, 2009). Thirdly, even if zero emissions cannot be achieved, there is not a big difference between the two policies in terms of overall net benefits[2], so it might be best to implement the most politically feasible option.

The final result relates to changes in post-transition steady-state social surplus. Recall, one of the main purposes for exploring a TPS in a dynamic model is the unique ability to view the response to the TPS during different segments of the time horizon, such as the initial policy response, the transition that takes place from imposition of policy to a new steady-state, and the post-transition steady-state itself. Introducing a discount rate results in a post-transition steady-state that is more cost-effective under a TPS than a CAP. This is true for all but the lowest discount rates. A purely static analysis could not yield this result due to the lack of a discount rate and its interaction with

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[2] Assumes marginal damages of 20 USD/metric ton of CO2 emitted. Lower marginal damages increase the % differences in net benefits, whereas higher marginal damages decrease % differences. However, the differences are most sensitive to how stringently the TPS is set. The more stringent, the lower the % differences in present value of abatement costs between a CAP and TPS.

the foresighted decision-maker. In fact, with a discount rate of zero, we know from the overall result that the post-transition steady-state must be more cost-effective under a CAP than a TPS, due to the fact that the steady-state surplus values sum to infinity and the CAP must be more cost-effective than the TPS overall. Discounting places a finite value on the perpetual stream of constant nominal benefit flows that accrue to either policy in the post-transition steady-state. This changes the abatement patterns across time relative to a zero-discount rate counterfactual.

This result has equity implications, in that some classes of future consumers – specifically those who do not stand to benefit from an intergenerational transfer of wealth – may prefer a TPS to a CAP. Policymakers concerned with the impact climate policies might have on lower income households can take this into consideration. Also, the literature (Nordhaus, 2007) on social discount rates and climate change tends to focus on the particular rate of discount chosen and determining whether the net present value of a policy is positive or negative, rather than a comparison of different policies. Philosophical arguments propose the use of a lower social discount rate in order to reflect the fact that institutions of society last longer than any one person and therefore must place greater weight on the well-being of posterity. If one assumes that government has a lower discount rate than the agents responding to policy, and government is responsible for policy choice and agents for policy response, the post-transition steady-state welfare result in this paper suggests that a TPS may have a rational appeal to policymakers who take a longer term view.

In addition to the benefits associated with a TPS compared to other policies noted by Fischer (2019), Popp (2019), and Goulder *et al.* (2019), the results in this work highlight a new cost-effectiveness feature of the TPS. Specifically, that it can lead to a post-transition steady-state that is more cost-effective than the alternative emissions cap. Additionally, over the entire infinite time horizon, while the TPS is less cost-effective than an emissions cap, it isn't much worse from a pure cost-effectiveness comparison perspective. The numerical section also highlights many research avenues that could be pursued in further exploration of the TPS in a dynamic setting and, additionally, provides a baseline for what to expect from a more applied model.

This paper proceeds with a discussion of the analytical intuition (section 1.2) where the initial period and steady-state policy responses are discussed in sections 1.2.1 and 1.2.2. Then I turn to the numerical results in section 1.3 which proceeds with a discussion of the model setup (section 1.3.1), the scenario definition (section 1.3.2), the evolution of the model variables through time (section 1.3.3), and a discussion of abatement cost and social surplus (section 1.3.4). Concluding remarks are provided in section 1.4.

1.2 Model

In this section I define an analytical model used to explore the initial and steady-state responses to the TPS policy instrument. Throughout this section, I use language applicable to the electricity sector. However, the discussion is relevant to other industrial sectors that are subject to long-lived capacity, large costs of investment, and capacity constraints. In section 1.2.1 I lay out a dynamic model and discuss the initial period response analytically. I also define the period-over-period emissions equivalent cap (CAP) and compare the policy response under perfectly inelastic demand. In section 1.2.2 I build upon the model and assumptions developed in section 1.2.1 and perform an analysis of the pre- and post-policy steady-states under different elasticity of demand assumptions and linearly increasing marginal investment costs. The results from this section should be used to inform expectations about the numerical model output.

1.2.1 Dynamic model and first-period policy response

While the following model is dynamic, framing the model statically proves useful in understanding how the prices and quantities in the model respond to the TPS policy instrument under various segments of the time horizon. By breaking down the dynamic model into component parts such as the first-period or the steady-state, I am effectively decomposing the dynamic model into static parts. It is also useful to discuss the intuition of a TPS as it compares to a CAP due to its ability to internalize the marginal external costs of the pollution externality at a relatively low cost. This section should highlight some of the key similarities and differences between a TPS and a CAP. Additionally, I discuss how changing the slopes of demand and supply curves can impact model output as well as how adding investment and capacity constraints can impact policy responses. The changes to the prices and quantities brought about by these policy instruments are important in understanding the implications for costs and benefits associated with a TPS. Costs and benefits of these policies are discussed in later sections. In this section, assumptions are relaxed step-by-step in order to provide a clear understanding of the policy instrument and the drivers of outcomes.

In the simple model to follow, I assume a perfectly competitive electricity sector with two sources of generation ($X_{f,t}$) – a high (H) carbon source and a low (L) carbon source. Combined generation ($\sum_f X_{f,t}$) from the two fuel sources (f) must equate with the level of electricity demanded (Q_t) in a given time period (t) that occurs in discrete intervals over an infinite time horizon. Over time, generation capacity ($K_{f,t}$) is retired at a rate of depreciation (δ). As capacity is retired, additional megawatts must be added through investment ($I_{f,t}$). Investment occurs contemporaneously with generation in a given period. Each fuel has an associated emissions intensity (ω_f) which determines the rate at which emissions are produced from generating electricity.

These characteristics of the electricity sector are represented in the maximization problem below:

$$\max_{X,I,Q} \quad \sum_t \Big[\int_0^{Q_t} P(Q)dQ - \sum_f C^I_{f,t}(I_{f,t}) - \sum_f C^X_{f,t}(X_{f,t}) \Big] \tag{1.1}$$

$$subject\ to:$$

$$\sum_f X_{ft} \geq Q_t \tag{1.2}$$

$$K_{ft} \geq X_{ft} \tag{1.3}$$

$$K_{f,t-1} * (1-\delta) + I_{f,t} \geq K_{f,t} \tag{1.4}$$

$$(CAP\ case) \quad \Omega_t \geq \sum_f \omega_f X_{f,t} \tag{1.5}$$

$$(TPS\ case) \quad \sigma_t \geq \frac{\sum_f \omega_f X_{f,t}}{\sum_f X_{f,t}} \tag{1.6}$$

$$X_{f,t},\ I_{f,t}\ Q_t\ \geq\ 0 \tag{1.7}$$

where $X_{f,t}$, $I_{f,t}$, and $K_{f,t}$ represent generation, investment, and capacity in period t for fuel type f, respectively. Equation 1.1 represents the sum of net benefits across the time horizon. Where benefits ($\int_0^{Q_t} P(Q)dQ$) are a function of quantity demanded (Q_t) which equals generation summed across all fuel sources in equation 1.2. $C^I_{f,t}(I_{f,t})$ and $C^X_{f,t}(X_{f,t})$ represent total costs of investment and generation, respectively. Net benefits are maximized in equation 1.1 by choosing generation and investment. The objective function is constrained by equations 1.2 - 1.7 using only one of equations 1.5 or 1.6. Equation 1.3 requires that generation not exceed capacity for each fuel type in a given time period. Equation 1.4 dictates the evolution of capacity via depreciation and investment in each time period for each fuel type. The depreciation rate (δ) is constant throughout the time horizon. Equation 1.5 represents the constraint for the CAP case which equates the aggregate emissions cap (Ω_t) with emissions being produced from generation. Equation 1.6 represents the constraint for the TPS which requires the rate of emissions from generation to be less than or equal to some intensity target (σ_t). The choice variables are greater than or equal to zero for all fuel types and time periods.

The Lagrangian for this optimization problem is as follows:

$$\begin{aligned}
\mathcal{L} = {} & \sum_t \Big[\int_0^{Q_t} P(Q)dQ - \sum_f C^I_{f,t}(I_{f,t}) - \sum_f C^X_{f,t}(X_{f,t}) \Big] \\
& - \sum_t PD_t\, (Q_t - \sum_f X_{f,t}) \\
& - \sum_t PK_{ft}\, (X_{ft} - K_{ft}) \\
& - \sum_t PI_{ft}\, (K_{ft} - K_{f,t-1}(1-\delta) - I_{f,t}) \\
(CAP\ case) \quad & - \sum_t PCAP_t [\sum_f \omega_f X_{f,t} - \Omega_t] \\
(TPS\ case) \quad & - \sum_t PTPS_t [\sum_f \omega_f X_{f,t} - \sigma_t \sum_f X_{f,t}]
\end{aligned} \tag{1.8}$$

where the rental rate on capacity ($PK_{f,t}$) is associated with the capacity constraint, the price of investment ($PI_{f,t}$) is associated with the equation of motion, and the permit prices are associated with each policy constraint ($PCAP_t$ and $PTPS_t$). The first order conditions for each case with respect to $X_{f,t}$ yield an equation that provides some useful intuition.

$$\mathcal{L}_X^{CAP}: \quad PD_t = MC^X_{f,t} + PK_{ft} + PCAP_t\omega_f \tag{1.9}$$
$$\mathcal{L}_X^{TPS}: \quad PD_t = MC^X_{f,t} + PK_{ft} + PTPS_t(\omega_f - \sigma_t) \tag{1.10}$$
$$\mathcal{L}_X^{BAU}: \quad PD_t = MC^X_{f,t} + PK_{ft} \tag{1.11}$$

Additionally note the following zero profit conditions with respect to $K_{f,t}$ and $I_{f,t}$:

$$\mathcal{L}_K: \quad PK_{f,t} = PI_{f,t} - PI_{f,t+1}(1-\delta) \tag{1.12}$$
$$\mathcal{L}_I: \quad PI_{f,t} = MC^I_{f,t} \tag{1.13}$$

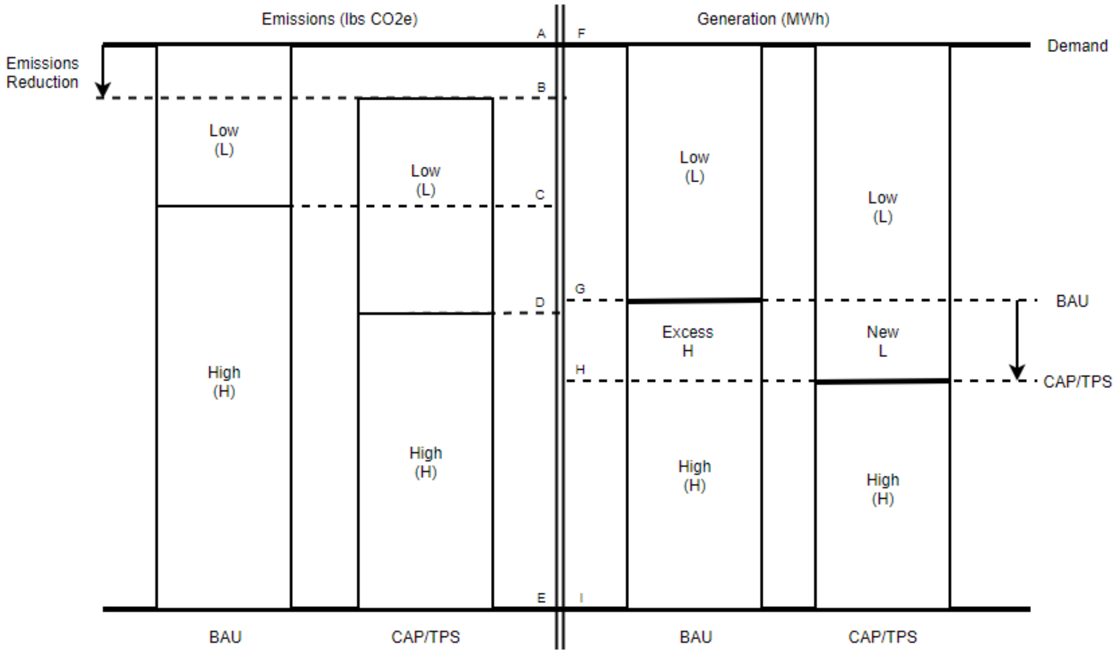

Figure 1.1: Fuel Switching as a form of emissions abatement

For now, assume that demand is perfectly inelastic. This means that we are minimizing costs subject to a fixed output level. Figure 1.1 illustrates in simple terms the behavior of a CAP or TPS as it compares to business-as-usual (BAU) under perfectly inelastic demand. The case of perfectly inelastic demand is useful in that it allows for examination of policy responses when total generation is fixed, which requires emissions regulations to be met via fuel switching.

Before exploring Figure 1.1 in more detail, further assumptions are needed. For simplicity, assume that marginal costs of generation ($\partial C^X(X_{f,t})/\partial X_{f,t} = MC^X_{f,t} > 0$) and an analogous marginal cost function for investment[3] are constant and that both fuels are operating at their physical capacities to generate in the BAU state. Further assume that $MC^X_{H,t} = MC^X_{L,t}$ and $MC^I_{H,t} = MC^I_{L,t}$. At this point, assuming that the emissions intensity for the high carbon fuel is higher than the emissions intensity for the low carbon fuel ($\omega_H > \omega_L > 0$) guarantees that under enforcement of either policy constraint (equation 1.5 or 1.6) coal will be the marginal fuel in production. In order to assess the policy instrument immediately upon enforcement, assume that the time horizon is a single period. Lastly, assume that the BAU case establishes benchmark levels for the average emissions intensity and the aggregate level of emissions, Φ_t and Ψ_t respectively. Φ_t and Ψ_t are related by generation in the BAU state such that $\Psi_t = \Phi_t \sum_f X^{BAU}_{f,t}$. These benchmark values are then reduced by a rate of emissions reduction (ρ_t) to establish the policy targets such that $\Omega_t = (1-\rho_t)\Psi_t$ and $\sigma_t = (1-\rho_t)\Phi_t$. This specification of Ω_t and σ_t defines the CAP and TPS policy cases respectively.

Returning to Figure 1.1 note that two states of the world exist, the BAU state and the CAP/TPS state. Given the assumptions above, Figure 1.1 illustrates how a CAP and TPS are equivalent policies in quantity space when quantity demanded is fixed. Total emissions and total generation are represented by the left and right hand sides of Figure 1.1 respectively. Quantity demanded is represented by the line segment FI. Quantity demanded is met by generation from H or L which are stacked in the columns on the right side of the diagram. In the BAU case, H produces half of the electricity and L produces half of the electricity, shown by the fact that line segment $FG = GI$. In order to meet demand, electricity is generated, which produces emissions of CO2. Under the BAU case, aggregate emissions are given by line segment AE. Again, emissions attributed to each fuel source are stacked in the columns on the left side of the diagram. Recall that the emissions intensity for H is greater than the emissions intensity for L ($\omega_H > \omega_L$). Given that H and L contribute equally to the generation mix in the BAU case, it follows that H produces a larger share of total emissions than that of L. This is represented by the fact that $AC < CE$ in Figure 1.1.

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[3] Marginal investment costs are defined: $\partial C^I(I_{f,t})/\partial I_{f,t} = MC^I_{f,t} > 0$

The CAP/TPS case imposes a policy that will reduce the average or aggregate emissions rate by the same percentage. This in combination with perfectly inelastic demand will lead to an equivalent reduction in aggregate emissions (given by segment AB) regardless of whether it is the rate (1.6) or level (1.5) of emissions that is regulated. This is because output of electricity will not change. Recall that H and L are operating at their physical capacities to generate in the BAU state. When emissions are reduced via a CAP or TPS, perfectly inelastic demand prevents consumers from abating emissions by reducing consumption of electricity. Abatement of emissions must occur via fuel switching. In order to reduce emissions via fuel switching, L must increase its share of generation and H must decrease its share in order to dilute aggregate emissions via relative differences in emissions intensity. In Figure 1.1, the switch from H to L is given by the line segment GH. Building new capacity in L for generation and leaving excess H capacity leads to a generation mix that is heavier in L production than in the BAU case. The new generation mix results in an emissions mix diluted by L relative to BAU. The result is represented in Figure 1.1 by the fact that emissions from L make up a higher share of the emissions mix in the CAP/TPS case than the BAU case (given by $BD/BE > AC/AE$). L capacity is constrained, thus more L capacity needs to be built in order to satisfy the policy. On the other hand, producers substitute away from H, leaving excess (unused) H capacity in the sector. This is how emissions can be reduced via fuel switching alone, which regardless of policy choice is the only abatement option given our assumptions.

In the case of perfectly inelastic demand total generation must meet the fixed level of quantity demanded ($Q_t = d_t$) such that:

$$\sum_f X_{f,t}^{BAU} = \sum_f X_{f,t}^{TPS} = \sum_f X_{f,t}^{CAP} = d_t \tag{1.14}$$

where $\sum_f X_{f,t}^{TPS}$ and $\sum_f X_{f,t}^{CAP}$ represent total generation after enforcing the TPS or CAP, respectively. Under perfectly inelastic demand, there is effectively no difference in quantity response between a CAP and TPS using the same rate of emissions reduction (ρ) to establish each policy target. Recall that Φ_t and Ψ_t are related by generation in the BAU state such that:

$$\Psi_t = \Phi_t \sum_f X_{f,t}^{BAU} \tag{1.15}$$

The benchmark values are then reduced by a rate of emissions reduction (ρ) to establish each respective policy target such that:

$$(CAP) \quad \Omega_t = (1-\rho)\Psi_t \tag{1.16}$$

$$(TPS) \quad \sigma_t = (1-\rho)\Phi_t \tag{1.17}$$

To formalize why establishing each policy target in such a way under perfectly inelastic demand results in emissions equivalent policy, I specify the CAP policy target (Ω_t) that results in the same level of annual emissions as a TPS ($\sigma_t \sum_f X_{f,t}^{TPS}$). Given that the TPS is specified according to equation 1.17, an emissions equivalent CAP is specified as follows:

$$\Omega_t = \sigma_t \sum_f X_{f,t}^{TPS} = (1-\rho)\Phi_t \sum_f X_{f,t}^{TPS} = (1-\rho)\Psi_t \frac{\sum_f X_{f,t}^{TPS}}{\sum_f X_{f,t}^{BAU}} \tag{1.18}$$

$$\Omega_t = \sigma_t \sum_f X_{f,t}^{TPS} = \sum_f X_{ft}^{TPS} \omega_f \tag{1.19}$$

This specification in equation 1.19 is used throughout the paper in reference to the CAP policy instrument, best understood as a sequence of emissions caps set to meet emissions in each period implied by the sequence of TPSs. Substituting equation 1.14 into equation 1.18 reduces to

$$\Omega_t = \sigma_t \sum_f X_{f,t}^{BAU} = (1-\rho)\Psi_t \tag{1.20}$$

which corresponds to equation 1.16.

While Figure 1.1 provides a high-level summary of how quantities can change under these policies, there are other factors at play. Prices are changing as well. Marginal policy costs ($PC_{f,t}$) are represented by the last term in equations 1.9 and 1.10 such that $PC_{f,t}^{CAP} \equiv PCAP_t \omega_f$ and $PC_{f,t}^{TPS} \equiv PTPS_t(\omega_f - \sigma_t)$. The CAP places a price on emissions from both L and H. This tax on all sources of generation will increase electricity prices via equation 1.9. Equations 1.9 and 1.10 show a larger marginal policy cost associated with the fuel with the higher emissions intensity. Given our other assumptions, this ensures that all production of electricity from H is abated prior to any L. In a situation such as Figure 1.1 where demand is perfectly inelastic, the CAP and the TPS will bind their emissions constraints (equation 1.5 and 1.6) to the same degree, producing identical emissions prices ($PCAP = PTPS$) but different marginal policy costs and electricity price by equations 1.9 and 1.10.

In the TPS, the implicit subsidy drives the difference in marginal policy costs. If we assume that $PK_{f,t}$ is fixed, electricity price will increase or decrease by the marginal policy cost associated with each fuel type and policy instrument. However, PD_t cannot scale with permit price because the marginal policy costs are different for each fuel type. An adjustment in the capacity rental rate ($PK_{f,t}$) is required in order to reconcile the differences between fuel types such that equations 1.5 and 1.6 hold. Permit prices are reflective of the fact that H produces only the amount at which it can equate rental prices to operating profits. When the capacity constraint no longer binds for H, as exhibited in Figure 1.1, the rental rate for H falls towards its lower bound at 0, where it is no longer considered scarce. Due to the fact that marginal investment costs are constant for each fuel ($\partial MC_f^I / \partial I_f = 0$) and complementary slackness associated with equation 1.3 holds, the capacity rental rate (PK_f) must be either positive and constant, or 0. This is supported by equations 1.12 and 1.13. We have also assumed that marginal operating costs are constant and equal across fuel types. This means that in each period prices equilibrate such that

$$\Delta PD = \Delta PK_f + \Delta PC_f \tag{1.21}$$

where Δ is the difference between the policy (CAP or TPS) case and the BAU (e.g. $\Delta PD = PD^{TPS} - PD^{BAU}$). Equation 1.21 is obtained by subtracting equation 1.11 from either of equations 1.9 or 1.10 and dropping the t index. Permit prices scale to the point where it is more cost effective to build a marginal unit of L than to continue producing a marginal unit of electricity with existing H. L will bind its capacity constraint. Equation 1.21 is used throughout this paper to explain the behavior of all variables in this model.

Further examination of equations 1.9 - 1.13 as they relate to L shows positive marginal policy costs for the CAP ($\Delta PC_L^{CAP} > 0$), negative marginal policy costs for the TPS ($\Delta PC_L^{TPS} < 0$), and zero change in the capacity rental rate for both cases ($\Delta PK_L = 0$). Given our assumptions, this implies that electricity price is higher under the CAP case ($\Delta PD^{CAP} > 0$) and lower under the TPS case ($\Delta PD^{TPS} < 0$) via equation 1.21.

Consider further, a situation where marginal investment costs are no longer constant but increasing in $I_{f,t}$. Increasing marginal investment costs can capture scarcity in capital and labor in the broader market (external adjustment costs) and scarcity in labor that is reallocated away from production and towards investment (internal adjustment costs). Due to the large costs of investment associated with the electricity sector, it is reasonable to assume that adjustment costs exist in some capacity for fossil fuels. While I abstract from renewable fuels in this analysis, increasing costs of investment can be used to represent renewable resource extraction and scarcity (Coulomb *et al.*, 2019) as well as other associated infrastructure challenges (e.g. transmission capacity). As $I_{f,t}$ increases within the period, marginal investment costs are equated to investment prices ($PI_{f,t}$) which will increase. As $PI_{f,t}$ increases, the rental rate of capital ($PK_{f,t}$) increases by equation 1.12. This becomes more important in later sections when I relax the assumption of perfectly inelastic demand, as this influences the level of output, emissions, and damages associated with a TPS. As shown in equations 1.9 and 1.10, electricity prices must be high enough to cover marginal operating, policy, and capacity rental costs in equilibrium. This intuition is expanded upon in section 1.2.2.

1.2.2 The steady-state policy response

In the previous section I discussed the initial response to the TPS policy under perfectly inelastic demand. In this section I build upon the model and assumptions developed in the previous section. I perform an analysis of the pre- and post-policy steady-state under different elasticity of demand assumptions and linearly increasing marginal investment costs. The pre-policy steady-state is the BAU steady-state. The BAU steady-state is one in which all prices and quantities are constant in perpetuity. I establish an analytical framework for predicting steady-state outcomes under a TPS. This framework accounts for changes in all prices and quantities and gives insight into steady-state periodic social surplus changes relative to the BAU scenario.

Climate change is a long-term problem, therefore the steady-state outcomes are important to take into consideration as social surplus accrues perpetually. It is also important to know where a policy will eventually lead us after planners have had ample time to respond to a policy. Emissions levels are a focus of the steady-state analysis because marginal damages from emissions are assumed to be constant. Therefore, emissions levels are a direct indicator of damages.

The primary intuitive result is that there exists a TPS policy target that does not change electricity price or quantity demanded in the steady-state. In order for this to be true, the standard must be set such that changes in capacity rental costs and marginal operating costs directly offset changes in marginal policy costs (Section 1.2.2.1). If the standard is more (less) stringent than this standard and the standard binds, electricity price will be higher (lower) and quantity demanded will be lower (higher) in the post-policy steady-state (Section 1.2.2.2). Emissions can be inferred from the quantity response. Social surplus changes inclusive of avoided damages can then be calculated.

1.2.2.1 Establishing a starting point for further analysis

In this section I set up the steady-state investment problem and show how to establish a TPS policy target (σ) that does not change electricity price or quantity demanded in the steady-state, regardless of the prevailing elasticity of demand. It is important to establish this policy target as a starting point for analysis in the following section. The assumptions and model setup developed in this section serve as a base with which to explore alternative TPS policy targets and specifications of demand elasticity in section 1.2.2.2.

Recall the first order conditions from our model developed in section 1.2.1. Assume that in a steady-state, the capacity constraint (1.3) and the policy constraint (1.6) bind in perpetuity. Note that in the steady-state all variables are unchanged across time, allowing us to drop the t index. The following first order conditions prove useful for the analysis:

$$\mathcal{L}_{PD}: \quad Q = \sum_f X_f \tag{1.22}$$
$$\mathcal{L}_{PK}: \quad K_f = X_f \tag{1.23}$$
$$\mathcal{L}_{PI}: \quad I_f = K_f \delta \tag{1.24}$$
$$\mathcal{L}_{PTPS}: \quad \sigma = \frac{\sum_f \omega_f X_f}{\sum_f X_f} \tag{1.25}$$
$$\mathcal{L}_{Q}: \quad P = PD \tag{1.26}$$
$$\mathcal{L}_{X}: \quad PD = MC_f^X(X_f) + PK_f + PTPS(\omega_f - \sigma) \tag{1.27}$$
$$\mathcal{L}_{K}: \quad PK_f = PI_f \delta \tag{1.28}$$
$$\mathcal{L}_{I}: \quad PI_f = MC_f^I(I_f) \tag{1.29}$$

I will use these first order conditions (1.22 - 1.29) to derive a reduced form of the model. Substituting (1.29) into (1.28) yields:

$$PK_f = MC_f^I(I_f)\delta \tag{1.30}$$

Substituting (1.30) into (1.27) yields:

$$PD = MC_f^X(X_f) + MC_f^I(I_f)\delta + PTPS(\omega_f - \sigma) \tag{1.31}$$

Further substitution of (1.23) and (1.24) into (1.31) yields the reduced form:

$$PD = MC_f^X(K_f) + MC_f^I(K_f\delta)\delta + PTPS(\omega_f - \sigma) \tag{1.32}$$

where MC_f^X is constant. Equation 1.32 shows how marginal investment costs and marginal policy costs determine the electricity price in a steady-state where the only investment is the replacement of steady-state capacity. Noting equation 1.30 and expanding upon it, the capacity rental rate (PK_f) in the steady state is given by:

$$PK_f = MC_f^I(I_f)\delta = MC_f^I(K_f\delta)\delta \tag{1.33}$$

At this point I will establish the TPS policy target at which electricity price and total quantity remains unchanged in the post-policy steady state. The first step is to solve for the policy target (σ) that leaves electricity price unchanged. I begin by differentiating 1.27 which yields the following:

$$dPD = dPK_f + dPTPS(\omega_f - \sigma) \tag{1.34}$$

where a variable prefixed with a d represents a change in the variable from the BAU to the TPS steady-state as a result of the policy. I am trying to solve for the policy target (σ) that results in zero change in electricity price ($dPD = 0$). Setting the left hand side of equation 1.34 equal to 0 and solving for σ yields,

$$\sigma_0 = \frac{dPK_f}{dPTPS} + \omega_f \tag{1.35}$$

Where σ_0 corresponds to the policy standard that ensures $dPD = 0$. Assuming that only a high carbon (H) and low carbon (L) fuel exist I can set the policy target equal for each fuel:

$$\sigma_0^L = \sigma_0^H \tag{1.36}$$

$$\frac{dPK_L}{dPTPS} + \omega_L = \frac{dPK_H}{dPTPS} + \omega_H \tag{1.37}$$

solving (1.37) for $dPTPS$ yields:

$$dPTPS = \frac{dPK_L - dPK_H}{\omega_H - \omega_L} \tag{1.38}$$

Substituting (1.38) into (1.35) results in the following:

$$\sigma_0 = \frac{dPK_f(\omega_H - \omega_L)}{dPK_L - dPK_H} + \omega_f \tag{1.39}$$

Equation 1.39 is a general form of the TPS target that results in $dPD = 0$. Recall that marginal policy costs are given by $PC \equiv PTPS(\omega_f - \sigma)$. This equation specifies the policy target (σ_0) that will ensure that equation 1.21 is equal to 0 as follows:

$$dPD = dPK + dPC = 0 \tag{1.40}$$

To fully appreciate equation 1.39 it is necessary to consider how the marginal investment cost function drives dPK and hence σ_0. First, I reiterate the assumptions that demand can take on any elasticity and the marginal investment cost curves are increasing in investment ($\partial MC_f^I(I_f)/\partial I_f > 0$). The relationship between the capacity rental rate and the marginal investment cost curves in the steady-state follows from equation 1.33 such that:

$$dPK_f = \delta dMC_f^I(I_f) = \delta dMC_f^I(K_f\delta) \tag{1.41}$$

In the steady-state, the change in the capacity rental rate is the change in the marginal investment cost multiplied by the depreciation rate. By assuming that the policy target binds ($\sigma < \Phi$), it follows from equation 1.41 that $dPK_L > 0$, $dPK_H < 0$, $dMC_L^I > 0$, and $dMC_H^I < 0$. Finally, assuming that the marginal investment cost curves are linear means:

$$dMC_L^I(I_L) = \frac{\partial MC_L^I(I_L)}{\partial I_L} dI_L = \gamma_L dI_L = \Delta MC_L^I(I_L) \tag{1.42}$$

$$dMC_H^I(I_H) = \frac{\partial MC_H^I(I_H)}{\partial I_H} dI_H = \gamma_H dI_H = \Delta MC_H^I(I_H) \tag{1.43}$$

where γ_f is some constant marginal cost. Substituting 1.41 into 1.39 yields:

$$\sigma_0 = \frac{\delta dMC_f^I(\omega_H - \omega_L)}{\delta(dMC_L^I - dMC_H^I)} + \omega_f \tag{1.44}$$

Cancelling the δs and substituting (1.42) and (1.43) results in the value of σ_0 specified in terms of the characteristics of the linear marginal investment cost functions, given below:

$$\sigma_0 = \omega_L + \frac{\gamma_L dI_L(\omega_H - \omega_L)}{\gamma_L dI_L - \gamma_H dI_H} \tag{1.45}$$

Equation 1.45 establishes a relationship between the relative slopes of the marginal cost functions for each fuel and the placement of a standard that will result in $dPD = 0$. In order for PD to remain unchanged, $Q = \sum_f X_f = \sum_f K_f = \sum_f I_f/\delta$ needs to remain unchanged. This implies that it is always the case that $dI_H = -dI_L$. Given this fact, equation 1.45 reduces to:

$$\sigma_0 = \omega_L + \frac{\gamma_L(\omega_H - \omega_L)}{\gamma_L + \gamma_H} \tag{1.46}$$

Consider the case where the marginal investment cost functions for the high and low carbon fuels are linear and of the same slope ($\gamma_L = \gamma_H$). In this case, equation (1.46) reduces to,

$$\sigma_0 = \omega_L + \frac{\omega_H - \omega_L}{2} = \omega_H - \frac{\omega_H - \omega_L}{2} \tag{1.47}$$

which places σ_0 at the midpoint between ω_H and ω_L. Changes in PK_H and PK_L also need to directly offset PC_H and PC_L as $PTPS$ scales with equation 1.25, respectively.

Lemma 1 *For a demand function of any slope, given an initial interior solution, there exists a standard (σ_0) that does not change electricity price or quantity demanded in the post-policy steady-*

state. This standard may or may not lie in a binding position.

Lemma 1 provides a useful starting point for examining the steady-state policy responses. The exercise in section 1.2.2.2 conceptualizes Lemma 1 and then uses it as a benchmark from which to perform different counterfactual experiments.

1.2.2.2 Counterfactual experiments using a simple example

In this section I set up a simple example to help illustrate the steady-state response to a TPS set at different positions relative to σ_0. I explore how different demand elasticities impact outcomes when the standard is not set at σ_0. I find that if the standard is more (less) stringent than σ_0 and the standard binds, electricity price will be higher (lower) and quantity demanded will be lower (higher) in the post-policy steady-state.

To begin the analysis I set up a simple example and reiterate some important assumptions. For the moment, assume that demand can take on any elasticity between 0 (perfectly inelastic) and negative infinity (perfectly elastic). Figure 1.2 illustrates the initial BAU steady-state. The BAU steady state is defined by linearly increasing marginal investment cost curves of identical slope. Marginal investment cost for the low carbon fuel is greater than marginal investment cost for the high carbon fuel. Steady-state investment in the low carbon fuel is half of steady-state investment from the high carbon fuel (i.e. $2I_L^{BAU} = I_H^{BAU}$). Steady-state price of investment for the low carbon fuel is equal to that of the high carbon fuel.

Given the example setup in Figure 1.2, we can calculate σ_0 using equation 1.45. As previously discussed, due to the fact that $\frac{\partial MC_H^I/\partial I_H}{\partial MC_L^I/\partial I_L} = 1$, σ_0 reduces to equation 1.47. Additionally, setting the policy target within the system of equations 1.23 - 1.29 at this level results in a binding policy constraint such that $\sigma = \sigma_0 < \Phi$. Upon enforcement of this policy, a new steady-state is eventually reached where the following results:

$$\Delta PC_H/\Delta PC_L = -1$$
$$\Delta PK_H/\Delta PK_L = -1$$
$$\Delta PD = PD^{TPS} - PD^{BAU} = 0$$

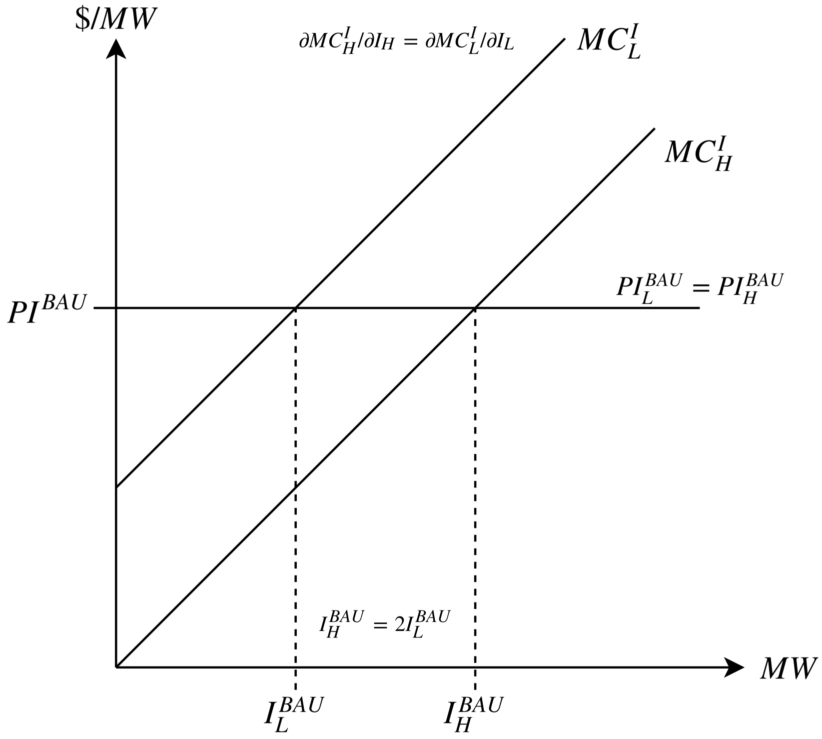

Figure 1.2: Definition of the BAU Steady-State using Marginal Investment Cost curves

Δ is the difference between the TPS steady-state variable and the BAU steady-state variable. In this section, I use ΔPC_f and PC_f interchangeably, as marginal policy costs are always zero in the BAU steady-state.

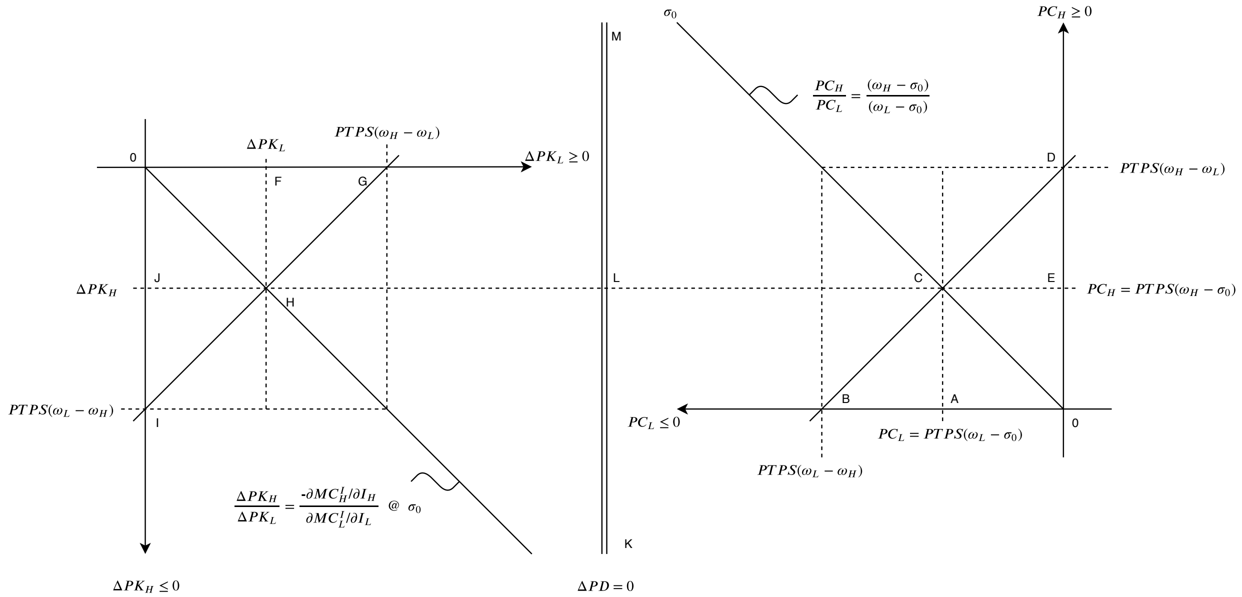

Figure 1.3: Phase 0 - $\sigma = \sigma_0$ such that $\Delta PD = \Delta PK_f + \Delta PC_f = 0$

In order to visually illustrate the policy response in this example, I turn attention to Figure 1.3. Figure 1.3 shows features related to the policy target (right panel) and policy response (left panel). The interaction of the features in the left and right panels of Figure 1.3 show how the capacity rental rate and associated policy costs respond to a given policy target, respectively. Taken together, the sum of ΔPK_f and PC_f result in the change in the price of output (ΔPD) as a result of the TPS.

Before discussing how to use the graphical analytical tool depicted in Figure 1.3 to perform counterfactual analysis, I discuss the features of the tool. The right panel of Figure 1.3 relates to the policy target, which is associated with σ. The origin denoted by a 0 in the right panel is associated with the policy target as well. Note the horizontal (PC_L) and vertical (PC_H) axes associated with the policy target origin. The feasible set of values that marginal policy costs can take on lies to the left ($PC_L \leq 0$) and above ($PC_H \geq 0$) the origin, as L always receives a subsidy and H is always taxed. The line emanating from the origin, referred to from this point forward as the “policy target line”, represents the relative marginal policy costs, which is dictated by the placement of the policy target (σ). Each policy target line is associated with a specific policy target choice. In the case of Figure 1.3, the slope is equal to 1, indicating that σ_0 is the midpoint between ω_L and ω_H. The line BD represents the feasible combinations of marginal policy costs (PC_f), given a binding policy constraint associated with $PTPS > 0$. The policy target line intersects line BD at point C. Point C establishes the marginal policy costs (PC_L and PC_H) associated with a given policy target choice.

The left panel of Figure 1.3 relates to the policy response. Responses to policy arise as a result of changes in investment levels, which cause changes in the capacity rental rate (ΔPK_f) when marginal investment costs are not constant. The origin, denoted by a 0 in the top left of the panel, is associated with the features of Figure 1.3 that relate to the policy response. The feasible set of values that ΔPK can take lies in the space to the right of ($\Delta PK_L \geq 0$) and below ($\Delta PK_H \leq 0$) the origin, as L will always see increases in investment and H will always see decreases as a result of the TPS. The line emanating from the origin, referred to from this point forward as the “policy response line”, represents the relative changes in the capacity rental rate ($\frac{\Delta PK_H}{\Delta PK_L}$) associated with a given policy target choice, marginal investment cost function, and elasticity of demand assumption. The line GI represents the set of feasible combinations of capacity rental rate responses to the binding policy constraint associated with $PTPS > 0$. The intersection of the policy response line and GI occurs at point H. Point H represents the optimal response (ΔPK_L and ΔPK_H) to the TPS given a policy target choice, marginal investment cost functions for L and H, and an elasticity of demand assumption.

As in Figure 1.3, if the policy target is set such that $\sigma = \sigma_0$, then the policy target line and the policy response line will have the same slope ($\frac{\Delta PK_H}{\Delta PK_L} = \frac{PC_H}{PC_L}$). Recalling equation 1.21, note that in Figure 1.3 the marginal policy cost and change in capacity rental rate sum to 0 for a given fuel, such that $\Delta PD = \Delta PK_f + \Delta PC_f = 0$. The dividing double line (KM) in Figure 1.3 links the policy response and policy target. For example, in Figure 1.3, $\Delta PK_H + PC_H = 0 = \Delta PD$ is shown by the intersection of KM and EJ at point L.

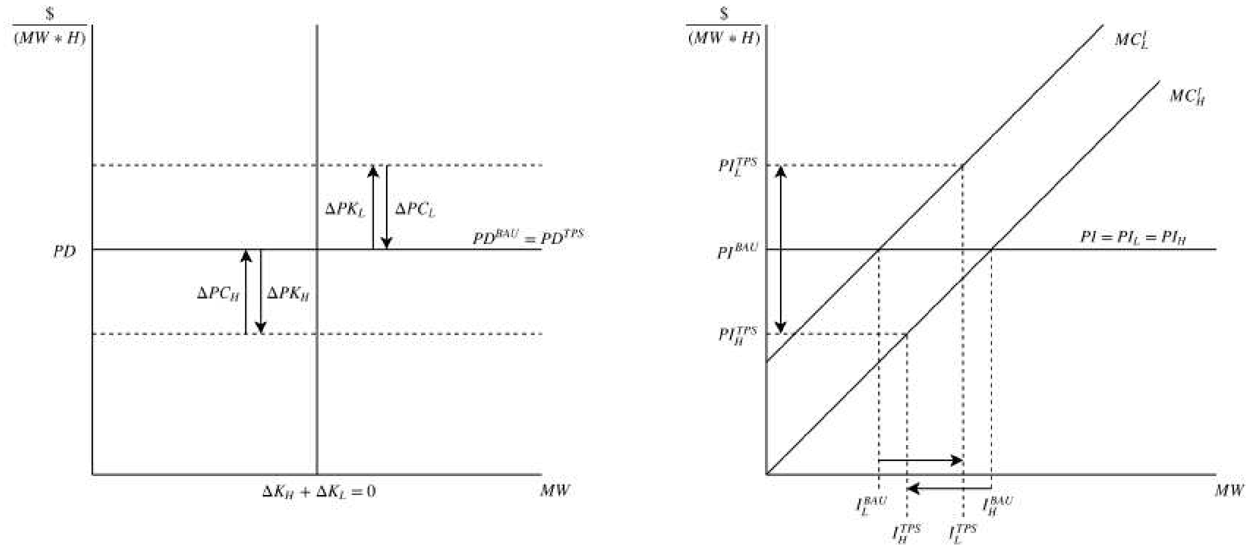

Figure 1.4: Maps Figure 1.3 into price and quantity space

The following analysis proceeds in phases. Phase 0 is represented in Figure 1.3 and Figure 1.4. Phase 0 serves as a benchmark from which counterfactual experiments in phases 1 and 2 are performed. An important assumption I make in the counterfactual analysis is that once Phase 0 establishes a level of $PTPS$, I hold fixed $PTPS$ at the level established in Phase 0. This is done in order to improve tractability of the analytical model without losing the core intuition by preventing lines BD and GI from shifting. Phase 1 explores the case of perfectly inelastic demand and a stricter policy target set such that $\sigma < \sigma_0$. Phase 2 explores the case of perfectly elastic demand under the stricter policy target established in phase 1. Together, phases 1 and 2 establish the range of possible outcomes under different demand elasticities.

Before continuing to phases 1 and 2, it is necessary to explore how the phase 0 intensity map impacts output in Figure 1.4. Figure 1.4 shows electricity price as a function of total capacity (left panel) and investment price as it relates to investment (right panel). Figure 1.4 shows price and quantity responses for the policy target established in Figure 1.3. Figure 1.4 reiterates the fact that the magnitude of marginal policy costs are equal and the slopes of the investment cost curves are equal. Changes in investment levels and investment prices for the low and high carbon fuel perfectly offset. This translates into perfectly offsetting changes in capacity and capacity rental rate, resulting in a zero change in total capacity. Marginal policy costs exactly offset changes in capacity rental rates, resulting in a zero change in electricity price. A zero change in electricity price corresponds to a zero change in total capacity. A summary of the phase 0 result is below:

$$\Delta PD = \Delta PK_f + \Delta PC_f = 0 \tag{1.48}$$

$$\Delta PC_H / \Delta PC_L = (\omega_H - \sigma)/(\omega_L - \sigma) = -1 \tag{1.49}$$

$$\Delta PK_H / \Delta PK_L = \Delta PI_H / \Delta PI_L = -1 \tag{1.50}$$

$$\Delta I_H + \Delta I_L = 0 \tag{1.51}$$

$$\Delta K_H + \Delta K_L = 0 \implies \Delta \sum_f X_f = 0 \tag{1.52}$$

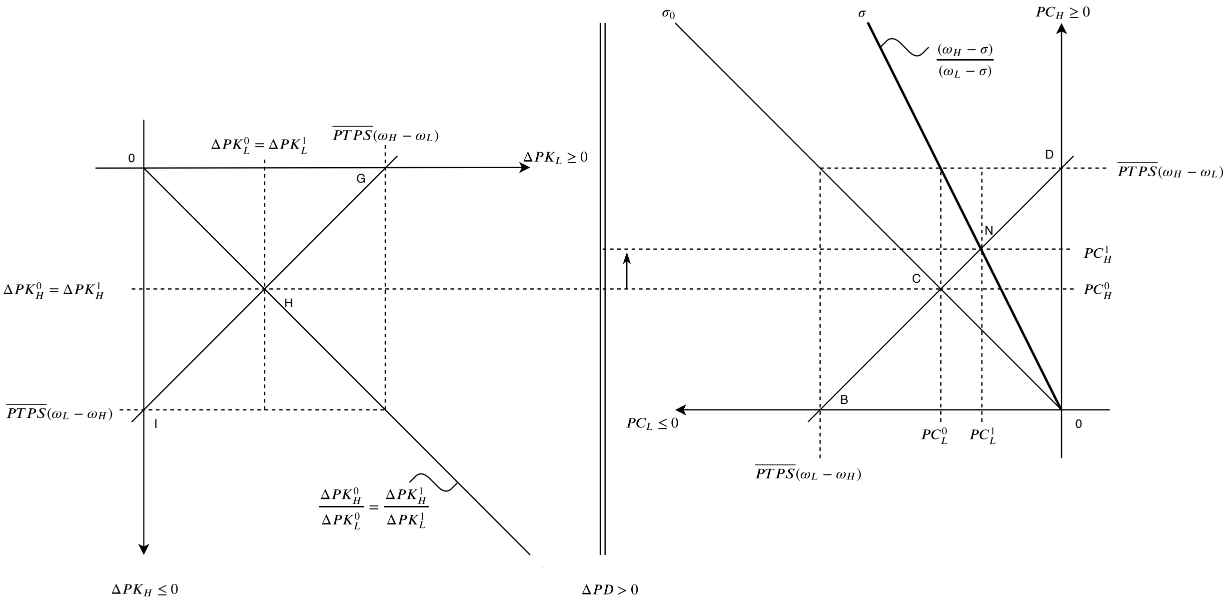

Figure 1.5: Phase 1 - $\sigma < \sigma_0$ under perfectly inelastic demand such that $\Delta PD = \Delta PK_f + \Delta PC_f > 0$

Figures Figure 1.5 and Figure 1.6 are associated with phase 1. In Figure 1.5, any reference to "1" indicates an element associated with phase 1. Phase 1 shows the response to a stricter standard ($\sigma < \sigma_0$) under perfectly inelastic demand. The stricter policy target is represented by a rotation of the policy target line clockwise, effectively making the slope of the policy target line steeper. By placing the standard closer to the low carbon fuel, the high carbon fuel bears a higher burden of the cost of compliance. Hence, marginal policy costs for the high carbon fuel are greater in magnitude than the low carbon fuel. This is represented by the intersection of the new policy

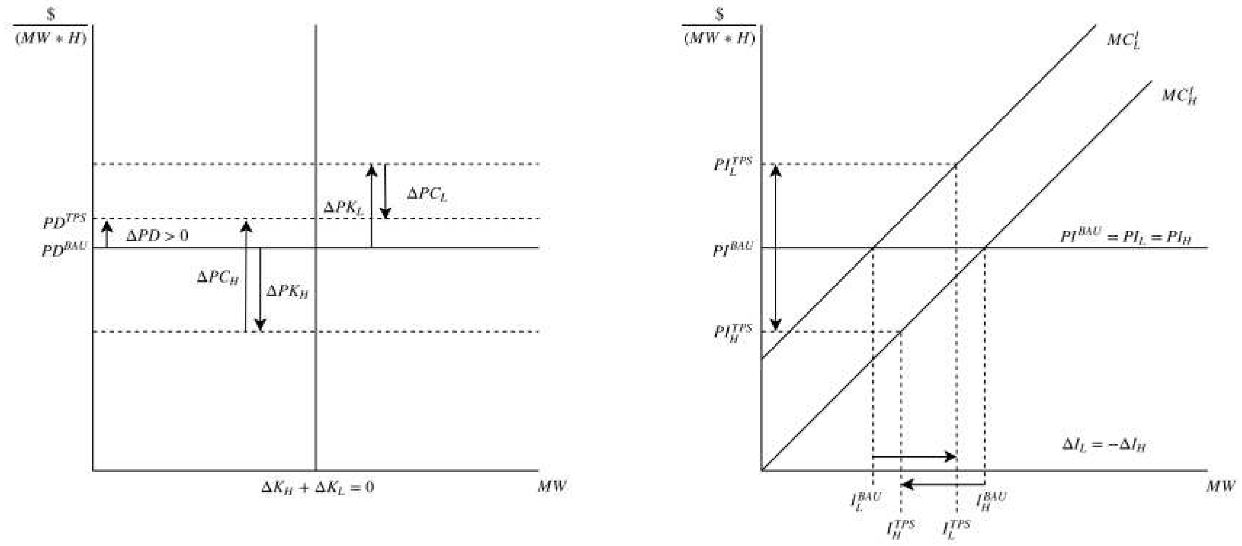

Figure 1.6: Maps Figure 1.5 into price and quantity space

target line with BD at point N. The result is that $PC^1_H > PC^1_L$ and $PC^1_f > PC^0_f$. Turning attention to the policy response, perfectly inelastic demand prevents deviation from phase 0 (noting that $PTPS$ is assumed fixed). Total capacity will remain unchanged due to perfectly inelastic demand. This means that electricity price must increase in order to ensure that $\Delta PD = \Delta PK_f + \Delta PC_f$.

Turning to Figure 1.6, it can be seen how changing relative marginal policy costs via the policy target relative to phase 0 impacts quantities under perfectly inelastic demand. As expected, quantities do not change relative to phase 0 under perfectly inelastic demand. An increase in electricity price is the only way to balance the phase 1 marginal policy costs and capacity rental rates associated with a zero change in total capacity, as depicted in the left panel of Figure 1.6. See below for a summary of results from phase 1:

$$\Delta PD = \Delta PK_f + \Delta PC_f > 0 \tag{1.53}$$

$$\Delta PC_H / \Delta PC_L = (\omega_H - \sigma)/(\omega_L - \sigma) < -1 \tag{1.54}$$

$$\Delta PK_H / \Delta PK_L = \Delta PI_H / \Delta PI_L = -1 \tag{1.55}$$

$$\Delta I_H + \Delta I_L = 0 \tag{1.56}$$

$$\Delta K_H + \Delta K_L = 0 \implies \Delta \sum_f X_f = 0 \tag{1.57}$$

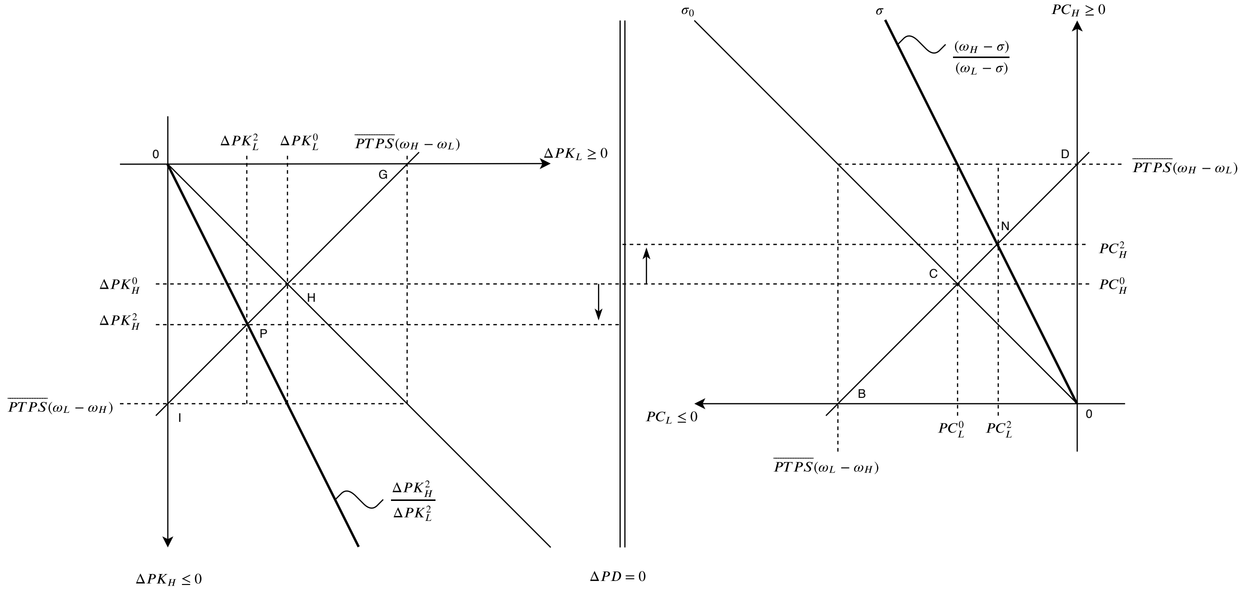

Figure 1.7: Phase 2 - $\sigma < \sigma_0$ under perfectly elastic demand such that $\Delta PD = \Delta PK_f + \Delta PC_f = 0$

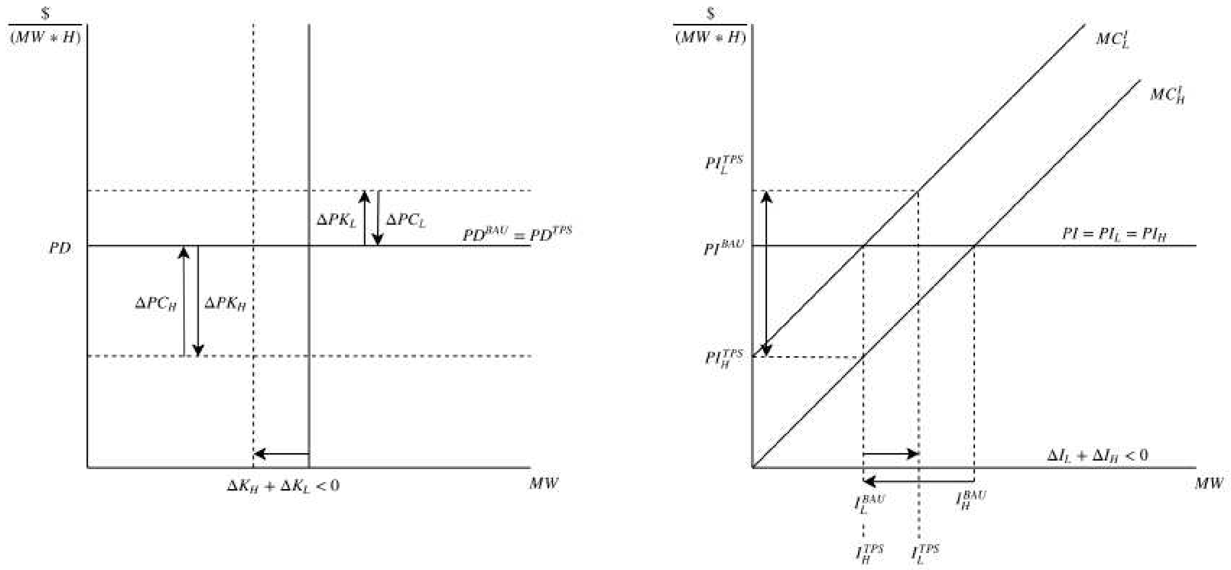

Figure 1.8: Maps Figure 1.7 into price and quantity space

Phase 2, given in figures Figure 1.7 and Figure 1.8, assumes the same adjustment to the policy target line as phase 1 but allows for perfectly elastic demand. This effectively allows for adjustments in total capacity in order to maintain the prevailing electricity price, forcing $\Delta PD = 0$. Again, any reference to a "2" in Figure 1.7 indicates an element associated with phase 2. First, the rotation of the policy target line in phase 2 (Figure 1.7) is identical to the rotation of the policy target line in phase 1 (Figure 1.5). This carries the same implications regarding relative marginal policy costs as phase 1. The difference between figures Figure 1.7 and Figure 1.5 is that in Figure 1.7 the policy response line rotates clockwise around the origin. The policy response line rotates until its slope is identical to that of the policy target line. The intersection of the new policy response line and GI at point P dictates the changes in capacity rental rates for H and L. The policy response line rotates until its slope is just equal to that of the policy target line, coinciding with a zero change in electricity price ($\Delta PD = \Delta PK_f + \Delta PC_f = 0$).

Figure 1.8 shows how electricity price and quantities adjust to the stricter policy target under perfectly elastic demand. In order to ensure that electricity price remains unchanged, quantities must respond such that changes in the capacity rental rate for each respective fuel perfectly offset changes to marginal policy costs brought about by the policy. In order for this to be true, investment in the low carbon fuel will increase, but by less than in phase 0. Investment in the high carbon fuel will decrease by a larger amount than in phase 0. As depicted in the right panel of Figure 1.8, investment in the low carbon fuel will increase by less than investment in the high carbon fuel decreases. As a result, the price associated with investment in the low carbon fuel will increase by less than the investment price associated with the high carbon fuel decreases. This results in a steady-state comprised of a smaller amount of total capacity than in phase 0 (or the BAU steady-state). A summary of results from phase 2 is below:

$$\Delta PD = \Delta PK_f + \Delta PC_f = 0 \tag{1.58}$$
$$\Delta PC_H / \Delta PC_L = (\omega_H - \sigma)/(\omega_L - \sigma) < -1 \tag{1.59}$$
$$\Delta PK_H / \Delta PK_L = \Delta PI_H / \Delta PI_L < -1 \tag{1.60}$$
$$\Delta PC_H / \Delta PC_L = \Delta PK_H / \Delta PK_L < -1 \tag{1.61}$$
$$\Delta I_H + \Delta I_L < 0 \tag{1.62}$$
$$\Delta K_H + \Delta K_L < 0 \implies \Delta \sum_f X_f < 0 \tag{1.63}$$

Phase 1 and phase 2 place boundaries on the possibilities for steady-state outcomes given varying demand elasticities. Any demand elasticity that is not perfectly inelastic will cause a clockwise rotation in the policy response line for any standard that is placed such that $\sigma < \sigma_0$. Additionally, not depicted in Figure 1.7 due to the assumption that $PTPS$ is fixed, the policy target frontier will shift towards the origin relative to its phase 1 position. This is due to a loosening of the policy constraint (1.25) brought about via abatement of consumption. In phase 1, all abatement is achieved through fuel switching via investment. In phase 2, a mix of the two forms of abatement occurs. The analysis above leaves us with the following intuitive result:

Proposition 1 *If the standard (σ) is more (less) stringent than σ_0 and the standard binds ($\sigma < \Phi$), electricity price is higher (lower) and quantity demanded is lower (higher) in the post-policy steady-state.*

The intuitive exercise discussed in this section highlights some of the key drivers underlying the TPS and the model construct. Most notably, the policy outcome is sensitive to the placement of the policy target, the relative slopes of the marginal investment cost curves, the degree of difference between the rate at which marginal policy costs and capacity rental rates scale, and the elasticity of demand. This analytical framework also provides a policy response for all prices and quantities in the steady-state. This allows for calculation of emissions levels in the post-policy steady-state and further analysis of damages, abatement cost, and social surplus.

This result is not limited to dynamic models as it is static in nature. In fact, due to the assumptions made, PK could simply be represented by an upward sloping marginal cost function of any kind. The analytical results here can be referenced in lieu of a detailed decomposition of the output effects of a TPS in the case of most applied analyses.

1.3 Numerical Results

In the previous sections I established analytical intuition for the behavior of the dynamic model under the initial and steady-state responses to the TPS policy instrument. In section 1.3.3, I use a numerical version of the model to examine the evolution of the model variables through time under a TPS. In section 1.3.4, I discuss the costs and benefits associated with the TPS policy, and compare the TPS results to the BAU scenario and that of an emissions equivalent CAP. Prior to discussing the results, I relay some important details related to the numerical model setup and define the model scenarios in sections 1.3.1 and 1.3.2.

1.3.1 Numerical model setup

Before discussing the scenario definition and model results, it is important to make note of some characteristics that place this model within the context of electricity markets. While electricity markets are the subject of this analysis, a detailed representation is beyond the scope of the study. A highly detailed representation is not necessary for determining the underlying relationship between investment costs, capacity constraints, policy stringency, and time. However, electricity markets are subject to large investment costs and long-lived generation capacity. These features subject the markets to capacity constraints which may be either binding or non-binding. These features are relevant in many industrial sectors of an economy.

Given the scope of the numerical analysis, it is important to maintain the relationship between costs of generation and investment. Particularly the fact that investment costs are large and that investment produces capacity which can be used over an extended period for the purpose of generating electricity at an additional operating cost. Table 1.1 provides some of the key parameters used within the numerical model, as well as their values.

The parameters are chosen to loosely represent operating costs relative to investment costs within the electricity sector (EIA, 2018a,b,c; IEA, 2018; NREL, 2018). The value for elasticity

Table 1.1: Key Model Parameters

Parameter	Value	Description
$\overline{d}_t$	100	MW - constant reference demand for each period (t)
$MC^X_{f,t}$	30	$\$/MWh$ - constant operating costs for each fuel (f)
ω_H	2000	$lb\ CO2e/MWh$ - emissions intensity for H
ω_L	0	$lb\ CO2e/MWh$ - emissions intensity for L
δ	0.05	depreciation/asset decay rate
ε	-0.3	elasticity of demand
r	0.01	rate of time preference used for discounting
hiy	8760	operating hours in each period (t)

of demand was chosen to represent consumer responses to price over the medium to long term (Deryugina *et al.*, 2020). The values for exogenous demand and the depreciation rate were chosen to ease interpretation of the results. Furthermore, the emissions intensity of L relative to H does not have a major impact on the intuition obtained from the numerical results. However, when $\omega_L = 0$ it has the added benefit of showing convergence in social surplus between the CAP and TPS as the standard approaches zero. The number of operating hours in each year are included to make sure that costs over each period (t) are aligned in terms of operations and investment. For example, generation must meet demand which is modeled in megawatts (MW). The cost of generating at 100 MW over the course of a year is $100 * MC_{f,t} * hiy$ in dollars, because 100 megawatts generated over 1 period of 8760 hours is $100 * 8760$ megawatt-hours (MWh). If the depreciation rate is 0.05 and the capacity constraint binds, then 100 MW of capacity must be maintained every period in the steady-state. This means that investment must replace the 5 MW of depreciated capacity at a high cost (e.g. $1,000,000/MW).

In the numerical model I choose the slope and intercept of the marginal investment cost curves. The intercept term is always positive and identical across fuel types while the slope can vary for the scenarios modeled. I choose the slope and intercept so that the business-as-usual (BAU) steady-state is one in which $\overline{d}_t$ is constant throughout the time horizon at an initial period marginal price of investment ($PI_{f,t=0}$) equal to \$1,000,000/MW. The value of \$1,000,000/MW was chosen to place investment costs in the general vicinity of US electricity sector costs. The slopes are determined by the following function:

$$PI_{f,t} = [(1/(1+r))^t] * [\alpha + \beta_f * I_{f,t}] \tag{1.64}$$

where α is the intercept term of the marginal investment cost function and β_f is the slope term. In an example where the slopes are identical (i.e. $\beta_L = \beta_H$) the BAU steady-state is such that $I_{f,t} = \frac{\overline{d}_t * \delta}{2}$. In the BAU steady-state, $\overline{d}_t = \sum_f X_{f,t} = \sum_f K_{f,t} = 100$ and and $\delta = 0.05$. The BAU steady-state corresponds to one where capacity is split equally between each fuel such that $K_{H,t} = K_{L,t} = 50\ MW$ and investment is such that $I_{f,t} = \delta K_{f,t} = 2.5\ MW$. This is due to the identical intercepts and slopes. Setting $\alpha = 0$, $PI_{f,t=0} = 1e6$, and $I_{f,t} = 2.5$ in equation 1.64 and solving for the slope yields $\beta_f = 4e5$.

Once I have the slope and intercept term established, I solve the system of equations with exogenous demand fixed at $\overline{d}_t$. The marginal value from the market clearance condition equating total generation ($\sum_f X_{f,t}$) to quantity demanded ($\overline{d}_t$) determines the reference level for the discounted electricity price ($\overline{pd}_t$) which falls at a rate of $(1+r)$ over time in the BAU steady-state. The first order condition of the Lagrangian to this problem with respect to the total quantity demanded shows that the benchmark electricity price $\overline{pq}_t$ is equal to $\frac{\overline{pd}_t}{(1/(1+r))^t}$. Therefore, $\overline{pq}_t$ is constant across the entire time horizon.

Using these new values for $\overline{pd}_t$ and $\overline{pq}_t$ I allow for price responsive demand where the following equilibrium conditions hold:

$$(\frac{1}{1+r})^t * \overline{pq}_t * (\frac{Q_t}{\overline{d}_t})^{1/\varepsilon} \geq PD_t \quad \perp Q_t \tag{1.65}$$

$$\sum_f X_{f,t} \geq Q_t \quad \perp PD_t \tag{1.66}$$

where Q_t is total quantity demanded. Solving the model with the updated benchmark values for $\overline{pq}_t$ and $\overline{d}_t$ will replicate the BAU steady-state. This provides a basis for comparison with counterfactual policy scenarios allowing for price-responsive demand.

A full set of numerical model equations can be found in appendix A.

1.3.2 Scenario definition

In order to explore the TPS further, I have decided upon a set of scenarios indicating different model assumptions by varying the slopes of the marginal investment cost curves and policy stringencies. See Table 1.2 for details.

Table 1.2: Scenario Definition

Scenario	Slopes	Policy Stringency
S1A	High/Steep	Low/Loose
S1B	High/Steep	High/Strict
S2A	Low/Flat	Low/Loose
S2B	Low/Flat	High/Strict

The number (e.g. 1,2) in the scenario name corresponds to the specification of the marginal investment cost functions whereas the letter (e.g. A, B) corresponds to the policy stringency. Scenario S1A corresponds to identical and linear marginal investment cost curves of relatively steep slope with a policy target set at 0.7 times σ_0. The marginal cost curves for each fuel type emanate from the same point for each scenario, therefore σ_0 equals the reference average emissions rate (Φ). This means that a standard set at 0.9 times σ_0 corresponds to a 10% reduction from the reference emissions rate ($\sigma = \sigma_0 * 0.7 = \Phi * (1 - 0.3)$). Scenario S2A corresponds to identical and linear marginal investment cost curves of relatively flat slope with a policy target set at 0.7 times σ_0. The policy target associated with the highly stringent policy is set at 0.3 times σ_0.

The slope and intercept associated with scenario 1 corresponds to $\beta_f = 4e5$ and $\alpha_f = 0$. The slope and intercept for scenario 2 corresponds to $\beta_f = 4e4$ and $\alpha_f = 9e5$. The relatively flat marginal investment cost curves associated with scenario 2 are probably closer to that of the electricity sector than those in scenario 1.

1.3.3 Evolution of model variables through time

In this section I discuss the evolution of the model variables through time. I discuss the initial period response to the TPS policy followed by a discussion of the transition to the steady-state. I refer back to the theory developed in the previous section where applicable.

Figure 1.9: Initial period response to TPS — ΔPC_f, ΔPK_f, ΔPD

Figure 1.9 shows the initial period response to the TPS policy. Recall that the relationship between electricity price, the capacity rental rate, and the policy cost is defined by the following equation:

$$\Delta PD = \Delta PK_f + \Delta PC_f \tag{1.67}$$

Figure 1.9 shows that this relationship holds for each scenario and each fuel type (i.e. H and L on the right axis). Marginal policy costs (left column) for H are greater than zero in each scenario. This is associated with a permit price that is greater than zero and an emissions intensity for H that is greater than the intensity standard. The capacity rental rate is 0. Therefore, the change in the capacity rental rate from the BAU (middle column) for H is less than zero for all cases. A capacity rental rate of zero suggests that the capacity constraint does not bind in the initial period for H, as expected. The change in electricity price (right column) is the sum of the change in marginal policy cost and change in capacity rental rate, which is positive.

L sees a negative marginal policy cost, which indicates a net subsidy is received by producers of the low carbon fuel. Changes in the capacity rental rate from the BAU are greater than zero. This indicates that investment changes from the BAU for L are also greater than zero. This increase in investment comes at a higher cost, which is reflected in the capacity rental rate. The sum of the subsidy associated with the marginal policy cost and the increase in the capacity rental rate is equal to the change in the output price from the BAU level, which is positive.

The increase in the output price indicates that total quantity demanded falls, hence total generation falls. The increase in the capacity rental rate for L is associated with an increase in investment for L, which is associated with an increase in capacity to generate. The capacity rental rate would not increase unless the capacity constraint were binding. This means that generation associated with L increases. If total generation decreases, and generation of L increases, then generation of H must decrease. If total generation decreases, then aggregate emissions decrease.

Note in comparing scenarios S1A with S2A, the scenario with the steeper marginal investment cost curves (S1A) results in a higher capacity rental rate and smaller subsidy for L, which results in a higher electricity price. This is due to the fact that responding to policy is more costly when the marginal investment cost curves are steeper. Additionally, a more stringent rate standard results in a larger marginal policy cost for H and smaller subsidy for L given identical cost structures across policy scenarios (e.g. S1A vs. S1B). The more stringent standard also increases investment required in order to meet it, as depicted by the increased rental rates for L and electricity price when comparing policy case A versus B. All of this intuition can be derived from the results referenced in Figure 1.9.

Total quantity demanded falls in the initial period. This is due to the fact that the slopes of the marginal investment cost curves are steep enough in all scenarios to cause consumers to abate consumption in the initial period. Rather than choosing to invest enough in L to reach the steady-state capacity level immediately, investment is delayed in order to save by spreading costs across multiple periods. This is the result of a foresighted effort to maximize the difference between benefits and costs across the entire time horizon.

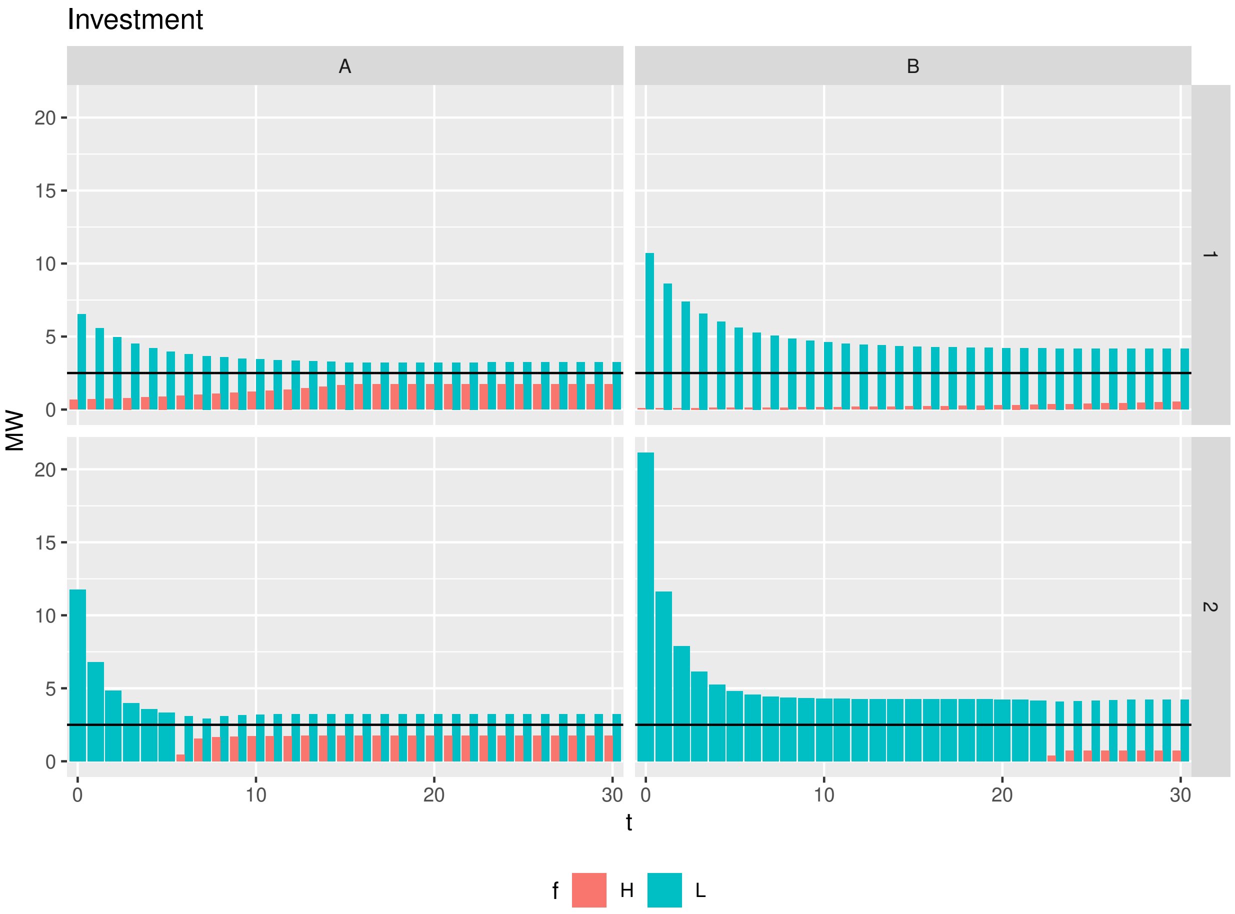

Figure 1.10: Path of Investment — $I_{f,t}$

Figure 1.10 shows investment levels relative to the BAU scenario by fuel type and time period. The horizontal black line indicates the BAU steady-state level of investment for each fuel type.

Changes can be inferred relative to this line. The first row of Figure 1.10 corresponds to scenarios S1A (left column) and S1B (right column) and the second row corresponds to scenarios S2A and S2B. In comparing the first and second rows, three key observations can be made. First, it is clear that scenario S1A shows lower initial levels of investment in L than S1B. This validates the previous discussion related to the initial policy response. Second, S2A reaches steady-state levels of investment sooner than S1A. This is due to the fact that investment is more costly in S1A and it is therefore more cost effective to consume less and spread the costs across the time horizon. Thirdly, related to the second observation, H investment begins to re-enter in S2A sooner than S1A. This is due in part to the flatter marginal investment cost curves in S2A. Investment in L can be increased at a lower marginal cost in S2A and decreased investment in H does not lower marginal investment costs as much. This skews the investment path in favor of L, allows H to depreciate without investment for longer, and allows H investment to re-establish a new steady-state rental rate faster at relatively low marginal costs.

In comparing the less stringent policy (left column) and the more stringent policy (right column) of Figure 1.10 it is clear that more investment is made in L in order to satisfy the policy initially and across the entire time horizon. This shows that an unexpected immediate increase in policy stringency can have significant implications on investment levels and costliness of the TPS initially and through the transition period. While not explicitly modeled, these results highlight the intuition that there may be benefits to allowing time to plan ahead for the TPS policy.

Figure 1.11 shows the capacity utilization rate by scenario with scenarios grouped in columns by the policy stringency. Figure 1.11 supports the intuition above. It shows full capacity utilization is reached sooner in the scenarios associated with the relatively flat marginal investment cost functions (i.e. S2A and S2B). This is a requirement for reaching the steady-state. This figure also highlights the differences between policy stringencies. The stricter policy takes longer for the capacity constraint to bind for H and to reach a steady-state as investment is smoothed over time in order to reduce overall costs.

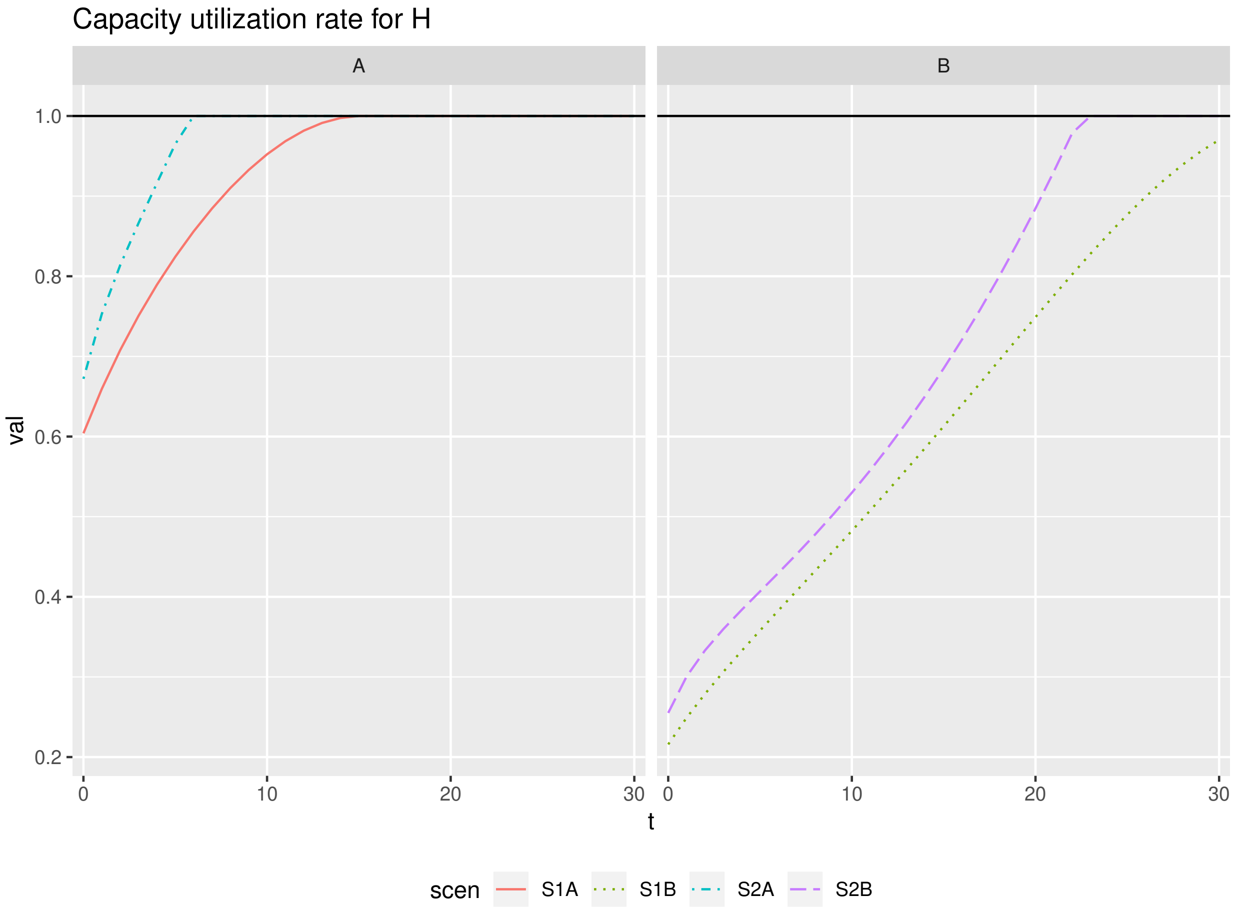

Figure 1.11: Capacity utilization for H

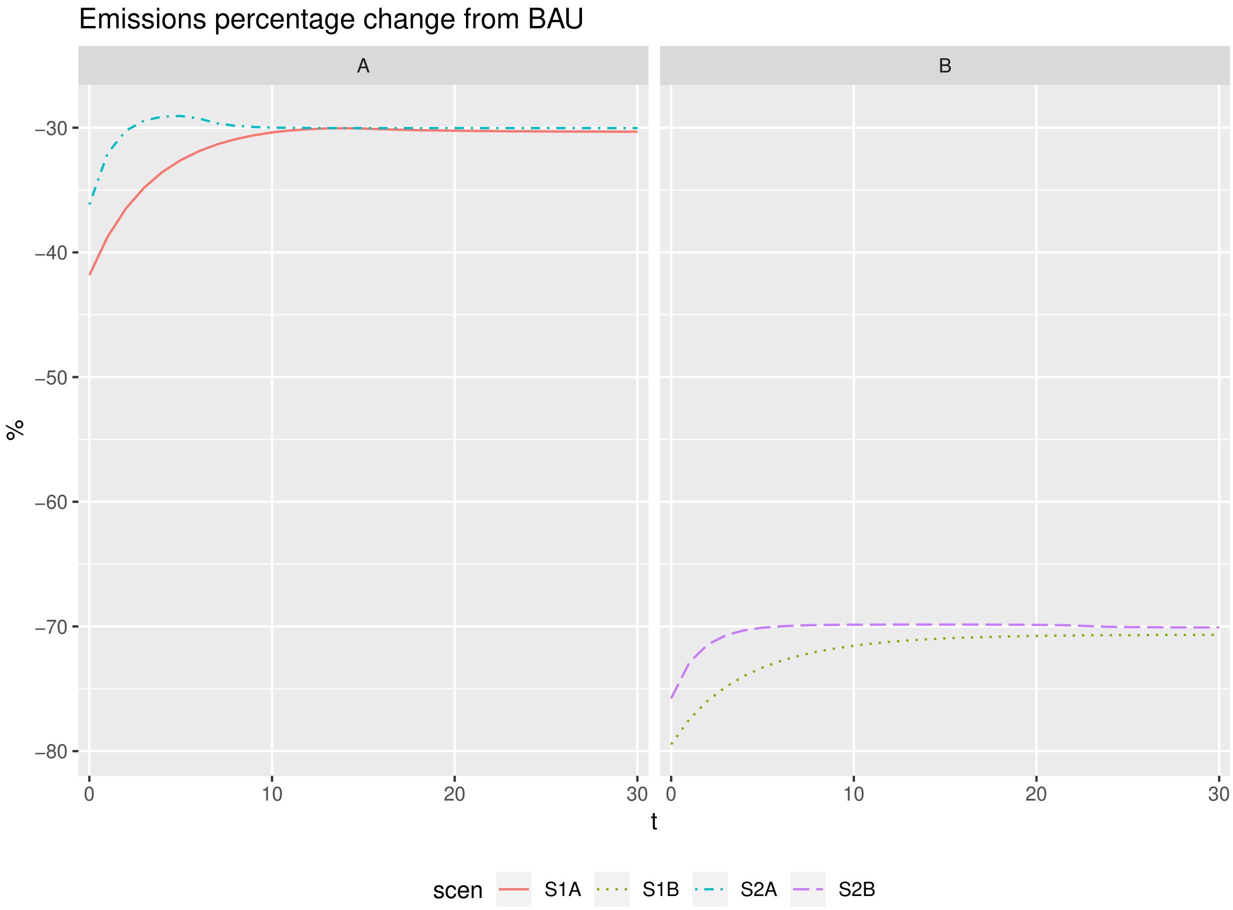

Figure 1.12: Percentage reduction in emissions from BAU

Figure 1.12 shows the percentage change in emissions from the BAU case for each TPS scenario grouped by policy stringency. As expected, the more stringent policy target associated with column B shows a larger reduction in aggregate emissions levels. Additionally, S1A shows larger emissions reductions than S2A due to steeper marginal investment cost curves associated with S1A. In short, more damages are avoided due to the higher costs of investment associated with the steeper marginal investment cost curves. Consumers prefer to reduce more consumption at higher marginal costs of investment. The capacity rental rate increases as a result of higher marginal investment costs which outstrip the net subsidy for production of L. This increases the price of output and decreases quantity produced referenced in equation 1.67. Reducing consumption comes with the added benefit of avoiding damages from emitting. This result has important implications in assessing the damages avoided as a result of the TPS, an important element of the social surplus calculation.

Figure 1.13 shows the steady-state period-over-period changes in marginal policy cost (ΔPC_f), changes in capacity rental rate (ΔPK_f), and changes in output price (ΔPD) in each column from left to right. The top row is associated with H and the bottom row is associated with L. As a discount rate of 1% was used in this model, the price output from the model is adjusted to a future value in order to view the steady-state in terms of perpetually constant values instead of values perpetually decreasing at the rate of $\frac{1}{1+r}$. Regardless of discounting, the values are of the same proportion to one another.

The results in Figure 1.13 validate the theory developed in section 1.2.2. The emissions rate standard (σ) is chosen such that $\sigma < \sigma_0$, where the definition of σ_0 is established in relation to lemma 1. Since σ_0 is equal to the reference period-over-period average emissions intensity in the BAU steady-state such that $\sigma_0 = \Phi$, the standard is binding. Following from proposition 1, due to the fact that σ is more stringent than σ_0 and demand is price responsive, the output price will increase and total quantity demanded will decrease. If quantity demanded decreases, we know from Holland *et al.* (2009) that emissions levels will decrease as well.

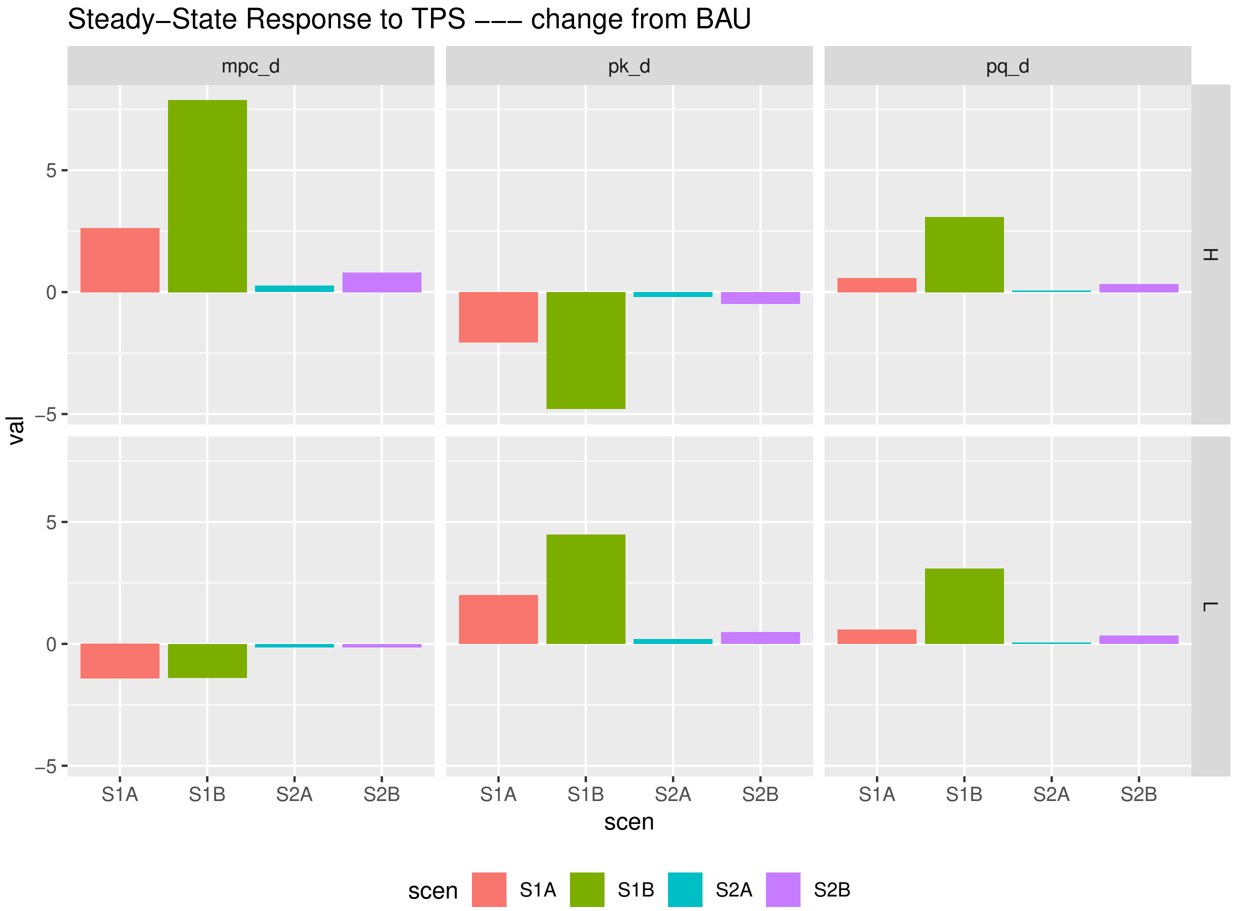

Figure 1.13: Steady-state response to TPS — ΔPC_f, ΔPK_f, ΔPD

Additionally, steeper marginal investment cost curves result in a greater steady-state reduction in quantity demanded from the BAU. This can be seen by comparing S1A with S2A in the right column of Figure 1.13. As expected, more stringent policy is associated with a higher steady-state electricity price. This is evidenced by comparing S1A with S1B for example.

1.3.4 Abatement cost and social surplus

Table 1.3: Present Value of change in surplus measures for TPS from BAU ($/(hour*year))

Scenario	ΔCS	ΔPS	$\Delta CInv$	ΔAC	ΔDam	ΔSS	$\Delta SS_{TPS-CAP}$
S1A	-13029	11920	3653	5123	28129	23006	-170
S1B	-50775	45636	16855	23921	65162	41240	-105
S2A	-1526	1390	784	956	27568	26612	-34
S2B	-7236	6511	4132	5054	64297	59243	-19

Turning attention to costs and benefits associated with the TPS policy, I begin by discussing the results in Table 1.3. Table 1.3 shows present value of changes in the key metrics associated with the social surplus calculation. Please see appendix B for detailed surplus calculations. All values except for the rightmost column represent changes from the BAU value for each metric (i.e. $\Delta = TPS - BAU$). The far right column represents social surplus changes relative to an emissions equivalent CAP. Each scenario initially defined in Table 1.2 is listed in the far left column of Table 1.3. The column headings correspond to present value changes in consumer surplus (ΔCS), producer surplus (ΔPS), investment costs ($\Delta CInv$), abatement costs (ΔAC), avoided damages (ΔDam), and social surplus (ΔSS) summed across time, such that:

$$\Delta AC = -1 * (\Delta CS + \Delta PS) + \Delta CInv \tag{1.68}$$

$$\Delta SS = \Delta Dam - \Delta AC \tag{1.69}$$

The values themselves are less important than the relationships between scenarios and across the different elements of the surplus calculation. For example, ΔAC is larger for S1A than S2A. This is due to the fact that S2A corresponds to the scenario with the flatter marginal investment cost curves. Steeper marginal investment cost curves associated with S1A and S1B result in a larger change in electricity price initially, through the transition, and into the steady-state. This has implications for the magnitude of changes in consumer and producer surplus, the sum of which always represents a positive net cost for the scenarios modeled. Changes in total investment costs will also be larger for S1A and S1B than in S2A and S2B.

Marginal damages are constant across time and all levels of emissions. Therefore, the choice of the value can influence whether or not social surplus changes are positive. For the scenarios modeled, avoided damages exceed abatement costs at a marginal damage level of \$20/mt CO2e, indicating positive changes in social surplus relative to the BAU scenario.

The far right column of Table 1.3 shows the difference between changes in social surplus from the TPS relative to the period-over-period emissions equivalent CAP. The CAP always shows greater present value of social surplus changes summed across time than the TPS except for the case where the emissions intensity of L is zero ($\omega_L = 0$) and the standard is set to zero ($\sigma = 0$). If $\omega_L = 0$, as the standard is tightened, the difference between the present value of ΔSS_{TPS} and ΔSS_{CAP} approaches zero. This movement can be seen in Table 1.3 by comparing scenarios A and B for a given marginal investment cost curve.

Additionally, it is worth noting that the difference in the present value of social surplus changes between a TPS and a CAP is small relative to present value of social surplus gains from either policy. The surplus differences due to the policy choice itself accounts for roughly 0.74% and 0.03% of ΔSS under the TPS for scenarios S1A and S2B respectively.

As it relates to abatement cost and social surplus measures, there are two key observations from the numerical output listed below.

Numerical Result 1 *The present value of all social surplus changes from the benchmark case will always be lower for the TPS than for the period-over-period emissions equivalent CAP, except when $\sigma = 0$ and $\omega_L = 0$. So, dynamic considerations do not change the well-known result in the literature that an emissions cap is more cost-effective than a TPS overall, from $t = 0$ to $t = \infty$.*

Numerical Result 2 *Once the steady-state is reached in period T, after the costly transition has occured between periods $t = 0$ to $t = T$, the value of the perpetuity*[4] *of steady-state social surplus changes can be higher or lower for the TPS relative to the emissions equivalent CAP. Meaning, when discounting is present, the sequence of TPSs can be more cost-effective than a sequence of emissions equivalent caps* <u>*only over specific segments*</u> *of the infinite time horizon, such as the steady-state segment existing between periods $t = T$ to $t = \infty$.*

Table 1.4: Ratio of periodic steady-state social surplus change ($\Delta SS_T^{TPS}/\Delta SS_T^{CAP}$)

Slope MC_f^I Discount rate (r)	Steeper (1)	Flatter (2)
0	0.998864	0.999988
0.01	1.004387	1.000573
0.03	1.018866	1.002116

When taken together, numerical results 1 and 2 state that, while the present value of social surplus must always be greater under a CAP, the value of the net benefit flows accruing to the TPS in the post-transition, steady-state period can be greater than those accruing to the CAP. Table 1.4 shows the ratio of changes in periodic steady-state social surplus under the TPS versus the CAP for a TPS policy target that is more stringent than σ_0. A value greater (less) than 1 indicates the TPS (CAP) has greater steady-state social surplus change. Table 1.4 shows that for all but the smallest discount rates, the TPS shows greater steady-state changes in social surplus than the CAP. Also note that steeper marginal investment cost functions exacerbate the sensitivity to the discount rate.

These results can be viewed through the lens of a comparison in abatement response betweeen a zero-discount rate and a positive discount rate. First, in response to a higher discount rate, the TPS shifts investment in the low carbon fuel towards the present. This leads to a shift in output increase towards the present. Effectively, output is shifted towards the earlier periods in the

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[4] The term "perpetuity" here is a financial term indicating the value of a perpetual constant nominal stream of cash flows. Given a net benefit flow in period T, ΔSS_T, where T is a single period within the steady-state, the value of the "perpetuity" is $\Delta SS_T/r$, where r is the periodic effective rate of interest, or discount rate. Therefore, an infinite stream of constant cash flows has a finite value when discounting is present.

transition and away from the later periods of the transition and throughout the steady-state. This means that emissions follow a similar path. The endogenously determined emissions level in each period changes, showing an increase in earlier periods and a decrease in later periods, compared to a zero-discount rate counterfactual. The sequential CAP is set to the endogenously determined periodic emissions levels by the TPS. The CAP responds by decreasing investment across the entire time horizon (a shift). Also, the CAP increases output in the earlier periods of the transition, sacrificing output in the later periods of the transition and throughout the steady-state. Effectively, the difference in output between the TPS and CAP compared between the zero discount rate and high discount rate case, show a much larger output difference under the high discount rate across the time horizon. Abatement costs are similarly front-loaded in the time horizon. The CAP shows a reduction in costs related to investment early in the time horizon, and a slight reduction into the steady-state. However, the CAP shows a decrease in consumer and producer surplus across the entire time horizon. The reductions to investment costs outweigh the reductions in consumer and producer surplus in the earlier periods, however the reductions in consumer and producer surplus outweigh the gains in investment cost reduction in the later periods and throughout the steady-state. These dynamics lead to a greater cost-effectiveness for the CAP (than the TPS) in the earlier periods under a high discount rate, and lower cost-effectiveness for the CAP (than the TPS) in the later periods and into the steady-state.

In summary, a higher discount rate causes the TPS to invest more in the earlier periods. This leads to higher endogenously determined emissions levels early-on. Over time, the emissions levels implied by the TPS more closely approach the zero-discount rate levels, though emissions are slightly lower in the steady-state when discount rates are high. The CAP sees the higher emissions in the earlier periods and lower emissions in later periods and responds accordingly. This leads to a reduction in abatement costs compared to the TPS in the early periods and an increase relative to the TPS in the later periods. In the post-transition steady-state, the TPS is more cost-effective than the CAP.[5]

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[5] Note that this result should be checked for robustness to an endogenously specified TPS that meets an exogenously specified emissions cap.

1.4 Conclusion

In this paper I explore the behavior of a TPS in a dynamic setting. I define an analytical model and discuss the initial and steady-state responses to the TPS policy instrument intuitively. I also use a numerical model to provide additional validation of the analytical results, further explore the transition of the model variables from the initial policy response to the steady-state, and discuss abatement cost and social surplus relative to a no-policy case and a period-over-period emissions equivalent cap.

The intuitive analysis uncovers an emissions intensity standard that does not change the price of electricity in the post-policy steady-state. If the emissions intensity target is set more stringently than the standard that leaves price unchanged, electricity price will rise and quantity demanded will fall. In this case the TPS will result in a lower level of steady-state emissions. The numerical analysis validates this analytical result. Additionally, the numerical model finds that investment levels and abatement costs are sensitive to the slopes of the marginal investment cost curves as well as the policy stringency. Steeper marginal investment cost curves cause investment to be spread out further across the time horizon, as consumers reduce consumption to a greater degree. Abatement costs are also larger in environments with steep marginal investment cost curves.

In comparing the TPS surplus measures to that of a period-over-period damage equivalent CAP, the present value of social surplus changes from the no-policy case is smaller for the TPS than the CAP, though not by much. Discounting exacerbates the cost-effectiveness advantage that the CAP has over the TPS in general. However, introducing a discount rate leads to a situation where the post-transition steady-state is more cost-effective for the TPS than for the CAP. This suggests that some classes of future consumers may prefer a TPS to a CAP. Finally, as expected, if the TPS policy target is set to an emissions intensity of zero at the outset, there is no difference in the present value of social surplus between the TPS and CAP across time, regardless of the discount rate.

Future research could explore the ability for decision makers to plan for expected policy with and without policy uncertainty. Different representations of capital accumulation and adjustment could be a valuable addition to this research. Alternative methods for specifying the TPS and comparison policies across the time horizon as well as methods for use of permit or tax revenue from a cap and trade system or carbon tax (i.e. banking and borrowing of permits). Other research could surround policy implementation in a dynamic context. For example, given a carbon budget, determine the best way to set the TPS policy target. Furthermore, other factors such as technology cost improvements could be explored. Applied models that account for capital adjustment, price responsive demand, and foresight can use these results to inform expectations about model output. An applied model that includes these aspects could provide more reliable projections related to a specific industry in question. A final aspect that this work does not consider is the fact that different mixes of power generation come with different risk and variability characteristics. This could be another interesting feature to incorporate in comparing a TPS to a CAP.

CHAPTER 2

GENERAL EQUILIBRIUM IMPACTS ON THE U.S. ECONOMY OF A DISRUPTION TO CHINESE COBALT SUPPLY

In this work, I explore the short-run welfare consequences of a disruption to Chinese cobalt supply under various electric vehicle deployment futures. I find that the cost of a 25% reduction in Chinese exports is small, and as of 2017, likely less than a 0.005% reduction in U.S. personal consumption expenditures. A complete halt to Chinese cobalt exports is more costly, however, the high EV deployment case based on projections for 2030 shows little to no difference in welfare changes relative to the current (2017) state of the cobalt markets. This is partly due to assumptions surrounding decreased intensity of cobalt use in future battery applications, faster electric vehicle growth in China than other regions of the world, and the global supply landscape. In addition, increased EV deployment and associated cobalt use can be substituted for conventional vehicle types. Vehicle substitution between conventional and electric types frees up cobalt for use in sectors with less ability to substitute away from cobalt, providing a channel for U.S. cost reduction in response to a disruption. Diversification of U.S. vehicle technologies, along with continued good-standing trade relationships outside of China, can help the U.S. avoid significant short-term costs of a disruption to Chinese cobalt supply.

2.1 Introduction

Global concerns surrounding climate change have led to the development of clean substitutes to conventional sources of greenhouse gas emissions. As of 2019, clean technologies such as renewable energy and electric vehicles (EVs) are seeing considerable growth, with more expected to come (IEA, 2018, 2019). A feature common to many of the technologies at the forefront of the transition from dirty to clean is the use of battery storage. Large additions to global battery storage capacity are necessary to see mass adoption of variable renewable energy sources and electric vehicles.

Among the available battery technologies, lithium-ion batteries have emerged as a main contender in the electric vehicle space and some forms of stationary storage. Cobalt provides performance benefits unique to mobile applications, and is expected to be used in varying quantities in nearly all electric vehicle applications now and through the coming decade. The cobalt supply chain lacks diversity in that the majority of cobalt is mined in the Democratic Republic of the Congo (DRC) and refined in China. Finally, few, if any substitutes exist for cobalt in electric vehicle batteries. These features of cobalt highlight risks to users in securing the needed cobalt supply in support of global greenhouse gas abatement efforts. The United States (U.S) is particularly reliant on imports of cobalt and products that contain cobalt such as batteries.

The major risks to the global and U.S. economies are twofold. First, achievement of greenhouse gas abatement and other environmental goals could be thwarted should cobalt become physically unavailable or much more expensive than at present due to resource depletion. Secondly, there is a risk that a supply-side or demand-side disruption could lead to a short-term change in global cobalt availability. This could arise unintentionally and affect all users of cobalt equally, it could arise intentionally due to a geopolitical dispute and benefit one region while damaging others, or an unintentional problem could create the need for intentional protectionist trade action.

In this work, I focus on the second major risk, and explore intentional policy measures that could be taken by China in an effort to reduce trade with the rest of the world. I ask, what are the costs to the U.S. economy of a disruption to Chinese cobalt supply? In particular, how much would the U.S. be willing to pay to avoid a Chinese export quota on refined cobalt?[6] Finally, given that rapid deployment of battery technology in electric vehicles is expected through 2030, is there cause for concern? Particular emphasis is placed on the channels that drive cost increases and decreases. Policymakers can use this information to proactively address uncertainties associated with the potential for a future supply disruption.

In this paper, I explore these questions using a global multi-regional, multi-good, static computable general equilibrium (CGE) model coupled with the Global Trade Analysis Project (GTAP9)

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[6] I use changes in a money-metric consumption index in economics known as equivalent variation to measure this welfare effect.

database (Aguiar *et al.*, 2016). Light-duty vehicles production and substitution amongst conventional, plug-in hybrid, and battery electric vehicles in production is explicitly incorporated into the model. This allows for examination of substitution towards less cobalt-intensive vehicle types as a result of an increase in the cost of cobalt contained within an electric vehicle. Furthermore, I model the use of cobalt in non-EV applications as well. These features allow for a more precise accounting of impacts on the motor vehicles sector and interactions with the economy as a whole.

I perform a counterfactual policy experiment, representing a global supply disruption via an export quota. Two different export quotas are modeled; a less stringent export quota requiring a 25% reduction in Chinese exports and a more stringent quota indicating an export ban. These two policies are chosen so a comparison can be made that illustrates the way markets respond to increasing policy stringency. In the former case, Chinese exports still exist, and flow where they are most needed, mitigating the need for extreme changes in global cobalt trade and production. This case is meant to represent a situation where China chooses to strategically curtail exports in an effort to inflict damage to the United States. In the latter case, Chinese exports are non-existent, which highlights the adjustments needed from the rest of the world on the supply-side and demand-side more clearly. This case is meant to represent a less-likely situation where China, in the name of national or global security, chooses to shut off refined cobalt exports to the rest of the world.

The export quota is imposed against each of three different global benchmarks. The first benchmark is designed to represent the state of the cobalt markets in 2017 (CUR). The second and third benchmarks embed expectations for the year 2030, obtained from the International Energy Agency's (IEA) New Policies Scenario (NPS) and more aggressive EV 30% global adoption target scenario (E30), respectively. Each of these scenarios contain different assumptions about the degree of electric vehicle penetration in different regions of the world as well as lithium-ion battery capacity and intensity of cobalt used within each battery. Furthermore, the benchmark is embedded with assumptions about the global distribution of cobalt supply and demand for cobalt in non-ev applications.

I find that cobalt supply disruptions can be costly in the event of an extreme supply disruption such as an export ban. When imposed against a 2017 global benchmark, short-run welfare changes range from a -0.0118% to -0.1171% reduction in U.S. consumption expenditures. Under a 25% reduction in Chinese exports, the implications for the USA are much smaller, ranging from -0.0018% to -0.0059% in 2017. Given U.S. personal consumption expenditures of roughly 13 trillion USD in 2017, the welfare losses to the U.S. for a 25% export quota range from 0.234 to 0.767 billion USD. Taheripour & Tyner (2018) use a CGE model to estimate the welfare impacts from a 30% Chinese tariff on soybeans imported from the U.S. Their results suggest welfare losses ranging from 2.745 to 3.869 billion USD. Our cobalt results for a comparable policy measure are much lower. Especially considering that China engages in protectionist policy not just bilaterally with the U.S., as in Taheripour & Tyner (2018), but with all trading partners in our study.

Most notably, under an export ban, the welfare losses are smaller for the future EV deployment cases under certain model assumptions. Substitution away from cobalt intensive EV production towards conventional vehicle production provides a channel by which other cobalt intensive industries can reduce costs. Substitutability between conventional and electric vehicles is low as of 2017 (Xing *et al.*, 2019). However, improvements to EV charging infrastructure that accompany higher adoption of EVs into 2030 are expected to significantly relieve range anxiety, effectively increasing substitutability between vehicle types (Wood *et al.*, 2017). The results under the export ban indicate a significant diversification benefit associated with a diverse portfolio of vehicle types.

This is not to say that there aren't other factors influencing this result. Namely, embedded into the E30 and NPS global benchmarks are decreased intensity of cobalt use in lithium-ion batteries for EVs, a fixed global cobalt production mix relative to 2017, and electric vehicle adoption in China outpacing the rest of the world. These forces decrease the share of global cobalt output attributable to exports from China, hence lowering damages felt as a result of an export ban. Nonetheless, the results clearly show that greater substitution between conventional and electric vehicles can provide a significant cost reduction.

The results highlight areas for policymakers to focus on in reducing potential costs from a supply disruption. Many of these are well-known, but include (*i*) decreasing the cobalt required in lithium-ion batteries, (*ii*) developing cobalt extraction as byproducts or primary products outside of the DRC, (*iii*) diversifying the locations of cobalt refining capacity outside of China, (*iv*) diversifying the locations of li-ion battery component manufacturing, (*v*) cultivating relationships with trading partners outside of China, and (*vi*) developing the ability to obtain secondary cobalt supply from recycled battery products.[7] Finally, if it is assumed that increased EV deployment drives increased substitutability between EVs and conventional vehicles types, and other regions outside of China increase production by any amount in response to increased demand from EVs, then a commitment to deep penetration of electric vehicles in the United States can provide a rich base of cobalt containing products that can be reallocated in times of crisis to serve more critical non-EV industries such as aerospace, defense, and mobile communications.[8] Policymakers can use the results from this work to help prioritize different strategies to reduce the risk of a supply disruption. Specifically, they should consider the design of policy instruments able to achieve climate goals without eliminating the possibility of short-term substitution between conventional and electric vehicle types.

Currently, there is no examination of the welfare impacts of a cobalt supply disruption in the literature. Criticality assessments and various studies of the world's ability for supply to meet demand over the coming years exist in the literature.[9] Most of the models used to assess future cobalt supply and demand use a mass balance method, sometimes in conjunction with a system dynamics model. These studies are bottom-up representations of an economic or physical system that also

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[7] Recycling of batteries is not explicitly modeled. However the impact of a robust secondary supply of cobalt can be speculated on. If secondary supply can be obtained on short notice, this will be cost-reducing, and one way to increase secondary supply is to increase the stock of electric vehicles.

[8] To clearly illustrate the benefits to some of these policy goals and to help policymakers prioritize different risk mitigation strategies, future iterations of this work should explore the implications of changing the 2030 benchmark global production mix so that (*i*) all new production from now to 2030 is provided by China and alternatively (*ii*) that the production mix scales so that China's export share of global output remains the same in the 2030 benchmarks as in present day.

[9] Details in this realm are provided in the following works: Chung *et al.* (2015); Dias *et al.* (2018); Leader & Gaustad (2019); Leader *et al.* (2019); Nguyen *et al.* (2020); Olivetti *et al.* (2017); Sverdrup *et al.* (2017); Tisserant & Pauliuk (2016); Valero *et al.* (2018)

tend to represent only a single sector or region. While the analysis here abstracts over some of the finer details of the cobalt supply chain and its interconnectedness to other minerals upstream, it has the unique benefit of capturing high-level interactions amongst downstream industries within a region and across regions of the world. Furthermore, the top-down CGE model allows us to quantify the costs associated with a supply disruption.

Other studies in the economics literature explore trade implications in commodities markets. Specifically, Fally & Sayre (2018) develop a general equilibrium model of production, consumption, and input-output linkages to explore gains from trade in primary commodities. They find that aggregate gains from trade are largely understated in models that do not account for key features of primary commodities such as inelastic supply, inelastic demand, and regional differences in natural resources. Their model is analyzed in terms of aggregate indexes of different types of commodities rather than a single critical commodity as we explore here. In fact, little consideration is given to production and use of cobalt in their analysis, which limits their ability to capture specific concerns around cobalt use in batteries and electric vehicles, as I do here.

The rest of the paper proceeds as follows. Section 2.2 discusses pertinent cobalt background information related to production and use. Particular attention is paid to the global distribution of production and use in batteries and electric vehicles. Section 2.3 discusses the strategy employed, including model structure and assumptions. Section 2.4 pertains to the setup and assumptions embedded in the benchmark global economy. Section 2.5 lays out the three global benchmarks and policy counterfactuals in detail. Section 2.6 contains a discussion of the model output and welfare results. Concluding remarks are provided in section 2.7.

2.2 Cobalt background

In this section I introduce the cobalt supply chain. I first discuss cobalt production and use of cobalt at a high level. I then discuss some notable aspects of cobalt use in batteries, and some important specifics related to the EV supply chain. The information contained within this section is drawn upon in later sections when making key model assumptions and establishing the benchmark global economy.

2.2.1 Production and use

Mining of cobalt is highly concentrated and the USA and China mine very little cobalt domestically. The majority of cobalt is produced as a byproduct of copper or nickel production. Over 70% of global cobalt production in 2017 was mined in the Democratic Republic of Congo (DRC) and Zambia (Roskill, 2018). Most of the cobalt ore and concentrate is exported prior to being refined into a cobalt metal or chemical product. China imports more than 95% of all imported cobalt ores and concentrates from the DRC and is also responsible for over 95% of DRC exports (Roskill, 2018). China clearly has a relationship with various west and central African sources of mineral resources. This relationship is evidenced in its Going Out Strategy, initiated around the year 2000 in which China encouraged entities to expand overseas (outward) foreign direct investment (OFDI) (Davies, 2013; OECD, 2008). Additional support for Chinese governmental interest in these areas is evidenced in The Belt and Road Initiative (BRI) (Foster *et al.*, 2009). These programs have helped China establish deep economic and cultural ties with the DRC and suggest a likelihood that China exercises a significant degree of control over natural resource extraction in the region.

The cobalt refining process is also highly concentrated. Cobalt is extracted and then refined into a metal or chemical product. Different use cases of cobalt require different refined versions of cobalt. China is a large importer of cobalt ores and concentrates from mines in the DRC. It refines the cobalt further into a useable product in chemical or metal form. In 2017, China was responsible for roughly 60% of total refined production, 80% of refined chemical production, and 30% of refined metal production (Roskill, 2018). This places China in a position of global importance in the cobalt supply chain.

Cobalt is used widely in industries at the forefront of the aerospace, technology, and energy sectors. First uses of cobalt chemicals include lithium-ion batteries, NiMH batteries, catalysts, soaps, and pigments. Cobalt metals are used first to produce super-alloys, wear-resistant alloys, magnetic alloys, hard metals, fabricated metal products, and coatings. These products are typically used as inputs in further production within the manufacturing or energy sectors. For example, lithium-ion batteries are used in electric mobility and portable electronics applications. Cobalt containing catalysts are used in oil and gas desulphurization as well as in production of recyclable plastic bottles. Pigments are used to provide color to glass and ceramic products as well as to add color to inks. Super-alloys are used to produce high strength heat-resistant turbine blades in gas turbine engines for use in the aerospace and energy sectors. Other wear-resistant alloys are used to produce medical prosthetics, vehicle engine components, and cemented carbides. Hard metals are used to produce hand tools and power tool attachments. Magnetic alloys are used in magnets and magnet containing products such as recording and storage devices or generators. Metals are also used for electroplating and wear resistant coatings in electronics and spacecraft.[10]

2.2.2 Cobalt and lithium-ion batteries

A closer look into the lithium-ion battery supply chain proves useful in illustrating the complexities of the cobalt supply chain. Lithium-ion batteries are also a major source of concern as adoption of electric vehicles accelerates over the coming decades. Additionally, electric light-duty vehicle production is explicitly incorporated into the model, therefore a close examination of the supply chain will help drive model assumptions in later sections.

Overviews and assessments of the battery materials supply chain exist in the literature.[11] One key takeaway from this literature is that not all lithium-ion batteries are the same. Lithium-ion batteries have many different characteristics and not all lithium-ion batteries contain cobalt. Some sectors of the economy, while reliant on lithium-ion battery storage, may not be as reliant on a cobalt-containing battery chemistry and thus will not be directly affected by a change in cobalt price. Also, lithium-ion battery packs, cells, other battery components, and refined raw materials, such as cobalt, are often not produced in the same region.

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[10] A rich description of different uses of cobalt can be found at CobaltInst (2019)

[11] Overviews and projections for cobalt supply and demand in the face of electric vehicle adoption and battery development can be found in the following works: Chung *et al.* (2015); Coffin & Horowitz (2018); DeCarlo & Matthews (2019); Mayyas *et al.* (2019); Olivetti *et al.* (2017); Tsiropoulos *et al.* (2018)

Table 2.1: Cobalt Content of different li-ion battery chemistries

Type	kg Co/kwh	Details
NCA	0.13	Electric vehicles
NCM111	0.4	Power tools, electric vehicles
NCM433	0.35	
NCM523	0.23	
NCM622	0.19	
NCM811	0.09	
LCO	0.6	Portable electronics
LFP	0	Electric buses, grid storage
LMO	0	Power-tools, some EVs

Table 2.1 shows the elemental cobalt contained within a given li-ion battery chemistry. Note that there are various NCM and NCA chemistries that are used in electric vehicle applications. Also note that portable electronics employ the LCO chemistry which requires a higher cobalt content. The LFP and LMO chemistries contain no cobalt. The LFP chemistry is preferred for grid storage applications as well as larger storage applications in the mobility sector such as electric buses and trains (IEA, 2018, 2019; RMI, 2019).

The typical lithium-ion battery supply chain consists of three main stages: cell manufacturing, module manufacturing, and pack assembly. The cell consists of a cathode, anode, and an electrolyte. The module consists of multiple cells in a case attached to terminals. The battery pack is the final stage of production which consists of modules, electrical connections, and cooling equipment. Packs and modules tend to be produced at the same location. In the case of electric vehicles the pack is assembled in close proximity to production of the electric vehicle itself (Coffin & Horowitz, 2018). However, it is often the case that cell production and pack assembly occur at different locations. For example, the U.S. imports a majority of cells and li-ion battery components from Japan for assembly into modules and packs domestically (Coffin & Horowitz, 2018). Also, the U.S. imports a significant portion of batteries for non-EV use from Japan, China, and South Korea (Coffin & Horowitz, 2018). The tendency for pack assembly to take place close to the EV manufacturing facility provides support for the assertion that most EV battery packs produced in the US obtain cells from Japan or South Korea.

China has made significant investments in li-ion battery production capacity resulting in an increase in production and exports from 2013-2017. According to Coffin & Horowitz (2018), reported imports of Chinese lithium-ion batteries are more likely battery components such as cells rather than packs themselves. While China still produces most cells domestically, this suggests that China also imports cells and other components from Japan, South Korea, and the rest of the world for use in production of batteries domestically.

Consider that cobalt containing li-ion battery cathodes require a chemical product. Global cobalt chemical refining capacity is split between Belgium, Finland, and China (Roskill, 2018). Japan and South Korea require cobalt in chemical form in order to produce battery cathodes and cells. This requires imports of refined cobalt metal and the ability to refine metal product into a chemical via some vertically integrated production process. Alternatively, it requires direct imports of cobalt in refined chemical form (oxide or sulphate). While the data is ambiguous, the general conclusion can be drawn that some portion of Japanese and South Korean cobalt imports are sourced from China (Coffin & Horowitz, 2018). At that juncture, some portion of Chinese cobalt is used to produce battery cells that are exported back to China where packs are produced for export and subsequent use in production of goods domestically.

2.3 Model and assumptions

In the previous section, I introduced cobalt and some facts around the cobalt supply chain. In this section, I define the model and establish some important underlying assumptions. After discussing the setup here, I explain the calibration of the model to existing data in section 2.4. I leverage information in the previous section to provide context and justification to the model structure and assumptions. A detailed algebraic representation of the full model is provided in appendix D. In this section I simplify the discussion by using nesting diagrams and pointing to key model equations for clarification, instead of a full algebraic representation.

The model chosen to answer the research question is a multi-region, multi-good, static computable general equilibrium model. This type of model allows me to capture sectoral tradeoffs and international trade patterns that arise from a policy outside of the control of the U.S. Furthermore, due to the global nature of the cobalt and battery supply chains, this type of model allows me to capture some of the regional patterns of production and use that define cobalt. The model is global in nature with regional production, consumption, and trade. As the objective is to assess the impact on the USA of a supply disruption stemming from China I choose to account for three explicit regions: the United States (USA), China (CHN), and the rest of the world (ROW). This regional aggregation provides enough detail to answer the research question. The highly aggregated ROW region also provides benefits in simplifying the some of the intricacies of the cobalt supply chain.

I choose to model 6 aggregated sectors of the economy. Details of these sectors are listed in Figure C.1. These six sectors are associated with the goods that are consumed in producing output associated with these six sectors. Of these six sectors, the most notable are the cobalt (COB) sector, the extraction and refining of chemicals, metals, and minerals (CMM) sector, the motor vehicles (MVH) sector, and the other manufacturing sectors that contain cobalt (OMC) in their finished products.

A discussion of each of these sectors is to follow. I begin with a discussion of the structure of the CGE model and how the COB sector fits into this model. Figure 2.1 shows the model structure for a single region with detail regarding a single production sector (OMC) to provide a picture of how COB moves from refined production through the model to impact final consumption. The model assumes a single representative agent (RA) who is endowed with capital (K), labor (L), and a fixed cobalt natural resource factor (RCO). The RA employs these factors to produce income with which it consumes a money-metric index of utility (C). This consumption index is defined by a constant elasticity of substitution (CES) utility function. Consumption occurs on an Armington composite of all of the 6 sectors except for COB (Armington, 1969). I assume that there is no final demand for COB, it is only used in production of other goods. The RA employs K and L as well as an Armington composite of the five intermediate goods (INT) to produce an index of INT

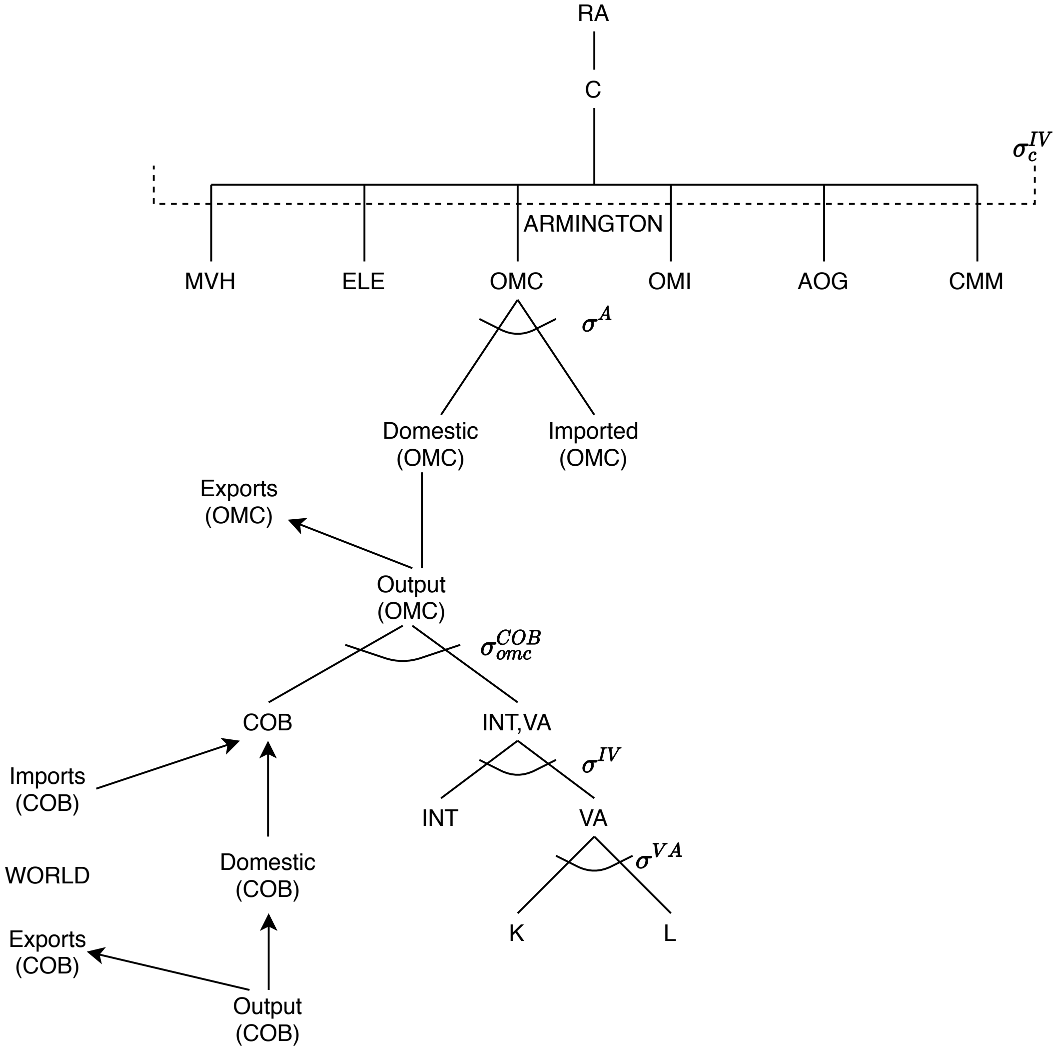

Figure 2.1: Structure of CGE Model with detailed OMC nest

and value-added (VA) that is substitutable with COB in production. For example, in Figure 2.1 the index INT,VA is substitutable with COB in production of OMC at the substitution elasticity given by σ^{LDV}. OMC is then exported or used domestically in other production sectors or in final consumption (C).

It is important to note that COB is the value of elemental cobalt contained at a given stage of production. It is assumed that cobalt clears in a global world market as there is no COB product differentiation based on region of origin. For example, COB produced in CHN is either consumed domestically in other production sectors or exported to the world market where price clears at the world price. Alternatively, the USA imports COB from the world market at the global market clearing price. COB used in a given production sector is the sum of imported cobalt and cobalt produced for domestic use.

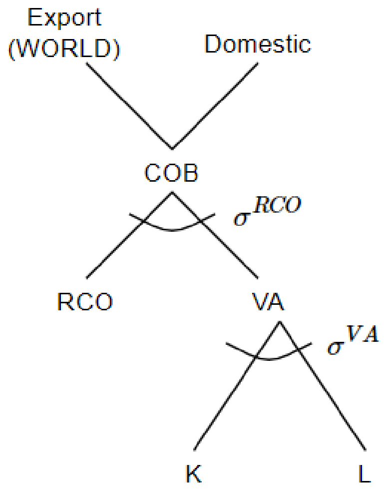

Figure 2.2: COB Production Block - Nesting Structure

The structure depicted in Figure 2.1 and outlined thus far shows how cobalt interacts with the global economy downstream and its relationship to the OMC sector. I begin with a description of the cobalt production structure, shown in the nesting diagram in Figure 2.2. I assume that cobalt production is defined by a constant elasticity of supply function. Using methods detailed in Rutherford (2002), I can calibrate the substitution elasticity between RCO and the VA,INT index (σ^{RCO}) to an exogenously specified constant elasticity of supply curve. Upward sloping supply is consistent with the increases in marginal costs associated with optimizing byproduct production in the short-term as well as in capturing some of the sector specific short-term increasing marginal costs of capital adjustment associated with refinery expansion. It is assumed that the resource stock and sector specific capital are embedded in RCO. Additionally, the decision to model cobalt as a refined product at 100% purity is an abstraction from reality. This assumption implies the ability to costlessly transform refined metal into chemical and vice versa which is beneficial in terms of model tractability and in establishing the benchmark global economy. I defer an assessment of the implications of this assumption until the results are discussed in section 2.6.

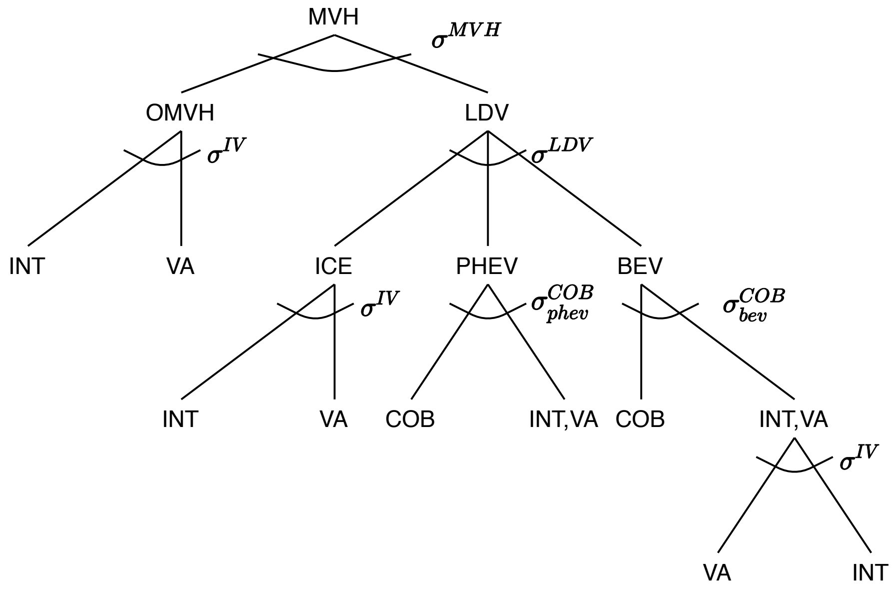

Figure 2.3: MVH Production Block - Nesting Structure

OMC is not the only sector in which COB is used. COB is also used in production of electric vehicles, which is embedded in the MVH production structure. Figure 2.3 shows the production structure of the MVH CES production nest. Note that there are five additional goods that determine the MVH index. The MVH nesting structure was developed to be tractable with the GTAP database. A more detailed discussion of the GTAP database is contained in the next section. MVH consists of light-duty vehicles (LDV) and other motor vehicles and parts (OMVH). LDV is an index of conventional vehicles (ICE), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV). Hybrid electric vehicles are contained within the ICE production block. ICE is assumed to use no COB. PHEV and BEV use COB but at different intensities. BEV requires the use of more COB than PHEV per dollar of output. The interaction of these five MVH sub-sectors determines the activity level of the MVH index as a whole. MVH is the traded good and the good used in production in other sectors.

σ_g^{COB} shows the substitution elasticity between COB and INT,VA. The intuition behind this parameter indicates that if the price of COB increases relative to the price of other inputs, BEV and PHEV producers are incentivized to shift towards battery chemistries that require less COB. While different battery chemistries are not modeled explicitly at the component level, the elasticity of substitution determines the degree to which this shift towards less cobalt intensive battery chemistries occurs, given an increase in the relative price of cobalt.

To clarify the modifications related to cobalt in particular, I describe some of the key zero profit conditions algebraically. First, cobalt is produced using some fixed natural resource factor and a value-added composite consisting of capital and labor inputs. The unit profit function for this behavior is shown below:

$$\Pi^Y_{cob,r} = p^Y_{cob,r} - \left[\theta^{RCO}_{cob,r} {p^{RCO}_{cob,r}}^{1-\sigma^{RCO}} + (1-\theta^{RCO}_{cob,r}) {p^{VA}_{cob,r}}^{1-\sigma^{RCO}}\right] \leq 0 \tag{2.1}$$

where $p^Y_{cob,r}$ is the price of cobalt in region r, $p^{RCO}_{cob,r}$ is the price of the fixed natural resource factor, and $p^{VA}_{cob,r}$ is the price of the value-added composite. The substitution elasticity (σ^{RCO}) can be calibrated to an exogenously specified elasticity of supply using information on the cost share of the fixed natural resource factor in cobalt output ($\theta^{RCO}_{cob,r}$). COB is then either consumed domestically or exported to the world market, where it is then imported by other regions for use in production.

The unit profit function for other output blocks that use cobalt in production is shown below:

$$\Pi^Y_{g,r} = p^Y_{g,r} - \left[\theta^{cob}_{g,r} {p^{Y}_{cob,r}}^{1-\sigma^{COB}_g} + (1-\theta^{cob}_{g,r}) {p^{IV}_{g,r}}^{1-\sigma^{COB}_g}\right]^{\frac{1}{1-\sigma^{COB}_g}} \leq 0 \tag{2.2}$$

where $p^Y_{g,r}$ is the price of output good g in region r. $p^{IV}_{g,r}$ is the price index associated with the INT,VA composite good in production of good g. $\theta^{COB}_{g,r}$ is the benchmark cost of cobalt used as a share of total output of good g in region r. The substitution elasticity σ^{COB}_g determines the ability of good g to substitute away from cobalt and into the composite of other inputs.

A final key equation relates to the production of the LDV composite good. Below is the unit profit function that allows for substitution between vehicle types in production of the LDV good:

$$\Pi^{Y}_{ldv,r} = p^{Y}_{ldv,r} - \left[\sum_{i} \theta^{LDV}_{i,g,r} \, p^{Y^{1-\sigma^{LDV}}}_{i,r} \right]^{\frac{1}{1-\sigma^{LDV}}} \leq 0 \tag{2.3}$$

where $i \in [BEV, PHEV, ICE]$. The other zero profit conditions as well as market clearance, income balance, and constraints are provided in appendix D.

The model structure allows for the examination of a cobalt supply disruption under various PHEV and BEV penetration scenarios. It also allows for explicit representation of potential substitution away from cobalt at the battery chemistry level and substitution away from BEV and PHEV into ICE as a result of an increase in the relative price of COB. Furthermore, interactions and substitution with other uses of cobalt can be represented via the OMC sector. In the next section I discuss the model calibration and data used to establish the benchmark global economy.

2.4 Benchmark calibration methodology

In this section I discuss the mapping of GTAP data to model sectors, the calibration of the model, and other calculations and assumptions necessary to produce the global benchmark. The global benchmark is a necessary requirement in order to produce a baseline from which counterfactual policy analysis can be performed.

Before continuing, it is important to keep some key pieces of information about the reality of the cobalt supply chain in mind. Mainly, in assessing the regional implications of cobalt production and use it is important to consider the complications that arise as a result of this complex and diverse supply chain within the context of the research question. Specifically, the locations of various aspects of the cobalt supply chain play a role in the impact a supply disruption might have. Data relating to use of a given raw material in terms of elemental content is unlikely to be readily available, which creates complications in establishing a basis of comparison of cobalt used in different technologies and at each step of the supply chain. Calculations based on assumptions about the regional and sectoral distributions of production and use as well as the physical characteristics of a given technology prove valuable in determining what industries and regions rely on cobalt and to what extent.

Figure C.1 shows a concordance between the model sectors, GTAP 9 sectors (McDougall *et al.*, 2013), and the ISIC revision 3.1 (UN, 2002) classification codes associated with the UNIDO IDSB database (UNIDO, 2019). The model draws upon data from the GTAP 9 2011 database and uses data from the UNIDO database to inform some of the calculations and assumptions in the calibration process. This concordance defines the initial model aggregation scheme.

After aggregating the GTAP sectors into the 5 model sectors it is necessary to determine the values required for the COB production sectors in each region as well as the values required for the MVH production nests (PHEV, BEV, ICE). I also need to determine how much COB is used in the PHEV, BEV, and OMC sectors within each region.

Cobalt production data is obtained from the USGS and the Roskill cobalt reports (Roskill, 2018; USGS, 2019). The production quantities used for modeling purposes are the quantities of combined refined chemical and metal production in tons of elemental cobalt. The average annual price of cobalt metal is expected to be somewhere between 15-20 USD/lb through the next decade (Roskill, 2018). I use a value of 20 USD/lb in the model calibration to calculate the output value of cobalt for each modeled region (USA, CHN, and ROW). I assume that China exercises complete control over the upstream supply of cobalt ores and concentrate which are sent to China for processing into a refined product. The motivation behind this assumption has been discussed in section 2.2, but relates to China's strategic interest and degree of influence in the DRC. In assuming "complete control", I assume that the resources in the DRC may as well exist within Chinese borders. This allows me to treat extraction and refining of cobalt as a vertically integrated process that takes place within China. This process is governed by a constant elasticity of supply function that is calibrated to short-run supply elasticity estimates from the literature (Fally & Sayre, 2018). I use the global refined production share of cobalt by each region and total global production in 2017 to inform usage estimates, which are detailed below.

Before continuing to a discussion of EV production and cobalt usage calculations it is important to note some of the driving factors behind the aggregation methodology. For the sake of transparency, it is also important to understand the assumptions embedded into the benchmark calibration. A complication arises due to the fact that cobalt can be refined into many different metal or chemical products, such as metal powder, metal cathode, sulfate chemical, oxide chemical, etc. While the metals tend to consist of high concentrations of cobalt, a sulfate might consist of only 30% elemental cobalt. Additionally, just because a metal product is refined in China, does not mean that it will not be refined further into a chemical in Japan or South Korea prior to use in a battery cell.

A major assumption is that cobalt is produced and consumed in elemental contained form as an input to sectors representing the final stage of manufacturing prior to consumption or use in services. Hence, all reference to COB indicates elemental cobalt contained in the manufactured product. For example, in reality, cobalt is used to produce lithium-ion battery cathodes, which are used to produce cells, which are subsequently assembled into a pack and installed into an electric vehicle, laptop, computer, or smartphone. Rather than modeling each different type of battery chemistry I simply assume that different applications of batteries require different concentrations of COB. Therefore, given that electric vehicles use a specific mix of battery chemistries on average, I can determine how much COB is used in the PHEV and BEV sectors. Alternatively, consider super-alloy production. Rather than model super-alloys explicitly, I simply assume that cobalt in conjunction with other goods are used to produce jet engine turbines in the aerospace industry. The assumptions detailed above provide a more precise indicator of reliance a specific region and sector has to cobalt while keeping the model tractable. With some additional assumptions detailed towards the end of this section, this can be relied upon to capture the impact of a Chinese supply disruption.

The first step in determining COB usage in the MVH and OMC sectors for each region is to begin with the LDV nest. Vehicle sales and production statistics from the IEA are used to determine the number of BEVs, PHEVs, and ICEs, which yields LDVs (IEA, 2018; Lutsey *et al.*, 2018). Given assumptions about average battery size and the average battery chemistry, I can determine the cobalt contained within the BEV and PHEV sectors for each region. Data related to the cobalt content of a battery chemistry in kg/KWh as well as average battery capacity in KWh allows me to calculate the cobalt content of the average vehicle within a region.[12] Multiplying by the number of vehicles yields the cobalt use in the PHEV and BEV sectors. To calculate the value share of cobalt used in production of electric vehicles, I need to determine PHEV and BEV output. This requires data for costs of different types of electric vehicles (Lutsey & Nicholas, 2019). I use the cost data to determine the output of the BEV and PHEV sectors. I use the cobalt price and cobalt use in the PHEV and BEV sectors to compute the value share of cobalt used in production of PHEV and BEV.

The next step is to determine the cobalt used within the OMC sector. The cobalt used in the OMC sector is the cobalt that remains after use in production of PHEV and BEV. In order to determine the global distribution of cobalt within the OMC sector I use the UNIDO IDSB revision 4 database (UN, 2007; UNIDO, 2019) in combination with cobalt first-use data at the global level (DeCarlo & Matthews, 2019; Dias *et al.*, 2018; Roskill, 2018). The UNIDO data provides output data for 4-digit ISIC codes at the country level. The cobalt first-use data provides shares of global use (assumed to equal global production). Figure C.2 provides a mapping between the first-use category and the final use in manufacturing category. Additionally, Table 2.2 shows the global shares of first-uses of cobalt and the regional share of global final use output in manufacturing associated with the first-use categories.

Assume that the leftmost column of Table 2.2 indicates a set of first-use categories (u). The next column to the right indicates the share of global cobalt use attributable to each element of set u, defined as θ_u^{FIR}. The three right-most columns in Table 2.2 indicate the regional (r) output share of global output associated with each final-use in manufacturing group of ISIC categories established in Figure C.2, defined as $\theta_{u,r}^{FIN}$. The product of first-use share (θ_u^{FIR}) with regional-output share of global ($\theta_{u,r}^{FIN}$) and global production net of EV use, determines how much cobalt

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[12] Many different works provide data related to cobalt contained within a battery chemistry: (Chung *et al.*, 2015; Dias *et al.*, 2018; Lutsey & Nicholas, 2019; Lutsey *et al.*, 2018; Mayyas *et al.*, 2019)

Table 2.2: Cobalt use and regional distribution of use

First-use		Final-use in Mfg.		
Category	World	USA	CHN	ROW
batt	0.48	0.08	0.68	0.24
supa	0.19	0.42	0.17	0.41
hard	0.09	0.07	0.50	0.43
mago	0.09	0.10	0.58	0.32
cata	0.06	0.11	0.12	0.77
pigm	0.06	0.11	0.65	0.24
soap	0.03	0.32	0.21	0.47

is used in final-use in manufacturing within each region. Summing across first-use groupings (u) yields cobalt use in the OMC sector by region.

To clarify algebraically, assume that the quantity of cobalt used in a given sector (i, j) and region (r, s), is given by $\overline{qco}_{i,r}$ in tons of cobalt. We have already calculated $\overline{qco}_{i,r}$ for the BEV and PHEV sectors. Assume that cobalt production (tons Co) for a given region is given by $\overline{prod}_r$. Furthermore, data regarding global distribution of portable electronics battery capacity (KWh) use in production obtained from Roskill (2018) is given by $portcap_r$. Cobalt use in OMC is calculated as follows:

$$
\begin{aligned}
\overline{qco}_{omc,r} = & \sum_{u \neq \text{``}batt\text{''}} [\theta_u^{FIR} \theta_{u,r}^{FIN} \sum_s \overline{prod}_s] \\
& + \sum_{u = \text{``}batt\text{''}} \left[\theta_u^{FIR} \sum_s \overline{prod}_s - \sum_s \left(\overline{qco}_{bev,s} + \overline{qco}_{phev,s} + portcap_s * 0.6 * \frac{2.204}{2000}\right)\right] \theta_{u,r}^{FIN} \\
& + portcap_r * 0.6 * \frac{2.204}{2000}
\end{aligned}
$$

where 0.6 is the kg of cobalt contained per kwh of battery capacity for the LCO battery chemistry common to portable electronics applications.

At this point, I can determine the global distribution of cobalt use by region and sector. Using information for $\overline{qco}_{i,r}$ and the price of cobalt I calculate the value of cobalt used in OMC, BEV, and PHEV as a share of total value of cobalt used by each country. However, I still need output in the base year for each vehicles index within the MVH production block. I use the UNIDO database

(UNIDO, 2019) to determine the constant average growth rate of automobiles output (roughly 8%) by region and discount the 2017 output calculated earlier for PHEV, BEV, and ICE back to 2011. I use these values to disaggregate the MVH sectoral output into OMVH and LDV, and then LDV into PHEV, BEV, and ICE. I then determine cobalt value in use of electric vehicles using the 2017 cobalt intermediate input shares of BEV and PHEV output.

To clarify, let $\theta_{i,r}^{QCO}$ be the quantity share of regional cobalt use by sector, given by:

$$\theta_{i,r}^{QCO} = \frac{\overline{qco}_{i,r}}{\sum_j \overline{qco}_{j,r}} \tag{2.4}$$

Also, let $\theta_{i,r}^{VCO}$ be the value share of cobalt use in production of good i in region r. Firstly, I already calculated this for BEV and PHEV in the 2017 year as follows:

$$\theta_{bev,r}^{VCO} = \frac{\overline{qco}_{bev,r} * cobalt\ price}{2017 BEV output} \tag{2.5}$$

The calculation for PHEV is analogous to that of BEV. After discounting 2017 BEV output back to the base year for the GTAP database (2011), I calculate the cobalt value in use ($\overline{vco}_{i,r}$) and value shares for all sectors that use cobalt. Assume that benchmark output is defined by $\bar{y}_{i,r}$. This requires two steps. First, take the COB intermediate input share of BEV output ($\theta_{bev,r}^{VCO}$) multiplied by output in the BEV sector ($\bar{y}_{bev,r}$) to obtain the benchmark value for cobalt in use of BEV production in the base year ($\overline{vco}_{bev,r}$). Secondly, in order to calculate the cobalt value in use for the OMC aggregate, use the following method:

$$\overline{vco}_{omc,r} = \frac{\theta_{omc,r}^{QCO} \overline{vco}_{bev,r}}{\theta_{bev,r}^{QCO}} \tag{2.6}$$

This ensures that the distribution of 2011 cobalt use across i and r is proportional to that of 2017. The intermediate input shares of cobalt use in sector i are now easily obtainable by dividing $\overline{vco}_{i,r}$ by $\bar{y}_{i,r}$. Finally, it is necessary to calculate cobalt output by region ($\bar{y}_{cob,r}$). This is obtained by summing $\overline{vco}_{i,r}$ across all regions and sectors, then multiplying this by each region's share of global cobalt production. Regional cobalt production shares are shown in the first row of Table 2.3.

I just discussed how to obtain COB production by region and COB use by region and sector scaled to the 2011 benchmark GTAP database. This data allows me to determine the value of net

Table 2.3: Refined cobalt production share of global in 2017

	USA	CHN	ROW
COB	0.003	0.619	0.379
metal	0.000	0.274	0.726
chemical	0.004	0.860	0.136

imports for each of the 3 regions as the difference between $\sum_i \overline{vco}_{i,r}$ and $\bar{y}_{cob,r}$. A discussion of benchmark output, use, and net import data is saved for section 2.5. However, the general outcome is as follows. ROW and USA use more cobalt than they produce. CHN produces more COB than it uses. In order for the world market for COB to clear, CHN must be exporting to the world, and USA and ROW must be importing from the world such that global use equals global production. Cobalt trade occurs free of transportation cost or benchmark tariffs.

The final steps are to apply the default GTAP MVH cost structure to the OMVH, ICE, BEV, and PHEV sectors proportionally. Additionally, I need to balance the benchmark economy by disaggregating cobalt production, use, and trade from the CMM sector and RCO from K in the CMM sector.

At this point it is necessary to highlight some final key assumptions implied by this benchmark setup. Most importantly, given the setup, it is not clear whether a modeled export quota truly represents the reality of an export quota. In order for the quota to be reflective of the current state of the global economy, I need to assume that all battery packs exported from CHN that end up in the USA contain cells that are produced in ROW, otherwise the Chinese cobalt quota would create a strategic trade advantage in Chinese battery production. Given information discussed in section 2.2, this assumption is not completely unreasonable. Additionally, any first-use of cobalt metal product (e.g. superalloys, magnets, cemented carbides, etc) consumed by ROW or USA that requires Chinese cobalt is produced outside of China. If these assumptions are dropped, the export quota might be more reflective of a production quota. An example would be a supply disruption in the DRC which causes CHN to stop producing products for export that use cobalt as well as the export of cobalt itself. Either interpretation could be considered useful.

2.5 Three global benchmarks and counterfactual scenario definition

In order to assess the impacts of a supply disruption and address concerns about costliness of a supply disruption in a future with significant electric vehicle adoption I define 3 different global benchmarks for comparison. The first global benchmark corresponds to the current (2017) state of global cobalt use (CUR). Two other global benchmarks are established based on the IEA's NPS baseline EV penetration scenario (NPS) and EV 30@30 scenario (E30) (IEA, 2018). These two projections from the IEA are chosen because they are well documented and output from these projections is used in other cobalt modeling studies (Nguyen *et al.*, 2020). Embedded within each of these global benchmarks are assumptions about the share of LDVs attributable to BEV and PHEV, battery sizes, battery chemistries, and vehicle costs. See Table 2.4 and Table 2.5 for a comprehensive list of scenario specific parameter specifications and sources for data.

Table 2.4: CUR - Scenario Setup

parameter	units	USA	CHN	ROW	Source
EV shr	EV/LDV	0.019	0.024	0.01	IEA (2018); Lutsey *et al.* (2018)
EV mix	BEV/EV	0.51	0.81	0.51	IEA (2018); Lutsey *et al.* (2018)
BEV cap	kwh/BEV	65	27	39	Chung *et al.* (2015); IEA (2018, 2019); Lutsey *et al.* (2018)
PHEV cap	kwh/PHEV	12	15	12	Chung *et al.* (2015); IEA (2018, 2019); Lutsey *et al.* (2018)
Implied Batt Chem	kg Co/kwh	0.23	0.23	0.23	Dias *et al.* (2018); IEA (2018)
COB Supply Elasticity	value	0.2	0.2	0.2	Fally & Sayre (2018)

Table 2.5: NPS and E30 - Scenario Setup

parameter	units	NPS	E30	Source
World EV shr	EV/LDV	0.15	0.33	IEA (2018)
USA EV shr	EV/LDV	0.08	0.30	IEA (2018)
CHN EV shr	EV/LDV	0.26	0.42	IEA (2018)
EV mix	BEV/EV	0.5	0.7	IEA (2019)
BEV cap	kwh/BEV	75	75	IEA (2018, 2019)
PHEV cap	kwh/PHEV	15	15	IEA (2018, 2019)
Batt Chem	kg Co/kwh	0.135	0.135	IEA (2018, 2019)
COB Supply Elasticity	value	0.2	0.2	Fally & Sayre (2018)

Table 2.4 shows the various parameters for the CUR scenario. The first row (EV shr) of Table 2.4 shows the share of EVs in total LDV produced for each model region. EV mix shows the share of BEVs in total EV. BEV cap and PHEV cap show the battery capacity of each battery electric and plug-in hybrid vehicle, respectively. The Implied Batt Chem indicates how many kg of cobalt is contained in each KWh of battery capacity. This is calculated using data related to total EV battery capacity and total use of cobalt in EVs globally.

Table 2.5 shows the same data as Table 2.4 but in a slightly different format. Each column is associated with the benchmark calibration point. The first row represents the global EV share in global LDV. Using the second and third rows, the EV share for ROW can be computed. Note the assumptions surrounding elasticity of cobalt supply shown in the last row of Table 2.4 and Table 2.5. These elasticity estimates represent short-run estimates for supply elasticity obtained from the literature. The values in these tables combined with detail from section 2.4, fully inform the benchmark calibration point for each of the three global benchmarks.

An additional defining aspect of these global benchmarks is that each region's share of global production is the same across all three global benchmarks. This assumption warrants discussion. By construction, the benchmark calibration points established in Table 2.4 and Table 2.5 change the global distribution of cobalt use. Notice that more electric vehicles are assumed to exist in China in the NPS and E30 scenarios relative to other regions. Also, notice that when compared to the CUR scenario, China sees much larger growth in EV adoption. Furthermore, notice that the battery capacity in China grows much more from CUR to the NPS and E30 cases than in other regions. Finally, note that the battery chemistry decreases cobalt used per kwh across all regions as we move into the future. Combining this with the assumption that the global cobalt production mix is fixed, implies that Chinese exports occupy a smaller share of global trade in the NPS and E30 benchmarks than in the CUR benchmark, as cobalt trade is determined by production net of use in a given region. This will naturally decrease the cost of an identical export quota imposed against the NPS and E30 benchmarks relative to the CUR benchmark.

Table 2.6: Benchmark Output, Use, and Net Imports of refined/contained cobalt USD billions

	CHN	ROW	USA	World
		CUR		
Output	1.820	1.114	0.008	2.942
Use	1.204	1.225	0.512	2.942
Net Imports	-0.616	0.111	0.505	0.000
CHN Export Share of Global Output				0.209
		NPS		
Output	2.864	1.753	0.012	4.629
Use	2.206	1.813	0.610	4.629
Net Imports	-0.658	0.060	0.598	-0.000
CHN Export Share of Global Output				0.142
		E30		
Output	4.963	3.038	0.021	8.021
Use	3.354	3.500	1.167	8.021
Net Imports	-1.609	0.462	1.146	0.000
CHN Export Share of Global Output				0.201

Table 2.6 shows data for output, use, and net imports for each region and global benchmark. Recall from section 2.4 that this data relates to the value of contained cobalt produced and used. The difference between production and use for each region determines trade. First notice that the cobalt output is higher in NPS than CUR, and even higher in E30. This is due entirely to assumptions related to EV adoption. The final row of each benchmark subsection of Table 2.6 shows the share of global cobalt output attributable to Chinese cobalt exports. Notice that Chinese exports occupy a much smaller share of global output in the NPS relative to the CUR or E30 benchmarks. This is representative of the fact that China increases domestic demand more quickly than other regions relative to CUR but produces at the same share of global output. The difference results in a raw value of exports that is close to the CUR benchmark, even though output is 50-100% higher in NPS. When the export quota is levied on the NPS benchmark, it is possible that costs to other regions as a result of the policy are lower. The E30 benchmark shows a benchmark share that is roughly in line with CUR. However, due to the larger global output, this implies that

Chinese cobalt exports are much larger in absolute terms.

I assume the supply disruption enters as a Chinese export quota on refined cobalt. I explore two policy scenarios, a 25% reduction in exports and an export ban (100% reduction). These two policies are chosen so a comparison can be made that illustrates the way markets respond to increasing policy stringency. In the former case, Chinese exports still exist, and flow where they are most needed, mitigating the need for extreme changes in global cobalt trade and production. This case is meant to represent a situation where China chooses to strategically curtail exports in an effort to inflict damage to the United States, or to exploit its global dominance by collecting quota rents. In the latter case, Chinese exports are non-existent, which highlights the adjustments needed from the rest of the world on the supply-side and demand-side more clearly. This case is meant to represent a less-likely situation where China, in the name of national or global security, chooses to shut off refined cobalt exports to the rest of the world.

There remain a couple of parameters in which quality estimates do not exist. Where estimates are non-existent, I inform the baseline values based on anecdotal information and run different sensitivity scenarios to clearly illustrate the impact a specific parameter has on the output. I do this with respect to two important parameters. First, the elasticity of substitution between COB and all other inputs to production of OMC (σ_{omc}^{COB}). Estimates from the literature place the short-run demand elasticity for cobalt somewhere between -0.24 and -0.09 for the World, and closer to -0.029 for the USA (Fally & Sayre, 2018). However, due to the fact that the OMC sector is highly aggregated, the value of cobalt used in OMC relative to output is small. Substitution elasticities at near zero levels in highly aggregated indices, such as OMC, can result in overestimations of the cost associated with a particular policy. Therefore, I model two different substitution elasticities of 0 and 0.2, to show how important this channel is in changing the results. I assume that the true substitution elasticity falls somewhere in between, and that it depends on how short-term the analysis is. For our purposes, I assume short-term amounts to less than one or two years.

The second parameter relates to the substitutability between light duty vehicle types (σ^{LDV}). This elasticity parameter defines how easy it is to substitute from a conventional vehicle to a battery electric vehicle, and vice versa. I model three different values for this parameter of 0.1, 0.5, and 2. The degree of substitutability in the LDV nest can influence the results in meaningful ways. Recent literature suggests that while BEV and ICE may not be highly substitutable today, in the future, it is likely that they will be more substitutable. I note this piece of information here, and defer a detailed discussion until the next section.

2.6 Results

In this section I discuss model output from the scenarios defined in the previous section. I first discuss the impact the quota has on sectoral output, intermediate demand for cobalt, factor demand, and trade. I then proceed with a discussion of how U.S. welfare changes as a result of the Chinese export quota.

Recall from section 2.5 that I choose to model two different values for σ_{omc}^{COB} and three different values for σ^{LDV}. σ_{omc}^{COB} can take on a value of 0 or 0.2 and σ^{LDV} can take on a value of 0.1, 0.5, or 2. Furthermore, I allow the export quota to take on two different stringencies. One corresponding to a 25% reduction in Chinese cobalt exports and another corresponding to a 100% reduction. Due to the difficulty of clearly illustrating the output response using all of these scenarios for each sector, region, and global benchmark, I choose a specific combination of these parameters that clearly illustrates the intuition behind the output responses. For clarity of the output response, I choose to examine the E30 global benchmark and the U.S. response to a 100% reduction in Chinese cobalt exports and selectively show data related to different substitution elasticities.

Upon imposition of the Chinese export quota, the global quantity of COB is reduced. This increases the global price of COB. Table 2.7 shows changes in activity levels and prices from benchmark values (1.0) associated with modeled sectors/commodities in the USA for the E30 global benchmark. Table 2.7 shows COB output in the USA increases across all elasticity combinations. This is due to the fact that the USA and ROW import COB from CHN. Domestic production in these regions needs to increase in order to respond to the quota. Increases in production of COB are associated with increases in price, shown in the bottom half of Table 2.7.

Table 2.7: Activity and Price Levels for the USA - E30 Benchmark - Export Ban

σ^{COB}_{omc}	σ^{LDV}	cob	omc	mvh	omvh	ldv	ice	phev	bev	cmm	omi	aog
ACTIVITY LEVELS % Δ FROM BENCHMARK												
0	0.10	48.92	-0.09	-1.39	-1.07	-1.91	-1.50	-1.87	-3.21	0.21	0.12	-0.01
	2.00	37.73	-0.05	-0.65	-0.51	-0.89	2.98	-0.64	-13.35	0.10	0.06	-0.00
0.2	0.10	34.71	-0.02	-0.56	-0.44	-0.76	-0.60	-0.75	-1.30	0.07	0.04	-0.00
	2.00	29.52	-0.02	-0.39	-0.31	-0.53	1.72	-0.33	-7.93	0.05	0.03	-0.00
PRICE LEVELS % Δ FROM NUMERAIRE PRICE												
0	0.10	1405.38	0.27	2.03	0.43	4.80	0.43	4.29	19.70	-0.04	-0.03	-0.07
	2.00	658.67	0.13	0.90	0.19	2.13	0.19	2.00	9.22	-0.02	-0.01	-0.03
0.2	0.10	536.11	0.08	0.77	0.16	1.83	0.16	1.63	7.51	-0.02	-0.01	-0.03
	2.00	373.11	0.06	0.52	0.11	1.23	0.11	1.13	5.22	-0.01	-0.01	-0.02

Values represent % changes in index relative to the E30 global benchmark (1.0) for the USA subject to a Chinese export ban

Taking a closer look at the vehicles sector (MVH) in Table 2.7, higher cobalt prices increase the costs of producing PHEV and BEV. This drives substitution away from EVs towards conventional vehicles (ICE). In the case of high substitution elasticities ($\sigma^{LDV} = 2.0$), ICE output actually increases in response to substitution away from BEVs and PHEVs. LDV output decreases in all cases as substitution towards less cobalt intensive transportation modes (OMVH) occurs. The end result is a decrease in MVH sectoral output across all cases.

Table 2.8: Intermediate cobalt demand by select sector in USA

σ^{COB}_{omc}	σ^{LDV}	bev	omc	phev
0	0.10	0.9679	0.9991	0.9813
	2.00	0.8665	0.9995	0.9936
0.2	0.10	0.9870	0.6907	0.9925
	2.00	0.9207	0.7328	0.9967

Values represent intermediate input quantities relative to the E30 global benchmark (1.0) for the USA subject to a Chinese export ban

The results in Table 2.7 show that all sectors in which cobalt is used also show lower output. This is reflective of demand and supply adjusting in order to find a new equilibrium. Higher COB prices increase costs to produce goods that use COB. Production that requires the use of COB chooses to substitute away from COB as consumers of the final product abate consumption due to higher prices of final goods. Table 2.8 shows intermediate demand for cobalt as an input relative to the benchmark quantity. When $\sigma_{omc}^{COB} = 0$ the battery electric vehicles sector uses less cobalt than when $\sigma_{omc}^{COB} = 0.2$. Due to the fact that the substitution elasticity between cobalt and other goods in production of BEV and PHEV is zero, we can attribute this decrease entirely to output reduction in the BEV sector. Also, notice that when σ^{LDV} becomes larger, the BEV sector requires less cobalt when σ_{omc}^{COB} is lower. The assumption that cobalt is used in fixed-proportion to other inputs in production of battery electric vehicles implies that BEV output is being reduced, partly through substitution towards other vehicle types that are less cobalt intensive, shown in Table 2.7. When σ_{omc}^{COB} is low and σ^{LDV} is high, cobalt can be redistributed from BEV towards OMC. If BEV could substitute away from cobalt use in production, this effect would be even more prominent.

Table 2.9: % change in imports by region for selected sectors

				cob			omc			mvh	
Quota	σ_{omc}^{COB}	σ^{LDV}	CHN	ROW	USA	CHN	ROW	USA	CHN	ROW	USA
25%	0	0.10	-	-85.67	-0.38	0.01	-0.01	-0.02	-0.48	-0.07	-0.06
		2.00	-	-83.69	-1.18	0.00	-0.00	-0.01	-0.44	-0.06	-0.05
100%	0	0.10	-	-99.24	-2.82	-0.19	-0.06	-0.20	-3.97	-1.03	-0.99
		2.00	-	-100.00	-8.28	-0.10	-0.03	-0.08	-2.15	-0.44	-0.40

Values represent % changes in import index relative to the E30 global benchmark (1.0) for the each region and select sectors subject to different quota stringencies

Decreased imports of COB also accompany the export quota, as more COB is produced domestically. Table 2.9 shows that the USA relies on COB imports from ROW under an export ban. Particularly, note that ROW becomes a net exporter under a Chinese export ban, as they now have the advantage in production due to the higher benchmark quantity relative to the USA. This highlights the cost-reducing role that trade relationships with ROW play in reducing policy costs in the

USA.

The total impact of the supply disruption is a reduction in aggregate consumption. Lower output aligns with lower factor prices. Labor and capital move from cobalt intensive industries to non-cobalt intensive industries. Lower factor prices allow for higher factor employment in non-cobalt intensive sectors such as OMI and AOG, leading to increases in output.

Table 2.10: Welfare Results - % Δ from benchmark consumption

Quota Stringency		25%			100%		
σ^{COB}_{omc}	σ^{LDV}	E30	NPS	CUR	E30	NPS	CUR
0	0.10	-0.013	-0.004	-0.006**	-0.188	-0.043	-0.117**
	2.00	-0.010**	-0.004**	-0.006	-0.085**	-0.031**	-0.098
0.2	0.10	-0.007	-0.002	-0.002*	-0.066	-0.011	-0.012*
	2.00	-0.007*	-0.002*	-0.002	-0.045*	-0.010*	-0.012

* Best case scenarios with higher $\sigma^{COB}_{omc} = 0.2$

** Worst case scenarios with lower $\sigma^{COB}_{omc} = 0$

Values are the % difference between the benchmark consumption index (1.0) and the counterfactual consumption index. A measure of hicksian equivalent variation.

Table 2.10 shows the percentage reduction in USA welfare associated with different scenarios and substitution elasticities. To simplify interpretation of the data in Table 2.10, consider that if consumption expenditures in the USA are 13 trillion USD, a -0.1% change in benchmark consumption amounts to a welfare loss of 13 billion USD. The results show a reduction in welfare across all global benchmarks, elasticities, and quota stringencies. Table 2.10 shows two cases of quota stringency associated with each EV deployment scenario in the top two column headings. The two left-most columns show different values for substitution elasticity between COB and INT,VA in production of OMC ($\sigma^{COB}_{omc} \in [0,\ 0.2]$) and different values for the elasticity of substitution between vehicle types ($\sigma^{LDV} \in [0.1,\ 2]$). The best case scenarios are indicated by an asterisk and worst case scenarios indicated by a double asterisk in Table 2.10. What differentiates the best and worst case scenarios is the value of σ^{COB}_{omc}. Realistic scenarios for σ^{LDV} are based on the intuition that vehicle types will be more substitutable in the future, also indicated by either a single or double asterisk. The welfare results vary, but they establish reasonable bounds on potential outcomes of a supply disruption and highlight some interesting features of substitution patterns.

The results in Table 2.10 suggest that policy costs increase in most cases as a result of greater EV penetration, a more stringent export quota, and lower substitution elasticities (σ_{omc}^{COB} and σ^{LDV}). These results are expected. However, an interesting result appears in the top right quadrant of Table 2.10. When σ_{omc}^{COB} is low, σ^{LDV} is high, and the supply disruption is significant (export ban) welfare losses are actually less negative in the E30 and NPS benchmarks, relative to CUR. The difference in policy costs between the E30 and CUR benchmarks narrows, with E30 eventually becoming less costly as the substitutability between vehicle types increases.

There are a few factors influencing the welfare result in the top right quadrant of Table 2.10. A comparison between the assumptions embedded into the NPS and E30 global benchmarks compared to the CUR benchmark highlights how the benchmark calibration influences this result. First, embedded into the NPS and E30 global benchmarks are decreased intensity of cobalt use in lithium-ion batteries for electric vehicles relative to the CUR benchmark. Second, growth in electric vehicle adoption and battery capacity per vehicle in CHN outpaces the USA and ROW. Third, and very importantly, the global cobalt production share attributable to each region is assumed to be the same in NPS and E30 as in CUR. These benchmark calibration assumptions decrease the share of global cobalt output attributable to exports from China in the E30 and NPS benchmarks relative to the CUR benchmark, which decreases the share of exports being removed from the global market as a result of the quota, effectively reducing costs of the E30 and NPS counterfactuals relative to the CUR counterfactual.

Nevertheless, the results in the top right quadrant of Table 2.7 clearly show that substitution between conventional and electric vehicles can be a significant channel for cost reduction. The E30 benchmark counterfactual makes this abundantly clear. This substitution pattern is influenced by the third assumption about global cobalt production shares. As long as the USA and ROW increase global production outside of CHN — in absolute terms — in the years between the CUR and 2030 benchmarks in response to increased cobalt demand from electric vehicles, and BEVs become more substitutable with other vehicle types, this channel of cost reduction will remain relevant.

This result suggests that increased use of cobalt within the U.S. vehicles sector and in the economy as a whole may not coincide with increased cost of a supply disruption, especially when cobalt is subject to highly inelastic demand in other sectors and when the supply disruption is extreme. A study by Xing *et al.* (2019) suggests that current substitution between vehicle types is low and that battery electric vehicle consumers are in a transportation class of their own. Plug-in hybrid consumers are more likely to substitute towards conventional vehicles than battery electric in the event of a price increase. Battery electric vehicle owners are unlikely to switch to plug-in hybrid or conventional vehicles. The rationale for this behavior is that the current lack of transportation infrastructure and relatively slow refueling times associated with BEVs cause range anxiety. However, in the future, charging infrastructure is expected to improve, effectively relieving range anxiety (Wood *et al.*, 2017). This suggests that the substitution elasticity (σ^{LDV}) associated with the NPS and E30 scenarios is likely higher than the CUR scenario. A high value of σ^{LDV} allows the vehicles sector to abate consumption of COB so that it can be reallocated towards sectors where COB is more costly to substitute away from. As long as the absolute value of production outside of China increases as electric vehicle adoption occurs, increased cobalt use via EV growth will provide a diversification benefit to the USA, should a supply disruption occur in China. A relatively low value of σ^{COB}_{omc} representing inelastic demand for cobalt in aerospace, electronics, etc highlights this effect. While the elasticity of substitution is probably not zero, it is very close to zero in the short run for the aerospace and electronics industries. The OMC sector is very large and contains other industries that might not be subject to the risks of cobalt, therefore, $\sigma^{COB}_{omc} = 0$ probably over-estimates the costs associated with a supply disruption. However, it still proves useful in highlighting this result and serves as a worst-case scenario parameterization.

Given the above information, Table 2.10 shows a worst-case scenario short-run USA welfare loss associated with a Chinese export ban of -0.0851%, -0.0310%, and -0.1171% for the E30, NPS, and CUR scenarios, respectively. The CUR scenario assumes low substitutability ($\sigma^{LDV} = 0.1$) between vehicle types whereas the E30 and NPS scenarios assume high substitutability ($\sigma^{LDV} =$

2). Under a best case scenario for an export ban, the welfare costs are -0.0454%, -0.0104%, -0.0118% for E30, NPS, and CUR respectively. The results for a 25% reduction in exports are a bit less concerning, amounting from a -0.0059% to -0.0018% reduction in welfare from the CUR benchmark depending on the value of σ_{omc}^{COB}.

There exist model assumptions that can change the magnitude of the results, though I expect the main conclusions to remain in tact. A feature that could increase the costs of a supply disruption is related to the differentiation of cobalt in chemical and metal forms. As modeled, it is assumed that chemicals and metals are produced jointly with an infinite transformation elasticity. Furthermore, cobalt contained in various first-uses also has an infinite transformation elasticity. This implies that chemicals and metals can be costlessly transformed from one product to another, which mitigates the need for any product differentiation. In reality, there are costs associated with this transformation process. This is a limitation that could increase the costs associated with a supply disruption if included. It could also decrease the ability of the USA to substitute away from cobalt via substitution between BEV and ICE in the extreme policy scenario. However, global production needs to be increased by a large amount in response to the export quota, therefore lower amounts of transformation are actually occurring. The type of cobalt needed is known and production is scaled up accordingly, mitigating most of the need to transform existing production.

Additionally, in 2030 there may be climate policies in place that prevent or disproportionately disincentivize substitution away from BEVs into LDVs. This would imply a lower elasticity of substitution due to policy restrictions, which would increase total costs of the supply disruption.

Future iterations of this work should explore the implications of changing the 2030 global production mix so that (*i*) all new production from now to 2030 is provided by China and (*ii*) that the production mix scales so that China's export share of global output remains the same in the 2030 benchmarks as in present day. These two alternative cases will give policymakers much more information to work with when prioritizing different policy goals.

2.7 Conclusion

In this paper I develop an applied general equilibrium model to determine the cost to U.S. consumers of a Chinese disruption to cobalt supply in present day (2017) and in different electric vehicle deployment futures (2030). I find that outside of the extreme case of an export ban, even under the most pessimistic assumptions, the costs to U.S. consumers are small. In the extreme case of an export ban, the costs are significantly larger. However, in future EV penetration scenarios in which cobalt share of global output is 2-4 times what it is today due to increased EV penetration, there appears to be little difference between the welfare costs associated with a supply disruption today or in 2030. Under certain assumptions, the supply disruption is less costly. This is not only because demand for cobalt progresses more rapidly in China than in the United States and the rest of the world, but also because electric vehicle adoption implies a more diversified vehicles sector. A more diversified vehicles sector provides an additional channel by which cobalt can be abated in the event of a supply disruption. Effectively, a cobalt price increase will lead to substitution away from electric vehicles towards conventional vehicles. The cobalt previously used in electric vehicles can be employed in other sectors with less ability to substitute away from cobalt such as aerospace, defense, and mobile communications. The adoption of EVs adds a new, flexible channel through which to respond to supply disruptions in the short-term.

CHAPTER 3

INDUCED INNOVATION AND DIFFUSION OF END-OF-PIPE CARBON-SAVING TECHNOLOGY

This chapter was written in collaboration with Dr. Jared C. Carbone[†] and Dr. Andreas Löschel[‡]

In this paper, we explore the ability of regional climate policy to induce innovation in energy-saving and end-of-pipe carbon-saving technologies at home and abroad. We employ a global computable general equilibrium model of North-South trade, coupled with different assumptions about technology creation and diffusion, to show how these assumptions influence investment in research and development (R&D), emissions leakage, output, as well as abatement cost and welfare. We discuss how these factors interact with a Northern emissions cap as well as a carbon tariff levied on Northern imports from Southern regions. We find that innovation tends toward R&D in carbon-saving technology, and that this channel of innovation provides unique benefits in terms of leakage reduction and abatement cost savings. This is due to the fact that the carbon-saving technology allows the North to meet CO2 restrictions without abating as much fossil fuel use, leaving demand for fossil fuels closer to pre-policy levels in the North, and global prices similarly high. As a result, the South does not increase emissions by as much. Spillovers do not impact leakage rates significantly under an emissions cap. However, when carbon tariffs are implemented, spillovers lead to a larger reduction in leakage, as the South now has a motive to adopt carbon-saving technology developed in the North.

3.1 Introduction

As of 2020, unilateral global action to reduce greenhouse gas emissions is hindered due to a lack of coordination amongst developed and developing regions of the world. In particular, if the

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developed world were to implement a carbon tax or emissions cap, the developing world would be incentivized to take advantage of lower fuel prices. Also, firms in emissions-intensive industries with exposure to international trade could relocate from developed to developing regions. The outcome is an increase in developing-world emissions that partially offset the reduction by the developed world. This phenomenon — known as carbon leakage — combined with the low prospect of a unilateral policy solution, has led to the consideration of piecemeal efforts to address the global climate challenge, such as regional emissions caps or carbon taxes combined with methods of border carbon adjustment (Climate Leadership Council, 2020). Additionally, arguments have been made that technologies capable of extracting CO2 from the atmosphere or at the source will play an important role in achieving the global temperature goals established by the Paris agreements (Anderson & Newell, 2004; Barrett, 2009; Global CCS Institute, 2020). In fact, efforts to incentivize the development and implementation of these carbon capture and storage technologies have recently been undertaken (Carbon Capture Coalition, 2019). Furthermore, attention has been given to the fact that climate policy should drive development of new technology, and that this technology could be passively transferred to the developing world to help reduce emissions there as well (Keller, 2004).

In this work, we explore features of technological change and diffusion in the face of piecemeal policy efforts by developed regions of the world to promote developing world emissions reductions. We construct a calibrated numerical model of North-South trade. In the model, the North seeks to control global CO2 emissions. It has the possibility of affecting the cost of carbon abatement by investing in research and development (R&D), whereas the South does not. The knowledge created by the R&D process is only partially appropriable so that a positive externality exists. In this way, not only do Northern countries benefit from the R&D efforts of other Northern countries, but countries in the South benefit from the R&D efforts of countries in the North.

In addition to being linked by technological spillovers, the countries trade in carbon intensive goods, non-carbon intensive goods, and fossil-based energy. This gives countries in the South a motive to adopt new innovations, as the South is assumed to have either no interest in curbing CO2 emissions or no ability to do so. Southern regions may choose to adopt new technologies to the extent that they reduce usage of costly factors of production or allow a region to exploit a new terms of trade advantage.

A key feature of our model is the differentiation of knowledge capital by sector of use. R&D for a given sector and region is produced using intermediate goods. This allows R&D to influence output in a few ways. First, by investing in R&D, more output can be achieved in a given industry with the same use of conventional inputs. Second, increased demand for R&D in an energy-intensive industry requires increased use of certain conventional inputs, which causes cost to increase in other industries, and can impact output in those sectors. Third, increased demand for R&D in an energy-intensive industry can lead to a redistribution of the initial R&D endowment by redirecting intermediate input use away from the R&D efforts of non-energy intensive industries and towards those most affected by a given policy. Therefore, investment in technology change can respond to different incentives presented by CO2 restrictions and the structure of international commodity markets.

Unique to our model is the inclusion of an R&D good targeted specifically at developing "carbon-saving" technologies — technologies that directly affect the emissions requirement of an economic activity without changing the energy or other input requirements that one normally associates with the production of carbon emissions. Real world examples of this type of technology exist under the umbrella of carbon capture and storage (Global CCS Institute, 2020). This type of R&D is produced in the same way as conventional R&D. All else equal, R&D in carbon-saving technology allows for the same use of fossil inputs — and the same sectoral output — at lower proportional marginal emissions levels. Our work highlights the importance of this technology in reducing emissions leakage and abatement costs.

We model two policy scenarios. First, we model the implementation of a system of domestically tradable emission permits in each Northern region that results in a 10% reduction in emissions relative to the benchmark level. Second, we introduce carbon tariffs levied only on imports to Northern regions from Southern regions as a means to incentivize Southern adoption of carbon-saving technology. Carbon tariffs and full border carbon adjustment measures have been studied extensively as a means to reduce leakage rates, by incentivizing the South to take part in the abatement effort (Boehringer *et al.*, 2012b). Due to spillovers, a positive R&D externality exists which can lead to the underprovision of knowledge services or underinvestment in carbon-saving R&D. A carbon-tariff on non-abating regions could be employed to incentivize Northern regions to invest more in carbon-saving R&D, helping to reduce carbon leakage further while also incentivizing non-abating regions in the South to adopt carbon-saving technology developed in the North. The carbon tariff rate endogenously responds to the changing carbon content of Southern goods as a result of technology diffusion associated with the carbon-saving technology. The results highlight the implications of these two policies in the face of four different assumptions about knowledge creation and diffusion. The assumptions include (*i*) No R&D is allowed, (*ii*) R&D is allowed but no spillovers are allowed, (*iii*) R&D is allowed with spillovers only amongst regions in the North, and (*iv*) R&D is allowed with full spillovers amongst all Northern regions and from Northern regions to Southern regions.

Under the first policy scenario, the Northern emissions cap reduces demand and increases costs associated with emissions intensive production, putting downward pressure on prices of energy goods. This induces a standard carbon leakage effect, as Southern regions take advantage of these lower prices (Felder & Rutherford, 1993). We find that the ability of the North to invest in new technology and the ability of the South to capture the benefits associated with these innovations both tend to reduce the leakage rate. R&D investment patterns associated with conventional sectors show increased R&D where emissions are most intensive, such as electricity and energy-intensive consumer goods. R&D patterns in other sectors show decreases or ambiguity. However, large amounts of carbon-saving R&D are present. This carbon-saving innovation allows for greater use of fossil energy in the North under the same carbon restrictions. As a result, prices of fossil fuels are higher with R&D, causing less energy use and energy intensive production to migrate to the South. This suggests that the operative channel for leakage reduction is through investment in carbon-saving R&D.

Spillovers tend to mute the R&D response induced by the emissions cap. The primary channel for this is in spillovers between Northern countries. If knowledge is more freely available, then a given Northern region has less incentive to invest in R&D, as the cost savings from this new knowledge is not completely contained within the region. Due to the fact that Northern countries can make better use of freely available knowledge and can adjust their R&D investment in response, less knowledge is created. Leakage rates increase slightly when North-only spillovers are modeled. North to South spillovers further mute the R&D investment response in the North by a small amount, but also decrease the leakage rate.

Under an emissions cap without carbon tariffs, spillovers from North to South have a minor effect on the leakage rate. This is partly because there is no incentive for Southern regions to adopt carbon-saving technology, as emissions are not priced in these regions. This fact suggests that additional benefits could be realized if the North were to incentivize the South to adopt these technologies via a carbon tariff.

Introducing the carbon tariff causes a reduction in leakage regardless of whether R&D or technology spillovers are represented in the model. Conventional R&D associated with energy intensive industries and carbon-saving R&D are higher in the North under a tariff than without. Notably, spillovers from North to South drive a larger percentage reduction in the leakage rate compared to the no-tariff case. This is due to the fact that Southern regions now have a motive to adopt carbon-saving technology developed in the North. Sensitivity analysis shows that under highly elastic demand for carbon-saving technology, the carbon tariff's interaction with the carbon-saving technology can induce a reduction in southern emissions, yielding a negative leakage rate.

Our core scenarios show that carbon-saving R&D is a major cost-reducing factor. Furthermore, the carbon-saving R&D results in smaller increases in Southern emissions relative to the case without R&D. The net effect of carbon-saving R&D is a significant boost to global welfare. Spillovers tend to reduce welfare in the no-tariff case. As Southern consumption falls and Northern consumption increases, reductions in Southern emissions do not offset this difference due to the fact that the large Northern investment in carbon-saving technology does not spill over into the South.

Our baseline parameterization with a carbon tariff results in lower welfare than without a tariff for each R&D assumption. Note that this result is due almost entirely to the fact that intermediate goods are used in fixed proportion with one another in a given industry's production function. Future iterations of this work should explore different parameterizations in this aspect of the model. However, because the carbon tariff incentivizes the South to adopt carbon-saving technology, spillovers elicit a more muted output response to the carbon tariff. How muted this output response is determines whether or not spillovers increase or decrease welfare. For example, sensitivity analysis shows, if it is more difficult to reduce CO2 emissions by increasing carbon-saving R&D, less carbon-saving R&D investment will take place, which reduces the spillover benefit the South receives from the North. Additionally, these spillovers to the South have less of an impact on the effective carbon content. The resulting lower spillover benefit causes Southern regions to substitute output away from exports to the North and towards use in the Southern regions. The opposite is true when it is easier to reduce CO2 emissions with carbon-saving R&D, as trade flows are otherwise less disrupted.

There is an extensive literature that uses calibrated numerical models to study the effects of induced technological change on the costs of greenhouse gas abatement and optimal abatement levels over time.[13] Most are based on macro-style growth models that do not model different sectors of the world economy. Grubler *et al.* (2002), Popp (2004), and Buonanno *et al.* (2003) are some of the more prominent examples of studies from this branch of the literature. Acemoglu *et al.* (2012) fits in with the growth literature, however it models a dirty and clean good in a more theoretical framework focused on optimal policy and timing. Goulder & Schneider (1999) develops a country-level computable general equilibrium (CGE) model with sector-specific R&D activities and technology spillovers, but the analysis takes place in a closed-economy setting. Similarly, Gerlagh (2008) models R&D-based technology changes that can be directed at specific inputs in specific sectors of the economy, but does not model regional economies and cannot therefore comment on the effects of international trade, carbon leakage, or technology spillovers to developing countries. Gerlagh &

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[13] For overviews of the literature and methods used to account for technological change, see: Loeschel (2002); Popp *et al.* (2010); Wing (2006)

Kuik (2014) focus on the potential for technology change and international technology spillovers to modify the magnitude and sign of carbon leakage effects. The specification of technology change is based on a reduced-form specification rather than knowledge stock with spillovers approach as we use here. Also, Gerlagh & Kuik (2014) does not specifically model carbon-saving R&D, a key aspect of our analysis. Gerlagh & van der Zwaan (2003) and Popp (2006) are two noteworthy growth models which introduce carbon-saving technological change via a carbon-free backstop technology and endogenous technological change via learning by doing. However, the backstop technology is a substitute for fossil-based energy production so it is fundamentally different from the end-of-pipe type of carbon-saving technology that we are imagining here. Additional work exists that models technological innovation in the face of carbon capture and storage, but sectoral R&D patterns, international trade, technology diffusion, and leakage effects are not emphasized together (Otto & Reilly, 2008; Otto *et al.*, 2008; Schroyen & Durmaz, 2019)

There is also a theoretical literature on the impacts of induced technological change on pollution policy. Our experiment is most closely linked to Di Maria & Smulders (2005) and Di Maria & van der Werf (2008), both of which explore the impacts of induced technological change in North-South models of trade. The former, however, does not focus specifically on greenhouse gas emissions and the trade linkages that are particular to this policy setting. The latter concentrates on carbon leakage effects but does not model a carbon-saving technology.

The literature covering border carbon adjustments and carbon tariffs is extensive. The Energy Modeling Forum (EMF) 29 study outlines a cooperative effort to explore various features of these policy instruments (Boehringer *et al.*, 2012b).[14] However, this literature does not consider interaction between induced technological change and border carbon adjustments. In particular, no consideration is given to the unique ability for border carbon adjustments to incentivize adoption of carbon-saving technology in regions not subject to emissions regulation.

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[14] Other related works from the EMF 29 study include: Alexeeva-Talebi *et al.* (2012); Boehringer *et al.* (2012a,c); Boeters & Bollen (2012); Caron (2012); Springmann (2012). Additional work outside of the EMF 29 study by Boehringer *et al.* (2014b) and Boehringer *et al.* (2018) should be noted as well.

The rest of the paper proceeds as follows: Section 3.2 describes the structure of the simulation model with particular emphasis on the specification of R&D creation and technology spillovers. Section 3.3 covers the data and assumptions used to calibrate the model. Section 3.4 describes the results of the counterfactual policy experiments. Section 3.5 explores the sensitivity of the model to key parameter choices.

3.2 Model description

The model is a static, multi-regional, multi-commodity, computable general equilibrium (CGE) model whose basic underlying structure has been used in a number of previous studies at the intersection of trade and climate policy (Arrow & Debreu, 1954; Lanz & Rutherford, 2016; Shoven & Whalley, 1984). The GTAP 9 database (Aguiar *et al.*, 2016) provides the benchmark calibration point for the conventional sectors and production activities in the model. The base year in the model is 2011. Production and consumption technologies are modeled as nested CES production functions. International trade is represented via Armington composites of foreign and domestic varieties of traded commodities (Armington, 1969). The different varieties enter nested CES production functions, where benchmark value shares and substitution elasticity parameters determine the mix of imported versus domestically produced varieties consumed by a given region. Primary fossil fuel production makes use of specific resource factors that ensure upward sloping supply schedules for these commodities (Rutherford, 2002). Carbon is modeled as an input which firms and consumers must use in fixed proportion to their demand for fossil energy inputs. While we realize that there is a difference between "Carbon" and "CO2", we use these terms interchangeably throughout this text in reference to CO2 emissions. If a distinction provides new intuition, we will note this explicitly. There are seven regions and eight sectors of the world economy represented in the model. Because these aspects of the design are conventional, we forgo a more detailed description here.

It is worth noting that the majority of models designed to explore the interaction of technology and climate policy are explicitly dynamic. They typically contain mechanisms for either recursive or foresighted management of the physical capital, knowledge stocks, and climate processes represented within the model. This is a natural modeling choice to make due to the fact that the impacts of climate change and cost savings associated with technological progress take time to manifest themselves. If our objective was to characterize the discounted value of abatement cost savings due to technology change or the optimal investment path over time, a dynamic modeling approach would be well-suited. However, the focus of our experiment is on characterizing the sectoral pattern of R&D investments and technology spillovers that may arise from efforts to control CO2 emissions. Therefore, for tractability and clarity of policy response, we deviate from the conventional dynamic modeling approach.

3.2.1 Modeling knowledge demand and supply

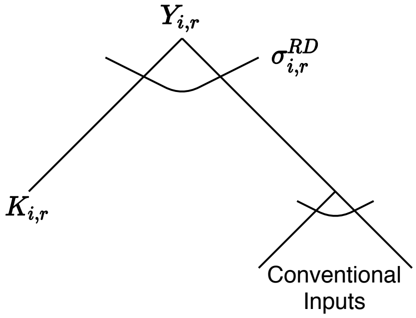

Figure 3.1: R&D as an input to production

A novel part of the model is the specification and the calibration of knowledge creation, utilization, and spillovers. Knowledge is assumed to be a factor of production in each conventional sector of the economy. Figure 3.1 presents a schematic representation of how the knowledge good enters the production block for a generic good in the model. $Y_{i,r}$ is the level of output in sector i of region r. The modification of the production structure in our CGE model is made by nesting the original production structure based on conventional inputs in a nested CES structure with knowledge services, $K_{i,r}$. In the specification of each sector's production function, the top-level elasticity of substitution parameters in CES production functions, $\sigma^{R}_{i,r}$, along with the benchmark value shares of knowledge services implied by our R&D data, determine the demand responsiveness of knowledge in that sector. Employing this type of nesting structure allows us to calibrate $\sigma^R_{i,r}$ to a pre-specified elasticity of demand (Rutherford, 2002).

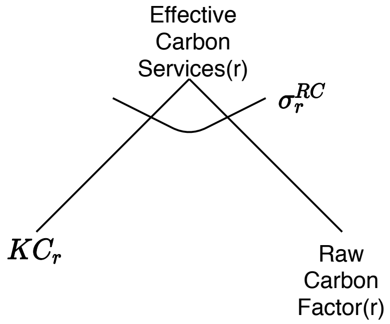

Figure 3.2: R&D as an input to production of effective carbon

In addition to modeling the use of knowledge inputs in the production of conventional goods, we also assume that innovation can be useful in the production of effective carbon services. Effective carbon is produced using raw carbon emissions and knowledge based on investment in carbon-saving R&D. The technology for producing effective carbon follows the specification in Figure 3.1 with the difference being that the raw carbon emissions input replaces the nest of conventional inputs, shown in Figure 3.2. Effective carbon then enters the conventional nesting structure at fixed proportion to the fossil energy inputs in production of a given good.

The supply of knowledge comes from two distinct sources. New technologies can be invented by investing in R&D, which requires reallocating resources from other sectors in the economy. We assume that there is a common technology using conventional intermediate goods in the model that can produce new knowledge for any sector of the economy equally well. These inputs enter a simple CES production function. The second source of knowledge comes from pre-existing stocks of knowledge that are based on spillovers from previous R&D activity either in a firm's home country or from abroad. We assume that this type of knowledge cannot be flexibly reallocated from one sector to another – once a new technology has been developed for use in a given sector, it can be of no use to the firms producing in other sectors. Additionally, in our model we assume that only countries in the "North" are capable of producing R&D. Countries in the "South" are assumed to derive their knowledge stock services purely from pre-existing knowledge based on spillover effects.

The modifications represented in Figure 3.1 and Figure 3.2 can be clarified algebraically by discussing some key zero profit and market clearance conditions. A full model description is provided in appendix G. Assume that output ($Y_{i,r}$) in sector i region r is produced using knowledge services ($K_{i,r}$) and an index of non-R&D goods ($NRD_{i,r}$). $K_{i,r}$ consists of new knowledge production ($R_{i,r}$) and pre-existing conventional knowledge plus any spillovers ($SPL_{i,r}$). The unit profit function for output is given below:

$$\begin{aligned}&\Pi^{Y}_{i,r} = p^{Y}_{i,r} - \\ &\left[\theta^{RD}_{i,r} p^{R^{1-\sigma^{RD}}}_{i,r} + (1-\theta^{RD}_{i,r}) p^{NRD^{1-\sigma^{RD}}}_{i,r}\right]^{\frac{1}{1-\sigma^{RD}}} \\ &\leq 0\end{aligned} \tag{3.1}$$

where $p^{Y}_{i,r}$, $p^{R}_{i,r}$, and $p^{NRD}_{i,r}$ are the relative price indices associated with production of good i in region r, respectively. $\theta^{RD}_{i,r}$ represents the benchmark cost of $K_{i,r}$ as a share of output in industry i region r. The market clearance condition for knowledge services is shown below:

$$R_{i,r} + SPL_{i,r} \geq Y_{i,r} \frac{\partial \Pi^{Y}_{i,r}}{\partial p^{R}_{i,r}} \tag{3.2}$$

with supply of knowledge on the left-hand side (LHS) and demand for knowledge on the right-hand side (RHS). Demand for knowledge services on the LHS is representative of $K_{i,r}$ in Figure 3.1. Furthermore, knowledge investment ($RD_{i,r}$) is produced using a mix of intermediate goods governed by the following unit profit function:

$$\Pi^{R}_{i,r} = p^{R}_{i,r} - \left[\sum_{j} \theta^{R}_{j,i,r} p^{Y^{1-\sigma^{R}}}_{i,r}\right]^{\frac{1}{1-\sigma^{R}}} \leq 0 \tag{3.3}$$

where $p^{R}_{j,r}$ and $\theta^{R}_{j,i,r}$ indicate the price of conventional knowledge and the benchmark cost of conventional input good j for region r as a share of the value of conventional knowledge investment output for good i, respectively.

Turning attention to Figure 3.2, effective carbon services ($CRB_{i,r}$) enter the non-R&D goods index which enters the output block. The unit profit function for the non-R&D goods index is shown below:

$$\begin{aligned}&\Pi_{i,r}^{NRD} = p_{i,r}^{NRD} - \\ &\left[\theta_{VA,i,r}^{NRD} p_{i,r}^{VA} + \sum_{j \in FE} \theta_{j,i,r}^{NRD} (p_{i,r}^{A} + p_r^{CRB} a_{j,i,r}^{co2}) + \sum_{j \in NE} \theta_{j,i,r}^{NRD} p_{i,r}^{A}\right] \\ &\leq 0\end{aligned} \tag{3.4}$$

where $p_{i,r}^{VA}$, $p_{i,r}^{A}$, and p_r^{CRB} represent the value-added price index consisting of capital and labor, the Armington price index, and the price of effective carbon services, respectively. $\theta_{j,i,r}^{NRD}$ is the share of total non-R&D output attributable to each input j. $a_{i,g,r}^{co2}$ is the emissions coefficient associated with each fossil fuel energy good ($j \in FE$). NE represents non-fossil fuel energy goods. It is important to note that the fixed-proportions cost function is a simplification that leads to larger leakage responses and more costly abatement cost results. Future iterations of this work should employ a production structure more closely aligned with Boehringer *et al.* (2018) in order to capture substitutability amongst different uses of fossil fuels.

The unit profit function for effective carbon services illustrated in Figure 3.2 is shown below:

$$\Pi_r^{CRB} = p_r^{CRB} - \left[\theta_r^{CRB} p_r^{co2^{1-\sigma^{CRB}}} + (1 - \theta_r^{CRB}) p_r^{RC^{1-\sigma^{CRB}}}\right]^{\frac{1}{1-\sigma^{CRB}}} \leq 0 \tag{3.5}$$

where p_r^{co2} represents the price of the raw CO2 emissions factor. θ_r^{CRB} is the share of effective carbon services output attributable to the raw CO2 factor input. σ^{CRB} is the substitution elasticity associated with that profit function. The market clearance condition for effective carbon is shown below:

$$CRB_r \geq \sum_g Y_{i,r} \frac{\partial \Pi_{i,r}^{Y}}{\partial (p_{i,r}^{A} + p_r^{CRB} a_{j,i,r}^{co2})} a_{j,i,r}^{co2} \tag{3.6}$$

where supply of effective carbon services must cover demand for effective carbon services in production of good $Y_{i,r}$.

The unit profit function associated with Figure 3.2 is shown below:

$$\Pi_r^{RC} = p_r^{RC} - \left[\sum_i \theta_{ir}^{RC} p_{ir}^{Y^{1-\sigma^{RC}}} \right]^{\frac{1}{1-\sigma^{RC}}} \leq 0 \tag{3.7}$$

where θ_{ir}^{RC} is the share of carbon-saving R&D output attributable to input i. Market clearance for carbon-saving R&D is specified as follows:

$$RC_r + SPLC_r \geq CRB_r \frac{\partial \Pi_r^{CRB}}{\partial p_r^{RC}} \tag{3.8}$$

where supply of knowledge services consisting of new carbon-saving R&D (RC_r) and spillovers ($SPLC_r$) must cover demand for carbon-saving R&D in production of effective carbon-services.

Together, with some additional equations specified in appendix G, the above equations define the behavior of knowledge creation and the use of knowledge in output. The constraints containing logic for knowledge diffusion are discussed in section 3.3.2 and in appendix G.

In a dynamic model, it is natural to explicitly model investment and depreciation of the knowledge stocks. In a static setting, it is less clear what the most appropriate approach is regarding the supply of R&D. We have established the assumption that R&D is produced using intermediate goods. We further assume that the level of domestic investment in R&D may respond as aggregate demand rises and falls, meaning that the knowledge stock is not fixed across all sectors. The typical treatment of physical capital in CGE models is to assume a fixed endowment of physical capital available in the economy and a fixed level of investment dedicated to capital accumulation. An argument against treating the knowledge stock in a similar fashion is that it implies that each additional unit of energy-saving or carbon-saving R&D comes at the expense of one unit of R&D services elsewhere in the economy. Grubler *et al.* (2002) employs a model with fixed knowledge stock. Other models assume an exogenous fraction (often set equal to one half) of non-energy R&D that is crowded out by investment in energy-saving R&D (Popp, 2004). Still, other studies explicitly model the R&D creation process using a production function approach where supply is governed by the level of intermediate inputs to R&D creation and an assumption of zero profits in equilibrium (Goulder & Schneider, 1999). Due to the external nature of the problem climate policy attempts to address, it seems more reasonable to allow for the total stock of R&D to respond to the previously neglected price signal the market is receiving via the newly priced CO2. Therefore, we adopt a specification of knowledge creation closely resembling that used in Goulder & Schneider (1999).

Our description of technology spillovers involves two elements: *i*. specifying the relationship between the private and social returns to R&D; *ii*. describing the degree to which innovations in one country can be successfully employed in other regions in the world economy. For the first element, estimates indicate that social returns to R&D are somewhere between two and four times private returns to investors (Jones & Williams, 1998); we assume a value of three. For the second element, we use logic based on Bosetti *et al.* (2008). The study describes a set of absorption capacity weights based on a country's distance from the technological frontier. Absorption capacity for a given region is calculated as the value of its knowledge stock as a share of the world knowledge stock. Thus, the higher a region's state of technology is relative to the rest of the world, the easier it is for that region to take advantage of new ideas from abroad. We calculate these weights based on our regional R&D expenditure data. Furthermore, we assume that the technology spillover experienced by country A due to R&D investment in country B is measured by their absorption capacity weight multiplied by the value of country B's R&D investment above or below benchmark levels. Therefore, if country B invests more heavily in R&D in response to the counterfactual policy we model, country A will reap the benefits to the extent that it can absorb this new information. However, if R&D investment falls in country B, our specification would register this as a loss for country A. The total spillover effect experienced by country A is the sum of these effects across all countries weighted by country A's absorption parameter. This acquired knowledge is assumed to be specific to the sectoral investment pattern of the country in which the innovation originated.

3.3 Data and calibration

The 7x8 model is based on the GTAP9 database (Aguiar *et al.*, 2016). Seven regions are distinguished: Old EU member states (E15), New EU member states (E12), United States (USA), Rest of OECD (OEC), China (CHN), Former Soviet Union (RUS), Rest of the World (ROW). The

"North" in our model is defined as those countries capable of both producing new investment in R&D and imposing carbon restrictions on their citizens. The North includes model regions E15, USA, and OEC. The remainder regions belong to the "South" and are assumed to have the ability neither to innovate nor to restrict their CO2 emissions. The 57 sectors of the GTAP9 database are aggregated into eight sectors, namely "energy-intensive industries" (EII), "non-energy-intensive industries" (NEI), and five different energy sectors: Coal (COA), Crude oil (CRU), Gas (GAS), Gas transmission and distribution (GDT), Petroleum and coal products (OIL), and Electricity (ELE). The source sets from GTAP9 as well as the regional and sectoral mappings for our application are depicted in Figure F.1 and Figure F.2.

3.3.1 Incorporating R&D data

CGE models that build on input-output tables as part of the national accounts typically have difficulties accounting for knowledge capital since national input-output tables extended with satellite accounts on knowledge flows are scarce. Knowledge capital accounting requires the identification and capitalization of knowledge flows and subsequent incorporation of these flows in the national accounting matrix (de Haan & van Rooijen-Horsten, 2004). The UN expert group on the measurement and treatment of non financial assets focuses on the recording of R&D and intangible capital.[15]

For the calibration of our global model to knowledge capital data, we gather data on R&D expenditures and distribute these expenditures to the sectors in our model. Raw R&D expenditures and expenditures as a share of GDP can be obtained for most countries of the world from the UN (UNESCO, 2011). We use corresponding information for GDP and population in order to compute absolute values for R&D expenditures where necessary (OECD, 2011b; WBO, 2011). Afterward, R&D expenditures are added up according to the regional aggregation as described above. We use 2011 data, as this is the base year of the GTAP9 database. We then use ANBERD data provided by the OECD to calculate sectoral R&D expenditures (OECD, 2011a). We take

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[15] This group is better known as the Canberra II Group and is formed as part of the process of updating the 1993 System of National Accounts

weighted average OECD shares for each aggregate sector in non-OECD model regions to obtain sectoral R&D in non-OECD regions. The ANBERD data is provided using the ISIC revision 3 classification system (OECD, 2018). The GTAP9 database sectors are mapped to these ISIC industries in order to compute sectoral R&D (McDougall *et al.*, 2013; UN, 2002). In some cases, multiple GTAP9 sectors overlap with a single 2 digit ISIC category. In these cases, we use the value added shares of capital and labor for each GTAP sector in total value added for all GTAP sectors encompassed by the 2 digit ISIC category to disaggregate the 2 digit ISIC R&D data into the GTAP sectors.

Next we capitalize expenditures on R&D flows such that we can record services derived from the knowledge stocks in separate arrays in the national accounting matrix (Otto & Reilly, 2008). An additional (column) account then registers investments in the stock of knowledge capital, whereas an additional (row) account registers the derived services in the national accounting matrix. Originally, expenditures on R&D are reported as derived services. Regarding the capitalization itself, we use the perpetual inventory method, which is a commonly used method to measure capital stocks and is in line with the Frascati manual for surveys on R&D (OECD, 2002). A key parameter in the perpetual inventory method is the depreciation rate, for which additional information is required. A 20 percent depreciation rate for knowledge capital is assumed, which is in line with empirical evidence on patent renewals in the United Kingdom, Germany, France, The Netherlands and Switzerland studied in Pakes & Schankerman (1979). This is also consistent with data on life spans of applied R&D expenditures, which suggests an average service life of four to five years. We assume the model economies to be on a steady state, which implies a fixed relation between investments in and services derived from the sector specific stocks of knowledge capital. This relation then gives us the total column and row accounts for knowledge capital stemming from the knowledge flows.

There is also a question as to how to calibrate the benchmark technology for effective carbon. Effective carbon is the composite commodity produced using raw CO2 emissions and carbon-saving knowledge inputs. Because carbon is an unregulated public bad, it is generally assumed in assessments of this type that the benchmark price of this input is zero, an assumption that is consistent with the idea of firms using carbon up to the point where the marginal cost of abatement is zero. Following this logic, it should be the case that the price of effective carbon in our model is zero in the benchmark. However, an implication of this assumption is that the price of carbon-saving knowledge must also be zero. If the price is zero and R&D into new carbon-saving technologies makes use of costly inputs, then the non-negativity constraint in this sector is strongly binding. This is different than the current treatment used in the other R&D sectors where it is assumed that, in the benchmark, R&D firms operate at a level that is consistent with maintaining the benchmark level of knowledge stocks at zero profits.

To avoid double counting of the knowledge flows, we debit selected entries of the national accounting matrix. Debiting for expenditures on R&D is not straightforward, as the intermediate goods matrix of the national accounting matrix needs to be debited. In this case, we need to make an assumption as to which entries of the intermediate goods matrix to debit. One can either assume that R&D leads to disembodied knowledge or to knowledge embodied in tangible goods and services. If we assume that knowledge is embodied, the intermediate goods matrix can be debited proportionally to the intermediate input shares in total output of the sectors. The former assumption, however, necessitates the additional step of creating an interindustry technology matrix to debit the intermediate goods matrix proportionally to an R&D indicator such as the number of patents that a sector manufactures and uses. Since superiority of using R&D indicators is not immediately clear and their availability typically is patchy for non-industrial sectors such as services, we follow Terleckyj (1974) and use intermediate input shares for our purposes. We balance the national accounting matrix by adjusting the (row) account for labor.

The implication of our calibration procedure is that the proportions of the intermediate inputs used to produce R&D are equal to the shares of total R&D used in each of these intermediate goods sectors based on our benchmark R&D data. It is generally believed that the production of new technology is a high-skilled, labor-intensive process. Evidence also suggests that it is the productivity of labor that grows most when technological change occurs. Our calibration assumptions match both of these facts to the extent that most of the R&D expenditures occur in labor-intensive industries, a fact that is born out in our data.

3.3.2 Spillover calibration

The specification of international R&D spillovers in our model follows the approach by Bosetti *et al.* (2008) for international energy R&D spillovers. It concentrates on disembodied knowledge flows by introducing a transmission channel across R&D sectors in the different model regions. Technology spillovers depend on (i) the global knowledge pool, (ii) the absorption process by each country, and (iii) the way knowledge is used in the domestic R&D sectors. Bosetti *et al.* (2008) propose for the pool of international knowledge, a formulation in which the world's technological frontier is determined by the sum of the R&D stocks across high income countries. The knowledge pool for the different countries is given by the difference between this technological frontier and each country's R&D stock. The absorption capacity is modeled as the ratio of the country's R&D stock and the global technological frontier. This formulation takes into account that domestic R&D efforts are needed to absorb international knowledge (Keller, 2004). Calculated absorption rates by region and sector are reported in Table E.1. Spillover of international knowledge is obtained by multiplying the knowledge pool and the absorption capacity. The spillover use in the domestic R&D sector is different from Bosetti *et al.* (2008). In their formulation, spillovers enter the domestic R&D sector as an input in the innovation possibility frontier — next to the domestic investment in R&D and the past knowledge stock.

An algebraic representation of knowledge accounting and calibration is shown below. Details within the context of the greater model can be found in appendix G. First R&D expenditures data is obtained and assumed to equal benchmark demand for knowledge services ($\overline{dk}_{i,r}$), as shown below:

$$\overline{dk}_{i,r} = R\&D\ exp\ data_{i,r} \tag{3.9}$$

Then the absorption rate ($\gamma_{i,r}$) is calculated

$$\gamma_{i,r} = \frac{\overline{dk}_{i,r}}{\sum_{r \in nth} \overline{dk}_{i,r}} \tag{3.10}$$

and modified to allow for flows from region s to region r in ($\alpha^{ABS}_{i,s,r}$), shown below:

$$\begin{aligned} \alpha^{ABS}_{i,s,r} &= \gamma_{i,r} \\ \alpha^{ABS}_{i,r \in nth, r \in nth} &= 1 \\ \alpha^{ABS}_{i,s \in sth, r \in nth} &= 0 \\ \alpha^{ABS}_{i,s \in sth, r \in sth} &= 0 \end{aligned} \tag{3.11}$$

Note that this zeros specific flows from a given southern region ($s \in sth$) to other regions. Once the above absorption parameter is specified, before moving to spillovers, it is necessary to use the perpetual inventory method to determine benchmark R&D investment ($\overline{rd}_{i,r}$), given demand for knowledge services, the depreciation rate (δ), the population growth rate (g), and the rate of interest (r), below:

$$\overline{rd}_{i,r} = \frac{(\delta + g)\overline{dk}_{i,r}}{\delta + r} \tag{3.12}$$

Once investment is obtained, ensure that knowledge markets clear by specifying a pre-existing knowledge stock ($\overline{ks}_{i,r}$) that cannot be adjusted:

$$\overline{ks}_{i,r} = \overline{dk}_{i,r} - \overline{rd}_{i,r} \tag{3.13}$$

Now that knowledge accumulation has been specified, it is necessary to incorporate the process of spillover creation. This is shown for conventional knowledge,

$$SPL_{i,r} = \overline{ks}_{i,r} + 3 \sum_{s \in nth} \alpha^{ABS}_{i,s,r} (R_{i,s} - \overline{rd}_{i,s}) \tag{3.14}$$

and for carbon-saving knowledge,

$$SPLC_r = 0.01 * \overline{rdc}_r \overline{cb}_r + 3 \sum_{s \in nth} \Big[\sum_i (\frac{\alpha^{ABS}_{i,s,r}}{card(i)})(0.01 * \overline{rdc}_s \overline{cb}_s RC_s) \Big] \tag{3.15}$$

where $\overline{rdc}_r = 1$ and $\overline{cb}_r$ is benchmark raw co2 emissions. The value of three indicates the degree to which social returns to R&D are greater than private returns to R&D. The values for SPL_r and $SPLC_r$ enter the income balance and market clearance conditions discussed in appendix G.

The R&D expenditures data combined with our assumption regarding R&D investment and knowledge spillovers provide enough information to characterize the benchmark value of the knowledge stocks in the world economy. However, a second key determinant of how important endogenous technological change and spillovers are in our setting is how responsive we assume R&D is to the changes in relative prices induced by emission restrictions or other forms of climate change policy. In the core model simulations, we calibrate the top-level elasticity of substitution parameter in the nested CES production functions for each sector such that the own-price elasticity of demand for knowledge services in the production of other goods is set to unity (Rutherford, 2002). The exception to this rule is the primary energy sectors (COA, CRU, GAS) where we use the calibration of this elasticity parameter to imply an elasticity of supply of unity in each of these sectors (Rutherford, 2002), which is assumed to be unity for our scenarios. We also explore the implications of changing demand and supply elasticity values to which we calibrate the model in the sensitivity analysis described in section 3.5.

3.4 Results

The results discussed in this section relate to the imposition of a 10% reduction in CO2 emissions in each model region within the North. Each region is assumed to achieve this reduction by establishing a sectorally mobile but region-specific tradable emissions permit system. Specifically, we are interested in exploring the equilibrium effect of these policies on the global level of carbon emissions via leakage rates and the levels of R&D investment in different sectors of Northern economies. Furthermore, we are interested in how these outcomes are affected by the ability to invest in R&D with and without technology spillovers. Algebraic details are provided in appendix G.

After examining the results of the emissions restriction, we introduce a carbon tariff imposed by Northern regions on imports from Southern regions. We examine the impact of the carbon tariff in comparison to the results from the no-tariff scenario. Details to the specification of the tariff and how it fits into the larger model algebraically are provided in appendix G.

Finally, we discuss the welfare implications of the two policies under the prevailing R&D and spillover assumptions.

3.4.1 Core scenario

Table 3.1: Core Scenario Emissions

	% Difference from Benchmark				gigatons CO2
	No R&D	No SPL	North SPL	Full SPL	Benchmark
CHN	1.928	0.954	0.954	0.923	7.000
USA	-10.000	-10.000	-10.000	-10.000	5.107
RUS	3.100	1.491	1.491	1.487	1.668
E15	-10.000	-10.000	-10.000	-10.000	3.010
E12	12.357	5.768	5.769	5.765	0.650
OEC	-10.000	-10.000	-10.000	-10.000	3.257
ROW	3.966	1.995	1.995	1.991	7.709
Total	-1.989	-3.009	-3.009	-3.018	28.400
South	3.363	1.661	1.661	1.647	17.026
North	-10.000	-10.000	-10.000	-10.000	11.374
Leakage	0.503	0.249	0.249	0.246	0.000

Table 3.1 describes the results of the core scenario on regional and global CO2 emissions. Regional emissions data is shown in the first seven rows. The same emissions data for Northern and Southern regions as well as global total is shown below this. The leakage rate is shown in the final row of Table 3.1. Benchmark emissions are provided in gigatons of CO2 in the far right column. The emissions data in the first 4 columns are shown as percentage changes from the benchmark emissions level. The leakage rate is calculated as the change in carbon emissions generated by the South relative to the change in carbon emissions generated by the North. The columns in Table 3.1 describe emissions relative to the benchmark equilibrium for a counterfactual policy scenario and its interaction with different assumptions about the endogeneity of R&D investment and technology spillovers.

The No R&D results are generated by a model where knowledge production is fixed at benchmark levels and cannot respond to the CO2 restriction. The results serve as a benchmark from which we measure the impact of knowledge creation and spillovers. By construction, emissions levels in the North fall by 10% from benchmark levels. Emissions levels increase in the South due to the effects of carbon leakage. Both the decline in price for fossil fuels and the increase in the cost of producing energy-intensive goods drive demand for emissions from North to South. As a result, roughly 50% of the emission reductions in the North are offset by emissions increases in the South. [16]

The No Spl results model the effect of introducing endogenous R&D investment in the North without the effects of spillovers. The absorption parameters that describe the strength of spillover effects have been set to zero so that no region benefits from the innovations of others. Relative to the No R&D results, regions in the South reduce their emissions level in the counterfactual experiment. The North remains subject to the same 10% emissions restriction, so emissions in these regions remain unchanged. Global emissions decline further by roughly 1% relative to the No R&D results. The reduction in Southern emissions also implies a reduction in the leakage rate from roughly 0.503 to 0.249, a 50% reduction relative to the No R&D rate.

The North Spl column shows the model results when technology spillovers are only allowed across Northern regions. The leakage rate is unchanged to slightly higher than the No Spl result. Allowing for spillovers from North to South in the Full Spl column, yields a reduction in the leakage rate relative to the No Spl and the North Spl results, however, this reduction is small relative to the comparison between the No R&D and No Spl results.

In order to understand the factors that influence the emissions results in Table 3.1, it is useful to examine changes in the pattern of R&D investments. Table 3.2 shows percentage changes in conventional R&D investment levels relative to the benchmark equilibrium as well as carbon-saving R&D investment levels in billions of 2011 US dollars, by sector and version of the model aggregated across all Northern regions. The model versions are listed in the rows of Table 3.2. The

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[16] Estimates for leakage rates tend to fall in the range of 10-30% (Boehringer *et al.*, 2018). Our model deviates from this norm due to the lack of flexibility in substitution between different conventional input types, specifically fossil fuels. This production structure should be updated in future iterations of this work to reflect a more accurate representation of electricity production and fossil fuel use. However, the comparison across R&D assumptions to follow remains relevant, and is likely not to deviate in sign, only magnitude.

Table 3.2: Core Scenario Northern R&D

	% Δ from BMK								USD Bln
	coa	oil	gas	ele	gdt	eii	nei	cru	crb
No Spl	-4.979	-2.935	-8.221	24.485	-8.940	0.555	-0.574	-5.590	9.674
North Spl	-0.886	-0.503	-1.834	4.212	-1.609	0.105	-0.098	-0.988	8.152
Full Spl	-0.884	-0.503	-1.833	4.212	-1.608	0.104	-0.097	-0.987	8.151

sectors to which the R&D is directed are listed in the columns. The final column, crb, relates to carbon-saving R&D.

Comparing the benchmark levels of R&D to the equilibrium counterfactual levels that arise in the model without spillovers, we see that the general pattern of investment follows the carbon-intensity of the sectors where the investment takes place. Electricity generation (ELE) and energy-intensive goods production (EII) both see increases in R&D investment at the expense of investment in primary energy production and the production of non-energy goods. However, the largest increases in investment are directed at the development of new, carbon-saving technologies (CRB) which goes from inactivity in the benchmark equilibrium to producing services worth approximately 9.7 billion USD total across all Northern regions in the No Spl case. In fact, the net effect on total energy-saving R&D investment induced by the emissions cap is roughly -1.6 billion USD.[17] This means that total energy-saving R&D across all conventional sectors decreases due to the emissions cap, whereas carbon-saving R&D activity increases.

There are, in principle, two reasons why the R&D responses could impact the carbon leakage effect as described in Table 3.1. First, new R&D investment in EII reduces the fossil fuel inputs requirement and counteracts the increase in costs in this sector due to the carbon restrictions. Second, new investment in the carbon-saving technology directly reduces the raw carbon content of production in all upstream sectors. With less raw carbon content per unit of fossil energy used, these sectors may continue to use fossil energy at levels closer to the benchmark. In practice, the results in Table 3.2 tell us that the second channel – carbon-saving technology change – is the

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[17] Calculated as the sum of the raw difference between benchmark R&D investment and counterfactual R&D investment across conventional sectors and northern regions.

operative one in our simulations.

Comparing the R&D investment patterns between the No Spl and North Spl model results in Table 3.2, we see a significant retreat in the amount of new investment in the carbon-intensive sectors (EII and ELE) and in the carbon-saving technology as a result of spillovers. When knowledge is suddenly made freely available via spillover effects, it is less important for any given sector within a region to invest in knowledge creation, as the benefits of the new knowledge can no longer be fully internalized by the region and industry in question. Knowledge is appropriated by other regions, and their production decisions reflect the new, freely available knowledge. As previously discussed, Table 3.1 shows a slight increase in the leakage rate in the North Spl case. The cost reducing impact of Northern spillovers is slightly less than the cost increasing effect of reduced R&D, which leads to a slight reduction in northern carbon intensive output and fossil fuel demand. Lower fossil fuel demand in the North yields an increase in the leakage rate.

Allowing for spillovers from North to South in the Full Spl case, we see a slight reduction in Northern R&D relative to the North Spl result. Nonetheless, Table 3.1 shows that the carbon leakage rate falls slightly relative to the No Spl results. This is because the Northern R&D investment that remains is now accessible to firms in the South for cost reduction. The South does not have an R&D investment response. Rather, it adopts the Northern technologies for their reduced factor requirements, which results in lower emissions as a byproduct.

3.4.2 Introducing a carbon tariff

By construction, the fact that Southern regions have no interest in curbing CO2 emissions implies that they have no direct interest in implementing the carbon-saving technology to curb emissions. There is no price on emissions in the South, therefore spillovers associated with Northern investment in carbon-saving technology provide no cost reduction to Southern firms in emissions intensive industries. The large investment in carbon-saving R&D and lack of a spillover effect from this primary channel of Northern cost reduction suggests that further reductions in leakage could be obtained if the South cared about carbon-saving technology.

One way for the North to incentivize Southern adoption of carbon-saving R&D is to implement a carbon tariff. We introduce carbon tariffs to the model and examine the impact on leakage rates and R&D investment in comparison to the results without a carbon tariff. The tariff rate imposed on imports from a given Southern region is set equal to the price of CO2 emissions implied by the 10% emissions reduction in each Northern region. The specification of the tariff rate also allows spillovers from Northern carbon-saving R&D to impact the CO2 content of goods exported from South to North. For simplicity, the benchmark CO2 content applied to the embodied tariff consists of direct emissions from fuel consumption, the default calculation for the GTAP9 database. No carbon tariffs exist on trade between Northern regions.

Table 3.3: Tariff vs No-Tariff Leakage rate

	TARIFF?	NO R&D	NO SPL	NORTH SPL	FULL SPL	%ΔNO SPL	%ΔFULL SPL
BASE1	no	0.503	0.249	0.249	0.246	-50.50	-1.20
CTAR1	yes	0.447	0.197	0.197	0.188	-55.93	-4.57

%ΔNO SPL = % diff between No R&D and NO SPL
%ΔFULL SPL = % diff between NO SPL and FULL SPL

Table 3.3 shows leakage rates under a carbon tariff compared to the previously discussed no-tariff results. The table rows indicate whether or not a carbon tariff is present. The first 4 columns indicate the model versions and the R&D and technology spillover assumptions. The final two columns show the percentage reduction in the leakage rate in the NO SPL relative to the No R&D version as well as from FULL SPL relative to the NO SPL version, from left to right.

Generally, Table 3.3 shows that carbon tariffs decrease the leakage rate relative to the no-tariff case. The carbon tariff increases the cost of producing goods in the South that are destined for Northern regions. As a result, emissions intensive industries in the South curb output relative to the no-tariff version. When Northern R&D is allowed, the carbon tariff results in a larger percentage decrease in the leakage rate relative to no tariff (%ΔNO SPL). Furthermore, spillovers from North to South cause an additional reduction in the leakage rate. Under a carbon tariff, the leakage rate decreases by a larger percentage relative to the no-tariff result when spillovers are present (%ΔFULL

SPL).

Table 3.4: Tariff Northern R&D

	% Δ from BMK								USD Bln
	coa	oil	gas	ele	gdt	eii	nei	cru	crb
NO SPL	-5.024	-2.441	-4.261	25.424	-8.744	0.855	-0.642	-4.930	9.901
NORTH SPL	-0.894	-0.419	-1.089	4.378	-1.576	0.156	-0.109	-0.871	8.346
FULL SPL	-0.893	-0.420	-1.096	4.375	-1.575	0.154	-0.109	-0.872	8.342

Table 3.4 shows a comparison of R&D investment across various types of conventional R&D as well as the carbon-saving technology. The results are organized in the same fashion as Table 3.2 to facilitate a direct comparison between the carbon tariff and no-tariff R&D response.

Comparing Table 3.2 and Table 3.4, it is clear that the carbon tariff leads to larger amounts of R&D investment across virtually all industries under both the NO SPL and FULL SPL results. As expected, spillovers result in a more muted R&D investment response to the policy, primarily due to spillovers amongst Northern regions. Additionally, under the carbon tariff, the percentage difference in carbon-saving R&D between the FULL SPL and NO SPL shows a more negative response relative to the no-tariff scenario. Spillovers under the carbon tariff drive a larger percentage reduction in R&D levels for ELE and EII relative to the no tariff case. This is due in part to the fact that more knowledge can be appropriated via the carbon-saving technology now that the South is interested in reducing CO2 embodied in exports to the North. However, due to the fact that the South simply appropriates new knowledge and does not exhibit a counteracting R&D investment response, the leakage rate decreases with spillovers to the South.

In summary, the carbon tariff increases conventional and carbon-saving R&D in the North. Spillovers drive a larger percentage reduction in carbon-saving R&D investment when tariffs are present. However, when spillovers are present, carbon-saving R&D investment increases relative to the no tariff case. This suggests that the benefits associated with reduced leakage outweigh the costs to private Northern firms associated with additional appropriability of carbon-saving knowledge present in the South under the tariff. Finally, by incentivizing Northern carbon-saving R&D and spillovers of carbon-saving technology from North to South via a carbon tariff, the North can achieve greater improvements in leakage rates.

3.4.3 Welfare results

Table 3.5: No Tariff - Abatement Cost and Welfare

	NO R&D	NO SPL	NORTH SPL	FULL SPL
	Abatement Cost %Δ from BMK			
CHN	-0.208	-0.115	-0.115	-0.128
USA	-0.098	-0.013	-0.014	-0.010
RUS	0.016	-0.043	-0.043	-0.049
E15	-0.345	-0.115	-0.114	-0.114
E12	-0.135	-0.119	-0.119	-0.122
OEC	-0.769	-0.348	-0.347	-0.347
ROW	-0.214	-0.143	-0.143	-0.146
South	-0.191	-0.129	-0.129	-0.134
North	-0.368	-0.141	-0.140	-0.139
	Global Welfare %Δ from BMK			
No-Tariff	-0.236	-0.034	-0.034	-0.035

Table 3.5 and Table 3.6 show the abatement costs by each region and global welfare results for the core scenario and tariff case, respectively. Given our policy scenario setup, the different R&D assumptions and policy counterfactuals make it difficult to compare the global welfare impact strictly on a cost basis due to the emissions response from the South. Therefore, we calculate global welfare as avoided damages net of abatement costs. Abatement costs are calculated using changes in the consumption index from the benchmark — a measure of equivalent variation. A negative value for abatement cost indicates a net cost, whereas a positive value indicates a net benefit. Avoided damages are calculated as the difference from benchmark emissions resulting from the policy multiplied by the social cost of carbon, which is assumed to be 50 \$/ton of CO2. For reference, a 1% deviation from the benchmark value of global consumption expenditures plus emissions at the social cost of carbon amounts to roughly 435 billion USD.

Table 3.6: Tariff - Abatement Cost and Welfare

	No R&D	No Spl	North Spl	Full Spl
	Abatement Cost %Δ from BMK			
CHN	-1.253	-0.669	-0.669	-0.668
USA	0.051	0.074	0.074	0.075
RUS	-0.624	-0.413	-0.413	-0.413
E15	0.114	0.163	0.165	0.161
E12	-1.437	-0.839	-0.839	-0.832
OEC	-0.378	-0.121	-0.119	-0.122
ROW	-1.040	-0.597	-0.597	-0.595
South	-1.078	-0.614	-0.614	-0.611
North	-0.047	0.050	0.051	0.050
	Global Welfare %Δ from BMK			
Tariff	-0.296	-0.055	-0.054	-0.053

The welfare result for the no-tariff scenario in Table 3.5 shows a decrease in welfare across all R&D and spillover assumptions. [18] The reason for this is that abatement costs in the North and the South both decrease welfare by more than global emissions avoided increase welfare. However, welfare increases significantly in the presence of R&D. This can be seen by comparing the last row of the No R&D and No Spl columns of Table 3.5. The reason for this is twofold. First, abatement costs in the North and South decrease significantly in the presence of R&D, which has a positive welfare impact. Secondly, we see more damages avoided from smaller increases in Southern emissions in the presence of R&D, due primarily to carbon-saving technology.

In the no-tariff scenario shown in Table 3.5, welfare decreases further in the presence of spillovers from North to South. Spillovers increase abatement costs in the South and decrease them in the North. We know from the previous section that spillovers also decrease the leakage rate. This suggests that the increase in Southern abatement cost more than offsets the decrease in

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[18] Again, the welfare results are sensitive to the fact that our production structure shows a simplified fixed-proportion use of energy goods. Allowing for flexibility in the use of fossil energy inputs will decrease abatement costs and yield positive welfare responses. Future iterations of this work should update to a more accurate production structure, such as that employed in Boehringer *et al.* (2018).

abatement costs in the North combined with the benefits from decreased leakage.

The welfare results for the case of the carbon tariff are presented in Table 3.6. Given our baseline model parameterization, global welfare is lower under a tariff relative to no-tariff under all R&D assumptions. However, the intuition behind the relationships between R&D assumptions is the same as in the no-tariff scenario, except in the presence of spillovers. When full spillovers are present, our baseline model assumptions yield a global welfare increase relative to the case without spillovers. This is due to the fact that the carbon-saving technology developed in the North can be used by the South to reduce emissions embodied in trade.

It is worth noting that the carbon tariff decreases global welfare compared to the no-tariff scenario.[19] There are two main reasons for this. First, the fact that each Northern region implements an emissions cap without cross-border trade in permits means that each Northern region is subject to a different permit price. The prevailing permit price for a given region determines the carbon tariff rate. Exports from a Southern region initially intended for OEC, may be rerouted to the USA, where it is easier to reach a 10% reduction in CO2 emissions. Secondly, and more importantly, emissions intensive goods can also be diverted from Northern countries and used domestically or traded amongst regions in the South. The more easily the ability to re-route goods produced for export towards domestic use, the larger the welfare losses under a carbon tariff relative to the no-tariff case.[20] Carbon-saving R&D lessens this distortion by allowing goods to flow where they were originally intended, leading to welfare improvements.

3.5 Sensitivity analysis

All models of endogenous technical change face formidable data constraints and ours is no exception. We test the sensitivity of our main model results regarding emissions and R&D investment responses to key parameter values within our model. We first use a Monte-Carlo simulation to identify parameters to which the model output is most sensitive. Once the parameters are selected, a set of 6 scenarios for each of the no-tariff and tariff model versions produce results for

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[19] This result is sensitive to the production structure and fixed-proportions assumption. This should be updated in future iterations of this work.

[20] See Boehringer *et al.* (2014a) for a more detailed discussion.

examination. The key parameters identified relate to R&D demand and supply, the Armington trade elasticities, and the magnitude of Southern technology absorption rates.

Table 3.7: Scenario Definition

Scenario	Tariff?	pelasc	Armington Shift	pelasrd	Absorption Shift
BASE1	no	1	1	1	1
BASE2	no	0.5	1	1	1
BASE3	no	1	0.5	1	1
BASE4	no	1	1	2	1
BASE5	no	1	1	1	50
BASE6	no	1.5	1	1	1
CTAR1	yes	1	1	1	1
CTAR2	yes	0.5	1	1	1
CTAR3	yes	1	0.5	1	1
CTAR4	yes	1	1	2	1
CTAR5	yes	1	1	1	50
CTAR6	yes	1.5	1	1	1

The scenarios and associated parameterizations are provided in Table 3.7. The first two columns in Table 3.7 provide the unique scenario name and whether or not a carbon tariff is associated with that scenario. For simplicity, a scenario name that begins with "BASE" corresponds to a no-tariff case, whereas a scenario that begins with "CTAR" corresponds to a case with a carbon tariff in the North on imports from the South. Each scenario name also includes a number, which indicates the specific parameter set assigned to the scenario. Scenario Base1 and Ctar1 correspond to the core scenarios we discussed in section 3.4. The pelasc column indicates the elasticity of demand for carbon-saving R&D in the production of effective carbon. The Armington Shift column decreases the Armington elasticities for the aggregated EII and NEI sectors by half of the default weighted average value produced by the GTAP 9 aggregation routine. pelasrd relates to the demand elasticity for conventional R&D. Absorption Shift increases the Southern absorption parameters by 50 times their original value.

Table 3.8 and Table 3.9 show the results from scenario runs. Table 3.8 shows how leakage rates change as a result of the various scenarios with and without R&D and spillovers. Table 3.9

Table 3.8: Leakage Rate by Sensitivity Scenario

Scenario	No R&D	No Spl	North Spl	Full Spl	%ΔNo Spl	%ΔFull Spl
BASE1	0.503	0.249	0.249	0.246	-50.50	-1.20
BASE2	0.504	0.452	0.452	0.448	-10.32	-0.88
BASE3	0.404	0.185	0.185	0.183	-54.21	-1.08
BASE4	0.505	0.247	0.247	0.242	-51.09	-2.02
BASE5	0.503	0.249	0.249	0.205	-50.50	-17.67
BASE6	0.503	0.040	0.040	0.039	-92.05	-2.50
CTAR1	0.447	0.197	0.197	0.188	-55.93	-4.57
CTAR2	0.447	0.394	0.394	0.390	-11.86	-1.02
CTAR3	0.354	0.139	0.139	0.130	-60.73	-6.47
CTAR4	0.448	0.196	0.196	0.183	-56.25	-6.63
CTAR5	0.447	0.197	0.197	0.130	-55.93	-34.01
CTAR6	0.447	0.000	0.000	-0.025	-100.00	-Inf

%ΔNo Spl = % diff between No R&D and No Spl

%ΔFull Spl = % diff between No Spl and Full Spl

Table 3.9: R&D by Sensitivity Scenario

	ele			eii			nei			crb		
Scenario	No Spl	North Spl	Full Spl	No Spl	North Spl	Full Spl	No Spl	North Spl	Full Spl	No Spl	North Spl	Full Spl
BASE1	24.48	4.21	4.21	0.56	0.10	0.10	-0.57	-0.10	-0.10	9.674	8.152	8.151
BASE2	42.72	7.36	7.35	1.00	0.19	0.19	-1.03	-0.17	-0.17	1.155	0.969	0.969
BASE3	27.17	4.69	4.69	1.96	0.34	0.34	-0.81	-0.14	-0.14	10.577	8.924	8.922
BASE4	64.16	11.04	11.03	4.09	0.71	0.70	-1.71	-0.29	-0.29	9.601	8.091	8.088
BASE5	24.48	4.21	4.18	0.56	0.10	0.07	-0.57	-0.10	-0.09	9.674	8.152	8.118
BASE6	4.12	0.70	0.70	0.05	0.01	0.01	-0.10	-0.02	-0.02	7.100	5.944	5.944
CTAR1	25.42	4.38	4.38	0.86	0.16	0.15	-0.64	-0.11	-0.11	9.901	8.346	8.342
CTAR2	44.58	7.68	7.68	1.52	0.28	0.28	-1.15	-0.19	-0.19	1.172	0.984	0.984
CTAR3	27.89	4.81	4.81	2.07	0.35	0.35	-0.85	-0.14	-0.14	10.737	9.060	9.056
CTAR4	66.55	11.46	11.45	4.52	0.78	0.77	-1.82	-0.31	-0.31	9.824	8.281	8.275
CTAR5	25.42	4.38	4.33	0.86	0.16	0.11	-0.64	-0.11	-0.10	9.901	8.346	8.288
CTAR6	4.19	0.71	0.71	0.09	0.01	0.01	-0.11	-0.02	-0.02	7.134	5.973	5.972

is designed to capture the R&D investment response for select sectors of importance. The results in Table 3.9 for the CRB sector are given in USD billions whereas the other sectors are shown in percentage change from the benchmark value.

The model outcomes are most sensitive to the parameters governing the use of carbon-saving technology in the production of effective carbon services. Comparing BASE2 and CTAR2 to their core scenario counterparts in BASE1 and CTAR1, we can see the impact of more inelastic demand for carbon-saving R&D. The results show that the leakage rate remains relatively high in the No Spl case when PELASC is set to 0.5. Additionally, Table 3.9 shows that investment in the carbon-saving technology decreases dramatically. Together, these two aspects highlight how the importance of the carbon-saving technology in reducing leakage changes as a result of the ease with which the carbon-saving technology can reduce CO2. The more elastic demand for the carbon-saving technology is, the easier it is to reduce CO2 emissions. At higher elasticities under a carbon tariff it is possible to reach a negative leakage rate, shown by scenario CTAR6.

Due to the sensitivity of the model output to parameters dictating the behavior of carbon-saving R&D, it raises the question of how to achieve a justifiable calibration of this technology. The model produces a measure of marginal abatement cost which is a key decision factor in determining the feasibility of CCS technologies in the power sector and in general, such as direct air capture technologies. While current estimates of the marginal abatement cost for power sector CCS are near 45 USD/ton as of 2019 (Global CCS Institute, 2020), direct air capture technologies are more costly with marginal costs of capture near 200 USD/ton (Fasihi *et al.*, 2019). This is expected to decrease significantly over the coming decades as tangible regulation of CO2 emissions becomes more widespread. It is necessary to decide on a target breakeven cost of abatement for CCS, potentially using other analyses that project the deployment of CCS under different climate policy stringencies. However, once a target abatement cost for the basket of end-of-pipe technologies is decided upon, the substitution elasticity defining the production of effective carbon services can be calibrated to represent a post-policy cost of capture and storage.

Other parameters influence the results as well. Of these, the most interesting is the sensitivity to the southern absorption parameters. Small increases or decreases in the Southern absorption parameters do not matter much. However, in Table 3.9, the %ΔFull Spl column indicates that when large increases in Southern absorption capacity are modeled in BASE5/CTAR5, spillovers lead to large reductions in the leakage rate. In contrast to the result seen when North-only spillovers are modeled, this strong reduced leakage response to a Southern increase in absorption capacity arises out of the fact that the South has no ability to curtail R&D investment in response to the increased spillover benefits. Modeling Southern R&D would also not likely change this result, as benchmark R&D expenditures and absorption rates are low in the South relative to the North.

Table 3.10: Global Welfare Percentage Change from Benchmark

Scenario	No R&D	No Spl	North Spl	Full Spl
BASE1	-0.236	-0.034	-0.034	-0.035
BASE2	-0.236	-0.189	-0.194	-0.195
BASE3	-0.257	-0.033	-0.031	-0.030
BASE4	-0.236	-0.033	-0.031	-0.030
BASE5	-0.236	-0.034	-0.034	-0.067
BASE6	-0.236	0.102	0.104	0.103
CTAR1	-0.296	-0.055	-0.054	-0.053
CTAR2	-0.297	-0.241	-0.246	-0.246
CTAR3	-0.325	-0.054	-0.051	-0.050
CTAR4	-0.296	-0.053	-0.051	-0.048
CTAR5	-0.296	-0.055	-0.054	-0.080
CTAR6	-0.296	0.104	0.106	0.109

Table 3.10 shows the global welfare results for the sensitivity cases. The most noteworthy comparison relates to the importance that carbon-saving R&D plays in influencing welfare. The differences can be seen by comparing scenarios BASE1/CTAR1, BASE2/CTAR2, and BASE6/CTAR6. These show that the easier (more difficult) it is for carbon-saving R&D to reduce the raw CO2 required to produce goods, the greater (lower) the welfare benefits arising from R&D. When demand for carbon-saving R&D in production of effective carbon is relatively inelastic (BASE2/CTAR2) compared to the baseline scenarios, the welfare increase due to R&D is muted. However, when

demand is more elastic (BASE6/CTAR6), greater welfare gains can be realized by simply allowing for R&D. Additionally, the carbon tariff results in greater welfare relative to the no-tariff case when demand is relatively elastic. Finally, note the result in column Full Spl for CTAR2. This shows that when demand for carbon-saving R&D is relatively inelastic, spillovers decrease, rather than increase welfare.

3.6 Conclusion

In this paper, we explore the ability of regional climate policy to induce innovation in energy-saving and end-of-pipe carbon-saving technologies at home and abroad. We employ a global numerical model of North-South trade and different assumptions about technology creation and diffusion to show how these assumptions influence investment in R&D, emissions leakage, output, as well as abatement cost and welfare. We discuss how these factors interact with a Northern emissions cap as well as a carbon tariff levied on Northern imports from Southern regions.

Under conventional emissions policy counterfactual scenarios, we find that innovation tends toward R&D in carbon-saving technology, and that this channel of innovation provides significant benefits in terms of leakage reduction and abatement cost savings. This is due to the fact that the carbon-saving technology allows the North to meet CO2 restrictions without abating as much fossil fuel use. This leaves demand for fossil fuels closer to pre-policy levels in the North, and global prices similarly high. As a result, the South does not increase emissions by as much.

As spillovers associated with the carbon-saving technology are directly neglected by the South under a cap, we couple this with a carbon tariff. This is done to incentivize diffusion of this carbon-saving technology from North to South. We find that the carbon tariff exhibits typical characteristics such as a redistribution of abatement cost from North to South and a minimal-to-slight increase in abatement costs relative to a case without a tariff. Also, the carbon tariff provides further leakage reduction. R&D and spillovers from North to South drive further leakage reductions relative to a case without a tariff. Similarly to the no-tariff case, R&D drives significant cost reduction. However, assumptions about the ease with which carbon-saving R&D translates to lower levels of raw CO2 content significantly influences the degree to which technology diffusion and the carbon-saving technology impact welfare. In particular, the easier it is to reduce emissions embodied in output with carbon-saving R&D, the more attractive a carbon tariff looks in comparison to a Northern cap without a tariff.

The analysis is static in that we assume an initial steady-state and analyze this in comparison to a steady-state that results from a reduction in Northern emissions. Therefore, we neglect some of the dynamic aspects of the learning process — such as learning-by-doing — and abstract from some of the finer details related to renewable energy and clean backstop technologies. However, given the objective of this work, we have identified several unique benefits to end-of-pipe carbon-saving technology within the context of international commodity markets.

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APPENDIX A - TPS MODEL: NUMERICAL MODEL EQUATIONS

The discount factor for the purposes of the numerical model is given by:

$$df_t = (\frac{1}{1+r})^t \tag{A.1}$$

The equations of the numerical model for the TPS with discounting are shown below:

$$\sum_f X_{ft} \geq Q_t \quad \perp PD_t \geq 0 \tag{A.2}$$

$$K_{ft} \geq X_{ft} \quad \perp PK_{f,t} \geq 0 \tag{A.3}$$

$$I_{ft} + K_{f,t-1}(1-\delta) \geq K_{ft} \quad \perp PI_{f,t} \geq 0 \tag{A.4}$$

$$\sigma_t \geq \frac{\sum_f \omega_f X_{ft}}{\sum_f X_{ft}} \quad \perp PTPS_t \geq 0 \tag{A.5}$$

$$df_t * \overline{pq}_t * (\frac{Q_t}{\overline{d}_t})^{1/\epsilon} - PD_t \geq 0 \quad \perp Q_t \geq 0 \tag{A.6}$$

$$df_t MC^X_{ft}(X_{ft}) + PK_{ft} + PTPS_t(\omega_f - \sigma_t)hiy - PD_t \geq 0 \quad \perp X^{TPS}_{ft} \geq 0 \tag{A.7}$$

$$-PK_{ft} - PI_{f,t+1}(1-\delta) + PI_{ft} \geq 0 \quad \perp K_{ft} \geq 0 \tag{A.8}$$

$$df_t MC^I_{ft}(I_{ft}) - PI_{ft} \geq 0 \quad \perp I_{ft} \geq 0 \tag{A.9}$$

Where marginal investment costs are linear such that:

$$MC^I_{ft} = [\alpha + \beta_f * I_{f,t}] \tag{A.10}$$

And benchmark output prices a related by:

$$\overline{pq}_t = \frac{\overline{pd}_t}{df_t} \tag{A.11}$$

The equations for the model with the CAP are the same except I replace equations A.5 and A.7 with:

$$\Omega_t \geq \sum_f \omega_f X_{ft} \quad \perp PCAP_t \geq 0 \tag{A.12}$$

$$df_t MC^X_{ft}(X_{ft}) + PK_{ft} + PCAP_t \omega_f hiy - PD_t \geq 0 \quad \perp X^{CAP}_{ft} \geq 0 \tag{A.13}$$

APPENDIX B - TPS MODEL: WELFARE CALCULATIONS

Changes in periodic discounted consumer surplus are given by:

$$\Delta CS_t = -\frac{\overline{d}_t PD_t^{-\epsilon}(\overline{pd}_t PD_t^{\epsilon} - \overline{pd}_t^{\epsilon} PD_t)}{(\epsilon - 1)} \tag{B.1}$$

Changes in periodic discounted producer surplus are given by:

$$PS_t = PD_t \sum_f X_{ft} - df_t \sum_f MC_{ft}^X X_{ft} \tag{B.2}$$

$$\Delta PS_t^{policy} = PS_t^{policy} - PS_t^{BAU} \tag{B.3}$$

where marginal costs are constant. Revenues from the CAP are refunded to producers, leaving periodic changes in total policy cost equal to 0 when summed across fuel types. Policy costs are also 0 when summed across fuel types for the TPS.

Investment costs are obtained by integrating the marginal investment cost function from 0 to I_{ft}. The function is given below:

$$CInv_t = df_t \sum_f [\alpha_f I_{ft} + \frac{1}{2}\beta_f I_{ft}^2] \tag{B.4}$$

Change is analogous to that of ΔPS in that:

$$\Delta CInv_t^{policy} = CInv_t^{policy} - CInv_t^{BAU} \tag{B.5}$$

Change in periodic discounted avoided damages is given by:

$$Dam_t = 20 * mtCO2_t * df_t \tag{B.6}$$

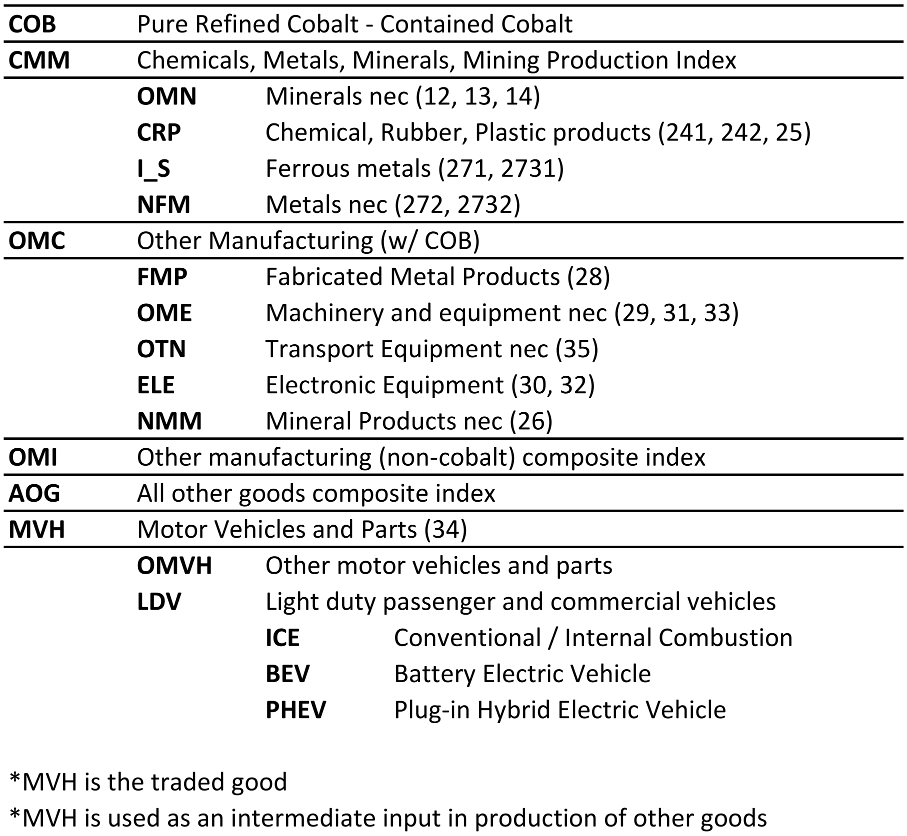
$$\Delta Dam_t = Dam_t^{BAU} - Dam_t^{policy} \tag{B.7}$$

Each of the equations listed thus far are indexed by time, hence, they are periodic discounted flows of the respective changes from the benchmark. In order to calculate the total present value of each figure, I sum from the present to the steady state, and then take the value for the final period and discount it perpetually as follows:

$$\Delta CS = \sum_{t=0}^{T} \Delta CS_t + \frac{\Delta CS_T}{r} \tag{B.8}$$

where T is a period within the steady-state. This same formula applies for any of the surplus components ΔPS, $\Delta CInv$, ΔAC, ΔDam, or ΔSS.

APPENDIX C - COBALT MODEL: SECTORAL AND FIRST-USE TO FINAL-USE MAPPING



COB	Pure Refined Cobalt - Contained Cobalt		
CMM	Chemicals, Metals, Minerals, Mining Production Index		
	OMN	Minerals nec (12, 13, 14)	
	CRP	Chemical, Rubber, Plastic products (241, 242, 25)	
	I_S	Ferrous metals (271, 2731)	
	NFM	Metals nec (272, 2732)	
OMC	Other Manufacturing (w/ COB)		
	FMP	Fabricated Metal Products (28)	
	OME	Machinery and equipment nec (29, 31, 33)	
	OTN	Transport Equipment nec (35)	
	ELE	Electronic Equipment (30, 32)	
	NMM	Mineral Products nec (26)	
OMI	Other manufacturing (non-cobalt) composite index		
AOG	All other goods composite index		
MVH	Motor Vehicles and Parts (34)		
	OMVH	Other motor vehicles and parts	
	LDV	Light duty passenger and commercial vehicles	
		ICE	Conventional / Internal Combustion
		BEV	Battery Electric Vehicle
		PHEV	Plug-in Hybrid Electric Vehicle

*MVH is the traded good

*MVH is used as an intermediate input in production of other goods

Figure C.1: Model to GTAP to ISIC Rev. 3.1 Concordance

First-use		Final-use in Mfg. (ISIC Rev. 4)
batt	Batteries	2818 Power-driven hand tools 3091 Motorcycles
supa	Superalloys	2811 Engines/turbines,excl.aircraft,vehicle engines 3030 Air and spacecraft and related machinery 3250 Medical and dental instruments and supplies
hard	Hard Metal Objects	2593 Cutlery, hand tools and general hardware
mago	Magnets / Other	26 Manufacture of computer, electronic, and optical products 2710 Electric motors,generators,transformers,etc.
cata	Catalysts	2220 Plastics products GTAP OIL and GAS Sectors
pigm	Pigments	2022 Paints,varnishes;printing ink and mastics 2029 Other chemical products n.e.c. 2310 Glass and glass products 2393 Other porcelain and ceramic products
soap	Soap/Detergent	2023 Soap,cleaning and cosmetic preparations

Figure C.2: Mapping – first-use to final-use in manufacturing

APPENDIX D - COBALT MODEL: ALGEBRAIC FORMULATION

D.1 Definitions

Sets and indices are listed in Table D.1. Activity levels are listed in Table D.2. Prices are listed in Table D.3. Income is listed in Table D.4. Cost shares and elasticities are listed in Table D.5 and Table D.6, respectively. Endowments and other parameters are listed in Table D.7.

Table D.1: Indices and sets

g	Index for sectors and goods. Includes private consumption good (C), govt (G), and investment (I)
i (*alias* j)	Subset of g representing goods not including C, G, I.
f	Index for factors. Capital and Labor.
r (*alias* s)	Index for Region

Table D.2: Variables - Activity Levels

$Y_{g,r}$	Output/production in sector g region r
$A_{i,r}$	Armington composite in sector i region r
$M_{i,r}$	Import composite in sector i region r
$X_{i,r}$	Exports of i from r
$QX_{i,r}$	Endogenous export tax implied by quota constraint

Table D.3: Variables - Price Levels

$p^{F}_{f,r}$	Price of factor f in region r
$p^{VA}_{g,r}$	Price index of VA used to produce g in region r
$p^{IV}_{g,r}$	Price index of Intermediate and value-added inputs used to produce g in region r
$p^{A}_{i,r}$	Price index of Armington good i in region r
$p^{M}_{i,r}$	Price index on imported goods
$p^{X}_{i,r}$	price of good i produced for export from southern region r to North
p^{W}_{i}	World price of good $i = COB$
$p^{Y}_{g,r}$	Price of output goods Y
$p^{RCO}_{g,r}$	Price of fixed natural resource factor for $g = COB$

Table D.4: Variables - Income Levels

ZRA_r	Household income for representative agent in region r

Table D.5: Cost shares

General Model	
$\theta^{VA}_{f,g,r}$	share of value-added attributable to factor f
$\theta^{INT}_{i,g,r}$	share of total intermediate input used in g attributable to input i
$\theta^{IV}_{g,r}$	share INT,VA attributable to VA composite
$\theta^{COB}_{g,r}$	share of output attributable to COB use
$\theta^{A}_{i,r}$	share of armington output attributable to domestic variety input i
$\theta^{M}_{i,r,s}$	share of imports of good i from region r to region s
$\theta^{MVH}_{i,g,r}$	share of $g = MVH$ output attributable to $i = OMVH, LDV$
$\theta^{LDV}_{i,g,r}$	share of $g = LDV$ output attributable to $i = ICE, BEV, PHEV$
$\theta^{RCO}_{g,r}$	share of $g = COB$ output attributable to fixed resource factor RCO

Table D.6: Elasticities

σ^{IV}	Substitution between intermediate inputs *i* and VA composite in production of IV composite
σ^{VA}	Substitution between factor inputs capital and labor in the VA composite
σ^{LDV}	Substitution between ICE, BEV, and PHEV in LDV output block
σ^{MVH}	Substitution between OMVH and LDV in MVH output block
σ^{RCO}	Substitution between RCO and VA in COB output block
σ_g^{COB}	Substitution between COB and IV in output block for non-cobalt
σ^{M}	Substitution between imports from different regions
σ^{A}	Substitution between the import aggregate (M) and the domestic input (Y)

Table D.7: Endowments and other parameters

$\overline{F}_{f,r}$	Factor endowment for capital or labor input
$\overline{RCO}_{g,r}$	Fixed natural resource factor endowment
$\overline{G}_r$	Fixed public good demand
$\overline{I}_r$	Fixed investment demand
$\overline{B}_r$	Balance of payment
$\overline{qr}_{i,r}$	Quota levied on exports of good *i* from region *r*

D.2 Zero Profit Conditions

D.2.1 Production of goods

The unit profit function for the value-added index is shown below:

$$\Pi^{VA}_{g,r} = p^{VA}_{g,r} - \left[\sum_{f} \theta^{VA}_{f,g,r}\, p^{F}_{f,r}{}^{1-\sigma^{VA}}\right]^{\frac{1}{1-\sigma^{VA}}} \leq 0 \tag{D.1}$$

Unit profit for index of intermediate inputs and value added:

$$\Pi^{IV}_{g,r} = p^{IV}_{g,r} - \left[\theta^{IV}_{g,r} p^{VA}_{g,r}{}^{1-\sigma^{IV}} + \sum_{i} (1-\theta^{IV}_{g,r})\theta^{INT}_{i,g,r}\, p^{A}_{i,r}{}^{1-\sigma^{IV}}\right]^{\frac{1}{1-\sigma^{IV}}} \leq 0 \tag{D.2}$$

Unit profit for all goods except MVH, LDV, and COB:

$$\Pi^{Y}_{g,r} = p^{Y}_{g,r} - \left[\theta^{COB}_{g,r}\, p^{Y}_{COB,r}{}^{1-\sigma^{COB}_{g}} + (1-\theta^{COB}_{g,r}) p^{IV}_{g,r}{}^{1-\sigma^{COB}_{g}}\right]^{\frac{1}{1-\sigma^{COB}_{g}}} \leq 0 \tag{D.3}$$

Unit profit for $g = MVH$:

$$\Pi^{Y}_{g,r} = p^{Y}_{g,r} - \left[\sum_{i} \theta^{MVH}_{i,g,r}\, p^{Y}_{i,r}{}^{1-\sigma^{MVH}}\right]^{\frac{1}{1-\sigma^{MVH}}} \leq 0 \tag{D.4}$$

Unit profit for $g = LDV$:

$$\Pi^{Y}_{g,r} = p^{Y}_{g,r} - \left[\sum_{i} \theta^{LDV}_{i,g,r}\, p^{Y}_{i,r}{}^{1-\sigma^{LDV}}\right]^{\frac{1}{1-\sigma^{LDV}}} \leq 0 \tag{D.5}$$

Unit profit for $g = COB$ production:

$$\Pi^{Y}_{g,r} = p^{Y}_{g,r} - \left[\theta^{RCO}_{g,r}\, p^{RCO}_{g,r}{}^{1-\sigma^{RCO}} + (1-\theta^{RCO}_{g,r}) p^{VA}_{g,r}{}^{1-\sigma^{RCO}}\right] \leq 0 \tag{D.6}$$

D.2.2 Armington Aggregate

Unit profit function for armington index:

$$\Pi^{A}_{i,r} = p^{A}_{i,r} - \left[(1-\theta^{A}_{i,r}) p^{M}_{i,r}{}^{1-\sigma^{A}} + \theta^{A}_{i,r} p^{Y}_{i,r}{}^{1-\sigma^{A}}\right]^{\frac{1}{1-\sigma^{A}}} \leq 0 \tag{D.7}$$

D.2.3 Trade

Unit profit function for imports of armington goods:

$$\Pi^{M}_{i,r} = p^{M}_{i,r} - \left[\sum_{s} \theta^{M}_{i,s,r} p^{Y}_{i,s}{}^{1-\sigma^{M}}\right]^{\frac{1}{1-\sigma^{M}}} \leq 0 \tag{D.8}$$

Unit profit function for COB imports:

$$\Pi^{M}_{i,r} = p^{Y}_{i,r} - \sum_{s} \theta^{M}_{i,s,r} p^{W}_{i} \leq 0 \tag{D.9}$$

Unit profit function for COB exports:

$$\Pi^{X}_{i,r} = \sum_{s} \theta^{M}_{i,r,s} p^{W}_{i} - p^{Y}_{i,r}(1 + QX_{i,r}) \leq 0 \tag{D.10}$$

D.3 Market Clearance Conditions

D.3.1 Factor Market Clearance

Market clearance for factors of production (capital and labor):

$$\overline{F}_{f,r} \geq \sum_{g} Y_{g,r} \frac{\partial \Pi^{Y}_{g,r}}{\partial p^{F}_{f,r}} \tag{D.11}$$

Market clearance for the fixed natural resource factor ($g \in COB$):

$$\overline{RCO}_{g,r} \geq Y_{g,r} \frac{\partial \Pi^{Y}_{g,r}}{\partial p^{RCO}_{g,r}} \tag{D.12}$$

D.3.2 Goods Market Clearance

Output enters Armington supply and import supply:

$$Y_{i,r} \geq \sum_{j} A_{j,r} \frac{\partial \Pi^{A}_{j,r}}{\partial p^{Y}_{i,r}} + \sum_{s} M_{i,s} \frac{\partial \Pi^{M}_{j,s}}{\partial p^{Y}_{i,r}} \tag{D.13}$$

Armington supply enters output supply:

$$A_{i,r} \geq \sum_{g} Y_{g,r} \frac{\partial \Pi^{Y}_{g,r}}{\partial p^{A}_{i,r}} \tag{D.14}$$

Import supply enters Armington supply:

$$M_{i,r} \geq A_{i,r} \frac{\partial \Pi^{A}_{i,r}}{\partial p^{M}_{i,r}} \tag{D.15}$$

Cobalt output enters the domestic supply and export supply associated with other goods:

$$Y_{i,r} \geq \sum_{j} Y_{j,r} \frac{\partial \Pi^{Y}_{j,r}}{\partial p^{Y}_{i,r}} + X_{i,r} \frac{\partial \Pi^{X}_{i,r}}{\partial (p^{Y}_{i,r}(1 + QX_{i,r}))} \tag{D.16}$$

Cobalt Export Supply enters world market:

$$X_{i,r} \geq \sum_{s} M_{i,s} \frac{\partial \Pi^M_{i,s}}{\partial p^W_i} \tag{D.17}$$

Cobalt import supply enters production of output goods:

$$M_{i,r} \geq \sum_{j} Y_{j,r} \frac{\partial \Pi^Y_{j,r}}{\partial p^Y_{i,r}} \tag{D.18}$$

LDV and OMVH Supply equals demand for LDV and OMVH in MVH:

$$Y_{i,r} \geq \sum_{j} Y_{j,r} \frac{\partial \Pi^Y_{j,r}}{\partial p^Y_{i,r}} \tag{D.19}$$

BEV, ICE, and PHEV supply equals demand for those goods in LDV:

$$Y_{i,r} \geq \sum_{j} Y_{j,r} \frac{\partial \Pi^Y_{j,r}}{\partial p^Y_{i,r}} \tag{D.20}$$

Public Consumption covers fixed govt demand:

$$Y_{G,r} \geq \overline{G}_r \tag{D.21}$$

Production of investment covers fixed investment demand:

$$Y_{I,r} \geq \overline{I}_r \tag{D.22}$$

Production of private consumption index covers private consumption demand:

$$Y_{C,r} \geq \frac{ZRA_r}{p^Y_{C,r}} \tag{D.23}$$

D.4 Income Balance Conditions

Income balance condition for representative agent:

$$\begin{aligned} ZRA_r = {} & p^F_{f,r}\overline{F}_r + p^{RCO}_{i,r}\overline{RCO}_{i,r} \\ & + \sum_i \frac{\partial \Pi^X_{i,r}}{\partial (p^Y_{i,r}(1 + QX_{i,r}))} X_{i,r} p^Y_{i,r} QX_{i,r} \\ & - p^Y_{I,r}\overline{Y}_{I,r} - p^Y_{G,r}\overline{Y}_{G,r} + \overline{B}_{rnum} \end{aligned} \tag{D.24}$$

D.5 Quota

The quota is specified as follows:

$$\overline{qr}_{i,r} \geq X_{i,r} \quad \perp QX_{i,r} \tag{D.25}$$

where $\overline{qr}_{i,r}$ is the COB export quota. $QX_{i,r}$ is the endogenous tariff rate extracted from the marginal of the constraint. This enters the COB export block as an endogenous tariff.

APPENDIX E - SPILLOVER MODEL: CALIBRATION DATA

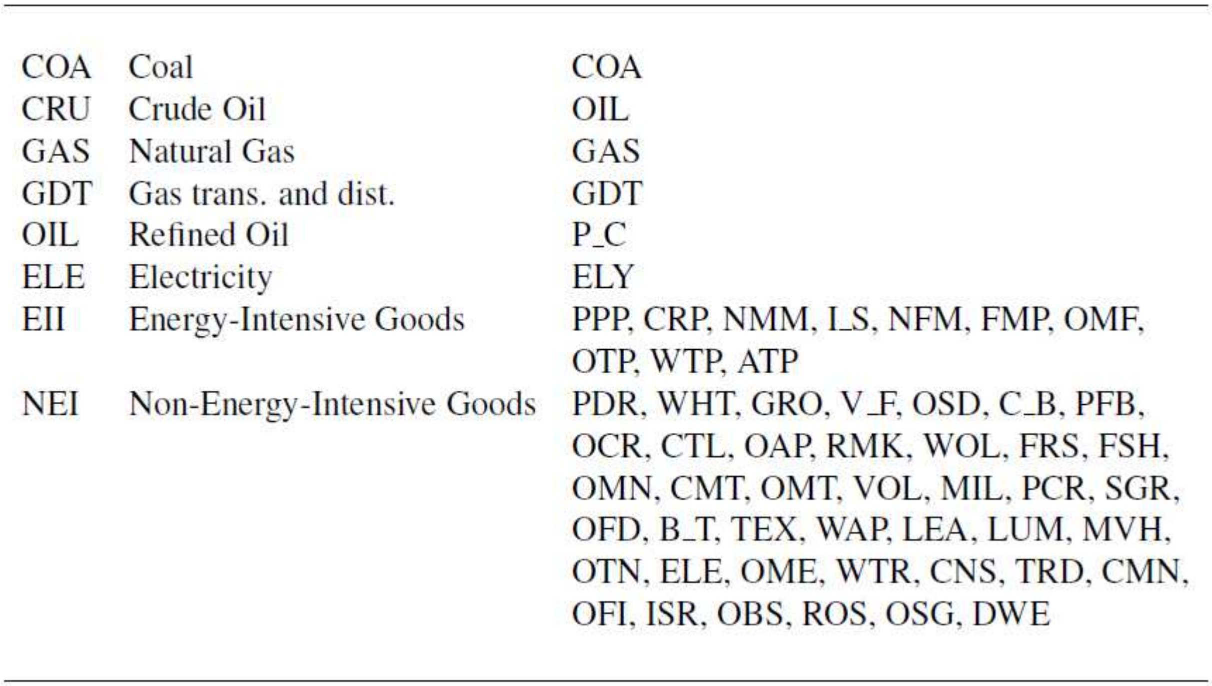
Table E.1: Calculated absorption capacity weights

	coa	oil	gas	ele	gdt	eii	nei	cru
CHN	2.507	0.576	0.000	0.424	0.000	0.383	0.234	0.524
USA	0.488	0.479	0.199	0.103	0.292	0.492	0.410	0.484
RUS	0.014	0.039	0.053	0.006	0.432	0.032	0.029	0.068
E15	0.071	0.195	0.078	0.454	0.499	0.234	0.295	0.058
E12	0.012	0.088	0.000	0.014	0.014	0.014	0.013	0.001
OEC	0.441	0.326	0.724	0.443	0.210	0.273	0.295	0.458
ROW	0.054	0.177	0.129	0.131	0.524	0.128	0.161	0.238

APPENDIX F - SPILLOVER MODEL: GTAP9 TO MODEL MAPPINGS

CHN	China	CHN
USA	United States	USA
E15	Old EU Member States	AUT, BEL, DNK, FIN, FRA, DEU, GBR, GRC, IRL, ITA, LUX, NLD, PRT, ESP, SWE
E12	New EU Member States	BGR, CYP, CZE, HUN, MLT, POL, ROM, SVK, SVN, EST, LVA, LTU
RUS	Russia	RUS, XSU
OEC	Other OECD	AUS, NZL, JPN, KOR, CAN, MEX, CHE, NOR, XEF, TUR
ROW	Rest of World	XOC, HKG, MNG, TWN, XEA, BRN, KHM, IDN, LAO, MYS, PHL, SGP, THA, VNM, XSE, BGD, IND, NPL, PAK, LKA, XSA, XNA, ARG, BOL, BRA, CHL, COL, ECU, PRY, PER, URY, VEN, XSM, CRI, GTM, HND, NIC, PAN, SLV, XCA, DOM, JAM, PRI, TTO, XCB, ALB, BLR, HRV, UKR, XEE, XER, KAZ, KGZ, ARM, AZE, GEO, BHR, IRN, ISR, JOR, KWT, OMN, QAT, SAU, ARE, XWS, EGY, MAR, TUN, XNR, BEN, BFA, CMR, CIV, GHA, GIN, NGA, SEN, TGO, XWF, XCF, XAC, ETH, KEN, MDG, MWI, MUS, MOZ, RWA, TZA, UGA, ZMB, ZWE, XEC, BWA, NAM, ZAF, XSC, XTW

Figure F.1: Mapping from GTAP9 Regions to Model Regions



COA	Coal	COA
CRU	Crude Oil	OIL
GAS	Natural Gas	GAS
GDT	Gas trans. and dist.	GDT
OIL	Refined Oil	P_C
ELE	Electricity	ELY
EII	Energy-Intensive Goods	PPP, CRP, NMM, I_S, NFM, FMP, OMF, OTP, WTP, ATP
NEI	Non-Energy-Intensive Goods	PDR, WHT, GRO, V_F, OSD, C_B, PFB, OCR, CTL, OAP, RMK, WOL, FRS, FSH, OMN, CMT, OMT, VOL, MIL, PCR, SGR, OFD, B_T, TEX, WAP, LEA, LUM, MVH, OTN, ELE, OME, WTR, CNS, TRD, CMN, OFI, ISR, OBS, ROS, OSG, DWE

Figure F.2: Mapping from GTAP9 Sectors to Model Sectors

APPENDIX G - SPILLOVER MODEL: ALGEBRAIC FORMULATION

G.1 Definitions

Sets and indices are listed in Table G.1. Activity levels are listed in Table G.2. Prices are listed in Table G.3. Income is listed in Table G.4. Cost shares and elasticities are listed in Table G.5 and Table G.6, respectively. Endowments and other parameters are listed in Table G.7.

Table G.1: Indices and sets

g	Index for sectors and goods. Includes private consumption good (C), govt (G), and investment (I)
i (*alias* j)	Subset of g representing goods not including C, G, I.
f	Index for factors. Capital and Labor.
r (*alias* s)	Index for Region
NE	Set of non-energy goods. Can also be used to represent aggregate index of these goods
FE	Set of final-energy goods, fuels with co2 emissions. Can also be used to represent aggregate index of these goods
XE	Set of primary fossil-fuel goods. Can also be used to represent aggregate index of these goods
STH	Set of regions in South
NTH	Set of regions in North

Table G.2: Variables - Activity Levels

$Y_{g,r}$	Output/production in sector g region r
$A_{i,r}$	Armington composite in sector i region r
$M_{i,r}$	Import composite in sector i region r
$R_{i,r}$	Conventional energy-saving R&D production
RC_r	End-of-pipe Carbon-saving R&D production
$SPL_{i,r}$	Pre-existing Conventional energy-saving knowledge plus Spillovers of new knowledge
$SPLC_r$	Pre-existing carbon-saving knowledge plus Spillovers of new knowledge
CRB_r	Effective carbon services provided to r
$SNC_{r,s}$	Effective carbon services in exports from r to s
$X_{i,r}$	Exports of i from r
$XS_{i,r,s}$	Exports of i from r to s
$D_{g,r}$	Southern output for domestic use or for export to other southern regions
$TAR_{r,s}$	Variable used to ration $\overline{cbim}_{r,s}$

G.2 Zero Profit Conditions

G.2.1 Production of goods

Production of commodities are captured by nested CES cost functions. At the top level, conventional knowledge services trade off with an index of sectoral output ex-R&D. At the second level, new conventional knowledge services are produced using intermediate goods. Also, non-r&d goods are produced using a combination of non-energy and energy intermediate goods that are substitutable with an aggregate index of value added factors. Final energy goods are used in fixed proportion with effective carbon services. At the third level, the value-added index is produced using capital and labor inputs. Effective carbon services are defined by a CES production function determined by carbon-saving knowledge services and a raw carbon factor. Finally, new carbon-saving knowledge services are produced using a combination of intermediate goods.

The unit profit function for new carbon-saving R&D is shown below:

Table G.3: Variables - Price Levels

$p^{R}_{i,r}$	Price of conventional energy-saving R&D (knowledge services)
p^{RC}_{r}	Price of carbon-saving R&D (knowledge services)
$p^{F}_{f,r}$	Price of factor f in region r
$p^{FE}_{i,r}$	Price index of FE used to produce i in region r
$p^{VA}_{i,r}$	Price index of VA used to produce i in region r
p^{CRB}_{r}	Price of effective carbon in region r
p^{co2}_{r}	Price of raw co2 emissions in region r
$p^{A}_{i,r}$	Price index of Armington good i in region r
$p^{NRD}_{g,r}$	Price index of NRD index. All goods ex-Conventional R&D
$p^{M}_{i,r}$	Price index on imported goods
$p^{Y}_{g,r}$	Price of output
$p^{RS}_{i,r}$	Price of fixed natural resource factor for $i \in XE$
$p^{SNC}_{r,s}$	Price of effective carbon in exports from r to s
$p^{snco2}_{r,s}$	Price of raw co2 emissions in exports from r to s
$p^{D}_{g,r}$	price of good g produced for domestic use in southern region r or for export by southern region r to other southern regions
$p^{X}_{i,r}$	price of good i produced for export from southern region r to North
$p^{XS}_{i,r,s}$	price of good i produced for export from southern region r to northern region s

Table G.4: Variables - Income Levels

ZHH_r	Household income for representative agent in region r

Table G.5: Cost shares

General Model	
θ_r^{CRB}	share of effective carbon services attributable to raw co2 emissions
$\theta_{i,r}^{RC}$	share of carbon-saving R&D attributable to intermediate input *i*
$\theta_{i,g,r}^{R}$	share of conventional R&D for sector *g* attributable to intermediate input *i*
$\theta_{f,g,r}^{VA}$	share of value-added attributable to factor *f*
$\theta_{i,g,r}^{FE}$	share fossil energy attributable to input $i \in FE$
$\theta_{*,g,r}^{NRD}$	share of non-R&D and non-resource factor output attributable to VA, FE, and $i \in NE$
$\theta_{g,r}^{RD}$	share of output attributable to conventional R&D services
$\theta_{*,g,r}^{RS}$	share of output in *g* attributable to RS or RD
$\theta_{i,r}^{A}$	share of armington output attributable to domestic variety input *i*
$\theta_{i,r,s}^{M}$	share of imports of good i from region *r* to region *s*

Southern Modification	
$\theta_{f,g,r,s}^{VA}$	share of value-added attributable to factor *f*
$\theta_{*,g,r,s}^{NRD}$	share of non-R&D and non-resource factor output attributable to VA, FE, and $i \in NE$
$\theta_{g,r,s}^{RD}$	share of output attributable to conventional R&D services
$\theta_{*,g,r,s}^{RS}$	share of output attributable to RS or RD
$\theta_{r,s}^{SNC}$	share of effective carbon services attributable to raw co2 emissions
$\theta_{g,r}^{D}$	share of output of good *g* of southern region *r* produced for domestic use in southern region *r* or for export by southern region *r* to other southern regions
$\theta_{i,r}^{X}$	share of output of good *i* of southern region *r* produced for export to North
$\theta_{i,r,s}^{XS}$	share of exports of good *i* of southern region *r* produced for export to northern region *s*.

Table G.6: Elasticities

σ^{RC}	Substitution between intermediate inputs i in production of carbon-saving R&D
σ^{CRB}	Substitution between carbon-saving R&D and raw co2 factor in the CRB composite
σ^{VA}	Substitution between factor inputs capital and labor in the VA composite
σ^{FE}	Substitution between final energy inputs in the FE composite
σ^{R}	Substitution between intermediate inputs in production of energy-saving R&D
σ^{NRD}	Substitution between the VA index, and all other inputs in the NRD composite
σ^{RD}	Substitution between R and NRD in output block for non-primary fossil resources
σ^{RS}	Substitution between RS, R, and NRD in the output block for primary-fossil resources
σ^{M}	Substitution between imports from different regions
σ^{A}	Substitution between the import aggregate (M) and the domestic input (Y)
σ^{X}	Substitution between exports for different regions (XS) in the South-North Export Composite (X)
σ^{DX}	Substitution between the Domestic (D) and Export (X) Composites in production of Southern Output (Y)

Table G.7: Endowments and other parameters

$\overline{F}_{f,r}$	Factor endowment for capital or labor input
$\overline{RS}_{g,r}$	Fixed natural resource factor endowment
$\overline{G}_r$	Fixed public good demand
$\overline{I}_r$	Fixed investment demand
$\overline{B}_r$	Balance of payment
$\overline{CO2}_r$	co2 emissions cap
$\overline{cbim}_{r,s}$	co2 emissions endowment in imports by region *r* from region *s*
$\overline{dk}_{i,r}$	benchmark demand for conventional knowledge services
$\overline{rd}_{i,r}$	benchmark new investment supply for conventional knowledge services
$\overline{ks}_{i,r}$	benchmark pre-existing supply of conventional knowledge services
$\overline{rdc}_r$	benchmark carbon-saving R&D scale parameter set to 1
$\overline{cb}_r$	benchmark demand for co2 emissions region *r*
$\gamma_{i,r}$	Absorption rate calculation
$\alpha^{ABS}_{i,r,s}$	Absorption rate modification for spillover constraint
$a_{i,g,r}$	co2 emissions coefficient for fuel *i* in sector *g* and region *r*
δ	Depreciation rate on knowledge
g	Growth rate
r	Interest rate

$$\Pi_r^{RC} = p_r^{RC} - \left[\sum_i \theta_{ir}^{RC} p_{ir}^{Y^{1-\sigma^{RC}}} \right]^{\frac{1}{1-\sigma^{RC}}} \leq 0 \tag{G.1}$$

The unit profit function for effective carbon-services is shown below:

$$\Pi_r^{CRB} = p_r^{CRB} - \left[\theta_r^{CRB} p_r^{co2^{1-\sigma^{CRB}}} + (1 - \theta_r^{CRB}) p_r^{RC^{1-\sigma^{CRB}}} \right]^{\frac{1}{1-\sigma^{CRB}}} \leq 0 \tag{G.2}$$

The unit profit function for the value-added index is shown below:

$$\Pi_{g,r}^{VA} = p_{g,r}^{VA} - \left[\sum_f \theta_{f,g,r}^{VA} \, p_{f,r}^{F\ 1-\sigma^{VA}} \right]^{\frac{1}{1-\sigma^{VA}}} \leq 0 \tag{G.3}$$

The unit profit function for the final energy index is shown below:

$$\Pi_{g,r}^{FE} = p_{g,r}^{FE} - \left[\sum_{i \in fe} \theta_{i,g,r}^{FE} \, (p_{i,r}^{A} + p_r^{CRB} a_{i,g,r}^{co2})^{1-\sigma^{FE}} \right]^{\frac{1}{1-\sigma^{FE}}} \leq 0 \tag{G.4}$$

The unit profit function for new energy-saving conventional knowledge services:

$$\Pi_{g,r}^{R} = p_{gr}^{R} - \left[\sum_i \theta_{igr}^{R} p_{ir}^{Y^{1-\sigma^{R}}} \right]^{\frac{1}{1-\sigma^{R}}} \leq 0 \tag{G.5}$$

The unit profit function for all goods except conventional knowledge services index shows substitution between VA, FE, and all other goods except r&d (NRD), below:

$$\begin{aligned} &\Pi_{g,r}^{NRD} = p_{g,r}^{NRD} - \\ &\left[\theta_{VA,g,r}^{NRD} p_{g,r}^{VA^{1-\sigma^{NRD}}} + \theta_{FE,g,r}^{NRD} p_{g,r}^{FE^{1-\sigma^{NRD}}} + \sum_{i \in NE} \theta_{i,g,r}^{NRD} \, p_{ir}^{A^{1-\sigma^{NRD}}} \right]^{\frac{1}{1-\sigma^{NRD}}} \\ &\leq 0 \end{aligned} \tag{G.6}$$

assuming FE is produced in fixed proportions ($\sigma^{FE} = 0$) and that NRD is in fixed proportions ($\sigma^{NRD} = 0$), substituting G.4 into G.6 and applying the elasticity values yields:

$$\begin{aligned} &\Pi_{g,r}^{NRD} = p_{g,r}^{NRD} - \\ &\left[\theta_{VA,g,r}^{NRD} p_{g,r}^{VA} + \sum_{i \in FE} \theta_{i,g,r}^{NRD} \, (p_{i,r}^{A} + p_r^{CRB} a_{i,g,r}^{co2}) + \sum_{i \in NE} \theta_{i,g,r}^{NRD} \, p_{i,r}^{A} \right] \\ &\leq 0 \end{aligned} \tag{G.7}$$

The unit profit function for non-fossil-fuel goods: $g \notin xe$

$$\begin{aligned}&\Pi^{Y}_{g,r} = p^{Y}_{g,r} - \\ &\left[\theta^{RD}_{g,r} p^{R\,1-\sigma^{RD}}_{g,r} + (1-\theta^{RD}_{g,r}) p^{NRD\,1-\sigma^{RD}}_{g,r}\right]^{\frac{1}{1-\sigma^{RD}}} \\ &\leq 0\end{aligned} \tag{G.8}$$

The unit profit function for fossil-fuel goods: $g \in xe$

$$\begin{aligned}&p^{Y}_{gr} = c^{Y}_{gr} = \\ &\left[\theta^{RS}_{RS,g,r} p^{RS\,1-\sigma^{RS}}_{gr} + \theta^{RS}_{RD,g,r} p^{R\,1-\sigma^{RS}}_{gr} + (1-\theta^{RS}_{RS,g,r} - \theta^{RS}_{RD,g,r}) p^{NRD\,1-\sigma^{RS}}_{gr}\right]^{\frac{1}{1-\sigma^{RS}}} \\ &\leq 0\end{aligned} \tag{G.9}$$

G.2.2 Armington Aggregate

Unit profit function for armington index:

$$\Pi^{A}_{i,r} = p^{A}_{i,r} - \left[(1-\theta^{A}_{i,r}) p^{M\,1-\sigma^{A}}_{i,r} + \theta^{A}_{i,r} p^{Y\,1-\sigma^{A}}_{i,r}\right]^{\frac{1}{1-\sigma^{A}}} \leq 0 \tag{G.10}$$

G.2.3 Import Aggregate

Unit profit function for imports:

$$\Pi^{M}_{i,r} = p^{M}_{i,r} - \left[\sum_{s} \theta^{M}_{i,s,r} p^{Y\,1-\sigma^{M}}_{i,s}\right]^{\frac{1}{1-\sigma^{M}}} \leq 0 \tag{G.11}$$

G.3 Market Clearance Conditions

G.3.1 Factor Market Clearance

Market clearance for factors of production (capital and labor):

$$\overline{F}_{f,r} \geq \sum_{g} Y_{g,r} \frac{\partial \Pi^{Y}_{g,r}}{\partial p^{F}_{f,r}} \tag{G.12}$$

Market clearance for the fixed natural resource factors ($g \in xe$):

$$\overline{RS}_{g,r} \geq Y_{g,r} \frac{\partial \Pi^{Y}_{g,r}}{\partial p^{RS}_{g,r}} \tag{G.13}$$

G.3.2 Goods Market Clearance

Knowledge market clearance - Supply of knowledge services from existing knowledge stock and spillovers ($SPL_{i,r}$) plus new knowledge investment ($R_{i,r}$) must meet or exceed demand for knowledge services:

$$R_{i,r} + SPL_{i,r} \geq Y_{i,r} \frac{\partial \Pi^{Y}_{i,r}}{\partial p^{R}_{i,r}} \tag{G.14}$$

Carbon-saving knowledge market clearance:

$$RC_r + SPLC_r \geq CRB_r \frac{\partial \Pi^{CRB}_{r}}{\partial p^{RC}_{r}} \tag{G.15}$$

Supply of effective carbon-services equals demand for effective carbon services:

$$CRB_r \geq \sum_g Y_{g,r} \frac{\partial \Pi^{Y}_{g,r}}{\partial (p^{A}_{g,r} + p^{CRB}_{r} a^{co2}_{i,g,r})} a^{co2}_{i,g,r} \tag{G.16}$$

Output enters the production of Armington goods, import supply, as well as conventional and carbon-saving R&D:

$$\begin{aligned} Y_{i,r} \geq & \sum_j A_{j,r} \frac{\partial \Pi^{A}_{j,r}}{\partial p^{Y}_{i,r}} + \sum_s M_{i,s} \frac{\partial \Pi^{M}_{j,s}}{\partial p^{Y}_{i,r}} \\ & + \sum_j R_{j,r} \frac{\partial \Pi^{R}_{j,r}}{\partial p^{Y}_{i,r}} + \sum_j RC_{j,r} \frac{\partial \Pi^{RC}_{j,r}}{\partial p^{Y}_{i,r}} \quad \perp p^{Y}_{i,r} \geq 0 \end{aligned} \tag{G.17}$$

Armington supply enters:

$$A_{i,r} \geq \sum_g Y_{g,r} \frac{\partial \Pi^{Y}_{g,r}}{\partial p^{A}_{i,r}} \tag{G.18}$$

Import supply enters:

$$M_{i,r} \geq A_{i,r} \frac{\partial \Pi^{A}_{i,r}}{\partial p^{M}_{i,r}} \tag{G.19}$$

Public Consumption covers fixed govt demand:

$$Y_{G,r} \geq \overline{G}_r \tag{G.20}$$

Production of investment covers fixed investment demand:

$$Y_{I,r} \geq \overline{I}_r \tag{G.21}$$

Production of private consumption index covers private consumption demand:

$$Y_{C,r} \geq \frac{ZHH_r}{p^Y_{C,r}} \tag{G.22}$$

G.4 Income Balance Conditions

Income balance condition for representative agent:

$$\begin{aligned} ZHH_r = {} & p^F_{f,r}\overline{F}_r + p^{RS}_{i,r}\overline{RS}_{i,r} \\ & + p^{co2}_r\overline{CO2}_r + p^R_{i,r} SPL_{i,r} + p^{RC}_r SPLC_r \\ & - p^Y_{I,r}\overline{Y}_{I,r} - p^Y_{G,r}\overline{Y}_{G,r} + \overline{B}_r + TR_r \end{aligned} \tag{G.23}$$

The model maintains the benchmark taxes provided by GTAP throughout. Tax revenues are indicated by TR_r.

G.5 Spillover Calibration and Constraints

Knowledge accounting and calibration is shown below. First R&D expenditures data is obtained and assumed to equal demand for knowledge services, as shown below:

$$\overline{dk}_{i,r} = R\&D\ exp\ data_{i,r} \tag{G.24}$$

Then the absorption rate is calculated:

$$\gamma_{i,r} = \frac{\overline{dk}_{i,r}}{\sum_{r \in nth} \overline{dk}_{i,r}} \tag{G.25}$$

and then modified to allow for flows from region r to region s, shown below:

$$\begin{aligned} \alpha^{ABS}_{i,s,r} &= \gamma_{i,r} \\ \alpha^{ABS}_{i,r \in nth, r \in nth} &= 1 \\ \alpha^{ABS}_{i,s \in sth, r \in nth} &= 0 \\ \alpha^{ABS}_{i,s \in sth, r \in sth} &= 0 \end{aligned} \tag{G.26}$$

Once the absorption parameter is specified, before moving to spillovers, it is necessary to use the perpetual inventory method to determine R&D investment, given demand for knowledge services, below:

$$\overline{rd}_{i,r} = \frac{(\delta + g)\overline{dk}_{i,r}}{\delta + r} \tag{G.27}$$

Once investment is obtained, ensure that knowledge markets clear by specifying a pre-existing knowledge stock that cannot be adjusted:

$$\overline{ks}_{i,r} = \overline{dk}_{i,r} - \overline{rd}_{i,r} \tag{G.28}$$

Now spillovers can be specified. Spillovers for conventional knowledge:

$$SPL_{i,r} = \overline{ks}_{i,r} + 3 \sum_{s \in nth} \alpha^{ABS}_{i,s,r} (R_{i,s} - \overline{rd}_{i,s}) \tag{G.29}$$

Spillovers for carbon-saving knowledge:

$$SPLC_r = 0.01 * \overline{rdc}_r \overline{cb}_r + 3 \sum_{s \in nth} \Big[\sum_i \big(\frac{\alpha^{ABS}_{i,s,r}}{card(i)} \big)(0.01 * \overline{rdc}_s \overline{cb}_s RC_s) \Big] \tag{G.30}$$

where $\overline{rdc}_r = 1$ and $\overline{cb}_r$ is benchmark raw co2 emissions.

G.6 Emissions cap and tariff constraints

Carbon emissions restriction is shown below:

$$\overline{CO2}_r = \sum_i \sum_g Y_{g,r} \frac{\partial \Pi^{Y}_{g,r}}{\partial (p^{A}_{i,r} + a^{co2}_{i,g,r} p^{CRB}_r)} \frac{\partial \Pi^{CRB}_r}{\partial p^{co2}_r} a^{co2}_{i,g,r} \tag{G.31}$$

Tariff is set by establishing a benchmark co2 endowment in the North due to imports from Southern regions. The tariff rate ($p^{co2}_{s,r}$) is set equal to the prevailing carbon factor price in the north (p^{co2}_r). The marginal of the constraint yields the adjustment to the benchmark imported CO2 endowment in the North ($TAR_{r,s}$).

$$p^{co2}_r = p^{snco2}_{s,r} \quad \perp TAR_{r,s} > 0 \tag{G.32}$$

$$\overline{cbim}_{s,r} * TAR_{s,r} = SNC_{r,s} \frac{\partial \Pi^{SNC}_{r,s}}{\partial p^{snco2}_{r,s}} \quad \perp p^{snco2}_{r,s} > 0 \tag{G.33}$$

Then modify the income balance equation for northern households to include the tariff revenues generated:

$$ZHH_r = \ \ ... \ \ + p_{s,r}^{snco2} * \overline{cbim}_{r,s} * TAR_{r,s} \tag{G.34}$$

Southern output for use in the South and Southern output for export to the North are disaggregated in the numerical model. Production of effective carbon services in the South for export to the North now allows a strictly positive carbon price $p_{r,s}^{co2}$ and carbon-saving knowledge spillovers from northern countries to influence production and export decisions.

G.7 Southern modifications to general model

G.7.1 Zero Profit Conditions

Southern output for use domestically or for export to other Southern regions is defined below:

The unit profit function for effective carbon-services is shown below, market clears with zero price:

$$\Pi_r^{SSC} = p_r^{SSC} - p_r^{ssco2} \le 0 \tag{G.35}$$

The unit profit function for all goods except conventional knowledge services index shows substitution between VA, FE, and all other goods except r&d (NRD). Assuming FE is produced in fixed proportions ($\sigma^{FE} = 0$) and that NRD is in fixed proportions ($\sigma^{NRD} = 0$), yields:

$$\begin{aligned}&\Pi_{g,r}^{NRD} = p_{g,r}^{NRD} - \\ &\left[\theta_{VA,g,r}^{NRD} p_{g,r}^{VA} + \sum_{i \in FE} \theta_{i,g,r}^{NRD} \left(p_{i,r}^{A} + p_r^{SSC} a_{i,g,r}^{co2}\right) + \sum_{i \in NE} \theta_{i,g,r}^{NRD} p_{i,r}^{A}\right] \\ &\le 0\end{aligned} \tag{G.36}$$

The unit profit function for non-fossil-fuel goods: $g \notin xe$

$$\begin{aligned}&\Pi_{g,r}^{D} = p_{g,r}^{D} - \\ &\left[\theta_{g,r}^{RD} p_{g,r}^{R^{1-\sigma^{RD}}} + (1-\theta_{g,r}^{RD}) p_{g,r}^{NRD^{1-\sigma^{RD}}}\right]^{\frac{1}{1-\sigma^{RD}}} \\ &\le 0\end{aligned} \tag{G.37}$$

The unit profit function for fossil-fuel goods: $g \in xe$

$$\begin{aligned}
&\Pi^{D}_{g,r} = p^{D}_{g,r} - \\
&\Big[\theta^{RS}_{RS,g,r} p^{RS}_{gr}{}^{1-\sigma^{RS}} \\
&+ \theta^{RS}_{RD,g,r} p^{R}_{gr}{}^{1-\sigma^{RS}} + (1 - \theta^{RS}_{RS,g,r} - \theta^{RS}_{RD,g,r}) p^{NRD}_{gr}{}^{1-\sigma^{RS}} \Big]^{\frac{1}{1-\sigma^{RS}}} \\
&\leq 0
\end{aligned} \tag{G.38}$$

Southern output for export to specific northern regions is defined below:

The unit profit function for effective carbon-services is shown below:

$$\Pi^{SNC}_{r,s} = p^{SNC}_{r,s} - \Big[\theta^{SNC}_{r,s} p^{snco2}_{r,s}{}^{1-\sigma^{CRB}} + (1 - \theta^{SNC}_{r,s}) p^{RC}_{r}{}^{1-\sigma^{CRB}} \Big]^{\frac{1}{1-\sigma^{CRB}}} \leq 0 \tag{G.39}$$

The unit profit function for the value-added index is shown below:

$$\Pi^{VA}_{g,r,s} = p^{VA}_{g,r,s} - \Big[\sum_{f} \theta^{VA}_{f,g,r,s} \, p^{F}_{f,r}{}^{1-\sigma^{VA}} \Big]^{\frac{1}{1-\sigma^{VA}}} \leq 0 \tag{G.40}$$

The unit profit function for all goods except conventional knowledge services index shows substitution between VA, FE, and all other goods except r&d (NRD). Assuming FE is produced in fixed proportions ($\sigma^{FE} = 0$) and that NRD is in fixed proportions ($\sigma^{NRD} = 0$), yields:

$$\begin{aligned}
&\Pi^{NRD}_{g,r,s} = p^{NRD}_{g,r,s} - \\
&\Big[\theta^{NRD}_{VA,g,r,s} p^{VA}_{g,r} + \sum_{i \in FE} \theta^{NRD}_{i,g,r,s} \, (p^{A}_{i,r} + p^{SNC}_{r,s} \, a^{co2}_{i,g,r}) + \sum_{i \in NE} \theta^{NRD}_{i,g,r,s} p^{A}_{i,r} \Big] \\
&\leq 0
\end{aligned} \tag{G.41}$$

The unit profit function for non-fossil-fuel goods: $g \notin xe$

$$\begin{aligned}
&\Pi^{XS}_{g,r,s} = p^{XS}_{g,r,s} - \\
&\Big[\theta^{RD}_{g,r,s} p^{R}_{g,r}{}^{1-\sigma^{RD}} \\
&+ (1 - \theta^{RD}_{g,r,s}) p^{NRD}_{g,r,s}{}^{1-\sigma^{RD}} \Big]^{\frac{1}{1-\sigma^{RD}}} \\
&\leq 0
\end{aligned} \tag{G.42}$$

The unit profit function for fossil-fuel goods: $g \in xe$

$$
\begin{aligned}
&\Pi^{XS}_{g,r,s} = p^{XS}_{g,r,s} - \\
&\Bigg[\theta^{RS}_{RS,g,r,s} {p^{RS}_{g,r}}^{1-\sigma^{RS}} \\
&+ \theta^{RS}_{RD,g,r,s} {p^{R}_{g,r}}^{1-\sigma^{RS}} + (1 - \theta^{RS}_{RS,g,r,s} - \theta^{RS}_{RD,g,r,s}) {p^{NRD}_{g,r,s}}^{1-\sigma^{RS}}\Bigg]^{\frac{1}{1-\sigma^{RS}}} \\
&\leq 0
\end{aligned}
\tag{G.43}
$$

Aggregating D, X, and XS into Y

Export aggregation amongst northern destinations:

$$
\Pi^{X}_{i,r} = p^{X}_{i,r} - \Big[\sum_{s} \theta^{XS}_{i,r,s} {p^{XS}_{i,r,s}}^{1-\sigma^{X}}\Big]^{\frac{1}{1-\sigma^{X}}} \tag{G.44}
$$

Aggregation between domestic and export to north:

$$
\Pi^{Y}_{g,r} = p^{Y}_{g,r} - \Big[\theta^{D}_{g,r} {p^{D}_{g,r}}^{1-\sigma^{DX}} + \theta^{X}_{g,r} {p^{X}_{g,r}}^{1-\sigma^{DX}}\Big]^{\frac{1}{1-\sigma^{DX}}} \tag{G.45}
$$

G.7.2 Market Clearance for South

Supply of exports from a given Southern region to a given Northern region enters the aggregated Export block of a given Southern regions exports to the North in general:

$$
XS_{i,r,s} \geq X_{i,r} \frac{\partial \Pi^{X}_{i,r}}{\partial p^{XS}_{i,r,s}} \quad \perp p^{XS}_{i,r,s} \geq 0 \tag{G.46}
$$

Exports from a given Southern region to the North enter the Southern output block:

$$
X_{i,r} \geq Y_{i,r} \frac{\partial \Pi^{Y}_{i,r}}{\partial p^{X}_{i,r}} \quad \perp p^{X}_{i,r} \geq 0 \tag{G.47}
$$

Southern production for domestic use or for export to other Southern regions enters the output block:

$$
D_{g,r} \geq Y_{g,r} \frac{\partial \Pi^{Y}_{g,r}}{\partial p^{D}_{g,r}} \quad \perp p^{D}_{g,r} \geq 0 \tag{G.48}
$$

Armington supply enters:

$$
A_{i,r} \geq \sum_{g} D_{g,r} \frac{\partial \Pi^{D}_{g,r}}{\partial p^{A}_{i,r}} + \sum_{j} \sum_{s} XS_{j,r,s} \frac{\partial \Pi^{XS}_{j,r,s}}{\partial p^{A}_{i,r}} \quad \perp p^{A}_{i,r} \geq 0 \tag{G.49}
$$

Output enters:

$$\begin{aligned} Y_{i,r} \geq \sum_j A_{j,r} \frac{\partial \Pi^{A}_{j,r}}{\partial p^{Y}_{i,r}} + \sum_s M_{i,s} \frac{\partial \Pi^{M}_{j,s}}{\partial p^{Y}_{i,r}} \\ + \sum_j R_{j,r} \frac{\partial \Pi^{R}_{j,r}}{\partial p^{Y}_{i,r}} + \sum_j RC_{j,r} \frac{\partial \Pi^{RC}_{j,r}}{\partial p^{Y}_{i,r}} \quad \perp p^{Y}_{i,r} \geq 0 \end{aligned} \tag{G.50}$$

Effective carbon services provided by a Southern region exported to a given Northern region enter:

$$SNC_{r,s} \geq \sum_i XS_{i,r,s} \frac{\partial \Pi^{XS}_{i,r,s}}{\partial p^{SNC}_{r,s}} a_{i,g,r} \quad \perp p^{SNC}_{r,s} \geq 0 \tag{G.51}$$

Factor market clearance:

$$\overline{F}_{f,r} \geq \sum_i D_{i,r} \frac{\partial \Pi^{D}_{i,r}}{\partial p^{F}_{f,r}} + \sum_i \sum_s XS_{i,r,s} \frac{\partial \Pi^{XS}_{i,r,s}}{\partial p^{F}_{f,r}} \quad \perp p^{F}_{f,r} \geq 0 \tag{G.52}$$

Fixed resource factor market clearance:

$$\overline{RS}_{i,r} \geq D_{i,r} \frac{\partial \Pi^{D}_{i,r}}{\partial p^{RS}_{i,r}} + \sum_s XS_{i,r,s} \frac{\partial \Pi^{XS}_{i,r,s}}{\partial p^{RS}_{i,r}} \quad \perp p^{RS}_{i,r} \geq 0 \tag{G.53}$$

Conventional R&D market clearance:

$$\overline{R}_{i,r} + SPL_{i,r} \geq Y_{i,r} \frac{\partial \Pi^{Y}_{i,r}}{\partial p^{R}_{i,r}} \quad \perp p^{R}_{i,r} \geq 0 \tag{G.54}$$

Carbon-saving R&D market clearance:

$$SPLC_{r} \geq SNC_{r,s} \frac{\partial \Pi^{SNC}_{r,s}}{\partial p^{RC}_{r}} \quad \perp p^{RC}_{i,r} \geq 0 \tag{G.55}$$

APPENDIX H - TPS MODEL CODE

Files included:

1. replicate.bat - calls run_tps.bat and run_sstps.bat and organizes output
2. run_tps.bat - calls model file for baseline tps analysis
3. run_sstps.bat - calls sensitivity scenarios for discount rate sensitivity and welfare results
4. v5LINdr_nolp_toy.gms - contains all cobalt models and calculations

replicate.bat

```
echo begin replication of results in tps paper

cd v5_nolp
call run_tps.bat

cd ..\v5_nolp_sstps
call run_sstps.bat

cd ..

del /Q media\*

copy v5_nolp\plots\merged\comp1_init_dg.pdf media\comp1_init_dg.pdf
copy v5_nolp\plots\merged\tps_i2_plot.pdf media\tps_i2_plot.pdf
copy v5_nolp\plots\merged\cap_util_plot.pdf media\cap_util_plot.pdf
copy v5_nolp\plots\merged\tps_emit_plot.pdf media\tps_emit_plot.pdf
copy v5_nolp\plots\merged\comp1_ss_dg.pdf media\comp1_ss_dg.pdf
copy v5_nolp\ss_ac.tex media\ss_ac.tex
copy v5_nolp_sstps\rep_ss.tex media\rep_ss.tex

echo end replication of results
```

run_tps.bat

```
echo begin

del /Q output\*
mkdir output

gams v5LINdr_nolp_toy.gms o=output\S1A.lst s=output\S1A lo=2 logFile=output\S1A.log
--gdxfile=output\S1A --scennum=1 --scenlet=A --slope=4e5 --inter=0 --scaleval=0.7 --drval=0.01
gams v5LINdr_nolp_toy.gms o=output\S2A.lst s=output\S2A lo=2 logFile=output\S2A.log
--gdxfile=output\S2A --scennum=2 --scenlet=B --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0.01
gams v5LINdr_nolp_toy.gms o=output\S3A.lst s=output\S3A lo=2 logFile=output\S3A.log
--gdxfile=output\S3A --scennum=3 --scenlet=C --swnoeq=3 --scaleval=0.7 --drval=0.01
gams v5LINdr_nolp_toy.gms o=output\S1B.lst s=output\S1B lo=2 logFile=output\S1B.log
--gdxfile=output\S1B --scennum=1 --scenlet=A --slope=4e5 --inter=0 --scaleval=0.3 --drval=0.01
gams v5LINdr_nolp_toy.gms o=output\S2B.lst s=output\S2B lo=2 logFile=output\S2B.log
--gdxfile=output\S2B --scennum=2 --scenlet=B --slope=4e4 --inter=9e5 --scaleval=0.3 --drval=0.01
gams v5LINdr_nolp_toy.gms o=output\S3B.lst s=output\S3B lo=2 logFile=output\S3B.log
--gdxfile=output\S3B --scennum=3 --scenlet=C --swnoeq=3 --scaleval=0.3 --drval=0.01

gdxmerge output\S*.gdx output=output\merged.gdx

Rscript plot_comp_tps.R

echo end


```

run_sstps.bat

```
echo begin

del /Q output\*
mkdir output

gams v5LINdr_nolp_toy.gms o=output\S1Aaa.lst s=output\S1Aaa lo=2 logFile=output\S1Aaa.log --gdxfile=output\S1Aaa
--scennum=1 --scenlet=Aaa --slope=4e5 --inter=0 --scaleval=0.7 --drval=0 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S1Baa.lst s=output\S1Baa lo=2 logFile=output\S1Baa.log --gdxfile=output\S1Baa
--scennum=1 --scenlet=Baa --slope=4e5 --inter=0 --scaleval=0.9 --drval=0 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S1Aab.lst s=output\S1Aab lo=2 logFile=output\S1Aab.log --gdxfile=output\S1Aab
--scennum=1 --scenlet=Aab --slope=4e5 --inter=0 --scaleval=0.7 --drval=0.01 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S1Bab.lst s=output\S1Bab lo=2 logFile=output\S1Bab.log --gdxfile=output\S1Bab
--scennum=1 --scenlet=Bab --slope=4e5 --inter=0 --scaleval=0.9 --drval=0.01 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S1Aac.lst s=output\S1Aac lo=2 logFile=output\S1Aac.log --gdxfile=output\S1Aac
--scennum=1 --scenlet=Aac --slope=4e5 --inter=0 --scaleval=0.7 --drval=0.03 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S1Bac.lst s=output\S1Bac lo=2 logFile=output\S1Bac.log --gdxfile=output\S1Bac
--scennum=1 --scenlet=Bac --slope=4e5 --inter=0 --scaleval=0.9 --drval=0.03 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S1Aba.lst s=output\S1Aba lo=2 logFile=output\S1Aba.log --gdxfile=output\S1Aba
--scennum=1 --scenlet=Aba --slope=4e5 --inter=0 --scaleval=0.7 --drval=0 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S1Bba.lst s=output\S1Bba lo=2 logFile=output\S1Bba.log --gdxfile=output\S1Bba
--scennum=1 --scenlet=Bba --slope=4e5 --inter=0 --scaleval=0.9 --drval=0 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S1Abb.lst s=output\S1Abb lo=2 logFile=output\S1Abb.log --gdxfile=output\S1Abb
--scennum=1 --scenlet=Abb --slope=4e5 --inter=0 --scaleval=0.7 --drval=0.01 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S1Bbb.lst s=output\S1Bbb lo=2 logFile=output\S1Bbb.log --gdxfile=output\S1Bbb
--scennum=1 --scenlet=Bbb --slope=4e5 --inter=0 --scaleval=0.9 --drval=0.01 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S1Abc.lst s=output\S1Abc lo=2 logFile=output\S1Abc.log --gdxfile=output\S1Abc
--scennum=1 --scenlet=Abc --slope=4e5 --inter=0 --scaleval=0.7 --drval=0.03 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S1Bbc.lst s=output\S1Bbc lo=2 logFile=output\S1Bbc.log --gdxfile=output\S1Bbc
--scennum=1 --scenlet=Bbc --slope=4e5 --inter=0 --scaleval=0.9 --drval=0.03 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S1Aca.lst s=output\S1Aca lo=2 logFile=output\S1Aca.log --gdxfile=output\S1Aca
--scennum=1 --scenlet=Aca --slope=4e5 --inter=0 --scaleval=0.7 --drval=0 --cil=200
gams v5LINdr_nolp_toy.gms o=output\S1Bca.lst s=output\S1Bca lo=2 logFile=output\S1Bca.log --gdxfile=output\S1Bca
--scennum=1 --scenlet=Bca --slope=4e5 --inter=0 --scaleval=0.9 --drval=0 --cil=200
gams v5LINdr_nolp_toy.gms o=output\S1Acb.lst s=output\S1Acb lo=2 logFile=output\S1Acb.log --gdxfile=output\S1Acb
--scennum=1 --scenlet=Acb --slope=4e5 --inter=0 --scaleval=0.7 --drval=0.01 --cil=200
gams v5LINdr_nolp_toy.gms o=output\S1Bcb.lst s=output\S1Bcb lo=2 logFile=output\S1Bcb.log --gdxfile=output\S1Bcb
--scennum=1 --scenlet=Bcb --slope=4e5 --inter=0 --scaleval=0.9 --drval=0.01 --cil=200
```

```
gams v5LINdr_nolp_toy.gms o=output\S1Acc.lst s=output\S1Acc lo=2 logFile=output\S1Acc.log --gdxfile=output\S1Acc
--scennum=1 --scenlet=Acc --slope=4e5 --inter=0 --scaleval=0.7 --drval=0.03 --cil=200
gams v5LINdr_nolp_toy.gms o=output\S1Bcc.lst s=output\S1Bcc lo=2 logFile=output\S1Bcc.log --gdxfile=output\S1Bcc
--scennum=1 --scenlet=Bcc --slope=4e5 --inter=0 --scaleval=0.9 --drval=0.03 --cil=200


gams v5LINdr_nolp_toy.gms o=output\S2Aaa.lst s=output\S2Aaa lo=2 logFile=output\S2Aaa.log --gdxfile=output\S2Aaa
--scennum=2 --scenlet=Aaa --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S2Baa.lst s=output\S2Baa lo=2 logFile=output\S2Baa.log --gdxfile=output\S2Baa
--scennum=2 --scenlet=Baa --slope=4e4 --inter=9e5 --scaleval=0.9 --drval=0 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S2Aab.lst s=output\S2Aab lo=2 logFile=output\S2Aab.log --gdxfile=output\S2Aab
--scennum=2 --scenlet=Aab --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0.01 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S2Bab.lst s=output\S2Bab lo=2 logFile=output\S2Bab.log --gdxfile=output\S2Bab
--scennum=2 --scenlet=Bab --slope=4e4 --inter=9e5 --scaleval=0.9 --drval=0.01 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S2Aac.lst s=output\S2Aac lo=2 logFile=output\S2Aac.log --gdxfile=output\S2Aac
--scennum=2 --scenlet=Aac --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0.03 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S2Bac.lst s=output\S2Bac lo=2 logFile=output\S2Bac.log --gdxfile=output\S2Bac
--scennum=2 --scenlet=Bac --slope=4e4 --inter=9e5 --scaleval=0.9 --drval=0.03 --cil=0
gams v5LINdr_nolp_toy.gms o=output\S2Aba.lst s=output\S2Aba lo=2 logFile=output\S2Aba.log --gdxfile=output\S2Aba
--scennum=2 --scenlet=Aba --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S2Bba.lst s=output\S2Bba lo=2 logFile=output\S2Bba.log --gdxfile=output\S2Bba
--scennum=2 --scenlet=Bba --slope=4e4 --inter=9e5 --scaleval=0.9 --drval=0 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S2Abb.lst s=output\S2Abb lo=2 logFile=output\S2Abb.log --gdxfile=output\S2Abb
--scennum=2 --scenlet=Abb --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0.01 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S2Bbb.lst s=output\S2Bbb lo=2 logFile=output\S2Bbb.log --gdxfile=output\S2Bbb
--scennum=2 --scenlet=Bbb --slope=4e4 --inter=9e5 --scaleval=0.9 --drval=0.01 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S2Abc.lst s=output\S2Abc lo=2 logFile=output\S2Abc.log --gdxfile=output\S2Abc
--scennum=2 --scenlet=Abc --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0.03 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S2Bbc.lst s=output\S2Bbc lo=2 logFile=output\S2Bbc.log --gdxfile=output\S2Bbc
--scennum=2 --scenlet=Bbc --slope=4e4 --inter=9e5 --scaleval=0.9 --drval=0.03 --cil=100
gams v5LINdr_nolp_toy.gms o=output\S2Aca.lst s=output\S2Aca lo=2 logFile=output\S2Aca.log --gdxfile=output\S2Aca
--scennum=2 --scenlet=Aca --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0 --cil=200
gams v5LINdr_nolp_toy.gms o=output\S2Bca.lst s=output\S2Bca lo=2 logFile=output\S2Bca.log --gdxfile=output\S2Bca
--scennum=2 --scenlet=Bca --slope=4e4 --inter=9e5 --scaleval=0.9 --drval=0 --cil=200
gams v5LINdr_nolp_toy.gms o=output\S2Acb.lst s=output\S2Acb lo=2 logFile=output\S2Acb.log --gdxfile=output\S2Acb
--scennum=2 --scenlet=Acb --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0.01 --cil=200
gams v5LINdr_nolp_toy.gms o=output\S2Bcb.lst s=output\S2Bcb lo=2 logFile=output\S2Bcb.log --gdxfile=output\S2Bcb
--scennum=2 --scenlet=Bcb --slope=4e4 --inter=9e5 --scaleval=0.9 --drval=0.01 --cil=200
gams v5LINdr_nolp_toy.gms o=output\S2Acc.lst s=output\S2Acc lo=2 logFile=output\S2Acc.log --gdxfile=output\S2Acc
```

```
--scennum=2 --scenlet=Acc --slope=4e4 --inter=9e5 --scaleval=0.7 --drval=0.03 --cil=200
gams v5LINdr_nolp_toy.gms o=output\S2Bcc.lst s=output\S2Bcc lo=2 logFile=output\S2Bcc.log --gdxfile=output\S2Bcc
--scennum=2 --scenlet=Bcc --slope=4e4 --inter=9e5 --scaleval=0.9 --drval=0.03 --cil=200

gdxmerge output\S*.gdx output=output\merged.gdx

python rep_ss.py

echo end file


```

v5LINdr_nolp_toy.gms

```
$TITLE analytical tps model
$ontext

Scenarios:
1: slope = 4.0e5, inter = 0
2: slope = 2.0e5, inter = 5e5
3: slope = 4.0e4, inter = 9e5
4: slope_l = 3e5, slope_h = 1.5e5, inter = 5e5 (swnoeq=3)

A: scaleval = 0.9
B: scaleval = 0.8
C: scaleval = 0.7

FUN (run to 800 periods):
*gams v3LINdr_nolp_toy.gms --gdxfile=fun --drval=0.02 --trepval=600 --cil=0 --swfunval=1 --swnoeq=3

---------
Add Discount rate/factor to model
---------

$offtext

$if not setglobal gdxfile $setglobal gdxfile "outputLIN"
$if not setglobal slope $setglobal slope 4e5
$if not setglobal inter $setglobal inter 0
$if not setglobal scaleval $setglobal scaleval 0.9
$if not setglobal swnoeq $setglobal swnoeq 0
$if not setglobal scenario $setglobal scenario %gdxfile%
$if not setglobal scennum $setglobal scennum 0
$if not setglobal scenlet $setglobal scenlet "Z"
$if not setglobal trepval $setglobal trepval 200
$if not setglobal drval $setglobal drval 0
$if not setglobal swlicval $setglobal swlicval 1
$if not setglobal swtival $setglobal swtival 0
$if not setglobal delasval $setglobal delasval -0.3
$if not setglobal cih $setglobal cih 2000
$if not setglobal cil $setglobal cil 0
```

```
$if not setglobal swfunval $setglobal swfunval 0
$if not setglobal tval $setglobal tval 500
$if not setglobal cdamval $setglobal cdamval 20

$show
*$exit

SETS
t                        time horizon        /1*%tval%/
f                        fuel type                /H,L/
tf(t)                first period
tl(t)                last period
tsl(t)                second to last period
trep(t)                periods used for reporting parameters
trepf(t)        last period used for reporting parameter
swCAP(t)        switch to enable [yes] or disable [no] CAP
swTPS(t)        switch to enable [yes] or disable [no] TPS
;

tf(t) = yes$(ord(t)=1);
tl(t) = yes$(ord(t)=card(t)) ;
tsl(t) = yes$(ord(t)=(card(t)-1)) ;
trep(t) = yes$(ord(t) le %trepval%) ;
trepf(t) = yes$(ord(t)=%trepval%) ;

alias(t,t2) ;

swCAP(t) = no ;
swTPS(t) = no ;

scalar swCAPS         switch to enable [1] disable [0] CAP         /0/;
scalar swTPSS         switch to enable [1] disable [0] TPS        /0/;
scalar swLIC        switch to enable [1] disable [0] linear investment cost         /0/;
scalar swTI                switch to enable [1] disable [0] terminal investment        /0/;
scalar swDE                switch to enable [1] disable [0] constraints related to elastic demand        /0/;
scalar swFUN        switch to enable [1] disable [0] FUN        /0/;

PARAMETERS
vc_x(f)                variable operating costs
```

```
k0(f,t)                initial capacity
d(t)                quantity demanded
delta                depreciation rate
i_in(f)                intercept for marginal investment cost function
i_sl(f)                slope term for marginal investment cost function
phi(t)                reference level of carbon intensity
psi(t)                reference level of aggregate emissions
sigma(t)        TPS policy target
sigma0                TPS policy target that results in 0 change in PD in SS
omega(t)        CAP policy target
ci(f)                carbon intensity of each fuel (co2 per mwh)
scale                used to scale sigma in relation to sigma0
delas                elasticity of demand < 0
pd0(t)                reference electricity price
ielas(f)        elasticity of investment > 0
i0(f,t)                reference investment level
pi0(f,t)        reference investment price (initial capital price)
hiy                        hours in year
dr                        discount rate
df(t)                discount factor
;

parameter i_ss(f,t) steady state investment for fix;

PARAMETERS
pis0(f)                SS reference investment price
is0(f)                SS reference investment level
pds0                SS reference electricity price
sigma_s                SS sigma
omega_s                SS omega
ds                        SS demand
;


POSITIVE VARIABLES
Q(t)                total quantity
X(f,t)                generation
I(f,t)                investment
K(f,t)                capacity
```

```
PD(t)                electricity price (shadow on demand constraint)
PK(f,t)                capacity rental rate
PI(f,t)                investment price
PIT(f,t)        shadow price of post-terminal capital
PTPS(t)                TPS emissions permit price
PCAP(t)                CAP emissions permit price
;
PD.L(t) = 1e-8;
PD.lo(t) = 1e-8;
Q.lo(t) = 1e-8 ;

*Steady State Variables
POSITIVE VARIABLES
XS(f)
IS(f)
KS(f)
PDS
PKS(f)
PIS(f)
PTPSS
PCAPS
;
PDS.lo=1e-4;

EQUATIONS
mkt_pd(t)        market clearance condition (PD)
mkt_pk(f,t)        market clearance condition (PK)
mkt_pi(f,t)        market clearance condition (PI)
zpf_q(t)        zero profit condition (Q)
zpf_x(f,t)        zero profit condition (X)
zpf_k(f,t)        zero profit condition (K)
zpf_i(f,t)        zero profit condition (I)
mkt_pit(f,t)        terminal investment constraint (PIT)
tpseq(t)        TPS policy constraint (PTPS)
capeq(t)        CAP policy constraint (PCAP)
;

*Steady State Equations
EQUATIONS
```

```
mkt_pd_ss
mkt_pk_ss
mkt_pi_ss
zpf_x_ss
zpf_k_ss
zpf_i_ss
tpseqss
capeqss
;

********************
* Define equations
********************

zpf_q(t)$[swDE]..                df(t)*(pd0(t)/df(t))*(Q(t)/d(t))**(1/delas) - PD(t) =g= 0 ;

mkt_pd(t)..                sum(f,X(f,t)) =g= Q(t)$[swDE] + d(t)$[not swDE] ;
*mkt_pd(t)..                sum(f,X(f,t)) =g= d(t)*(PQ(t)/pq0(t))**(delas) ;
*mkt_pd(t)..                sum(f,X(f,t)) =g= d(t)*((PD(t)/df(t))/(pd0(t)/df(t)))**(delas) ;


mkt_pk(f,t)..        K(f,t) =g= X(f,t) ;

mkt_pi(f,t)..        k0(f,t)$tf(t) + K(f,t-1) * (1-delta) + I(f,t) =g= K(f,t) ;
*mkt_pi(f,t)..        K(f,t-1) * (1-delta) + I(f,t) =g= K(f,t) ;

zpf_x(f,t)..        df(t)*vc_x(f)*hiy + PK(f,t) - PD(t)
+ PTPS(t)$(swTPS(t))*(ci(f) - sigma(t))*hiy
+ PCAP(t)$(swCAP(t))*(ci(f))*hiy
=g= 0 ;

zpf_k(f,t)..        -PK(f,t) - PI(f,t+1)*(1-delta) + PI(f,t)
+ delta*PIT(f,t)$(swTI$tl(t))
=g= 0 ;

* t indices tripping me up here:
* this means PK(f,t) =g= PI(f,t) - (PI(f,t+1)*(1-delta))*(1+dr)
********* PK(f,t) = (PI(f,t) - PI(f,t+1)) + PI(f,t+1)*delta
********* PK(f,t) = (PI(f,t) - PI(f,t+1)*(1+dr)) - PI(f,t+1)*(1+dr)*(-delta)
```

```
********* PK(f,t) = (PI(f,t) - PI(f,t+1)*(1+dr)) + PI(f,t+1)*(1+dr)*delta

zpf_i(f,t)..        df(t)*[i_in(f) + pi0(f,t)*(I(f,t)/i0(f,t))**(1/ielas(f))]$(not swlic)
+ df(t)*[i_in(f) + i_sl(f)*I(f,t)]$(swlic)
- PI(f,t)
- PIT(f,t)$[swTI$tl(t)]
=g= 0 ;

mkt_pit(f,tl)$(swTI)..        I(f,tl) - delta * K(f,tl) =g= 0 ;

tpseq(t)$swTPS(t)..                sigma(t) * sum(f,X(f,t)) =g= sum(f,X(f,t)*ci(f)) ;

capeq(t)$swCAP(t)..                omega(t) =g= sum(f,X(f,t)*ci(f)) ;


* Steady-State equations
mkt_pd_ss..                sum(f,XS(f)) =e= ds*(PDS/pds0)**(delas) ;

mkt_pk_ss(f)..        KS(f) =e= XS(f);

mkt_pi_ss(f)..        KS(f) * (1-delta) + IS(f) =e= KS(f) ;

zpf_x_ss(f)..        vc_x(f)*hiy + PKS(f) - PDS
+ PTPSS$(swTPSS)*(ci(f) - sigma_s)*hiy
+ PCAPS$(swCAPS)*(ci(f))*hiy
=e= 0 ;

zpf_k_ss(f)..        -PKS(f) - PIS(f) * (1-delta) + PIS(f) =e= 0 ;

zpf_i_ss(f)..        [i_in(f) + pis0(f)*(IS(f)/is0(f))**(1/ielas(f))]$(not swlic)
+ [i_in(f) + i_sl(f)*IS(f)]$(swlic)
- PIS(f)
=e= 0 ;

tpseqss$swTPSS..                sigma_s * sum(f,XS(f)) =e= sum(f,XS(f)*ci(f)) ;

capeqss$swCAPS..                omega_s =e= sum(f,XS(f)*ci(f)) ;

********************
```

```
* Define models
********************

model nolpMCP
/
mkt_pd.pd
mkt_pk.pk
mkt_pi.pi
zpf_q.q
zpf_x.x
zpf_k.k
zpf_i.i
mkt_pit.pit
tpseq.ptps
capeq.pcap
/
;


model ssMCP
/
mkt_pd_ss.pds
mkt_pk_ss.pks
mkt_pi_ss.pis
zpf_x_ss.xs
zpf_k_ss.ks
zpf_i_ss.is
tpseqss.ptpss
capeqss.pcaps
/
;

********************
* Initialize parameters
********************

* Hours in year
hiy = 8760 ;

```

```
*Variable operating plus fuel costs
vc_x(f) = 30 ;

*Initial capacity
k0(f,t) = 0;


*Asset depreciation rate / decay rate
delta = 0.05 ;

* lbs co2 / mwh
ci('H') = %cih% ;
ci('L') = %cil% ;

*Elasticity of demand - perfectly inelastic
delas = 0 ;

*Discount rate/factor
dr = %drval% ;
df(t)$(dr > 0) = (1/(1+dr))**(ord(t)-1) ;
df(t)$(dr = 0) = 1 ;
display df;

* Benchmark yearly demand initialized to 100 (MW)
d(t) = 100 ;
*d(t) = d(t) * ((1+dr)**(ord(t)-1));
*d(t) = d(t) * df(t) ;

* Slopes of investment cost curves initialization
ielas(f) = 1 ;
*ielas('L') = 0.5;

i_in(f) = %inter%;
i_sl(f) = %slope%;

*initialize empty parameters
sigma(t) = 1e10 ;
omega(t) = 1e10 ;
pd0(t) = 1 ;
```

```
i0(f,t) = 1 ;
pi0(f,t) = %slope%;

ds = 100 ;
sigma_s = 1e10;
omega_s = 1e10;
pds0 = 1;
is0(f) = 1;
pis0(f) = %slope%;

swlic = %swlicval% ;
swti = %swtival% ;
swDE = 1 - 1$[delas=0] ;


swfun = %swfunval% ;

* Switches for various cases
$ifthen.noeq1 %swnoeq%==1
i_in(f) = 5e5 ;
i_in('L') = 0 ;
i_sl(f) = 2e5 ;
i_sl('L') = i_sl('H') * 2 ;
$endif.noeq1

$ifthen.noeq2 %swnoeq%==2
i_in(f) = 5e5 ;
i_sl(f) = 2e5 ;
i_sl('L') = i_sl('H') * 2 ;
$endif.noeq2

$ifthen.noeq3 %swnoeq%==3
i_in(f) = 5e5 ;
i_sl('H') = 1.5e5 ;
i_sl('L') = 3e5 ;
$endif.noeq3

********************
*Steady State the Easy Way
```

```
********************

solve ssMCP using MCP;

PARAMETERS
rep_xf_ss
rep_kf_ss
rep_x_ss
rep_k_ss
rep_i_ss
rep_pd_ss
rep_pk_ss
rep_pi_ss
rep_emit_ss
rep_perm_ss
rep_mpc_ss
;

rep_xf_ss("SSEXOBAU") = sum(f,XS.l(f)) ;
rep_kf_ss("SSEXOBAU") = sum(f,KS.l(f)) ;
rep_x_ss(f,"SSEXOBAU") = XS.l(f) ;
rep_k_ss(f,"SSEXOBAU") = KS.l(f) ;
rep_i_ss(f,"SSEXOBAU") = IS.l(f) ;
rep_pd_ss("SSEXOBAU") = PDS.l/hiy ;
rep_pk_ss(f,"SSEXOBAU") = PKS.l(f) ;
rep_pi_ss(f,"SSEXOBAU") = PIS.l(f) ;
rep_emit_ss("SSEXOBAU") = sum(f,XS.l(f)*ci(f))*hiy ;

display rep_x_ss ;

*initialize BAU values
*PD.l(t) = PDS.l ;
*PK.l(f,t) = PKS.l(f);
*PI.l(f,t) = PIS.l(f);
*X.l(f,t) = XS.l(f);
*K.l(f,t) = KS.l(f);
*I.l(f,t) = IS.l(f);
*pd0(t) = PDS.l;
*i0(f,t) = IS.l(f);
```

```
*pi0(f,t) = PIS.l(f);
pds0=PDS.l;
is0(f) = IS.l(f);
pis0(f) = PIS.l(f) - i_in(f);
delas = %delasval% ;
swDE = 1 - 1$[delas=0] ;

ssMCP.iterlim = 0
solve ssMCP using MCP;
ssMCP.iterlim=100000;

rep_xf_ss("SSBAU") = sum(f,XS.l(f)) ;
rep_kf_ss("SSBAU") = sum(f,KS.l(f)) ;
rep_x_ss(f,"SSBAU") = XS.l(f) ;
rep_k_ss(f,"SSBAU") = KS.l(f) ;
rep_i_ss(f,"SSBAU") = IS.l(f) ;
rep_pd_ss("SSBAU") = PDS.l/hiy ;
rep_pk_ss(f,"SSBAU") = PKS.l(f) ;
rep_pi_ss(f,"SSBAU") = PIS.l(f) ;
rep_emit_ss("SSBAU") = sum(f,XS.l(f)*ci(f))*hiy ;

display rep_x_ss ;

scale = %scaleval%;
sigma0 = ci(’L’)+[(i_sl(’L’)*(ci(’H’) - ci(’L’)))/sum(f,i_sl(f))] ;
sigma_s = sigma0 * scale ;
sigma_s = (sum(f,XS.l(f)*ci(f)) / sum(f,XS.l(f)))*scale ;

swTPSS = 1 ;
swCAPS = 0 ;

solve ssMCP using MCP;

rep_xf_ss("SSTPS") = sum(f,XS.l(f)) ;
rep_kf_ss("SSTPS") = sum(f,KS.l(f)) ;
rep_x_ss(f,"SSTPS") = XS.l(f) ;
rep_k_ss(f,"SSTPS") = KS.l(f) ;
rep_i_ss(f,"SSTPS") = IS.l(f) ;
rep_pd_ss("SSTPS") = PDS.l/hiy ;
```

```
rep_pk_ss(f,"SSTPS") = PKS.l(f) ;
rep_pi_ss(f,"SSTPS") = PIS.l(f) ;
rep_emit_ss("SSTPS") = sum(f,XS.l(f)*ci(f))*hiy ;
rep_perm_ss("SSTPS") =         PTPSS.l ;
rep_mpc_ss(f,"SSTPS") = PTPSS.l * (ci(f) - sigma_s) ;

swTPSS = 0 ;
swCAPS = 1 ;

omega_s = sum(f,XS.l(f)*ci(f));

solve ssMCP using MCP;

rep_xf_ss("SSCAP") = sum(f,XS.l(f)) ;
rep_kf_ss("SSCAP") = sum(f,KS.l(f)) ;
rep_x_ss(f,"SSCAP") = XS.l(f) ;
rep_k_ss(f,"SSCAP") = KS.l(f) ;
rep_i_ss(f,"SSCAP") = IS.l(f) ;
rep_pd_ss("SSCAP") = PDS.l/hiy ;
rep_pk_ss(f,"SSCAP") = PKS.l(f) ;
rep_pi_ss(f,"SSCAP") = PIS.l(f) ;
rep_emit_ss("SSCAP") = sum(f,XS.l(f)*ci(f))*hiy ;
rep_perm_ss("SSCAP") =         PCAPS.l ;
rep_mpc_ss(f,"SSCAP") = PCAPS.l * ci(f) ;

display rep_x_ss, rep_k_ss, rep_i_ss, rep_pd_ss, rep_pk_ss, rep_pi_ss, rep_emit_ss ;

********************
*Steady State the Hard Way
********************
delas = 0 ;
swDE = 1 - 1$[delas=0] ;

PD.l(t) = pds0 ;
PK.l(f,t) = rep_pk_ss(f,"SSBAU");
PI.l(f,t) = pis0(f);
X.l(f,t) = rep_x_ss(f,"SSBAU");
K.l(f,t) = rep_k_ss(f,"SSBAU");
I.l(f,t) = is0(f);
```

```

*$goto skipssnolp
solve nolpMCP using MCP ;

parameter        ss_test(f)        used to test to see if steady state reached ;
parameter        sstest(f,t)        used to test to see if steady state reached ;
parameter        ss_start(t)        counter;
ss_start(t) = no;

sstest(f,t) = K.l(f,t)-K.l(f,t-1) ;

loop(t,
ss_start(t)=ord(t)$((abs(sstest('L',t)) <= 1e-4))
);

parameter last_ss;
parameter first_ss;
parameter teststart(t);

last_ss=smax(t,ss_start(t));
teststart(t) = card(t) ;
teststart(t)$(ss_start(t)) = ss_start(t);
first_ss = smin(t,teststart(t));


set swSSF(t);
set swSS(t) ;
set swSSM(t);
swSSF(t)=no;
swSS(t) = no;
swSSM(t) = no;
swSSF(t)=yes$(ord(t)=first_ss) ;
swSS(t) = yes$(ord(t)=last_ss) ;
swSSM(t)=yes$(ord(t)=round(((first_ss+last_ss)/2))) ;

ss_test(f) = sum(t$swSSM(t),I.l(f,t)-I.l(f,t-1)) ;
display ss_test, sstest, ss_start, swSS, swSSF, swSSM, first_ss, last_ss;
display X.l, I.l, K.l, PD.l;

```

```
loop(f,
abort$(abs(ss_test(f)) > 1e-4) "Model did not reach steady state", ss_test ;
);

*k0(f,t)          = sum(t2,K.l(f,t2)$tl(t2)) * (1-delta) ;
k0(f,t)        = sum(t2$swSSM(t2),K.l(f,t2)) * (1-delta);
display k0;


i_ss(f,t) = sum(t2$swSSM(t2),K.l(f,t2)) * delta ;
display i_ss ;

*$label skipssnolp

********************
* specify the steady state
********************
Q.l(t) = sum(f,X.l(f,t)) ;

solve nolpMCP using mcp;

PARAMETERS
rep_xf
rep_kf
rep_x
rep_k
rep_i
rep_pd
rep_pk
rep_pi
rep_perm
rep_emit
rep_mpc
rep_pq
rep_q
;

rep_xf(t,"EXOBAUMCP") = sum(f,X.l(f,t)) ;
rep_kf(t,"EXOBAUMCP") = sum(f,K.l(f,t)) ;
```

```
rep_x(f,t,"EXOBAUMCP") = X.l(f,t) ;
rep_k(f,t,"EXOBAUMCP") = K.l(f,t) ;
rep_i(f,t,"EXOBAUMCP") = I.l(f,t) ;
rep_pd(t,"EXOBAUMCP") = (PD.l(t)/hiy) ;
rep_pk(f,t,"EXOBAUMCP") = PK.l(f,t) ;
rep_pi(f,t,"EXOBAUMCP") = PI.l(f,t) ;
rep_emit(t,"EXOBAUMCP") = sum(f,X.l(f,t)*ci(f))*hiy ;

display rep_x, rep_k, rep_i, rep_pd, rep_pk, rep_pi, rep_emit;
*$exit
********************
* Replicate the benchmark with elastic demand
********************
*k0(f,t) = 0 ;
nolpMCP.iterlim = 0;
i0(f,t) = I.l(f,t) ;
pi0(f,t) = PI.l(f,t)/df(t) - i_in(f);
pd0(t) = PD.l(t);
*pd0(t) = sum(t2$tf(t2),PD.l(t2)) ;
*pd0(t) = pds0*df(t) ;
*pd0(t) = 1 ;
delas = %delasval% ;
swDE = 1 - 1$[delas=0] ;

display pi0, pd0 ;

solve nolpMCP using mcp;
abort$(nolpMCP.objval gt 1e-6) "Data calibration error. Cannot replicate benchmark.", nolpMCP.objval ;
abort$(nolpMCP.solvestat <> %solvestat.NormalCompletion%) "Model not normally completed", nolpMCP.solvestat ;
abort$(nolpMCP.modelstat <> %modelstat.Optimal%) "model not optimal", nolpMCP.modelstat ;

nolpMCP.iterlim = 100000;

rep_xf(t,"BAU") = sum(f,X.l(f,t)) ;
rep_kf(t,"BAU") = sum(f,K.l(f,t)) ;
rep_x(f,t,"BAU") = X.l(f,t) ;
rep_k(f,t,"BAU") = K.l(f,t) ;
rep_i(f,t,"BAU") = I.l(f,t) ;
rep_pd(t,"BAU") = PD.l(t)/hiy ;
```

```
rep_pk(f,t,"BAU") = PK.l(f,t)/df(t) ;
rep_pi(f,t,"BAU") = PI.l(f,t)/df(t) ;
rep_emit(t,"BAU") = sum(f,X.l(f,t)*ci(f))*hiy ;
rep_pq(t,"BAU") = PD.l(t)/hiy/df(t) ;
rep_q(t,"BAU") = Q.l(t) ;

display rep_x, rep_k, rep_i, rep_pd, rep_pk, rep_pi, rep_emit;
*execute_unload "output.gdx"
*$exit
********************
* Establish additional benchmark values
********************

psi(t) = sum(f,X.l(f,t)*ci(f)) ;
phi(t) = sum(f,X.l(f,t)*ci(f)) / sum(f,X.l(f,t)) ;
sigma0 = ci(’L’)+[(i_sl(’L’)*(ci(’H’) - ci(’L’)))/sum(f,i_sl(f))] ;
display phi, sigma0 ;
*display phi ;

********************
*Run TPS counterfactual case
********************

swTPS(t) = yes;

parameter fun(t)        variable scale that approaches zero ;

scale = %scaleval% ;
*fun(t) = 1$(ord(t)<=10) + [(1/(1.02))**(ord(t)-10)]$(ord(t)>10) ;
sigma(t) = sigma0 * scale ;
sigma(t)$[ord(t)<20] = ci(’H’) ;
sigma(t)$[not swFUN] = phi(t) * scale ;
*sigma(t)$[swFUN] = phi(t) * fun(t);

solve nolpMCP using MCP ;
abort$(nolpMCP.solvestat <> %solvestat.NormalCompletion%) "TPS Model not normally completed", nolpMCP.solvestat ;
abort$(nolpMCP.modelstat <> %modelstat.Optimal%) "TPS model not optimal", nolpMCP.modelstat ;

display K.l, I.l, PK.l, PI.l, PD.l, PTPS.l ;
```

```
rep_xf(t,"TPS") = sum(f,X.l(f,t)) ;
rep_kf(t,"TPS") = sum(f,K.l(f,t)) ;
rep_x(f,t,"TPS") = X.l(f,t) ;
rep_k(f,t,"TPS") = K.l(f,t) ;
rep_i(f,t,"TPS") = I.l(f,t) ;
rep_pd(t,"TPS") = (PD.l(t)/hiy) ;
rep_pk(f,t,"TPS") = PK.l(f,t)/df(t) ;
rep_pi(f,t,"TPS") = PI.l(f,t)/df(t) ;
rep_emit(t,"TPS") = sum(f,X.l(f,t)*ci(f))*hiy ;
rep_perm(t,"TPS") = PTPS.l(t)/df(t) ;
rep_mpc(f,t,"TPS") = (PTPS.l(t) * (ci(f) - sigma(t)))/df(t) ;
rep_pq(t,"TPS") = PD.l(t)/hiy/df(t) ;
rep_q(t,"TPS") = Q.l(t) ;

********************
*Run CAP counterfactual case that matches emissions to TPS
********************

swTPS(t) = no;
swCAP(t) = yes;

omega(t) = sum(f,X.l(f,t)*ci(f)) ;

solve nolpMCP using MCP ;
abort$(nolpMCP.solvestat <> %solvestat.NormalCompletion%) "CAP Model not normally completed", nolpMCP.solvestat ;
abort$(nolpMCP.modelstat <> %modelstat.Optimal%) "CAP model not optimal", nolpMCP.modelstat ;

rep_xf(t,"CAP") = sum(f,X.l(f,t)) ;
rep_kf(t,"CAP") = sum(f,K.l(f,t)) ;
rep_x(f,t,"CAP") = X.l(f,t) ;
rep_k(f,t,"CAP") = K.l(f,t) ;
rep_i(f,t,"CAP") = I.l(f,t) ;
rep_pd(t,"CAP") = (PD.l(t)/hiy) ;
rep_pk(f,t,"CAP") = PK.l(f,t)/df(t) ;
rep_pi(f,t,"CAP") = PI.l(f,t)/df(t) ;
rep_emit(t,"CAP") = sum(f,X.l(f,t)*ci(f))*hiy ;
rep_perm(t,"CAP") = PCAP.l(t)/df(t) ;
rep_mpc(f,t,"CAP") = (PCAP.l(t) * ci(f))/df(t) ;
```

```
rep_pq(t,"CAP") = PD.l(t)/hiy/df(t) ;
rep_q(t,"CAP") = Q.l(t) ;

display rep_x, rep_k, rep_i, rep_pd, rep_pk, rep_pi, rep_emit, phi, sigma ;



********************
*Reporting Parameters Declaration
********************

* Difference from BAU
parameters
xf_d                change in quantity demanded (total gen) for all t
kf_d                change in total capacity for all t
x_d                        change in generation for all t
k_d                        change in capacity for all t
i_d                        change in investment for all t
pd_d                change in electricity price for all t
pk_d                change in capacity rental rate for all t
pi_d                change in investment price for all t
mpc_d                change in marginal policy costs for all t
perm_d                change in permit prices for all t
emit_d                change in emissions levels for all t
pq_d                change in undiscounted electricity price
q_d                        change in quantity demanded
;

parameters
cs_d                change in consumer surplus for each t
cs_dt                change in consumer surplus total
ps                        producer surplus for each t
ps_d                change in producer surplus for each t
ps_dt                change in producer surplus total
pc_d                change in policy costs for each t
pc_dt                change in policy costs total
cinv                investment costs for each t
cinv_d                change in investment costs for each t
cinv_dt                change in investment costs total
```

```
dam                        damages for each t
dam_d                damages avoided for each t
dam_dt                damages avoided total
ac_d                abatement cost for each t
ac_dt                abatement cost total
ss_d                change in social surplus for each t
ss_dt                change in social surplus total
;

*"r" indicates discounted value
parameters
cs_dr                change in consumer surplus for each t DISCOUNTED
cs_dtr                change in consumer surplus total DISCOUNTED
psr                        producer surplus for each t DISCOUNTED
ps_dr                change in producer surplus for each t DISCOUNTED
ps_dtr                change in producer surplus total DISCOUNTED
pc_dr                change in policy costs for each t  DISCOUNTED
pc_dtr                change in policy costs total DISCOUNTED
cinvr                investment costs for each t DISCOUNTED
cinv_dr                change in investment costs for each t DISCOUNTED
cinv_dtr        change in investment costs total DISCOUNTED
damr                damages for each t DISCOUNTED
dam_dr                damages avoided for each t DISCOUNTED
dam_dtr                damages avoided total DISCOUNTED
ac_dr                abatement cost for each t DISCOUNTED
ac_dtr                abatement cost total DISCOUNTED
ss_dr                change in social surplus for each t DISCOUNTED
ss_dtr                change in social surplus total DISCOUNTED
;

parameters
ss_dr_perp                social surplus steady-state perpetuity
ac_dr_perp                abatement cost steady-state perpetuity
dam_dr_perp                damages avoided steady-state perpetuity
;

parameter        csps_d        consumer plus producer surplus difference;

*Steady-state
```

```
parameters
xf_d_ss                change in quantity demanded (total gen) for all t steady-state
kf_d_ss                change in total capacity for all t steady-state
x_d_ss                change in generation for all t steady-state
k_d_ss                change in capacity for all t steady-state
i_d_ss                change in investment for all t steady-state
pd_d_ss                change in electricity price for all t steady-state
pk_d_ss                change in capacity rental rate for all t steady-state
pi_d_ss                change in investment price for all t steady-state
mpc_d_ss        change in marginal policy costs for all t steady-state
perm_d_ss        change in permit prices for all t steady-state
emit_d_ss        change in emissions levels for all t steady-state
;

parameters
cs_d_ss                change in consumer surplus for each t steady-state
ps_ss                producer surplus for each t steady-state
ps_d_ss                change in producer surplus for each t steady-state
pc_d_ss                change in policy costs for each t  steady-state
cinv_ss                investment costs for each t steady-state
cinv_d_ss        change in investment costs for each t steady-state
dam_ss                damages for each t steady-state
dam_d_ss        damages avoided for each t steady-state
ac_d_ss                abatement cost for each t steady-state
ss_d_ss                change in social surplus for each t steady-state
;


********************
*Postprocess
********************

xf_d(t,"TPS")$[trep(t)] = rep_xf(t,"TPS") - rep_xf(t,"BAU") ;
xf_d(t,"CAP")$[trep(t)] = rep_xf(t,"CAP") - rep_xf(t,"BAU") ;

kf_d(t,"TPS")$[trep(t)] = rep_kf(t,"TPS") - rep_kf(t,"BAU") ;
kf_d(t,"CAP")$[trep(t)] = rep_kf(t,"CAP") - rep_kf(t,"BAU") ;

pd_d(t,"TPS")$[trep(t)] = rep_pd(t,"TPS") - rep_pd(t,"BAU") ;
```

```
pd_d(t,"CAP")$[trep(t)] = rep_pd(t,"CAP") - rep_pd(t,"BAU") ;

x_d(f,t,"TPS")$[trep(t)] = rep_x(f,t,"TPS") - rep_x(f,t,"BAU") ;
x_d(f,t,"CAP")$[trep(t)] = rep_x(f,t,"CAP") - rep_x(f,t,"BAU") ;

k_d(f,t,"TPS")$[trep(t)] = rep_k(f,t,"TPS") - rep_k(f,t,"BAU") ;
k_d(f,t,"CAP")$[trep(t)] = rep_k(f,t,"CAP") - rep_x(f,t,"BAU") ;

i_d(f,t,"TPS")$[trep(t)] = rep_i(f,t,"TPS") - rep_i(f,t,"BAU") ;
i_d(f,t,"CAP")$[trep(t)] = rep_i(f,t,"CAP") - rep_i(f,t,"BAU") ;

pk_d(f,t,"TPS")$[trep(t)] = rep_pk(f,t,"TPS") - rep_pk(f,t,"BAU") ;
pk_d(f,t,"CAP")$[trep(t)] = rep_pk(f,t,"CAP") - rep_pk(f,t,"BAU") ;

pi_d(f,t,"TPS")$[trep(t)] = rep_pi(f,t,"TPS") - rep_pi(f,t,"BAU") ;
pi_d(f,t,"CAP")$[trep(t)] = rep_pi(f,t,"CAP") - rep_pi(f,t,"BAU") ;

mpc_d(f,t,"TPS")$[trep(t)] = rep_mpc(f,t,"TPS");
mpc_d(f,t,"CAP")$[trep(t)] = rep_mpc(f,t,"CAP");

perm_d(t,"TPS")$[trep(t)] = rep_perm(t,"TPS");
perm_d(t,"CAP")$[trep(t)] = rep_perm(t,"CAP");

emit_d(t,"TPS")$[trep(t)] = rep_emit(t,"TPS") - rep_emit(t,"BAU") ;
emit_d(t,"CAP")$[trep(t)] = rep_emit(t,"CAP") - rep_emit(t,"BAU") ;

pq_d(t,"TPS")$[trep(t)] = rep_pq(t,"TPS") - rep_pq(t,"BAU") ;
pq_d(t,"CAP")$[trep(t)] = rep_pq(t,"CAP") - rep_pq(t,"BAU") ;

q_d(t,"TPS")$[trep(t)] = rep_q(t,"TPS") - rep_q(t,"BAU") ;
q_d(t,"CAP")$[trep(t)] = rep_q(t,"CAP") - rep_q(t,"BAU") ;

*Steady-state
xf_d_ss("SSTPS") = rep_xf_ss("SSTPS") - rep_xf_ss("SSBAU") ;
xf_d_ss("SSCAP") = rep_xf_ss("SSCAP") - rep_xf_ss("SSBAU") ;

kf_d_ss("SSTPS") = rep_kf_ss("SSTPS") - rep_kf_ss("SSBAU") ;
kf_d_ss("SSCAP") = rep_kf_ss("SSCAP") - rep_kf_ss("SSBAU") ;

```

```
pd_d_ss("SSTPS") = rep_pd_ss("SSTPS") - rep_pd_ss("SSBAU") ;
pd_d_ss("SSCAP") = rep_pd_ss("SSCAP") - rep_pd_ss("SSBAU") ;

x_d_ss(f,"SSTPS") = rep_x_ss(f,"SSTPS") - rep_x_ss(f,"SSBAU") ;
x_d_ss(f,"SSCAP") = rep_x_ss(f,"SSCAP") - rep_x_ss(f,"SSBAU") ;

k_d_ss(f,"SSTPS") = rep_k_ss(f,"SSTPS") - rep_k_ss(f,"SSBAU") ;
k_d_ss(f,"SSCAP") = rep_k_ss(f,"SSCAP") - rep_x_ss(f,"SSBAU") ;

i_d_ss(f,"SSTPS") = rep_i_ss(f,"SSTPS") - rep_i_ss(f,"SSBAU") ;
i_d_ss(f,"SSCAP") = rep_i_ss(f,"SSCAP") - rep_i_ss(f,"SSBAU") ;

pk_d_ss(f,"SSTPS") = rep_pk_ss(f,"SSTPS") - rep_pk_ss(f,"SSBAU") ;
pk_d_ss(f,"SSCAP") = rep_pk_ss(f,"SSCAP") - rep_pk_ss(f,"SSBAU") ;

pi_d_ss(f,"SSTPS") = rep_pi_ss(f,"SSTPS") - rep_pi_ss(f,"SSBAU") ;
pi_d_ss(f,"SSCAP") = rep_pi_ss(f,"SSCAP") - rep_pi_ss(f,"SSBAU") ;

mpc_d_ss(f,"SSTPS") = rep_mpc_ss(f,"SSTPS");
mpc_d_ss(f,"SSCAP") = rep_mpc_ss(f,"SSCAP");

perm_d_ss("SSTPS") = rep_perm_ss("SSTPS");
perm_d_ss("SSCAP") = rep_perm_ss("SSCAP");

emit_d_ss("SSTPS") = rep_emit_ss("SSTPS") - rep_emit_ss("SSBAU") ;
emit_d_ss("SSCAP") = rep_emit_ss("SSCAP") - rep_emit_ss("SSBAU") ;


********************
*Consumer Surplus
********************

* Undiscounted
cs_d(t,"BAU")$[trep(t)] =
-1*d(t) * (rep_pq(t,"BAU"))**(delas) *
((pd0(t)/hiy/df(t)) * (rep_pq(t,"BAU"))**(-delas) - (pd0(t)/hiy/df(t))**(-delas) * (rep_pq(t,"BAU"))) /
(-delas - 1)
;

```

```
cs_d(t,"TPS")$[trep(t)] =
-1*d(t) * (rep_pq(t,"TPS"))**(delas) *
((pd0(t)/hiy/df(t)) * (rep_pq(t,"TPS"))**(-delas) - (pd0(t)/hiy/df(t))**(-delas) * (rep_pq(t,"TPS"))) /
(-delas - 1)
;

cs_d(t,"CAP")$[trep(t)] =
-1*d(t) * (rep_pq(t,"CAP"))**(delas) *
((pd0(t)/hiy/df(t)) * (rep_pq(t,"CAP"))**(-delas) - (pd0(t)/hiy/df(t))**(-delas) * (rep_pq(t,"CAP"))) /
(-delas - 1)
;

* Discounted
cs_dr(t,"BAU")$[trep(t)] =
-1*d(t) * (rep_pq(t,"BAU")*df(t))**(delas) *
((pd0(t)/hiy) * (rep_pq(t,"BAU")*df(t))**(-delas) - (pd0(t)/hiy)**(-delas) * (rep_pq(t,"BAU")*df(t))) /
(-delas - 1)
;

cs_dr(t,"TPS")$[trep(t)] =
-1*d(t) * (rep_pq(t,"TPS")*df(t))**(delas) *
((pd0(t)/hiy) * (rep_pq(t,"TPS")*df(t))**(-delas) - (pd0(t)/hiy)**(-delas) * (rep_pq(t,"TPS")*df(t))) /
(-delas - 1)
;

cs_dr(t,"CAP")$[trep(t)] =
-1*d(t) * (rep_pq(t,"CAP")*df(t))**(delas) *
((pd0(t)/hiy) * (rep_pq(t,"CAP")*df(t))**(-delas) - (pd0(t)/hiy)**(-delas) * (rep_pq(t,"CAP")*df(t))) /
(-delas - 1)
;


*Steady-state
cs_d_ss("SSBAU") =
-ds * rep_pd_ss("SSBAU")**(delas)
* [(pds0/hiy) * rep_pd_ss("SSBAU")**(-delas) - (pds0/hiy)**(-delas) * rep_pd_ss("SSBAU")]
/ (-delas - 1)
;

```

```
cs_d_ss("SSTPS") =
-ds * rep_pd_ss("SSTPS")**(delas)
* [(pds0/hiy)*rep_pd_ss("SSTPS")**(-delas) - (pds0/hiy)**(-delas)*rep_pd_ss("SSTPS")]
/ (-delas - 1)
;

cs_d_ss("SSCAP") =
-ds * rep_pd_ss("SSCAP")**(delas)
* [(pds0/hiy)*rep_pd_ss("SSCAP")**(-delas) - (pds0/hiy)**(-delas)*rep_pd_ss("SSCAP")]
/ (-delas - 1)
;

*total across t
cs_dt("BAU") = sum(t,cs_d(t,"BAU"));
cs_dt("TPS") = sum(t,cs_d(t,"TPS"));
cs_dt("CAP") = sum(t,cs_d(t,"CAP"));

cs_dtr("BAU") = sum(t,cs_dr(t,"BAU"));
cs_dtr("TPS") = sum(t,cs_dr(t,"TPS"));
cs_dtr("CAP") = sum(t,cs_dr(t,"CAP"));


********************
*Producer Surplus
********************

ps(t,"BAU")$[trep(t)] =
(rep_pq(t,"BAU")) * rep_q(t,"BAU")
- sum(f,rep_x(f,t,"BAU")*vc_x(f))
;

ps(t,"TPS")$[trep(t)] =
(rep_pq(t,"TPS")) * rep_q(t,"TPS")
- sum(f,rep_x(f,t,"TPS")*vc_x(f))
;

ps(t,"CAP")$[trep(t)] =
(rep_pq(t,"CAP")) * rep_q(t,"CAP")
- sum(f,rep_x(f,t,"CAP")*vc_x(f))
```

```
;

psr(t,"BAU")$[trep(t)] =
(rep_pq(t,"BAU")*df(t)) * rep_q(t,"BAU")
- sum(f,rep_x(f,t,"BAU")*vc_x(f))*df(t)
;

psr(t,"TPS")$[trep(t)] =
(rep_pq(t,"TPS")*df(t)) * rep_q(t,"TPS")
- sum(f,rep_x(f,t,"TPS")*vc_x(f))*df(t)
;

psr(t,"CAP")$[trep(t)] =
(rep_pq(t,"CAP")*df(t)) * rep_q(t,"CAP")
- sum(f,rep_x(f,t,"CAP")*vc_x(f))*df(t)
;


ps_d(t,"TPS") = ps(t,"TPS") - ps(t,"BAU") ;
ps_d(t,"CAP") = ps(t,"CAP") - ps(t,"BAU") ;

ps_dr(t,"TPS") = psr(t,"TPS") - psr(t,"BAU") ;
ps_dr(t,"CAP") = psr(t,"CAP") - psr(t,"BAU") ;

*Steady-state
ps_ss("SSBAU") =
rep_pd_ss("SSBAU") * sum(f,rep_x_ss(f,"SSBAU"))
- sum(f,rep_x_ss(f,"SSBAU")*vc_x(f))
;

ps_ss("SSTPS") =
rep_pd_ss("SSTPS") * sum(f,rep_x_ss(f,"SSTPS"))
- sum(f,rep_x_ss(f,"SSTPS")*vc_x(f))
*        - sum(f,rep_x_ss(f,"SSTPS")*rep_perm_ss("SSTPS")*(ci(f)-sigma_s))
;

ps_ss("SSCAP") =
rep_pd_ss("SSCAP") * sum(f,rep_x_ss(f,"SSCAP"))
- sum(f,rep_x_ss(f,"SSCAP")*vc_x(f))
```

```
;

ps_d_ss("SSTPS") = ps_ss("SSTPS") - ps_ss("SSBAU") ;
ps_d_ss("SSCAP") = ps_ss("SSCAP") - ps_ss("SSBAU") ;


*total across t
ps_dt("TPS") = sum(t,ps_d(t,"TPS"));
ps_dt("CAP") = sum(t,ps_d(t,"CAP"));

ps_dtr("TPS") = sum(t,ps_dr(t,"TPS"));
ps_dtr("CAP") = sum(t,ps_dr(t,"CAP"));

csps_d(t,"TPS") = ps_d(t,"TPS") + cs_d(t,"TPS") ;
csps_d(t,"CAP") = ps_d(t,"CAP") + cs_d(t,"CAP") ;

parameter cpk        rental profits (cost) ;
parameter cpk_d        change in rental profits (cost) ;

cpk(t,"BAU")$[trep(t)] =
sum(f, rep_pk(f,t,"BAU")*rep_k(f,t,"BAU")) / hiy
;

cpk(t,"TPS")$[trep(t)] =
sum(f, rep_pk(f,t,"TPS")*rep_k(f,t,"TPS")) / hiy
;

cpk(t,"CAP")$[trep(t)] =
sum(f, rep_pk(f,t,"CAP")*rep_k(f,t,"CAP")) / hiy
;

cpk_d(t,"TPS") = cpk(t,"TPS") - cpk(t,"BAU") ;
cpk_d(t,"CAP") = cpk(t,"CAP") - cpk(t,"BAU") ;



********************
*Policy Costs
********************
```

```
*cpk + polc = ps if things are correct
*pc_d = 0 for all cases if revenues from cap refunded to producers
parameter polc policy costs no refunding used as check against cpk and ps;

polc(t,"TPS")$[trep(t)] =
sum(f,rep_x(f,t,"TPS")*mpc_d(f,t,"TPS"))
;

polc(t,"CAP")$[trep(t)] =
sum(f,rep_x(f,t,"CAP")*mpc_d(f,t,"CAP"))
;

pc_d(t,"TPS")$[trep(t)] =
sum(f,rep_x(f,t,"TPS")*mpc_d(f,t,"TPS"))
;

pc_d(t,"CAP")$[trep(t)] =
sum(f,rep_x(f,t,"CAP")*mpc_d(f,t,"CAP"))
*revenues refunded to producers
- sum(f,rep_x(f,t,"CAP")*mpc_d(f,t,"CAP"))
;

pc_dr(t,"TPS")$[trep(t)] =
sum(f,rep_x(f,t,"TPS")*mpc_d(f,t,"TPS"))*df(t)
;

pc_dr(t,"CAP")$[trep(t)] =
sum(f,rep_x(f,t,"CAP")*mpc_d(f,t,"CAP"))*df(t)
*revenues refunded to producers
- sum(f,rep_x(f,t,"CAP")*mpc_d(f,t,"CAP"))*df(t)
;


*Steady-state
pc_d_ss("SSTPS") =
sum(f,rep_x_ss(f,"SSTPS")*rep_perm_ss("SSTPS")*(ci(f)-sigma_s))
;

pc_d_ss("SSCAP") =
```

```
sum(f,rep_x_ss(f,"SSCAP")*rep_perm_ss("SSCAP")*ci(f))
*revenues refunded to producers
- sum(f,rep_x_ss(f,"SSCAP")*rep_perm_ss("SSCAP")*ci(f))
;

*total across t
pc_dt("TPS") = sum(t,pc_d(t,"TPS"));
pc_dt("CAP") = sum(t,pc_d(t,"CAP"));

pc_dtr("TPS") = sum(t,pc_dr(t,"TPS"));
pc_dtr("CAP") = sum(t,pc_dr(t,"CAP"));

********************
*Investment Costs
********************


cinv(t,"BAU")$[trep(t)] =
[sum(f,i_in(f)*rep_i(f,t,"BAU") + (1/2)*i_sl(f)*(rep_i(f,t,"BAU")**2))/hiy]$(swlic)
+ [sum(f,(1/(1/ielas(f)+1))*pi0(f,t)*(rep_i(f,t,"BAU")**(1/ielas(f) + 1))*(i0(f,t)**(-1/ielas(f))))/hiy]$(not swlic)
;

cinv(t,"TPS")$[trep(t)] =
[sum(f,i_in(f)*rep_i(f,t,"TPS") + (1/2)*i_sl(f)*(rep_i(f,t,"TPS")**2))/hiy]$(swlic)
+ [sum(f,(1/(1/ielas(f)+1))*pi0(f,t)*(rep_i(f,t,"TPS")**(1/ielas(f) + 1))*(i0(f,t)**(-1/ielas(f))))/hiy]$(not swlic)
;

cinv(t,"CAP")$[trep(t)] =
[sum(f,i_in(f)*rep_i(f,t,"CAP") + (1/2)*i_sl(f)*(rep_i(f,t,"CAP")**2))/hiy]$(swlic)
+ [sum(f,(1/(1/ielas(f)+1))*pi0(f,t)*(rep_i(f,t,"CAP")**(1/ielas(f) + 1))*(i0(f,t)**(-1/ielas(f))))/hiy]$(not swlic)
;


cinvr(t,"BAU")$[trep(t)] =
[sum(f,i_in(f)*rep_i(f,t,"BAU") + (1/2)*i_sl(f)*(rep_i(f,t,"BAU")**2))/hiy]*df(t)
;

cinvr(t,"TPS")$[trep(t)] =
[sum(f,i_in(f)*rep_i(f,t,"TPS") + (1/2)*i_sl(f)*(rep_i(f,t,"TPS")**2))/hiy]*df(t)
```

```
;

cinvr(t,"CAP")$[trep(t)] =
[sum(f,i_in(f)*rep_i(f,t,"CAP") + (1/2)*i_sl(f)*(rep_i(f,t,"CAP")**2))/hiy]*df(t)
;

cinv_d(t,"TPS") = cinv(t,"TPS") - cinv(t,"BAU") ;
cinv_d(t,"CAP") = cinv(t,"CAP") - cinv(t,"BAU") ;

cinv_dr(t,"TPS") = cinvr(t,"TPS") - cinvr(t,"BAU") ;
cinv_dr(t,"CAP") = cinvr(t,"CAP") - cinvr(t,"BAU") ;

*Steady-state
cinv_ss("SSBAU") =
[sum(f,i_in(f)*rep_i_ss(f,"SSBAU") + (1/2)*i_sl(f)*(rep_i_ss(f,"SSBAU")**2))]/hiy
;

cinv_ss("SSTPS") =
[sum(f,i_in(f)*rep_i_ss(f,"SSTPS") + (1/2)*i_sl(f)*(rep_i_ss(f,"SSTPS")**2))]/hiy
;

cinv_ss("SSCAP") =
[sum(f,i_in(f)*rep_i_ss(f,"SSCAP") + (1/2)*i_sl(f)*(rep_i_ss(f,"SSCAP")**2))]/hiy
;

cinv_d_ss("SSTPS") = cinv_ss("SSTPS") - cinv_ss("SSBAU") ;
cinv_d_ss("SSCAP") = cinv_ss("SSCAP") - cinv_ss("SSBAU") ;

*total across t
cinv_dt("TPS") = sum(t,cinv_d(t,"TPS"));
cinv_dt("CAP") = sum(t,cinv_d(t,"CAP"));

cinv_dtr("TPS") = sum(t,cinv_dr(t,"TPS"));
cinv_dtr("CAP") = sum(t,cinv_dr(t,"CAP"));

********************
*Abatement Costs
********************
* Abatement costs are positive (cost)
```

```
* ss_d = benefits - abatement costs
* ss_d = dam_d - ac_d

ac_d(t,"TPS")$[trep(t)] =
-1*(
*consumer surplus
cs_d(t,"TPS")
*producer surplus
+ ps_d(t,"TPS")
*policy cost
- pc_d(t,"TPS")
*investment cost
- cinv_d(t,"TPS")
)
;


ac_d(t,"CAP")$[trep(t)] =
-1*(
*consumer surplus
cs_d(t,"CAP")
*producer surplus
+ ps_d(t,"CAP")
*policy cost
- pc_d(t,"CAP")
*investment cost
- cinv_d(t,"CAP")
)
;

ac_dr(t,"TPS")$[trep(t)] =
-1*(
*consumer surplus
cs_dr(t,"TPS")
*producer surplus
+ ps_dr(t,"TPS")
*policy cost
- pc_dr(t,"TPS")
*investment cost
```

```
- cinv_dr(t,"TPS")
)
;


ac_dr(t,"CAP")$[trep(t)] =
-1*(
*consumer surplus
cs_dr(t,"CAP")
*producer surplus
+ ps_dr(t,"CAP")
*policy cost
- pc_dr(t,"CAP")
*investment cost
- cinv_dr(t,"CAP")
)
;


*Steady-state
ac_d_ss("SSTPS") =
-1*(
*consumer surplus
cs_d_ss("SSTPS")
*producer surplus
+ ps_d_ss("SSTPS")
*policy cost
- pc_d_ss("SSTPS")
*investment cost
- cinv_d_ss("SSTPS")
)
;

ac_d_ss("SSCAP") =
-1*(
*consumer surplus
cs_d_ss("SSCAP")
*producer surplus
+ ps_d_ss("SSCAP")
```

```
*policy cost
- pc_d_ss("SSCAP")
*investment cost
- cinv_d_ss("SSCAP")
)
;

*total across t
ac_dt("TPS") = sum(t,ac_d(t,"TPS"));
ac_dt("CAP") = sum(t,ac_d(t,"CAP"));

ac_dr_perp("TPS")$[dr>0] = sum(t$trepf(t),ac_dr(t,"TPS")) / dr ;
ac_dr_perp("CAP")$[dr>0] = sum(t$trepf(t),ac_dr(t,"CAP")) / dr ;

ac_dtr("TPS") = sum(t,ac_dr(t,"TPS")) + ac_dr_perp("TPS");
ac_dtr("CAP") = sum(t,ac_dr(t,"CAP")) + ac_dr_perp("CAP");

********************
*Damages
********************

parameter cdam        marginal cost of emissions (marginal damages) ;

cdam = %cdamval% ;

dam(t,"BAU")$[trep(t)] = cdam * rep_emit(t,"BAU") / 2204 / hiy ;
dam(t,"TPS")$[trep(t)] = cdam * rep_emit(t,"TPS") / 2204 / hiy ;
dam(t,"CAP")$[trep(t)] = cdam * rep_emit(t,"CAP") / 2204 / hiy ;

damr(t,"BAU")$[trep(t)] = [cdam * rep_emit(t,"BAU") / 2204 / hiy]*df(t) ;
damr(t,"TPS")$[trep(t)] = [cdam * rep_emit(t,"TPS") / 2204 / hiy]*df(t) ;
damr(t,"CAP")$[trep(t)] = [cdam * rep_emit(t,"CAP") / 2204 / hiy]*df(t) ;


*damages avoided (benefit)
dam_d(t,"TPS") = -1*(dam(t,"TPS") - dam(t,"BAU")) ;
dam_d(t,"CAP") = -1*(dam(t,"CAP") - dam(t,"BAU")) ;

dam_dr(t,"TPS") = -1*(damr(t,"TPS") - damr(t,"BAU")) ;
```

```
dam_dr(t,"CAP") = -1*(damr(t,"CAP") - damr(t,"BAU")) ;

*Steady-state
dam_ss("SSBAU") = cdam * rep_emit_ss("SSBAU") / 2204 / hiy ;
dam_ss("SSTPS") = cdam * rep_emit_ss("SSTPS") / 2204 / hiy ;
dam_ss("SSCAP") = cdam * rep_emit_ss("SSCAP") / 2204 / hiy ;

*damages avoided (benefit)
dam_d_ss("SSTPS") = -1*(dam_ss("SSTPS") - dam_ss("SSBAU")) ;
dam_d_ss("SSCAP") = -1*(dam_ss("SSCAP") - dam_ss("SSBAU")) ;

*total across t
dam_dt("TPS") = sum(t,dam_d(t,"TPS"));
dam_dt("CAP") = sum(t,dam_d(t,"CAP"));

dam_dr_perp("TPS")$[dr>0] = sum(t$trepf(t),dam_dr(t,"TPS")) / dr ;
dam_dr_perp("CAP")$[dr>0] = sum(t$trepf(t),dam_dr(t,"CAP")) / dr ;

dam_dtr("TPS") = sum(t,dam_dr(t,"TPS")) + dam_dr_perp("TPS");
dam_dtr("CAP") = sum(t,dam_dr(t,"CAP")) + dam_dr_perp("CAP");


********************
*Social Surplus
********************
* Change in Social Surplus = Benefit - Cost

ss_d(t,"TPS")$[trep(t)] = dam_d(t,"TPS") - ac_d(t,"TPS") ;
ss_d(t,"CAP")$[trep(t)] = dam_d(t,"CAP") - ac_d(t,"CAP") ;

ss_dr(t,"TPS")$[trep(t)] = dam_dr(t,"TPS") - ac_dr(t,"TPS") ;
ss_dr(t,"CAP")$[trep(t)] = dam_dr(t,"CAP") - ac_dr(t,"CAP") ;


*Steady-state
ss_d_ss("SSTPS") = dam_d_ss("SSTPS") - ac_d_ss("SSTPS") ;
ss_d_ss("SSCAP") = dam_d_ss("SSCAP") - ac_d_ss("SSCAP") ;
ss_d_ss("SSTPS-SSCAP") = ss_d_ss("SSTPS") - ss_d_ss("SSCAP") ;

```

```
*total across t
ss_dt("TPS") = sum(t,ss_d(t,"TPS"));
ss_dt("CAP") = sum(t,ss_d(t,"CAP"));

ss_dr_perp("TPS")$[dr>0] = sum(t$trepf(t), ss_dr(t,"TPS")) / dr ;
ss_dr_perp("CAP")$[dr>0] = sum(t$trepf(t), ss_dr(t,"CAP")) / dr ;

ss_dtr("TPS") = sum(t,ss_dr(t,"TPS")) + ss_dr_perp("TPS");
ss_dtr("CAP") = sum(t,ss_dr(t,"CAP")) + ss_dr_perp("CAP");

*SS Comparisons
ss_d(t,"TPS-CAP") = ss_d(t,"TPS") - ss_d(t,"CAP") ;
ss_dr(t,"TPS-CAP") = ss_dr(t,"TPS") - ss_dr(t,"CAP") ;
ss_dt("TPS-CAP") = ss_dt("TPS") - ss_dt("CAP") ;
ss_dtr("TPS-CAP") = ss_dtr("TPS") - ss_dtr("CAP") ;

ac_d(t,"TPS-CAP") = ac_d(t,"TPS") - ac_d(t,"CAP") ;
ac_dr(t,"TPS-CAP") = ac_dr(t,"TPS") - ac_dr(t,"CAP") ;
ac_dt("TPS-CAP") = ac_dt("TPS") - ac_dt("CAP") ;
ac_dtr("TPS-CAP") = ac_dtr("TPS") - ac_dtr("CAP") ;


*Key parameters for sensitivity
parameter ss_dtr_sens(*,*,*) sensitivity parameter for social surplus;

ss_dtr_sens("TPS","%scennum%","%scenlet%") = ss_dtr("TPS") ;
ss_dtr_sens("CAP","%scennum%","%scenlet%") = ss_dtr("CAP") ;
ss_dtr_sens("TPS-CAP","%scennum%","%scenlet%") = ss_dtr("TPS-CAP") ;

parameter ss_d_ss_sens(*,*,*) sensitivity for steady-state social surplus ;

ss_d_ss_sens("TPS","%scennum%","%scenlet%") = ss_d_ss("SSTPS") ;
ss_d_ss_sens("CAP","%scennum%","%scenlet%") = ss_d_ss("SSCAP") ;
ss_d_ss_sens("TPS-CAP","%scennum%","%scenlet%") = ss_d_ss("SSTPS-SSCAP") ;

* parameter ss_d_ss_sens_alt(*,*,*,*,*) alternate sens for ss social surplus;
* ss_d_ss_sens_alt("TPS","%scennum%","%scenlet%","%scaleval%","%drval%","%cil%") = ss_d_ss("SSTPS") ;
* ss_d_ss_sens_alt("CAP","%scennum%","%scenlet%","%scaleval%","%drval%","%cil%") = ss_d_ss("SSCAP") ;
* ss_d_ss_sens_alt("TPS-CAP","%scennum%","%scenlet%","%scaleval%","%drval%","%cil%") = ss_d_ss("SSTPS-SSCAP") ;
```

```

********************
*OUTPUT to readable format
********************

execute_unload "%gdxfile%" ;

```

APPENDIX I - COBALT MODEL CODE

Files included:

1. run_scenarios.bat - specifies setup for each benchmark and which calibration file to call
2. cur_data.gms - calibrates current benchmark scenario (CUR)
3. fut_data.gms - calibrates future benchmark scenarios (NPS or E30)
4. model_cob.gms - cobalt model

run_scenarios.gms

```
title Sensitivity Testing

del ..\scenout\runout\*.gdx

set run_name=%1
echo %run_name%

pause

::Scenario Name Key
::(CUR, NPS, E30) Current, NPS, EV30@30
::(1,2) quoteval (0.25,1)
::(A,B) swdelas (no, yes) or esomcval = 0
::(a,b,c) esldvval (0.5, 0.1, 2)

::Present Day / Current Scenario
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_1Aa --quoteval=025
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_2Aa --quoteval=100
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_1Ba --quoteval=025
--esldvieval=0 --esomcval=0
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_2Ba --quoteval=100
```

```
--esldvieval=0 --esomcval=0
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_1Ab --quoteval=025
--esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_2Ab --quoteval=100
--esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_1Ac --quoteval=025
--esldvval=2.00
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_2Ac --quoteval=100
--esldvval=2.00
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_1Bb --quoteval=025
--esldvieval=0 --esomcval=0 --esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_2Bb --quoteval=100
--esldvieval=0 --esomcval=0 --esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_1Bc --quoteval=025
--esldvieval=0 --esomcval=0 --esldvval=2.00
gams model_cob.gms --run_name=%run_name% --gdxname=CUR_2Bc --quoteval=100
--esldvieval=0 --esomcval=0 --esldvval=2.00

::NPS Scenario
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_1Aa --bmkyr=future
--swfutscen=NPS --capadj=notdefault --bcrep=0.135 --quoteval=025
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_2Aa --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=100
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_1Ba --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvieval=0 --esomcval=0
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_2Ba --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvieval=0 --esomcval=0
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_1Ab --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_2Ab --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_1Ac --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvval=2.00
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_2Ac --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvval=2.00
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_1Bb --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvieval=0 --esomcval=0 --esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_2Bb --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvieval=0 --esomcval=0 --esldvval=0.10
```

```
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_1Bc --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvieval=0 --esomcval=0 --esldvval=2.00
gams model_cob.gms --run_name=%run_name% --gdxname=NPS_2Bc --bmkyr=future --swfutscen=NPS
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvieval=0 --esomcval=0 --esldvval=2.00

::EV30@30 Scenario
gams model_cob.gms --run_name=%run_name% --gdxname=E30_1Aa --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=025
gams model_cob.gms --run_name=%run_name% --gdxname=E30_2Aa --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=100
gams model_cob.gms --run_name=%run_name% --gdxname=E30_1Ba --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvieval=0 --esomcval=0
gams model_cob.gms --run_name=%run_name% --gdxname=E30_2Ba --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvieval=0 --esomcval=0
gams model_cob.gms --run_name=%run_name% --gdxname=E30_1Ab --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=E30_2Ab --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=E30_1Ac --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvval=2.00
gams model_cob.gms --run_name=%run_name% --gdxname=E30_2Ac --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvval=2.00
gams model_cob.gms --run_name=%run_name% --gdxname=E30_1Bb --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvieval=0 --esomcval=0 --esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=E30_2Bb --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvieval=0 --esomcval=0 --esldvval=0.10
gams model_cob.gms --run_name=%run_name% --gdxname=E30_1Bc --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=025 --esldvieval=0 --esomcval=0 --esldvval=2.00
gams model_cob.gms --run_name=%run_name% --gdxname=E30_2Bc --bmkyr=future --swfutscen=E30
--capadj=notdefault --bcrep=0.135 --quoteval=100 --esldvieval=0 --esomcval=0 --esldvval=2.00


COPY runs_%run_name%.dat ..\scenout\runs_%run_name%.dat
DEL runs_%run_name%.dat


gdxmerge ..\scenout\runout\*.gdx output=..\scenout\runs_%run_name%.gdx


```

cur_data.gms

```
$title Data pre-processing for cobalt cge main model (Current Scenarios)

*========== Populate/update existing sets ==========
$onmulti
set g(*)    goods plus C and G /
cob     "refined cobalt general met/chem aggregate"
mcob    "refined cobalt metal"
ccob    "refined cobalt chemical"
ldv     "light duty vehicles index"
ice     "internal combustion vehicles within ldv"
bev     "battery electric vehicles within ldv"
phev    "plug-in hybrid electric vehicles within ice"
omvh    "other motor vehicles and parts - subsitutable with ldv index"
/;

$onmulti
set i(g)    goods /
cob     "refined cobalt general met/chem aggregate"
mcob    "refined cobalt metal"
ccob    "refined cobalt chemical"
ldv     "light duty vehicles index"
ice     "internal combustion vehicles within ldv"
bev     "battery electric vehicles within ldv"
phev    "plug-in hybrid electric vehicles within ldv"
omvh    "other motor vehicles and parts - subsitutable with ldv index"
/;

$onmulti
set f(*)    factors /
rco     "fixed cobalt resource factor"
/;

display g,i,f;

*add subsets for set control later
set cob(g) cobalt general /cob/;
set ccob(g) cobalt chemical /ccob/;
```

```
set mcob(g) cobalt metal /mcob/;
set cobmc(g) cobalt chem and met /ccob, mcob/;
set coball(g) all cobalt sets /cob, ccob, mcob/;

set cmm(g) cmm index /cmm/;
*set ele(g) ele index /ele/;
set omc(g) omc index /omc/;
set omi(g) omi index /omi/;
set aog(g) aog index /aog/;

set ldv(g) light duty vehicles /ldv/;
set ice(g) internal combustion /ice/;
set bev(g) battery electric /bev/;
set phev(g) plug-in hybrid /phev/;
set omvh(g) other mvh /omvh/;
set ev(g) EV technologies /bev, phev/;
set ldvie(g) ice and ev /ice, bev, phev/;
set ldvall(g) all ldv /ldv, ice, bev, phev/;

set mvh(g) mvh index /mvh/;
set mvhlo(g) ldv and omvh /ldv, omvh/;
set mvhall(g) all mvh /mvh, ldv, omvh/;
set mvhall2(g) all mvh /mvh, ldv, omvh, bev, phev, ice/;
set mvhall3(g) all mvh /ldv, omvh, bev, phev, ice/;

set rco(f) fixed cobalt resource /rco/;
set cap(f)  capital /cap/;
set lab(f)  labor   /lab/;


set chn(r) references china (chn) /chn/ ;
set usa(r) references usa (usa) /usa/ ;
set row(r) references row (row) /row/ ;

*specify mobile/sluggish factors (k and l are mobile)
mf(f)$[not rco(f)] = yes$(1/etrae(f)=0);
sf(f)$[not rco(f)] = yes$(1/etrae(f)>0);


```

```
*========== Raw Data ==========

parameters
prd_q0(g,r)     "benchmark production quantity"
prd_p0(g,r)     "benchmark production price"
prd_v0(g,r)     "benchmark production value(output) unadjusted for gtap base year"
;

*Cobalt DATA

table   cobprd_q0(r,i)      "Cobalt Production - table to import cobalt production (tons Co)"
COB   CCOB  MCOB
USA 300   300   0
CHN 72200 59000 13200
ROW 44200 9300  34900

;

scalar  pg_cob  "global cobalt price"   /20/;
prd_p0(i,r)$[cob(i)] = pg_cob ;


*LDV, BEV, PHEV, ICE DATA

table   ldvprd_q0(r,i)      "LDV Production - table to import ldv production (# of vehicles)"

LDV      BEV    PHEV   ICE
USA 11000000 104040 99960  10796000
CHN 25000000 486000 114000 24400000
ROW 39000000 201960 194040 38604000

;


parameter   ldv_sales(r)    "ldv sales by country"
/
USA     16000000
CHN     25000000
ROW     34000000
```

```
/
;

*https://www.statista.com/outlook/1000000/117/passenger-cars/china#market-pricePerUnit
*https://www.statista.com/statistics/425095/eu-car-sales-average-prices-in-by-country/
parameter   rep_ldvprice(r) "average ldv sales price by region"
/
USA     38000,
CHN     22000,
ROW     30000
/
;

scalar  avg_ldvprice    "average global ldv sale price";
avg_ldvprice = sum(r, ldv_sales(r) * rep_ldvprice(r)) / sum(r, ldv_sales(r));

parameter   ldv_cost_scale(r)   "Scaling factor for ldv costs - used for country level vehicle cost adjustments";
ldv_cost_scale(r) = rep_ldvprice(r) / avg_ldvprice ;

parameter   rep_ldvcost(i)  "production cost of representative vehicle"
/
ICE     25000,
BEV     40000,
PHEV    30000
/
;

parameter   rep_ldvcap(i)   "capacity of battery in representative vehicle"
/
ICE     0,
BEV     45,
PHEV    12
/
;

parameter   rep_packcost(i) "cost/kwh of battery pack in representative vehicle"
/
ICE     0,
BEV     175,
```

```
PHEV    175
/
;

table   avg_cap(r,i)    "average electric vehicle battery capacity (kwh)"

BEV PHEV
USA 65  12
CHN 27  15
ROW 39  12

;

parameter   ldv_battcap(i,r)    "total battery capacity in each ldv sector";
ldv_battcap(i,r)$[ldvie(i)] = ldvprd_q0(r,i) * avg_cap(r,i);

* Calculate benchmark indices for electric vehicles
prd_q0(i,r)$[ldvie(i)] = ldvprd_q0(r,i) ;
prd_p0(i,r)$[ldvie(i)] = [rep_ldvcost(i) + (avg_cap(r,i) - rep_ldvcap(i)) * rep_packcost(i)] * ldv_cost_scale(r) ;
prd_v0(i,r)$[ldvie(i)] = prd_q0(i,r) * prd_p0(i,r);

*Battery Capacity for Portable Electronics - ELE sector
*SOURCE: Roskill Cobalt Report

*A different source with some incomplete information suggesting consumer electronics
*are close to roskill shares
*https://intrepidsourcing.com/industry-reports/consumer-electronics-industry-report/

parameter   ele_battcap(r)  "portable electronics battery capacity (kwh)"
/
USA     4000000,
CHN     11000000,
ROW     21000000
/
;

*Battery Chemistry Data

set bc  "battery chemistry"
```

```
/
NCA,
NCM111,
NCM433,
NCM523,
NCM622,
NCM811,
LCO,
LFP,
LMO
/
;

parameter   rep_chem(bc)    "Cobalt contained within battery chemistry (kg/kwh)"
/
NCA     0.13,
NCM111  0.4,
NCM433  0.35,
NCM523  0.23,
NCM622  0.19,
NCM811  0.09,
LCO     0.6,
LFP     0,
LMO     0
/
;

set        u        "use categories"
/
batt        "battery",
supa        "superalloys",
hard        "hard metals/tools",
pigm        "pigments/inks/ceramics",
cata        "catalysts",
soap        "soaps and detergents",
mago        "magnets and other applications"
/
;

```

```
alias(u,z);
set batt(u) "battery chemistry" /batt/;

table sh_cob_globe_use(u,*) "data related to cobalt use and global distribution of use"
use  USA  CHN        ROW
batt 0.48 0.08 0.65        0.27
supa 0.19 0.42 0.17        0.41
hard 0.09 0.07 0.50        0.43
pigm 0.06 0.11 0.65        0.24
cata 0.06 0.11 0.12        0.77
soap 0.03 0.32 0.21        0.47
mago 0.09 0.10 0.58        0.32
;

display sh_cob_globe_use;

*========== Cobalt use (tons) ==========

parameter   cob_used(i,r)   "pure cobalt used in production of goods (kg or tons)";

*---------- Choose a Representative Chemistry ----------
*cobalt used in production of vehicles (tons)
*cob_used(i,r)$[ldvie(i)] = (ldv_battcap(i,r) * rep_chem("NCM111")) * (2.204 / 2000);
cob_used(i,r)$[ldvie(i)] = (ldv_battcap(i,r) * %bcrep%) * (2.204 / 2000);

*cobalt used in production of portable electronic devices (tons)
*cob_used(i,r)$[ele(i)] = (ele_battcap(r) * rep_chem("LCO")) * (2.204 / 2000);


*Determine cobalt use(tons co) by country in OMC sector after EV use accounted for
cob_used(i,r)$[omc(i)] =
[sum(u$(not batt(u)), sum(s,cobprd_q0(s,"cob"))*sh_cob_globe_use(u,"use")*sh_cob_globe_use(u,r))]
+ [sum(u$batt(u), (sum(s,cobprd_q0(s,"cob")) * sh_cob_globe_use(u,"use")
- sum((j,s)$ldvie(j),cob_used(j,s))
- sum(s,(ele_battcap(s) * rep_chem("LCO")) * (2.204 / 2000)))
* sh_cob_globe_use(u,r))]
*        - sum(j$ldvie(j),cob_used(j,r))
+ [(ele_battcap(r) * rep_chem("LCO")) * (2.204 / 2000)]
;
```

```

*OR...

*---------- What is the implied battery chemistry? ----------
*Rather than representative chemistry - use implied chemistry
parameter   cob_use_ev      "cobalt used in the EV sector 2017 (tons Co)";
*6% of global cobalt production is used in LDV EVs
*Source: IEA 2018 global ev outlook
cob_use_ev = sum(r,cobprd_q0(r,"cob")) * 0.06;

parameter   imp_chem    "implied battery chemistry (kg/kwh)";
imp_chem("IEA") = (cob_use_ev * 2000 / 2.204) / sum((i,r)$ldvie(i), ldv_battcap(i,r));

parameter   imp_cob_use(i,r)    "implied pure cobalt used in production of goods (kg or tons)";
imp_cob_use(i,r)$[ldvie(i)] = (ldv_battcap(i,r) * imp_chem("IEA")) * (2.204 / 2000) ;

parameter   jrc_cob_use(i,r)    "guess using shares from jrc report";

imp_chem("jrc") = rep_chem("NCM111")*.42 + rep_chem("NCM433")*.05 + rep_chem("NCM523")*.07
+ .07*rep_chem("LMO") + rep_chem("NCA")*.14 + rep_chem("LFP")*.24
;

jrc_cob_use(i,r) = (ldv_battcap(i,r) * imp_chem("jrc")) * (2.204 / 2000);

parameter share_cob_use_imp;

share_cob_use_imp("ncm111") = sum((i,r)$ldvie(i), cob_used(i,r)) / sum(r,cobprd_q0(r,"cob")) ;
share_cob_use_imp("IEA") = sum((i,r)$ldvie(i), imp_cob_use(i,r)) / sum(r,cobprd_q0(r,"cob")) ;
share_cob_use_imp("JRC") = sum((i,r)$ldvie(i), jrc_cob_use(i,r)) / sum(r,cobprd_q0(r,"cob")) ;

display rep_chem, imp_chem, share_cob_use_imp, cob_use_ev, imp_cob_use, cob_used, jrc_cob_use ;

*--------------------

*---------- Determine cobalt used in OMC Sector ----------

parameter   cob_globe_use(i)    "total cobalt use within each sector";

*If Scenario is Future --- Already have present day OMC data
```

```
*Need Switch or something to adjust cobalt production when running future scenarios
*--- this could go at beginning of the file
*I could hold cobalt use in omc the same as first benchmark setup... then adjust production accordingly
*I would also have no need for previous two lines of code or some of the lines below
*cob_used(i,r)$[omc(i)] = benchmark_cob_used(i,r);
*cob_globe_use(i) = sum(r, cob_used(i,r)) ;


*If Scenario is Current --- no OMC data Exists
*Given total value of OMC sectoral activity
*and total value of cobalt used after LDV and ELE use (global OMC cob use value)
*I assume cobalt is weighted in each region by OMC sector share of global to equate supply and demand globally

*cob_globe_use(i)$[not omc(i)] = sum(r,cob_used(i,r));
*cob_globe_use(i)$[omc(i)] = sum(r, cobprd_q0(r,"cob")) - sum(j,cob_globe_use(j));
cob_globe_use(i) = sum(r,cob_used(i,r));

Parameter check_sd_cob  "check to make sure production equals use (supply=demand)" ;
check_sd_cob("dem-sup") = sum(i,cob_globe_use(i)) - sum(r, cobprd_q0(r,"cob")) ;

display check_sd_cob, cob_globe_use, cob_used;


parameter vom_shrg(i,r) "output share of global";
vom_shrg(i,r)$[omc(i)] = vom(i,r) / sum(s,vom(i,s)) ;

*cob_used(i,r)$[omc(i)] = cob_globe_use(i) * vom_shrg(i,r) ;

check_sd_cob("dem-sup-alt") = sum((i,r), cob_used(i,r)) - sum(r, cobprd_q0(r,"cob"));

display check_sd_cob, cob_used;
*$exit
*NOTE:
*cob_used(i,r) contains cobalt use (tons Co) in all modeled sectors in current year (2017)

*====================

*========== MVH nesting structure in terms of values and value shares ==========

```

```
*Average new car price 2010 --- 28k
*Average new car price 2018 --- 36k
*Growth Rate --- (36/28)**(1/(2018-2010)) = 1 + r --- r = 0.03 (approximate) --

*unido db says 7-10% (approx) based on output in motor vehicles production (4 digit isic)

*Given r and unchanged vehicles production - 2011 value of automobiles can be determined
**This can be used to disaggregate mvh into omvh and ldv
**ldv can be further disaggregated given value shares calculated as a result of a given point in time
**Need to establish base year vehicles output in order to infer cobalt production based on sharing

$ontext
mvh omvh ldv ice bev phev
mvh
omvh  x
ldv   x
ice             x
bev             x
phev            x
aog        x        x   x   x
$offtext

*total value of all ldv
prd_v0(i,r)$[ldv(i)] = sum(j$ldvie(j), prd_v0(j,r)) ;

parameter   sh_ldv_v0(i,r)  "share of total ldv output attributable to BEV, PHEV, and ICE";
sh_ldv_v0(i,r)$[ldvall(i)] = prd_v0(i,r) / sum(j$ldv(j), prd_v0(j,r)) ;

*gtap base year (2011) - need to bring 2017-2018 figures back
scalar base_yr  "gtap base year" /2011/;
scalar data_yr  "year for cost data" /2017/;

*based on unido database cagr automobiles sector --- roughly 7-10% for period
*scalar cost_r   "annual growth rate" /0.08/;
parameter        cost_r(r) "annual automobiles unido growth rate (cagr) by country"
/
USA                0.08,
CHN                0.08,
ROW                0.08
```

```
/
;

*adjust current values so that they represent appropriate value shares of GTAP 2011 database
parameter prd_v0_base(i,r) "base year (2011) output value -- consistent with GTAP9";
*prd_v0_base(i,r)$[ldv(i)] = prd_v0(i,r) * [(1/(1+cost_r))**(data_yr-base_yr)];
prd_v0_base(i,r)$[ldv(i)] = prd_v0(i,r) * [(1/(1+cost_r(r)))**(data_yr-base_yr)];

parameter sh_vdfm(j,i,r) "share of input value /output";

*First compute share for LDV and OMVH in MVH
sh_vdfm(j,i,r)$[mvh(i)$ldv(j)] = 1e-9 * prd_v0_base(j,r) / vom(i,r) ;
sh_vdfm(j,i,r)$[mvh(i)$omvh(j)] = 1 - sh_vdfm("ldv",i,r);

*For reporting purposes/curiosity --- may come in handy as validation tool
parameter wt_avg_vh_cost(r) "weighted average ldv cost implied in benchmark";
wt_avg_vh_cost(r) = prd_v0("ldv",r) / ldvprd_q0(r,"ldv") ;

display prd_v0, sh_ldv_v0, prd_v0_base, sh_vdfm, wt_avg_vh_cost ;

*Define intermediate input shares in MVH sector
*There are different ways to share out - for now assume same structure as MVH in omvh and ldv
parameters
sh_vdfm_mvh0(j,i,r) "cost shares of mvh in original SAM (vdfm)"
sh_vifm_mvh0(j,i,r) "cost share of mvh in original SAM (vifm)"
sh_vfm_mvh0(f,i,r)  "cost share of mvh in original SAM (vfm)"
;

sh_vdfm_mvh0(j,i,r)$[mvh(i)] = vdfm(j,i,r) / vom(i,r);
sh_vifm_mvh0(j,i,r)$[mvh(i)] = vifm(j,i,r) / vom(i,r);
sh_vfm_mvh0(f,i,r)$[mvh(i)] = vfm(f,i,r) / vom(i,r);

parameter zpf_share_chk(i,r);
zpf_share_chk(i,r)$mvh(i) =
1*(1-rto(i,r))
- sum(j, sh_vdfm_mvh0(j,i,r)*(1+rtfd0(j,i,r)) + sh_vifm_mvh0(j,i,r)*(1+rtfi0(j,i,r)))
- sum(f, sh_vfm_mvh0(f,i,r)*(1+rtf0(f,i,r)))
;

```

```
display sh_vdfm_mvh0, sh_vifm_mvh0, sh_vfm_mvh0, zpf_share_chk ;

*recall sh_ldv_v0(i,r) from earlier
sh_vdfm(j,i,r)$[ldvie(j)$ldv(i)] = sh_ldv_v0(j,r) ;

*sh_vdfm lacks a representation of cobalt within it
*cobalt still contained within cmm input
display sh_vdfm;

*==========

*need cobalt value in use as a percentage of output in bev, phev, ele, omc
*if cobalt use in EV is x% of value of EV (same for base vs 2017)
*and cobalt price is assumed to be the same, then I can infer the value or amount of cobalt
*in other sectors based on the shares of cobalt use of country total

parameter cob_val_shr(i,r)  "share of cobalt used value / value in sector used" ;
parameter cob_v0(i,r)   "value of cobalt used in each sector i for each region r";

cob_v0(i,r) = cob_used(i,r) * sum(j$cob(j), prd_p0(j,r) * 2000);
cob_val_shr(i,r)$ldvie(i) = cob_v0(i,r) / prd_v0(i,r) ;

parameter sh_cob_use(i,r) "share of cobalt used in industry i of total country use";
sh_cob_use(i,r) = cob_used(i,r) / sum(j,cob_used(j,r)) ;

*calculate prd_v0_base(i,r) before this section

*once have base year ldv production
vom(i,r)$ldv(i) = prd_v0_base(i,r) * 1e-9 ;
vom(i,r)$ldvie(i) = sum(j$ldv(j), vom(j,r)) * sh_ldv_v0(i,r) ;
cob_v0(i,r)$ldvie(i) = vom(i,r)*cob_val_shr(i,r);
cob_v0(i,r)$[not ldvie(i)] = sh_cob_use(i,r) * cob_v0("bev",r) / sh_cob_use("bev",r);

cob_val_shr(i,r)$vom(i,r) = cob_v0(i,r) / vom(i,r);

parameter   cob_used_base(i,r)  "base year cobalt use (2011)";
cob_used_base(i,r) = cob_v0(i,r) / sum(j$cob(j), prd_p0(j,r) * 2000 * 1e-9);

display cob_v0, cob_val_shr, cob_used, cob_used_base;
```

```

*==========

* Calculate values for mvh nest
parameter
vdfm_mvh0   "vdfm for mvh0 nest"
vifm_mvh0
vfm_mvh0
;

vom(i,r)$[omvh(i)] = vom("mvh",r) * sh_vdfm(i,"mvh",r) ;

vdfm_mvh0(j,i,r)$[omvh(i)] = sh_vdfm_mvh0(j,"mvh",r) * vom(i,r) ;
vdfm_mvh0(j,i,r)$[ldvie(i)] = sh_vdfm_mvh0(j,"mvh",r) * vom(i,r) ;

vifm_mvh0(j,i,r)$[omvh(i)] = sh_vifm_mvh0(j,"mvh",r) * vom(i,r) ;
vifm_mvh0(j,i,r)$[ldvie(i)] = sh_vifm_mvh0(j,"mvh",r) * vom(i,r) ;

vfm_mvh0(f,i,r)$[omvh(i)] = sh_vfm_mvh0(f,"mvh",r) * vom(i,r) ;
vfm_mvh0(f,i,r)$[ldvie(i)] = sh_vfm_mvh0(f,"mvh",r) * vom(i,r) ;

rto(i,r)$[omvh(i) or ldvie(i)] = rto("mvh",r);
rtfd0(j,i,r)$[omvh(i) or ldvie(i)] = rtfd0(j,"mvh",r) ;
rtfi0(j,i,r)$[omvh(i) or ldvie(i)] = rtfi0(j,"mvh",r) ;
rtf0(f,i,r)$[omvh(i) or ldvie(i)] = rtf0(f,"mvh",r) ;

display vdfm_mvh0, vifm_mvh0, vfm_mvh0;

parameter zpf_chk(i,r);
zpf_chk(i,r)$[omvh(i) or ldvie(i)] = vom(i,r)*(1-rto(i,r))
- sum(j, vdfm_mvh0(j,i,r)*(1+rtfd0(j,i,r)) + vifm_mvh0(j,i,r)*(1+rtfi0(j,i,r)))
- sum(f, vfm_mvh0(f,i,r)*(1+rtf0(f,i,r)))
;
display zpf_chk;

*verify that there is enough cmm in bev and phev blocks to share out cobalt use
parameter cmm_size(i,r,*)   "check to make sure there is enough cmm to share out cob";

cmm_size(i,r,"vdfm")$[ldvie(i)] = vdfm_mvh0("cmm",i,r) - cob_v0(i,r);
```

```
*cmm_size(i,r,"vdfm")$[omc(i) or ele(i)] = vdfm("cmm",i,r) - cob_v0(i,r);
cmm_size(i,r,"vdfm")$[omc(i)] = vdfm("cmm",i,r) - cob_v0(i,r);

cmm_size(i,r,"vifm")$[ldvie(i)] = vifm_mvh0("cmm",i,r) - cob_v0(i,r);
*cmm_size(i,r,"vifm")$[ele(i) or omc(i)] = vifm("cmm",i,r) - cob_v0(i,r);
cmm_size(i,r,"vifm")$[omc(i)] = vifm("cmm",i,r) - cob_v0(i,r);

display cmm_size, cob_v0;

*==========

*Then determine global cobalt use - use the shares of cobalt production by region
*to determine new production levels in each region - then values can be computed for the upstream


parameter sh_cobprdg(i,r)   "cobalt production share of global by region";

sh_cobprdg(i,r)$[coball(i)] = cobprd_q0(r,i) / sum((s,j)$cob(j), cobprd_q0(s,j)) ;

display sh_cobprdg;

parameters
cob_v_globe
cob_use_globe
cob_prod_globe
cob_prod_r(r)
cob_vprod_r(r)

;

cob_v_globe = sum((i,r), cob_v0(i,r));
cob_use_globe("a") = sum((i,r), cob_used_base(i,r));
cob_use_globe("b") = 1e9 * cob_v_globe / (20 * 2000);

*Use and production shares used to determine base year production levels by region
cob_prod_globe = cob_use_globe("a") ;
cob_prod_r(r) = cob_prod_globe * sh_cobprdg("cob",r) ;
cob_vprod_r(r) = cob_prod_r(r) * 20 * 2000 * 1e-9 ;

```

```
display cob_v_globe, cob_use_globe;

*Check to make sure supply = demand
parameter chk_cob_use_prod;
chk_cob_use_prod("prd-use","world") = sum(r,cob_vprod_r(r)) - cob_v_globe;
display chk_cob_use_prod;

*Determine trade flows in terms of net trade with global market
parameter chk_impexp(*,*)   "net imports/exports of cobalt by country";
chk_impexp(r,"net imports") = sum(i,cob_v0(i,r)) - cob_vprod_r(r) ;
chk_impexp(r,"net exports") = cob_vprod_r(r) -  sum(i,cob_v0(i,r));
chk_impexp("world", "net imports") = sum(r, chk_impexp(r,"net imports"));
chk_impexp("world", "net exports") = sum(r, chk_impexp(r,"net exports"));
display chk_impexp;

* parameters
*   cob_vim(r)  "imports of cobalt by country r"
*   cob_vex(r)  "exports of cobalt by country r"
*   cob_vom(r)  "production of cobalt by country r"
*   cob_vdm(r)  "production of cobalt for domestic use by country r"
* ;

*========== Initialize SAM parameters =========
*update sam for mvh
*update sam for cobalt
*share out cobalt from all necessary sectors

parameters
vom0(g,r)
vdm0(g,r)
vex0(g,r)
vxmd0(i,r,s)
vim0(g,r)
vdfm0(i,g,r)
vifm0(i,g,r)
vfm0(f,g,r)
;

*NOTE THIS PARAMETER!!!
```

```
vom0(g,r) = vom(g,r) ;
vom0(g,r)$cob(g) = cob_vprod_r(r) ;

vdfm0(i,g,r)$[mvh(g)$mvhlo(i)] = vom(i,r);
vdfm0(i,g,r)$[ldv(g)$ldvie(i)] = vom(i,r);

vdfm0(i,g,r)$[ldvie(g)] = vdfm_mvh0(i,g,r) ;
vdfm0(i,g,r)$[omvh(g)] = vdfm_mvh0(i,g,r) ;

vifm0(i,g,r)$[ldvie(g)] = vifm_mvh0(i,g,r) ;
vifm0(i,g,r)$[omvh(g)] = vifm_mvh0(i,g,r) ;

vfm0(f,g,r)$[ldvie(g)] = vfm_mvh0(f,g,r) ;
vfm0(f,g,r)$[omvh(g)] = vfm_mvh0(f,g,r) ;

vdfm0(i,g,r)$[not mvhall2(g)] = vdfm(i,g,r) ;
vifm0(i,g,r)$[not mvhall2(g)] = vifm(i,g,r) ;
vfm0(f,g,r)$[not mvhall2(g)] = vfm(f,g,r) ;

rto(i,r)$[mvh(i) or ldv(i)] = 0;

*---------- add cobalt
parameters
sh_vex0(g,r)    "share of production of good i in country r that is exported"
sh_vdm0(g,r)    "share of production of good i in country r for domestic use"
sh_vfm0(f,g,r)  "share of production of good g in country r that is attributable to factor f"
sh_vdfm0(i,g,r) "share of production of good g in country r that is attributable to domestically produced good i"
sh_vifm0(i,g,r) "share of production of good g in country r that is attributable to imported good i"
sh_vxmd0(i,r,s) "share of exports of good i from country r that are sent to s (bilateral trade)"
;

*Add factors --- simple representation with no intermediate goods
sh_vfm0(f,g,r)$[rco(f)$cob(g)] = 0.8;
sh_vfm0(f,g,r)$[cap(f)$cob(g)] = 0.1;
sh_vfm0(f,g,r)$[lab(f)$cob(g)] = 0.1;

vfm0(f,g,r)$[cob(g)] = vom0(g,r) * sh_vfm0(f,g,r) ;

*Disaggregate SAM with cobalt representation
```

```

sh_vex0(i,r)$[cob(i)$chn(r)] = chk_impexp(r,"net exports") / vom0(i,r) ;
sh_vxmd0(i,r,s)$[cob(i)$chn(r)$(not chn(s))] = chk_impexp(s,"net imports") / chk_impexp(r,"net exports") ;

*sh_vfm0(f,g,r) = vfm0(f,g,r)/vom(g,r);

*Set very low share of exports to avoid source/sink error and allow bilateral trade
*sh_vex0(i,r)$[cob(i)$(not chn(r))] = 0.1 ;
*sh_vxmd0(i,r,s)$[cob(i)$usa(r)$(not usa(s))] = 0.5 ;
*sh_vxmd0(i,r,s)$[cob(i)$row(r)$(not row(s))] = 0.25 ;
*sh_vxmd0(i,r,s)$[cob(i)$row(r)$row(s)] = 0.5 ;

*Alternative method to ensure trade flows perfectly offset
sh_vex0(i,r)$[cob(i)$usa(r)] = 0.1;
vex0(i,r)$[cob(i)$usa(r)] = vom0(i,r)*sh_vex0(i,r);
sh_vex0(i,r)$[vom0(i,r)$cob(i)$row(r)] = vex0(i,"usa") / vom0(i,r);
sh_vxmd0(i,r,s)$[cob(i)$usa(r)$row(s)] = 1;
sh_vxmd0(i,r,s)$[cob(i)$row(r)$usa(s)] = 1;

sh_vdm0(i,r) = 1-sh_vex0(i,r) ;

vdm0(i,r)$[cob(i)] = vom0(i,r) * sh_vdm0(i,r) ;
vex0(i,r)$[cob(i)] = vom0(i,r) * sh_vex0(i,r) ;
vxmd0(i,r,s)$[cob(i)] = vex0(i,r) * sh_vxmd0(i,r,s) ;

*vdfm("cob",g,r) vs. vifm("cob",g,r);
parameters
sh_cob(g,r)     "cobalt use in sector g by country r share of total use in country r"
;

*NOTE THIS PARAMETER!!!!
sh_cob(i,r) = cob_v0(i,r) / sum(j, cob_v0(j,r)) ;
vim0(i,r)$[cob(i)] = sum(s, pvxmd(i,s,r) * vxmd0(i,s,r)) ;
vdfm0(j,i,r)$[cob(j)] = sh_cob(i,r) * vdm0(j,r) ;
vifm0(j,i,r)$[cob(j)] = sh_cob(i,r) * vim0(j,r) ;
*sh_cob used by sector g in r to determine allocation of cob use from domestic production and imports

vdm0(i,r) = sum(g, vdfm0(i,g,r));
vxmd0(i,r,s)$[not cob(i)] = vxmd(i,r,s) ;
```

```
*========== Disaggregate Cobalt from CMM ==========

*tax rates need updated
*convert tax rate to level
rto(g,r)    = rto(g,r) * vom0(g,r);
rtf0(f,j,r)  = rtf0(f,j,r) * vfm0(f,j,r);
rtfd0(i,g,r) = rtfd0(i,g,r) * vdfm0(i,g,r);
rtfi0(i,g,r) = rtfi0(i,g,r) * vifm0(i,g,r);
rtms0(i,r,s) = rtms0(i,r,s) * ((1-rtxs0(i,r,s)) * vxmd0(i,r,s) + sum(j,vtwr(j,i,r,s)));
rtxs0(i,r,s) = rtxs0(i,r,s) * vxmd0(i,r,s);

vom0("cmm",r) = vom0("cmm",r) - vom0("cob",r) ;
vdm0("cmm",r) = vdm0("cmm",r) - vdm0("cob",r) ;
vxmd0("cmm",r,s) = vxmd0("cmm",r,s) - vxmd0("cob",r,s);
vdfm0(i,"cmm",r) = vdfm0(i,"cmm",r) - vdfm0(i,"cob",r) ;
vdfm0("cmm",g,r) = vdfm0("cmm",g,r) - vdfm0("cob",g,r) ;
vfm0(f,"cmm",r)$[not rco(f)] = vfm0(f,"cmm",r) - vfm0(f,"cob",r) ;
vfm0("cap","cmm",r) = vfm0("cap","cmm",r) - vfm0("rco","cob",r) ;
vifm0(i,"cmm",r) = vifm0(i,"cmm",r) - vifm0(i,"cob",r);
vifm0("cmm",g,r) = vifm0("cmm",g,r) - vifm0("cob",g,r);

*recalculate tax rate
*convert back to rate
rto(g,r)$vom0(g,r) = rto(g,r) / vom0(g,r);
rtf0(f,j,r)$vfm0(f,j,r) = rtf0(f,j,r) / vfm0(f,j,r);
rtfd0(i,g,r)$vdfm0(i,g,r) = rtfd0(i,g,r) / vdfm0(i,g,r);
rtfi0(i,g,r)$vifm0(i,g,r) = rtfi0(i,g,r) / vifm0(i,g,r);
rtxs0(i,r,s)$vxmd0(i,r,s) = rtxs0(i,r,s) / vxmd0(i,r,s);
rtms0(i,r,s)$[(1-rtxs0(i,r,s)) * vxmd0(i,r,s) + sum(j,vtwr(j,i,r,s))]
= rtms0(i,r,s) / ((1-rtxs0(i,r,s)) * vxmd0(i,r,s) + sum(j,vtwr(j,i,r,s)));


pvxmd(i,s,r) = (1+rtms0(i,s,r)) * (1-rtxs0(i,s,r));
pvtwr(i,s,r) = 1+rtms0(i,s,r);

*====================

*========== Update SAM and GTAP Parameters ==========
```

```
parameters
evom0(f,r)
vb0
;

vom0("c",r) = sum(i, vdfm0(i,"c",r)*(1+rtfd0(i,"c",r)) + vifm0(i,"c",r)*(1+rtfi0(i,"c",r)))/(1-rto("c",r));
vom0("g",r) = sum(i, vdfm0(i,"g",r)*(1+rtfd0(i,"g",r)) + vifm0(i,"g",r)*(1+rtfi0(i,"g",r)))/(1-rto("g",r));
vom0("i",r) = sum(i, vdfm0(i,"i",r)*(1+rtfd0(i,"i",r)) + vifm0(i,"i",r)*(1+rtfi0(i,"i",r)))/(1-rto("i",r));

vdm0("c",r) = vom0("c",r);
vdm0("g",r) = vom0("g",r);
vim0(i,r) =  sum(g, vifm0(i,g,r));
evom0(f,r) = sum(g, vfm0(f,g,r));
vb0(r) = vom0("c",r) + vom0("g",r) + vom0("i",r)
- sum(f, evom0(f,r))
- sum(g,  vom0(g,r)*rto(g,r))
- sum(g,  sum(i, vdfm0(i,g,r)*rtfd0(i,g,r) + vifm0(i,g,r)*rtfi0(i,g,r)))
- sum(g,  sum(f, vfm0(f,g,r)*rtf0(f,g,r)))
- sum((i,s), rtms0(i,s,r) *  (vxmd0(i,s,r) * (1-rtxs0(i,s,r)) + sum(j,vtwr(j,i,s,r))))
+ sum((i,s), rtxs0(i,r,s) * vxmd0(i,r,s));

vb0("chksum") = sum(r, vb0(r));
display vb;

parameter zpf_chk0(i,r);

zpf_chk0(i,r) =
vom0(i,r)*(1-rto(i,r))
- sum(j, vdfm0(j,i,r)*(1+rtfd0(j,i,r)) + vifm0(j,i,r)*(1+rtfi0(j,i,r)))
- sum(f, vfm0(f,i,r)*(1+rtf0(f,i,r)))
;

parameter mprofit_chk0(i,r);
mprofit_chk0(i,r) = vim0(i,r) - sum(s, pvxmd(i,s,r)*vxmd0(i,s,r)+sum(j, vtwr(j,i,s,r))*pvtwr(i,s,r));

display zpf_chk0, mprofit_chk0;

vom(g,r) = 0;
```

```
vdm(g,r) = 0;
vxmd(i,r,s) = 0;
vdfm(i,g,r) = 0;
vifm(i,g,r) = 0;
vfm(f,g,r) = 0;
evom(f,r) = 0;
vim(i,r) = 0;

vom(g,r) = vom0(g,r);
vdm(g,r) = vdm0(g,r);
vxmd(i,r,s) = vxmd0(i,r,s);
vdfm(i,g,r) = vdfm0(i,g,r);
vifm(i,g,r) = vifm0(i,g,r);
vfm(f,g,r) = vfm0(f,g,r);
evom(f,r) = evom0(f,r);
vim(i,r) = vim0(i,r);
vb(r) = vb0(r) ;

rtf(f,j,r) = rtf0(f,j,r) ;
rtfd(i,g,r) = rtfd0(i,g,r) ;
rtfi(i,g,r) = rtfi0(i,g,r) ;
rtms(i,r,s) = rtms0(i,r,s) ;
rtxs(i,r,s) = rtxs0(i,r,s) ;

*define numeraire region for denominating international transfers:
rnum(r) = yes$(vom("c",r)=smax(s,vom("c",s)));
*rnum(r) = no;
*rnum(r)$usa(r) = yes;
display rnum, vb0;

*====================

*$exit

execute_unload "cur_bmk_data.gdx",
vom0
vex0
vdm0
vxmd0
```

```
vim0
vdfm0
vifm0
vfm0
evom0
rto
rtfd0
rtfi0
rtf0
rtms0
rtxs0
vb
zpf_chk0
mprofit_chk0
vom
vdm
vxmd
vim
vdfm
vifm
vfm
evom
i
g
r
f
;

*$include ..\build\structure_table
*$exit

execute_unload  "..\data11\cur_bmk.gdx";
```

fut_data.gms

```
$title Data pre-processing for cobalt cge main model (Future Scenarios)

*========== Populate/update existing sets ==========
$onmulti
set g(*)        goods plus C and G /
cob                "refined cobalt general met/chem aggregate"
mcob        "refined cobalt metal"
ccob        "refined cobalt chemical"
ldv                "light duty vehicles index"
ice                "internal combustion vehicles within ldv"
bev                "battery electric vehicles within ldv"
phev        "plug-in hybrid electric vehicles within ice"
omvh        "other motor vehicles and parts - subsitutable with ldv index"
/;

$onmulti
set        i(g)        goods /
cob                "refined cobalt general met/chem aggregate"
mcob        "refined cobalt metal"
ccob        "refined cobalt chemical"
ldv                "light duty vehicles index"
ice                "internal combustion vehicles within ldv"
bev                "battery electric vehicles within ldv"
phev        "plug-in hybrid electric vehicles within ldv"
omvh        "other motor vehicles and parts - subsitutable with ldv index"
/;

$onmulti
set f(*)        factors        /
rco                "fixed cobalt resource factor"
/;

display g,i,f;

*add subsets for set control later
set cob(g) cobalt general /cob/;
set ccob(g) cobalt chemical /ccob/;
```

```
set mcob(g) cobalt metal /mcob/;
set cobmc(g) cobalt chem and met /ccob, mcob/;
set coball(g) all cobalt sets /cob, ccob, mcob/;

set cmm(g) cmm index /cmm/;
*set ele(g) ele index /ele/;
set omc(g) omc index /omc/;
set omi(g) omi index /omi/;
set aog(g) aog index /aog/;

set ldv(g) light duty vehicles /ldv/;
set ice(g) internal combustion /ice/;
set bev(g) battery electric /bev/;
set phev(g) plug-in hybrid /phev/;
set omvh(g) other mvh /omvh/;
set ev(g) EV technologies /bev, phev/;
set ldvie(g) ice and ev /ice, bev, phev/;
set ldvall(g) all ldv /ldv, ice, bev, phev/;

set mvh(g) mvh index /mvh/;
set mvhlo(g) ldv and omvh /ldv, omvh/;
set mvhall(g) all mvh /mvh, ldv, omvh/;
set mvhall2(g) all mvh /mvh, ldv, omvh, bev, phev, ice/;
set mvhall3(g) all mvh /ldv, omvh, bev, phev, ice/;

set rco(f) fixed cobalt resource /rco/;
set cap(f)        capital /cap/;
set lab(f)        labor        /lab/;


set chn(r) references china (chn) /chn/ ;
set usa(r) references usa (usa) /usa/ ;
set row(r) references row (row) /row/ ;

*specify mobile/sluggish factors (k and l are mobile)
mf(f)$[not rco(f)] = yes$(1/etrae(f)=0);
sf(f)$[not rco(f)] = yes$(1/etrae(f)>0);


```

```
*========== Load in benchmark data from current scenario ==========
parameters
cob_used0(i,r)        "benchmark value of cobalt use"
sh_cobprdg0(i,r)        "benchmark cobalt production share of global by region"
cob_val_shr0(i,r)        "benchmark cobalt intermediate input share in output of i in r"
;

$gdxin ..\data11\cur_bmk.gdx
$load cob_used0=cob_used sh_cobprdg0=sh_cobprdg cob_val_shr0=cob_val_shr
$gdxin
*====================


*========== Raw Data ==========

parameters
prd_q0(g,r)                "benchmark production quantity"
prd_p0(g,r)                "benchmark production price"
prd_v0(g,r)                "benchmark production value(output) unadjusted for gtap base year"
;

*Cobalt DATA

table        cobprd_q0(r,i)                "Cobalt Production - table to import cobalt production (tons Co)"
COB   CCOB  MCOB
USA 300   300   0
CHN 72200 59000 13200
ROW 44200 9300  34900

;

scalar        pg_cob        "global cobalt price"        /20/;
prd_p0(i,r)$[cob(i)] = pg_cob ;


*LDV, BEV, PHEV, ICE DATA

table         ldvprd_q0(r,i)                "LDV Production - table to import ldv production (# of vehicles)"

```

```
LDV      BEV    PHEV   ICE
USA 11000000 104040 99960  10796000
CHN 25000000 486000 114000 24400000
ROW 39000000 201960 194040 38604000

;


*========== update EV penetration ==========

*First specify mixes for China and USA based on given percentages of EV and mix between phev and bev
ldvprd_q0("usa","bev") = %usaevpct% * %evmix% * ldvprd_q0("usa","ldv");
ldvprd_q0("usa","phev") = %usaevpct% * (1 - %evmix%) * ldvprd_q0("usa","ldv");

ldvprd_q0("chn","bev") = %chnevpct% * %evmix% * ldvprd_q0("chn","ldv");
ldvprd_q0("chn","phev") = %chnevpct% * (1 - %evmix%) * ldvprd_q0("chn","ldv");

*Given the mixes associated with CHN and USA, find the mix for ROW assuming global total% is x%
ldvprd_q0("row","bev") = %evmix% * [%evpct% * sum(r,ldvprd_q0(r,"ldv"))
- sum((j,r)$[ev(j)$(not row(r))], ldvprd_q0(r,j))]
;
ldvprd_q0("row","phev") = (1 - %evmix%) * [%evpct% * sum(r,ldvprd_q0(r,"ldv"))
- sum((j,r)$[ev(j)$(not row(r))], ldvprd_q0(r,j))]
;

*Adjust ICE to balance new LDV mix
ldvprd_q0(r,"ice") = ldvprd_q0(r,"ldv") - sum(i$ev(i), ldvprd_q0(r,i));

display ldvprd_q0;

parameter test_ldvprd;
test_ldvprd("shares",r,i) = ldvprd_q0(r,i) / ldvprd_q0(r,"ldv");
test_ldvprd("evshare","world",i) = sum(r,ldvprd_q0(r,i)) / sum(r,ldvprd_q0(r,"ldv"));
display test_ldvprd;

*$exit
*===================

parameter        ldv_sales(r)        "ldv sales by country"
```

```
/
USA                16000000
CHN                25000000
ROW                34000000
/
;

*https://www.statista.com/outlook/1000000/117/passenger-cars/china#market-pricePerUnit
*https://www.statista.com/statistics/425095/eu-car-sales-average-prices-in-by-country/
parameter        rep_ldvprice(r)        "average ldv sales price by region"
/
USA                38000,
CHN                22000,
ROW                30000
/
;

scalar        avg_ldvprice        "average global ldv sale price";
avg_ldvprice = sum(r, ldv_sales(r) * rep_ldvprice(r)) / sum(r, ldv_sales(r));

parameter        ldv_cost_scale(r)          "Scaling factor for ldv costs - used for country level vehicle cost adjustments";
ldv_cost_scale(r) = rep_ldvprice(r) / avg_ldvprice ;

parameter        rep_ldvcost(i)        "production cost of representative vehicle"
/
ICE                25000,
BEV                40000,
PHEV        30000
/
;

parameter         rep_ldvcap(i)        "capacity of battery in representative vehicle"
/
ICE                0,
BEV                45,
PHEV        12
/
;

```

```
parameter        rep_packcost(i)        "cost/kwh of battery pack in representative vehicle"
/
ICE                 0,
BEV                 175,
PHEV        175
/
;

table        avg_cap(r,i)        "average electric vehicle battery capacity (kwh)"

BEV PHEV
USA 65  12
CHN 27  15
ROW 39        12

;

parameter        ldv_battcap(i,r)        "total battery capacity in each ldv sector";
ldv_battcap(i,r)$[ldvie(i)] = ldvprd_q0(r,i) * avg_cap(r,i);

* Calculate benchmark indices for electric vehicles
prd_q0(i,r)$[ldvie(i)] = ldvprd_q0(r,i) ;
prd_p0(i,r)$[ldvie(i)] = [rep_ldvcost(i) + (avg_cap(r,i) - rep_ldvcap(i)) * rep_packcost(i)] * ldv_cost_scale(r) ;
prd_v0(i,r)$[ldvie(i)] = prd_q0(i,r) * prd_p0(i,r);


$if %capadj%==default        $goto endcapadj
*========== Update Battery/LDV Size/Cost Assumptions ==========
*Assumption: Battery Capacity per EV increases
*Does average and reference capacity increase via a growth rate?
*rep_ldvcap(i) = rep_ldvcap(i) * %capgrowth%;
*avg_cap(r,i) = avg_cap(r,i) * %capgrowth%;

*OR:
*Does average capacit equal some specified reference vehicle capacity for all regions
rep_ldvcap(i)$[bev(i)] = %capbev%;
rep_ldvcap(i)$[phev(i)] = %capphev%;
avg_cap(r,i)$[ev(i)] = rep_ldvcap(i);

```

```
*What does this mean for battery capacity in ev sectors
ldv_battcap(i,r)$[ev(i)] = ldvprd_q0(r,i) * avg_cap(r,i) ;

*Do battery pack costs change?
rep_packcost(i)$[ev(i)] = %bpackcost%;

*-----What set of EV cost assumptions are used?-----
*Do EV costs reach parity with ICE? Or does the cost calc method remain unchanged?
*rep_ldvcost(i) = rep_ldvcost(i);
rep_ldvcost(i)$[ev(i)] = rep_ldvcost("ice");

* Calculate benchmark indices for electric vehicles
prd_q0(i,r)$[ldvie(i)] = ldvprd_q0(r,i) ;
*prd_p0(i,r)$[ldvie(i)] = [rep_ldvcost(i) + (avg_cap(r,i) - rep_ldvcap(i)) * rep_packcost(i)] * ldv_cost_scale(r) ;
prd_p0(i,r)$[ldvie(i)] = rep_ldvcost(i) * ldv_cost_scale(r) ;
prd_v0(i,r)$[ldvie(i)] = prd_q0(i,r) * prd_p0(i,r);

*====================
$label endcapadj

*Battery Capacity for Portable Electronics - ELE sector
*SOURCE: Roskill Cobalt Report
parameter        ele_battcap(r)        "portable electronics battery capacity (kwh)"
/
USA                 4000000,
CHN                 11000000,
ROW                 21000000
/
;

*Battery Chemistry Data

set        bc        "battery chemistry"
/
NCA,
NCM111,
NCM433,
NCM523,
NCM622,
```

```
NCM811,
LCO,
LFP,
LMO
/
;

parameter        rep_chem(bc)        "Cobalt contained within battery chemistry (kg/kwh)"
/
NCA                 0.13,
NCM111        0.4,
NCM433        0.35,
NCM523        0.23,
NCM622        0.19,
NCM811        0.09,
LCO                 0.6,
LFP                 0,
LMO                 0
/
;


*========== Cobalt use (tons) ==========

parameter        cob_used(i,r)        "pure cobalt used in production of goods (kg or tons)";

*---------- Choose a Representative Chemistry ----------
*cobalt used in production of vehicles (tons)
*cob_used(i,r)$[ldvie(i)] = (ldv_battcap(i,r) * rep_chem("NCM111")) * (2.204 / 2000);
cob_used(i,r)$[ldvie(i)] = (ldv_battcap(i,r) * %bcrep%) * (2.204 / 2000);

*cobalt used in production of portable electronic devices (tons)
*cob_used(i,r)$[ele(i)] = (ele_battcap(r) * rep_chem("LCO")) * (2.204 / 2000);

*OR...

*NOTES:
*---------- What is the implied battery chemistry? ----------
*Rather than representative chemistry - use implied chemistry
```

```
parameter         cob_use_ev                "cobalt used in the EV sector 2017 (tons Co)";
*6% of global cobalt production is used in LDV EVs
*Source: IEA 2018 global ev outlook
cob_use_ev = sum(r,cobprd_q0(r,"cob")) * 0.06;

parameter        imp_chem        "implied battery chemistry (kg/kwh)";
imp_chem("IEA") = (cob_use_ev * 2000 / 2.204) / sum((i,r)$ldvie(i), ldv_battcap(i,r));

parameter         imp_cob_use(i,r)        "implied pure cobalt used in production of goods (kg or tons)";
imp_cob_use(i,r)$[ldvie(i)] = (ldv_battcap(i,r) * imp_chem("IEA")) * (2.204 / 2000) ;

parameter         jrc_cob_use(i,r)        "guess using shares from jrc report";

imp_chem("jrc") = rep_chem("NCM111")*.42 + rep_chem("NCM433")*.05 + rep_chem("NCM523")*.07
+ .07*rep_chem("LMO") + rep_chem("NCA")*.14 + rep_chem("LFP")*.24
;

jrc_cob_use(i,r) = (ldv_battcap(i,r) * imp_chem("jrc")) * (2.204 / 2000);

parameter share_cob_use_imp;

share_cob_use_imp("ncm111") = sum((i,r)$ldvie(i), cob_used(i,r)) / sum(r,cobprd_q0(r,"cob")) ;
share_cob_use_imp("IEA") = sum((i,r)$ldvie(i), imp_cob_use(i,r)) / sum(r,cobprd_q0(r,"cob")) ;
share_cob_use_imp("JRC") = sum((i,r)$ldvie(i), jrc_cob_use(i,r)) / sum(r,cobprd_q0(r,"cob")) ;

display rep_chem, imp_chem, share_cob_use_imp, cob_use_ev, imp_cob_use, cob_used, jrc_cob_use ;
*END NOTES
*--------------------

*---------- Determine cobalt used in OMC Sector ----------

parameter         cob_globe_use(i)        "total cobalt use within each sector";

*If Scenario is Future --- Already have present day OMC data
*Need Switch or something to adjust cobalt production when running future scenarios
*--- this could go at beginning of the file
*I could hold cobalt use in omc the same as first benchmark setup... then adjust production accordingly
*I would also have no need for previous two lines of code or some of the lines below
cob_used(i,r)$[omc(i)] = cob_used0(i,r);
```

```
cob_globe_use(i) = sum(r, cob_used(i,r)) ;

*update cobalt production numbers to satisfy new global use of cobalt
cobprd_q0(r,i) = sum(j,cob_globe_use(j)) * sh_cobprdg0(i,r) ;


*If Scenario is Current --- no OMC data Exists
*Given total value of OMC sectoral activity
*and total value of cobalt used after LDV and ELE use (global OMC cob use value)
*I assume cobalt is weighted in each region by OMC sector share of global to equate supply and demand globally

*cob_globe_use(i)$[not omc(i)] = sum(r,cob_used(i,r));
*cob_globe_use(i)$[omc(i)] = sum(r, cobprd_q0(r,"cob")) - sum(j,cob_globe_use(j));

Parameter check_sd_cob        "check to make sure production equals use (supply=demand)" ;
check_sd_cob("dem-sup") = sum(i,cob_globe_use(i)) - sum(r, cobprd_q0(r,"cob")) ;

display check_sd_cob, cob_globe_use, cob_used;


parameter vom_shrg(i,r)        "output share of global";
vom_shrg(i,r)$[omc(i)] = vom(i,r) / sum(s,vom(i,s)) ;

cob_used(i,r)$[omc(i)] = cob_globe_use(i) * vom_shrg(i,r) ;

check_sd_cob("dem-sup-alt") = sum((i,r), cob_used(i,r)) - sum(r, cobprd_q0(r,"cob"));

display check_sd_cob, cob_used;

*NOTE:
*cob_used(i,r) contains cobalt use (tons Co) in all modeled sectors in current year (2017)

*====================

*========== MVH nesting structure in terms of values and value shares ==========

*Average new car price 2010 --- 28k
*Average new car price 2018 --- 36k
*Growth Rate --- (36/28)**(1/(2018-2010)) = 1 + r --- r = 0.03 (approximate) --
```

```

*unido db says 7-10% (approx) based on output in motor vehicles production (4 digit isic)

*Given r and unchanged vehicles production - 2011 value of automobiles can be determined
**This can be used to disaggregate mvh into omvh and ldv
**ldv can be further disaggregated given value shares calculated as a result of a given point in time
**Need to establish base year vehicles output in order to infer cobalt production based on sharing

$ontext
mvh omvh ldv ice bev phev
mvh
omvh  x
ldv   x
ice             x
bev             x
phev            x
aog        x       x   x   x
$offtext

*total value of all ldv
prd_v0(i,r)$[ldv(i)] = sum(j$ldvie(j), prd_v0(j,r)) ;

parameter        sh_ldv_v0(i,r)        "share of total ldv output attributable to BEV, PHEV, and ICE";
sh_ldv_v0(i,r)$[ldvall(i)] = prd_v0(i,r) / sum(j$ldv(j), prd_v0(j,r)) ;

*gtap base year (2011) - need to bring 2017-2018 figures back
scalar base_yr         "gtap base year" /2011/;
scalar data_yr        "year for cost data" /2017/;

*based on unido database cagr automobiles sector --- roughly 7-10% for period
*scalar cost_r   "annual growth rate" /0.08/;
parameter        cost_r(r) "annual automobiles unido growth rate (cagr) by country"
/
USA                0.08,
CHN                0.08,
ROW                0.08
/
;

```

```
*adjust current values so that they represent appropriate value shares of GTAP 2011 database
parameter prd_v0_base(i,r) "base year (2011) output value -- consistent with GTAP9";
*prd_v0_base(i,r)$[ldv(i)] = prd_v0(i,r) * [(1/(1+cost_r))**(data_yr-base_yr)];
prd_v0_base(i,r)$[ldv(i)] = prd_v0(i,r) * [(1/(1+cost_r(r)))**(data_yr-base_yr)];

parameter sh_vdfm(j,i,r) "share of input value /output";

*First compute share for LDV and OMVH in MVH
sh_vdfm(j,i,r)$[mvh(i)$ldv(j)] = 1e-9 * prd_v0_base(j,r) / vom(i,r) ;
sh_vdfm(j,i,r)$[mvh(i)$omvh(j)] = 1 - sh_vdfm("ldv",i,r);

*For reporting purposes/curiosity --- may come in handy as validation tool
parameter wt_avg_vh_cost(r)        "weighted average ldv cost implied in benchmark";
wt_avg_vh_cost(r) = prd_v0("ldv",r) / ldvprd_q0(r,"ldv") ;

display prd_v0, sh_ldv_v0, prd_v0_base, sh_vdfm, wt_avg_vh_cost ;

*Define intermediate input shares in MVH sector
*There are different ways to share out - for now assume same structure as MVH in omvh and ldv
parameters
sh_vdfm_mvh0(j,i,r) "cost shares of mvh in original SAM (vdfm)"
sh_vifm_mvh0(j,i,r) "cost share of mvh in original SAM (vifm)"
sh_vfm_mvh0(f,i,r)         "cost share of mvh in original SAM (vfm)"
;

sh_vdfm_mvh0(j,i,r)$[mvh(i)] = vdfm(j,i,r) / vom(i,r);
sh_vifm_mvh0(j,i,r)$[mvh(i)] = vifm(j,i,r) / vom(i,r);
sh_vfm_mvh0(f,i,r)$[mvh(i)] = vfm(f,i,r) / vom(i,r);

parameter zpf_share_chk(i,r);
zpf_share_chk(i,r)$mvh(i) =
1*(1-rto(i,r))
- sum(j, sh_vdfm_mvh0(j,i,r)*(1+rtfd0(j,i,r)) + sh_vifm_mvh0(j,i,r)*(1+rtfi0(j,i,r)))
- sum(f, sh_vfm_mvh0(f,i,r)*(1+rtf0(f,i,r)))
;

display sh_vdfm_mvh0, sh_vifm_mvh0, sh_vfm_mvh0, zpf_share_chk ;

*recall sh_ldv_v0(i,r) from earlier
```

```
sh_vdfm(j,i,r)$[ldvie(j)$ldv(i)] = sh_ldv_v0(j,r) ;

*sh_vdfm lacks a representation of cobalt within it
*cobalt still contained within cmm input
display sh_vdfm;

*==========

*need cobalt value in use as a percentage of output in bev, phev, ele, omc
*if cobalt use in EV is x% of value of EV (same for base vs 2017)
*and cobalt price is assumed to be the same, then I can infer the value or amount of cobalt
*in other sectors based on the shares of cobalt use of country total

parameter cob_val_shr(i,r)        "share of cobalt used value / value in sector used" ;
parameter cob_v0(i,r)        "value of cobalt used in each sector i for each region r";

cob_v0(i,r) = cob_used(i,r) * sum(j$cob(j), prd_p0(j,r) * 2000);
cob_val_shr(i,r)$ldvie(i) = cob_v0(i,r) / prd_v0(i,r) ;

parameter sh_cob_use(i,r) "share of cobalt used in industry i of total country use";
sh_cob_use(i,r) = cob_used(i,r) / sum(j,cob_used(j,r)) ;

*calculate prd_v0_base(i,r) before this section

*once have base year ldv production
vom(i,r)$ldv(i) = prd_v0_base(i,r) * 1e-9 ;
vom(i,r)$ldvie(i) = sum(j$ldv(j), vom(j,r)) * sh_ldv_v0(i,r) ;
cob_v0(i,r)$ldvie(i) = vom(i,r)*cob_val_shr(i,r);
cob_v0(i,r)$[not ldvie(i)] = sh_cob_use(i,r) * cob_v0("bev",r) / sh_cob_use("bev",r);

cob_val_shr(i,r)$vom(i,r) = cob_v0(i,r) / vom(i,r);
cob_val_shr(i,r)$[omc(i)] = cob_val_shr0(i,r);
cob_v0(i,r)$[omc(i)] = cob_val_shr(i,r)*vom(i,r);

parameter         cob_used_base(i,r)        "base year cobalt use (2011)";
cob_used_base(i,r) = cob_v0(i,r) / sum(j$cob(j), prd_p0(j,r) * 2000 * 1e-9);

display cob_v0, cob_val_shr, cob_used, cob_used_base;

```

```
*==========

* Calculate values for mvh nest
parameter
vdfm_mvh0        "vdfm for mvh0 nest"
vifm_mvh0
vfm_mvh0
;

vom(i,r)$[omvh(i)] = vom("mvh",r) * sh_vdfm(i,"mvh",r) ;

vdfm_mvh0(j,i,r)$[omvh(i)] = sh_vdfm_mvh0(j,"mvh",r) * vom(i,r) ;
vdfm_mvh0(j,i,r)$[ldvie(i)] = sh_vdfm_mvh0(j,"mvh",r) * vom(i,r) ;

vifm_mvh0(j,i,r)$[omvh(i)] = sh_vifm_mvh0(j,"mvh",r) * vom(i,r) ;
vifm_mvh0(j,i,r)$[ldvie(i)] = sh_vifm_mvh0(j,"mvh",r) * vom(i,r) ;

vfm_mvh0(f,i,r)$[omvh(i)] = sh_vfm_mvh0(f,"mvh",r) * vom(i,r) ;
vfm_mvh0(f,i,r)$[ldvie(i)] = sh_vfm_mvh0(f,"mvh",r) * vom(i,r) ;

rto(i,r)$[omvh(i) or ldvie(i)] = rto("mvh",r);
rtfd0(j,i,r)$[omvh(i) or ldvie(i)] = rtfd0(j,"mvh",r) ;
rtfi0(j,i,r)$[omvh(i) or ldvie(i)] = rtfi0(j,"mvh",r) ;
rtf0(f,i,r)$[omvh(i) or ldvie(i)] = rtf0(f,"mvh",r) ;

display vdfm_mvh0, vifm_mvh0, vfm_mvh0;

parameter zpf_chk(i,r);
zpf_chk(i,r)$[omvh(i) or ldvie(i)] = vom(i,r)*(1-rto(i,r))
- sum(j, vdfm_mvh0(j,i,r)*(1+rtfd0(j,i,r)) + vifm_mvh0(j,i,r)*(1+rtfi0(j,i,r)))
- sum(f, vfm_mvh0(f,i,r)*(1+rtf0(f,i,r)))
;
display zpf_chk;

*verify that there is enough cmm in bev and phev blocks to share out cobalt use
parameter cmm_size(i,r,*)        "check to make sure there is enough cmm to share out cob";

cmm_size(i,r,"vdfm")$[ldvie(i)] = vdfm_mvh0("cmm",i,r) - cob_v0(i,r);
cmm_size(i,r,"vdfm")$[omc(i)] = vdfm("cmm",i,r) - cob_v0(i,r);
```

```
cmm_size(i,r,"vifm")$[ldvie(i)] = vifm_mvh0("cmm",i,r) - cob_v0(i,r);
cmm_size(i,r,"vifm")$[omc(i)] = vifm("cmm",i,r) - cob_v0(i,r);

display cmm_size, cob_v0;

*==========

*Then determine global cobalt use - use the shares of cobalt production by region
*to determine new production levels in each region - then values can be computed for the upstream


parameter sh_cobprdg(i,r)        "cobalt production share of global by region";

sh_cobprdg(i,r)$[coball(i)] = cobprd_q0(r,i) / sum((s,j)$cob(j), cobprd_q0(s,j)) ;

display sh_cobprdg;

parameters
cob_v_globe
cob_use_globe
cob_prod_globe
cob_prod_r(r)
cob_vprod_r(r)
;

cob_v_globe = sum((i,r), cob_v0(i,r));
cob_use_globe("a") = sum((i,r), cob_used_base(i,r));
cob_use_globe("b") = 1e9 * cob_v_globe / (20 * 2000);

*Use and production shares used to determine base year production levels by region
cob_prod_globe = cob_use_globe("a") ;
cob_prod_r(r) = cob_prod_globe * sh_cobprdg("cob",r) ;
cob_vprod_r(r) = cob_prod_r(r) * 20 * 2000 * 1e-9 ;

display cob_v_globe, cob_use_globe;

*Check to make sure supply = demand
parameter chk_cob_use_prod;
```

```
chk_cob_use_prod("prd-use","world") = sum(r,cob_vprod_r(r)) - cob_v_globe;
display chk_cob_use_prod;

*Determine trade flows in terms of net trade with global market
parameter chk_impexp(*,*)         "net imports/exports of cobalt by country";
chk_impexp(r,"net imports") = sum(i,cob_v0(i,r)) - cob_vprod_r(r) ;
chk_impexp(r,"net exports") = cob_vprod_r(r) -  sum(i,cob_v0(i,r));
chk_impexp("world", "net imports") = sum(r, chk_impexp(r,"net imports"));
chk_impexp("world", "net exports") = sum(r, chk_impexp(r,"net exports"));
display chk_impexp;

* parameters
*         cob_vim(r)        "imports of cobalt by country r"
*         cob_vex(r)        "exports of cobalt by country r"
*         cob_vom(r)        "production of cobalt by country r"
*         cob_vdm(r)        "production of cobalt for domestic use by country r"
* ;

*========== Initialize SAM parameters ==========
*update sam for mvh
*update sam for cobalt
*share out cobalt from all necessary sectors

parameters
vom0(g,r)
vdm0(g,r)
vex0(g,r)
vxmd0(i,r,s)
vim0(g,r)
vdfm0(i,g,r)
vifm0(i,g,r)
vfm0(f,g,r)
;

*NOTE THIS PARAMETER!!!
vom0(g,r) = vom(g,r) ;
vom0(g,r)$cob(g) = cob_vprod_r(r) ;

vdfm0(i,g,r)$[mvh(g)$mvhlo(i)] = vom(i,r);
```

```
vdfm0(i,g,r)$[ldv(g)$ldvie(i)] = vom(i,r);

vdfm0(i,g,r)$[ldvie(g)] = vdfm_mvh0(i,g,r) ;
vdfm0(i,g,r)$[omvh(g)] = vdfm_mvh0(i,g,r) ;

vifm0(i,g,r)$[ldvie(g)] = vifm_mvh0(i,g,r) ;
vifm0(i,g,r)$[omvh(g)] = vifm_mvh0(i,g,r) ;

vfm0(f,g,r)$[ldvie(g)] = vfm_mvh0(f,g,r) ;
vfm0(f,g,r)$[omvh(g)] = vfm_mvh0(f,g,r) ;

vdfm0(i,g,r)$[not mvhall2(g)] = vdfm(i,g,r) ;
vifm0(i,g,r)$[not mvhall2(g)] = vifm(i,g,r) ;
vfm0(f,g,r)$[not mvhall2(g)] = vfm(f,g,r) ;

rto(i,r)$[mvh(i) or ldv(i)] = 0;

*---------- add cobalt
parameters
sh_vex0(g,r)        "share of production of good i in country r that is exported"
sh_vdm0(g,r)        "share of production of good i in country r for domestic use"
sh_vfm0(f,g,r)        "share of production of good g in country r that is attributable to factor f"
sh_vdfm0(i,g,r)        "share of production of good g in country r that is attributable to domestically produced good i"
sh_vifm0(i,g,r)        "share of production of good g in country r that is attributable to imported good i"
sh_vxmd0(i,r,s) "share of exports of good i from country r that are sent to s (bilateral trade)"
;

*Add factors --- simple representation with no intermediate goods
sh_vfm0(f,g,r)$[rco(f)$cob(g)] = 0.8;
sh_vfm0(f,g,r)$[cap(f)$cob(g)] = 0.1;
sh_vfm0(f,g,r)$[lab(f)$cob(g)] = 0.1;

vfm0(f,g,r)$[cob(g)] = vom0(g,r) * sh_vfm0(f,g,r) ;

*Disaggregate SAM with cobalt representation

sh_vex0(i,r)$[cob(i)$chn(r)] = chk_impexp(r,"net exports") / vom0(i,r) ;
sh_vxmd0(i,r,s)$[cob(i)$chn(r)$(not chn(s))] = chk_impexp(s,"net imports") / chk_impexp(r,"net exports") ;

```

```
*sh_vfm0(f,g,r) = vfm0(f,g,r)/vom(g,r);

*Set very low share of exports to avoid source/sink error and allow bilateral trade
*sh_vex0(i,r)$[cob(i)$(not chn(r))] = 0.1 ;
*sh_vxmd0(i,r,s)$[cob(i)$usa(r)$(not usa(s))] = 0.5 ;
*sh_vxmd0(i,r,s)$[cob(i)$row(r)$(not row(s))] = 0.25 ;
*sh_vxmd0(i,r,s)$[cob(i)$row(r)$row(s)] = 0.5 ;

*Alternative method to ensure trade flows perfectly offset
sh_vex0(i,r)$[cob(i)$usa(r)] = 0.1;
vex0(i,r)$[cob(i)$usa(r)] = vom0(i,r)*sh_vex0(i,r);
sh_vex0(i,r)$[vom0(i,r)$cob(i)$row(r)] = vex0(i,"usa") / vom0(i,r);
sh_vxmd0(i,r,s)$[cob(i)$usa(r)$row(s)] = 1;
sh_vxmd0(i,r,s)$[cob(i)$row(r)$usa(s)] = 1;

sh_vdm0(i,r) = 1-sh_vex0(i,r) ;

vdm0(i,r)$[cob(i)] = vom0(i,r) * sh_vdm0(i,r) ;
vex0(i,r)$[cob(i)] = vom0(i,r) * sh_vex0(i,r) ;
vxmd0(i,r,s)$[cob(i)] = vex0(i,r) * sh_vxmd0(i,r,s) ;

*vdfm("cob",g,r) vs. vifm("cob",g,r);
parameters
sh_cob(g,r)                "cobalt use in sector g by country r share of total use in country r"
;

*NOTE THIS PARAMETER!!!!
sh_cob(i,r) = cob_v0(i,r) / sum(j, cob_v0(j,r)) ;
vim0(i,r)$[cob(i)] = sum(s, pvxmd(i,s,r) * vxmd0(i,s,r)) ;
vdfm0(j,i,r)$[cob(j)] = sh_cob(i,r) * vdm0(j,r) ;
vifm0(j,i,r)$[cob(j)] = sh_cob(i,r) * vim0(j,r) ;
*sh_cob used by sector g in r to determine allocation of cob use from domestic production and imports

vdm0(i,r) = sum(g, vdfm0(i,g,r));
vxmd0(i,r,s)$[not cob(i)] = vxmd(i,r,s) ;

*========== Disaggregate Cobalt from CMM ==========

*tax rates need updated
```

```
*convert tax rate to level
rto(g,r)    = rto(g,r) * vom0(g,r);
rtf0(f,j,r)  = rtf0(f,j,r) * vfm0(f,j,r);
rtfd0(i,g,r) = rtfd0(i,g,r) * vdfm0(i,g,r);
rtfi0(i,g,r) = rtfi0(i,g,r) * vifm0(i,g,r);
rtms0(i,r,s) = rtms0(i,r,s) * ((1-rtxs0(i,r,s)) * vxmd0(i,r,s) + sum(j,vtwr(j,i,r,s)));
rtxs0(i,r,s) = rtxs0(i,r,s) * vxmd0(i,r,s);

vom0("cmm",r) = vom0("cmm",r) - vom0("cob",r) ;
vdm0("cmm",r) = vdm0("cmm",r) - vdm0("cob",r) ;
vxmd0("cmm",r,s) = vxmd0("cmm",r,s) - vxmd0("cob",r,s);
vdfm0(i,"cmm",r) = vdfm0(i,"cmm",r) - vdfm0(i,"cob",r) ;
vdfm0("cmm",g,r) = vdfm0("cmm",g,r) - vdfm0("cob",g,r) ;
vfm0(f,"cmm",r)$[not rco(f)] = vfm0(f,"cmm",r) - vfm0(f,"cob",r) ;
vfm0("cap","cmm",r) = vfm0("cap","cmm",r) - vfm0("rco","cob",r) ;
vifm0(i,"cmm",r) = vifm0(i,"cmm",r) - vifm0(i,"cob",r);
vifm0("cmm",g,r) = vifm0("cmm",g,r) - vifm0("cob",g,r);

*recalculate tax rate
*convert back to rate
rto(g,r)$vom0(g,r) = rto(g,r) / vom0(g,r);
rtf0(f,j,r)$vfm0(f,j,r) = rtf0(f,j,r) / vfm0(f,j,r);
rtfd0(i,g,r)$vdfm0(i,g,r) = rtfd0(i,g,r) / vdfm0(i,g,r);
rtfi0(i,g,r)$vifm0(i,g,r) = rtfi0(i,g,r) / vifm0(i,g,r);
rtxs0(i,r,s)$vxmd0(i,r,s) = rtxs0(i,r,s) / vxmd0(i,r,s);
rtms0(i,r,s)$[(1-rtxs0(i,r,s)) * vxmd0(i,r,s) + sum(j,vtwr(j,i,r,s))]
= rtms0(i,r,s) / ((1-rtxs0(i,r,s)) * vxmd0(i,r,s) + sum(j,vtwr(j,i,r,s)));


pvxmd(i,s,r) = (1+rtms0(i,s,r)) * (1-rtxs0(i,s,r));
pvtwr(i,s,r) = 1+rtms0(i,s,r);

*====================

*========== Update SAM and GTAP Parameters ==========

parameters
evom0(f,r)
vb0
```

```
;

vom0("c",r) = sum(i, vdfm0(i,"c",r)*(1+rtfd0(i,"c",r)) + vifm0(i,"c",r)*(1+rtfi0(i,"c",r)))/(1-rto("c",r));
vom0("g",r) = sum(i, vdfm0(i,"g",r)*(1+rtfd0(i,"g",r)) + vifm0(i,"g",r)*(1+rtfi0(i,"g",r)))/(1-rto("g",r));
vom0("i",r) = sum(i, vdfm0(i,"i",r)*(1+rtfd0(i,"i",r)) + vifm0(i,"i",r)*(1+rtfi0(i,"i",r)))/(1-rto("i",r));

vdm0("c",r) = vom0("c",r);
vdm0("g",r) = vom0("g",r);
vim0(i,r) =  sum(g, vifm0(i,g,r));
evom0(f,r) = sum(g, vfm0(f,g,r));
vb0(r) = vom0("c",r) + vom0("g",r) + vom0("i",r)
- sum(f, evom0(f,r))
- sum(g,  vom0(g,r)*rto(g,r))
- sum(g,  sum(i, vdfm0(i,g,r)*rtfd0(i,g,r) + vifm0(i,g,r)*rtfi0(i,g,r)))
- sum(g,  sum(f, vfm0(f,g,r)*rtf0(f,g,r)))
- sum((i,s), rtms0(i,s,r) *  (vxmd0(i,s,r) * (1-rtxs0(i,s,r)) + sum(j,vtwr(j,i,s,r))))
+ sum((i,s), rtxs0(i,r,s) * vxmd0(i,r,s));

vb0("chksum") = sum(r, vb0(r));
display vb;

parameter zpf_chk0(i,r);

zpf_chk0(i,r) =
vom0(i,r)*(1-rto(i,r))
- sum(j, vdfm0(j,i,r)*(1+rtfd0(j,i,r)) + vifm0(j,i,r)*(1+rtfi0(j,i,r)))
- sum(f, vfm0(f,i,r)*(1+rtf0(f,i,r)))
;

parameter mprofit_chk0(i,r);
mprofit_chk0(i,r) = vim0(i,r) - sum(s, pvxmd(i,s,r)*vxmd0(i,s,r)+sum(j, vtwr(j,i,s,r))*pvtwr(i,s,r));

display zpf_chk0, mprofit_chk0;

vom(g,r) = 0;
vdm(g,r) = 0;
vxmd(i,r,s) = 0;
vdfm(i,g,r) = 0;
vifm(i,g,r) = 0;
```

```
vfm(f,g,r) = 0;
evom(f,r) = 0;
vim(i,r) = 0;

vom(g,r) = vom0(g,r);
vdm(g,r) = vdm0(g,r);
vxmd(i,r,s) = vxmd0(i,r,s);
vdfm(i,g,r) = vdfm0(i,g,r);
vifm(i,g,r) = vifm0(i,g,r);
vfm(f,g,r) = vfm0(f,g,r);
evom(f,r) = evom0(f,r);
vim(i,r) = vim0(i,r);
vb(r) = vb0(r) ;

rtf(f,j,r) = rtf0(f,j,r) ;
rtfd(i,g,r) = rtfd0(i,g,r) ;
rtfi(i,g,r) = rtfi0(i,g,r) ;
rtms(i,r,s) = rtms0(i,r,s) ;
rtxs(i,r,s) = rtxs0(i,r,s) ;

*define numeraire region for denominating international transfers:
rnum(r) = yes$(vom("c",r)=smax(s,vom("c",s)));
*rnum(r) = no;
*rnum(r)$usa(r) = yes;
display rnum, vb0;

*====================

*$exit

execute_unload "fut_bmk_data.gdx",
vom0
vex0
vdm0
vxmd0
vim0
vdfm0
vifm0
vfm0
```

```
evom0
rto
rtfd0
rtfi0
rtf0
rtms0
rtxs0
vb
zpf_chk0
mprofit_chk0
vom
vdm
vxmd
vim
vdfm
vifm
vfm
evom
i
g
r
f
;

*$include ..\build\structure_table
*$exit

*execute_unload        "..\data11\cur_bmk.gdx";


```

model_cob.gms

```
$title Cobalt CGE Model File

$if not set sd $set sd 1

option seed=%sd%;

$if not setglobal run_name $setglobal run_name base

*========== Switches, includes, and command line variables ==========
*specify name of gdx file to be unloaded
$if not set gdxname $set gdxname output_cur_cob

*specify whether running current year scenario or future projection scenario (current, future)
$if not set bmkyr $set bmkyr current

*switch to determine evmix in 2030 (current, NPS, E30)
*corresponds to IEA No policies scenario or EV30@30
$if not set swfutscen $set swfutscen current

$if %swfutscen%==current         $goto endswfutscen
$if %swfutscen%==E30        $goto endNPS
*(NPS) EV deployment in terms of percentage of LDVs by country
$if not set evpct $set evpct 0.15
$if not set usaevpct $set usaevpct 0.08
$if not set chnevpct $set chnevpct 0.26

*(NPS) Mix of EVs that are BEV (1-BEV = PHEV)
$if not set evmix $set evmix 0.5

$label endNPS

$if %swfutscen%==NPS        $goto endE30
*(EV30) EV deployment in terms of percentage of LDVs by country
$if not set evpct $set evpct 0.33
$if not set usaevpct $set usaevpct 0.3
$if not set chnevpct $set chnevpct 0.42

```

```
*(EV30) Mix of EVs that are BEV (1-BEV = PHEV)
$if not set evmix $set evmix 0.7

$label endE30
$label endswfutscen

$if not set scale30 $set scale30 current

$if not %swfutscen%==current        $goto endcurblock
$if "%scale30%"="current"        $goto endcurblock2

$if not set evpct $set evpct 0.1
$if not set usaevpct $set usaevpct 0.1
$if not set chnevpct $set chnevpct 0.1

*(EV30) Mix of EVs that are BEV (1-BEV = PHEV)
$if not set evmix $set evmix 0.5


$label endcurblock
$label endcurblock2

*adjust battery capacity and vehicle cost assumptions (default, notdefault)
$if not set capadj $set capadj default

*Average/Representative Battery Capacity of BEV and PHEV (kwh)
$if not set capbev $set capbev 75
$if not set capphev $set capphev 15
*Alternatively specify a growth rate
$if not set capgrowth $set capgrowth 1.5

*Battery Chemistry Assumptions - implied/representative chemistry
$if not set bcrep $set bcrep 0.23

***
*EV Cost - Assume EVs and LDVs same price (parity or some switch that changes costs)
$if not set evcost $set evcost parity

*Cost of EV battery pack per $/kwh
```

```
$if not set bpackcost $set bpackcost 175

***
*Global Cobalt Production Mix (default, or other scenarios)
$if not set cobmix $set cobmix default

*Cobalt Supply Elasticity
$if not set esupcobval $set esupcobval 0.2

*Cobalt demand elasticity (yes/no)
$if not set swdelas $set swdelas no

*Cobalt Demand Elasticity
$if not set edemldvieval $set edemldvieval 0.2
$if not set edemomcval $set edemomcval 0.2
$if not set edemeleval $set edemeleval 0.2

*Various Substitution Elasticities
*--substitution between omvh and ldv
$if not set esmvhval $set esmvhval 0.2
*--subsitution between ice, bev, phev
$if not set esldvval $set esldvval 0.5
*--cobalt in ldvie, omc, ele with other goods
$if not set esldvieval $set esldvieval 0
$if not set esomcval $set esomcval 0.2
$if not set eseleval $set eseleval 0.1
*--cobalt elasticity of export transformation
$if not set etcobval $set etcobval 20
*--elasticity of substition between various intermediate goods and va index
$if not set esubval $set esubval 0.2

*Policy/Quota Stringency (% reduction in exports)
$if not set quoteval $set quoteval 25

*-----Initial Pre-processing-----
*Load data from gtap gdx file post-aggregation
$if not set yr $set yr 11
$if not set ds $set ds cob_main3
$include ..\build\gtap9data
```

```
*-----Further Pre-processing-----
*include prelude file for present day benchmark setup or future setup
$if not %bmkyr%==current        $goto future
$include cur_data
$label future

$if %bmkyr%==current                $goto current
$include fut_data
$label current
*====================
*$exit
*========== Specify Elasticity parameters and other initial model setup ==========
parameter        esub(g)                Top-level elasticity indemand;

esub(g) = %esubval%;

*tweak this as well - maybe this is less than 1
esub("C") = 1 ;


*initialize values for cobalt
* esub(g)$cob(g) = 0;
* esubva(g)$cob(g) = 0 ;
* esubd(i)$cob(i) = 0 ;

*esubva(g)$omvh(g) = esubva('mvh');
*esubva(g)$ldvie(g) = esubva('mvh');
*esubva(g)$cob(g) = esubva('cmm') ;

PARAMETERS
esupcob(g,r)                elasticity of supply cobalt
edemcob(g,r)                elasticity of demand cobalt
cobsshr(f,g,r)                value share of fixed factor in production of g
cobdshr(g,r)                value share of cobalt in production of g
cobishr(i,r)                value share of exports in global output (used for reporting)
escob(g,r)                        elasticity of substitution top-level cob block
escobd(g,r)                        elasticity of substitution top-level g block with cobalt input
escall(g,r)                        elasticity of substitution of cobalt int with other inputs in prod of g
```

```
etcob(g,r)                        elasticity of transformation in output
quote(i,r)                        policy target (quota - reduction in emissions)
esmvh                                elasticity of substitution in top level mvh nest
esldv                                elastitiy of substitution at top level of ldv nest
;

cobishr(i,r)$cob(i) = vex0(i,r) / sum(s, vom(i,s));

*Calibrate cobalt production block to supply elasticity (Rutherford Notes)
esupcob(i,r)$cob(i) = %esupcobval% ;
cobsshr(f,i,r)$(rco(f)$cob(i)) = vfm(f,i,r) / vom(i,r) ;
escob(i,r)$cob(i) = sum(f$rco(f),(cobsshr(f,i,r)*esupcob(i,r)) / (1-cobsshr(f,i,r))) ;


*Substitution elasticities of other inputs with cobalt
escall(g,r) = 0 ;
escall(g,r)$[ldvie(g)] = %esldvieval%;
escall(g,r)$[omc(g)] = %esomcval%;
*escall(g,r)$[ele(g)] = %eseleval%;

cobdshr(i,r)$[vom(i,r)] = (vdfm("cob",i,r)+vifm("cob",i,r)) / vom(i,r) ;
*initialize/define
edemcob(g,r) = 0;
escobd(g,r) = 0;

$if not %swdelas%==yes         $goto endescall
*Calibrate to elasticity of demand
edemcob(g,r)$[ldvie(g)] = %edemldvieval%;
edemcob(g,r)$[omc(g)] = %edemomcval%;
*edemcob(g,r)$[ele(g)] = %edemeleval%;

escobd(i,r) = edemcob(i,r) * cobdshr(i,r) / (1-cobdshr(i,r)) ;
escall(g,r) = escobd(g,r) ;



display edemcob, escobd, escall;

$label endescall
```

```

*Substitution between omvh and ldv
esmvh = %esmvhval%;
*Substitution between bev, phev, ice
esldv = %esldvval%;

*Elasticity of transformation in cobalt export versus production
etcob(i,r)$cob(i) = %etcobval%;

*% reduction in exports for benchmark
quote(i,r) = 0 ;

* Convert to armington specification of trade



*=====================

*========== Declare Model ==========
$ontext
$model:gtap9

$sectors:
y(g,r)$vom(g,r)                ! Supply
m(i,r)$vim(i,r)                ! Imports
yt(j)$vtw(j)                ! Transportation services
ft(f,r)$(sf(f) and evom(f,r))        ! Specific factor transformation
x(i,r)$[vex0(i,r)$cob(i)]        ! Exports - Cobalt


$commodities:
p(g,r)$vom(g,r)                ! Domestic output price
pm(j,r)$[vim(j,r)$(not cob(j))]               ! Import price
pt(j)$vtw(j)                ! Transportation services
pf(f,r)$evom(f,r)        ! Primary factors rent
ps(f,g,r)$(sf(f) and vfm(f,g,r))        ! Sector-specific primary factors
*        px(j,r)$[vex0(j,r)$cob(j)]                ! Export price - cobalt
pg(j)$cob(j)                ! Global price - cobalt

```

```
$consumers:
ra(r)                        ! Representative agent

$auxiliary:
QX(g,r)$[vex0(g,r)$cob(g)$chn(r)]        ! Variable associated with export quota constraint

*All but COB and MVH
$prod:y(g,r)$[vom(g,r)$(not cob(g))$(not mvhall2(g))]        s:escall(g,r) e:esub(g)  i.tl(e):esubd(i) va(e):esubva(g)
o:p(g,r)                                q:vom(g,r)        a:ra(r)  t:rto(g,r)
i:p(i,r)$[not cob(i)]        q:vdfm(i,g,r)        p:(1+rtfd0(i,g,r)) i.tl:  a:ra(r) t:rtfd(i,g,r)
i:pm(i,r)$[not cob(i)]        q:vifm(i,g,r)        p:(1+rtfi0(i,g,r)) i.tl:  a:ra(r) t:rtfi(i,g,r)
i:p(i,r)$[cob(i)]                q:(vdfm(i,g,r)+vifm(i,g,r))
i:ps(sf,g,r)                        q:vfm(sf,g,r)        p:(1+rtf0(sf,g,r))  va:    a:ra(r) t:rtf(sf,g,r)
i:pf(mf,r)                                q:vfm(mf,g,r)        p:(1+rtf0(mf,g,r))  va:    a:ra(r) t:rtf(mf,g,r)

*===== MVH =====
*Top Level MHV
$prod:y(g,r)$[vom(g,r)$mvh(g)] s:esmvh
o:p(g,r)        q:vom(g,r)
i:p(i,r)        q:vdfm(i,g,r)

*Top Level LDV
$prod:y(g,r)$[vom(g,r)$ldv(g)] s:esldv
o:p(g,r)        q:vom(g,r)
i:p(i,r)        q:vdfm(i,g,r)

*BEV, PHEV, ICE
$prod:y(g,r)$[vom(g,r)$ldvie(g)]        s:escall(g,r) e:esub(g)  i.tl(e):esubd(i) va(e):esubva(g)
o:p(g,r)        q:vom(g,r)        a:ra(r)  t:rto(g,r)
i:p(i,r)$[not cob(i)]        q:vdfm(i,g,r)        p:(1+rtfd0(i,g,r)) i.tl:  a:ra(r) t:rtfd(i,g,r)
i:pm(i,r)$[not cob(i)]         q:vifm(i,g,r)        p:(1+rtfi0(i,g,r)) i.tl:  a:ra(r) t:rtfi(i,g,r)
i:p(i,r)$[cob(i)]        q:(vdfm(i,g,r)+vifm(i,g,r))
i:ps(sf,g,r)        q:vfm(sf,g,r)        p:(1+rtf0(sf,g,r))  va:    a:ra(r) t:rtf(sf,g,r)
i:pf(mf,r)                q:vfm(mf,g,r)        p:(1+rtf0(mf,g,r))  va:    a:ra(r) t:rtf(mf,g,r)

*OMVH
$prod:y(g,r)$[vom(g,r)$omvh(g)]        s:esub(g)  i.tl:esubd(i)        va:esubva(g)
o:p(g,r)        q:vom(g,r)        a:ra(r)  t:rto(g,r)
i:p(i,r)        q:vdfm(i,g,r)        p:(1+rtfd0(i,g,r)) i.tl:  a:ra(r) t:rtfd(i,g,r)
```

```
i:pm(i,r)         q:vifm(i,g,r)        p:(1+rtfi0(i,g,r)) i.tl:  a:ra(r) t:rtfi(i,g,r)
i:ps(sf,g,r)        q:vfm(sf,g,r)        p:(1+rtf0(sf,g,r))  va:    a:ra(r) t:rtf(sf,g,r)
i:pf(mf,r)                q:vfm(mf,g,r)        p:(1+rtf0(mf,g,r))  va:    a:ra(r) t:rtf(mf,g,r)
*===== End MVH =====

*COB
$prod:y(g,r)$[vom(g,r)$cob(g)]        s:escob(g,r) T:etcob(g,r) e:esub(g)        i.tl(e):esubd(i)        va(e):esubva(g)
o:p(g,r)                q:vom(g,r)
*        o:p(g,r)                q:(vom(g,r)-vex0(g,r))
*        o:px(g,r)                q:vex0(g,r)                                a:ra(r)        N:qx(g,r)$[vex0(g,r)$cob(g)$chn(r)]
i:pf(mf,r)                q:vfm(mf,g,r)        va:
i:pf(rco,r)                q:vfm(rco,g,r)

*Transport services
$prod:yt(j)$vtw(j)  s:1
o:pt(j)                q:vtw(j)
i:p(j,r)        q:vst(j,r)

*Imports Armington
$prod:m(i,r)$[vim(i,r)$(not cob(i))]        s:esubm(i)  s.tl:0
o:pm(i,r)        q:vim(i,r)
i:p(i,s)        q:vxmd(i,s,r)        p:pvxmd(i,s,r) s.tl: a:ra(s) t:(-rtxs(i,s,r)) a:ra(r) t:(rtms(i,s,r)*(1-rtxs(i,s,r)))
i:pt(j)#(s)        q:vtwr(j,i,s,r) p:pvtwr(i,s,r) s.tl: a:ra(r) t:rtms(i,s,r)

*Imports COB
*cobalt clears in global market
$prod:m(i,r)$[vim(i,r)$cob(i)]
o:p(i,r)        q:vim(i,r)
i:pg(i)                q:(sum(s,vxmd(i,s,r)))

*Exports COB
$prod:x(i,r)$[vex0(i,r)$cob(i)]
o:pg(i)                q:(sum(s,vxmd(i,r,s)))
i:p(i,r)        q:vex0(i,r)        a:ra(r)        N:qx(i,r)$[vex0(i,r)$cob(i)$chn(r)]

*Sluggish factor transformation
$prod:ft(sf,r)$evom(sf,r)  t:etrae(sf)
o:ps(sf,j,r)        q:vfm(sf,j,r)
i:pf(sf,r)        q:evom(sf,r)
```

```

$demand:ra(r)
d:p("c",r)        q:vom("c",r)
e:p("c",rnum)        q:vb(r)
e:p("g",r)        q:(-vom("g",r))
e:p("i",r)        q:(-vom("i",r))
e:pf(f,r)        q:evom(f,r)

$constraint:QX(i,r)$[vex0(i,r)$cob(i)$chn(r)]
(1-quote(i,r)) =g= x(i,r)$[vex0(i,r)$cob(i)$chn(r)] ;

$report:
v:IDd(i,g,r)                i:p(i,r)        prod:y(g,r)
v:IDm(i,g,r)                i:pm(i,r)        prod:y(g,r)
v:FD(f,g,r)                        i:pf(f,r)        prod:y(g,r)


$offtext

$sysinclude mpsgeset gtap9

*-----Replicate benchmark-----


p.fx("c",r)$usa(r) = 1 ;

gtap9.workspace = 128;
gtap9.iterlim = 0;
$include gtap9.gen
solve gtap9 using mcp;

*$exit

gtap9.iterlim = 100000;

*====================

*========== Specify, Run, Save Output from Counter Factual Scenario(s) ==========
*$if exist runs_%run_name%.dat $include runs_%run_name%.dat
```

```

$if not defined yra parameter yra;
$if not defined y_r PARAMETER y_r;
$if not defined m_r PARAMETER m_r;
$if not defined x_r PARAMETER x_r;
$if not defined p_r PARAMETER p_r;
$if not defined pm_r PARAMETER pm_r;
$if not defined pg_r PARAMETER pg_r;
$if not defined pf_r PARAMETER pf_r;
$if not defined ra_r PARAMETER ra_r;
$if not defined qx_r PARAMETER qx_r;
$if not defined idd_r PARAMETER idd_r;
$if not defined idm_r PARAMETER idm_r;
$if not defined ida_r PARAMETER ida_r;
$if not defined fd_r PARAMETER fd_r;
$if not defined welf_r PARAMETER welf_r;
$if not defined welfa_r PARAMeTER welfa_r;

$if not defined evom_r PARAMETER evom_r;
$if not defined escall_r parameter escall_r;
$if not defined esub_r parameter esub_r;
$if not defined esubd_r parameter esubd_r;
$if not defined esubva_r parameter esubva_r;
$if not defined esmvh_r parameter esmvh_r;
$if not defined esldv_r parameter esldv_r;
$if not defined escob_r parameter escob_r;
$if not defined escobd_r parameter escobd_r;
$if not defined etcob_r parameter etcob_r;
$if not defined esupcob_r parameter esupcob_r;
$if not defined edemcob_r parameter edemcob_r;
$if not defined quote_r parameter quote_r;
$if not defined cobdshr_r parameter cobdshr_r;
$if not defined cobishr_r parameter cobishr_r;
$if not defined cobtab_r parameter cobtab_r;

*save BAU - no quota results in reporting parameters

y_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = Y.L(g,r);
m_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,r) = M.L(i,r);
```

```
x_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,r) = X.L(i,r);
p_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = P.L(g,r);
pm_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,r) = PM.L(i,r);
pg_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i) = PG.L(i);
pf_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",f,r) = PF.L(f,r);
ra_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",r) = RA.L(r);
qx_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = QX.L(g,r);
idd_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,g,r)$[vdfm(i,g,r)] =
IDd.L(i,g,r) / vdfm(i,g,r);
idm_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,g,r)$[vifm(i,g,r)] =
IDm.L(i,g,r) / vifm(i,g,r);
ida_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,g,r)$[vdfm(i,g,r) or vifm(i,g,r)] =
(IDm.L(i,g,r) + IDd.L(i,g,r)) / (vdfm(i,g,r)+vifm(i,g,r));
fd_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",f,g,r)$[vfm(f,g,r)] =
FD.L(f,g,r) / vfm(f,g,r);
quote_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,r) = quote(i,r);
welf_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",r) = (Y.L("c",r) - 1);
welfa_r("BAU","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",r) = (Y.L("c",r) - 1)*11000;

*Change quota stringency for policy counterfactual
quote(i,r)$[cob(i)$chn(r)] = %quoteval%/100 ;

display quote ;

$include gtap9.gen
solve gtap9 using mcp;

*save Quota - quota results in reporting parameters
y_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = Y.L(g,r);
m_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,r) = M.L(i,r);
x_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,r) = X.L(i,r);
p_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = P.L(g,r);
pm_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,r) = PM.L(i,r);
pg_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i) = PG.L(i);
pf_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",f,r) = PF.L(f,r);
ra_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",r) = RA.L(r);
qx_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = QX.L(g,r);
idd_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,g,r)$[vdfm(i,g,r)] =
IDd.L(i,g,r) / vdfm(i,g,r);
```

```
idm_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,g,r)$[vifm(i,g,r)] =
IDm.L(i,g,r) / vifm(i,g,r);
ida_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,g,r)$[vdfm(i,g,r) or vifm(i,g,r)] =
(IDm.L(i,g,r) + IDd.L(i,g,r)) / (vdfm(i,g,r)+vifm(i,g,r));
fd_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",f,g,r)$[vfm(f,g,r)] =
FD.L(f,g,r) / vfm(f,g,r);
quote_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,r) = quote(i,r);
welf_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",r) = (Y.L("c",r) - 1);
welfa_r("Quota","%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",r) = (Y.L("c",r) - 1)*11000;

*save other parameters in report variables
evom_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",f,r) = evom(f,r);
escall_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = escall(g,r);
esub_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g) = esub(g);
esubd_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i) = esubd(i);
esubva_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g) = esubva(g);
esmvh_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%") = esmvh;
esldv_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%") = esldv;
escob_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = escob(g,r);
*escobd_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = escobd(g,r);
etcob_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = etcob(g,r);
esupcob_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = esupcob(g,r);
*edemcob_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = edemcob(g,r);
cobdshr_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",g,r) = cobdshr(g,r);
cobishr_r("%gdxname%","%swfutscen%","%quoteval%","%esomcval%","%esldvval%",i,r) = cobishr(i,r);

*====================

cobtab_r("%swfutscen%","Output",r) = vom0("cob",r);
cobtab_r("%swfutscen%","Use",r) = sum(i, cob_v0(i,r));
cobtab_r("%swfutscen%","NetImp",r) = vim0("cob",r) - vex0("cob",r);
cobtab_r("%swfutscen%","ExpShrCHN",r) = cobishr("cob",r);
cobtab_r("%swfutscen%","Output","World") = sum(r,vom0("cob",r));
cobtab_r("%swfutscen%","Use","World") = sum((i,r), cob_v0(i,r));
cobtab_r("%swfutscen%","NetImp","World") = sum(r, vim0("cob",r) - vex0("cob",r));
cobtab_r("%swfutscen%","ExpShrCHN","World") = cobishr("cob","CHN");


* Save model results for this run:
```

```

execute_unload "..\scenout\runout\%gdxname%.gdx";
execute_unload "..\scenout\final_%run_name%.gdx";

*FILE out /runs_%run_name%.dat/;

*put out;


* $libinclude gams2prm y_r
* $libinclude gams2prm m_r
* $libinclude gams2prm x_r
* $libinclude gams2prm p_r
* $libinclude gams2prm pm_r
* $libinclude gams2prm pg_r
* $libinclude gams2prm pf_r
* $libinclude gams2prm ra_r
* $libinclude gams2prm qx_r
* $libinclude gams2prm idd_r
* $libinclude gams2prm idm_r
* $libinclude gams2prm ida_r
* $libinclude gams2prm fd_r
* $libinclude gams2prm welf_r
* $libinclude gams2prm welfa_r

* $libinclude gams2prm evom_r
* $libinclude gams2prm escall_r
* $libinclude gams2prm esub_r
* $libinclude gams2prm esubd_r
* $libinclude gams2prm esubva_r
* $libinclude gams2prm esmvh_r
* $libinclude gams2prm esldv_r
* $libinclude gams2prm escob_r
* *$libinclude gams2prm escobd_r
* $libinclude gams2prm etcob_r
* $libinclude gams2prm esupcob_r
* *$libinclude gams2prm edemcob_r
* $libinclude gams2prm quote_r
* $libinclude gams2prm cobdshr_r
```

```
* putclose out;
```

APPENDIX J - SPILLOVER MODEL CODE

Files included:

1. run_lim.bat - passes key parameters into model for various scenarios
2. rd_ctar_lim.gms - Loads input data, calibration, model, and reporting

run_lim.bat

```
echo begin

::Carbon Limit

::No Tariff
gams rd_ctar_lim --sd=BASE1 --carblimval=0.9 --pelascval=1 --esubdshft=1 --pelasrdval=1 --tarval=no
gams rd_ctar_lim --sd=BASE2 --carblimval=0.9 --pelascval=0.5 --esubdshft=1 --pelasrdval=1 --tarval=no
gams rd_ctar_lim --sd=BASE3 --carblimval=0.9 --pelascval=1 --esubdshft=0.5 --pelasrdval=1 --tarval=no
gams rd_ctar_lim --sd=BASE4 --carblimval=0.9 --pelascval=1 --esubdshft=1 --pelasrdval=2 --tarval=no
gams rd_ctar_lim --sd=BASE5 --carblimval=0.9 --pelascval=1 --esubdshft=1 --pelasrdval=1 --tarval=no --thtashftval=50
gams rd_ctar_lim --sd=BASE6 --carblimval=0.9 --pelascval=1.5 --esubdshft=1 --pelasrdval=1 --tarval=no --thtashftval=1

::Tariff
gams rd_ctar_lim --sd=CTAR1 --carblimval=0.9 --pelascval=1 --esubdshft=1 --pelasrdval=1 --tarval=yes
gams rd_ctar_lim --sd=CTAR2 --carblimval=0.9 --pelascval=0.5 --esubdshft=1 --pelasrdval=1 --tarval=yes
gams rd_ctar_lim --sd=CTAR3 --carblimval=0.9 --pelascval=1 --esubdshft=0.5 --pelasrdval=1 --tarval=yes
gams rd_ctar_lim --sd=CTAR4 --carblimval=0.9 --pelascval=1 --esubdshft=1 --pelasrdval=2 --tarval=yes
gams rd_ctar_lim --sd=CTAR5 --carblimval=0.9 --pelascval=1 --esubdshft=1 --pelasrdval=1 --tarval=yes --thtashftval=50
gams rd_ctar_lim --sd=CTAR6 --carblimval=0.9 --pelascval=1.5 --esubdshft=1 --pelasrdval=1 --tarval=yes --thtashftval=1

gdxmerge output\runs_rd_ctar_lim*.gdx output=output\runs_lim.gdx
gdxmerge output\runs_rd_ctar_lim_BASE1.gdx output\runs_rd_ctar_lim_CTAR1.gdx output=output\runs_comp1.gdx

echo end

```

rd_ctar_lim.gms

```
$title         Replicate the GTAP9 Benchmark in MPSGE

* Batch file scenario management
$if not set pelasrdval $set pelasrdval 1
$if not set pelascval $set pelascval 1
$if not set esubdshft $set esubdshft 1
$if not set thtashftval $set thtashftval 1
$if not set sauswval $set sauswval no
$if not set tarmanval $set tarmanval no
$if not set tarval $set tarval no
$if not set carblimval $set carblimval 0.9
$if not set ctaxval $set ctaxval 100

*========== Monte-Carlo Seed ==========
$if not set sd $set sd 1

*option seed=%sd%;
*====================

$if not set yr $set yr 11
$if not set ds $set ds rd_toy3
$if not set dsomn $set dsomn rd_toy3_omn
$if not set df $set df df_r1i
$include gtap9data

*Unload bmk data from gtap9data.gms for safekeeping
*execute_unload "%ds%_gtap9data.gdx";

*Load in bmk RD expenditures in production

parameter rdin(*,*)        "bmk R&D expenditures in production"
/
$ondelim
$include %df%.csv
$offdelim
/;
```

```

*rdin(*,*) = round(rdin(*,*), 4);
display rdin;

alias (f,ff), (i,j,k);
alias (r,s,rr,ss);

set mapr(r,rr);
mapr(r,rr) = yes$(sameas(r,rr));

* ========== Adjust R&D data to work with gtap sectors ==========
*Need to somehow figure out how to get value added from "OMN" sector...
*... into raw(i) set, so that r&d (rdin) can be shared out
*create a second aggregation routine --- rd_toy3_omn.gdx

parameter vfm_omn(f,*,r);
set gomn(*);
set iomn(gomn);

$if exist %dsomn%.gdx $gdxin "%dsomn%.gdx"
$if not exist %dsomn%.gdx $gdxin "%datadir%%dsomn%.gdx"
$load vfm_omn=vfm
$load gomn=g, iomn=i
$gdxin

display vfm_omn, gomn, iomn;
*$exit

set nei(i)        "nei"        /nei/;
set omn(iomn)  "omn"        /omn/;
set vkl(f)        "value added set"        /cap, lab/;
set raw(i)        "gtap raw set"                /cru, gas, coa/;
set raw_omn(iomn)        "gtap raw set"                /cru, gas, coa, omn/;
set ene(i)        "gtap ene set"                /ele, gdt/;
set ren                "raw and ene"                /raw,ene/;
set nren(i)        "not raw or ene";
nren(i)$[not raw(i) or not ene(i)] = yes;
display nren;
set coa(i)        "coal"        /coa/;
```

```
set chn(r)         "chn"        /chn/;

parameter
vaene(i,r)        "value added share of total ENE"
varaw(iomn,r)        "value added share of total RAW"
;

vaene(i,r)$[ene(i)] = sum(f, vfm(f,i,r)) / sum((f,ene), vfm(f,ene,r));
*varaw(i,r)$[raw(i)] = sum(f, vfm(f,i,r)) / (sum((f,raw), vfm(f,raw,r)) + sum((f,omn), vfm(f,omn,r)));
varaw(iomn,r)$[raw_omn(iomn)] = sum(f, vfm_omn(f,iomn,r)) / sum((f,raw_omn), vfm_omn(f,raw_omn,r));

display vaene, varaw;

parameter
rdexp0        "R&D expenditures under gtap sets"
;
rdexp0(r,i)$[nren(i)] = rdin(r,i);
rdexp0(r,'cru') = varaw('cru',r) * rdin(r,"RAW");
rdexp0(r,'gas') = varaw('gas',r) * rdin(r,"RAW");
rdexp0(r,'coa') = varaw('coa',r) * rdin(r,"RAW");
rdexp0(r,i)$[nei(i)] = rdexp0(r,i) + varaw('omn',r)*rdin(r,"RAW");
rdexp0(r,i)$[ene(i)] = vaene(i,r) * rdin(r,"ENE");

display rdexp0;
*$exit
*====================

*==========Determine N-S regional sets==========
$ifthen.rdtoy2 '%ds%'=='rd_toy2'
set
sth(r)        "Regions that belong to the South"        /SOU/
nth(r)         "Regions that belong to the North"
;
$endif.rdtoy2

$ifthen.rdtoy1 '%ds%'=='rd_toy1'
set
sth(r)        "Regions that belong to the South"        /E12, RUS, CHN, ROW/
nth(r)         "Regions that belong to the North"
```

```
;
$endif.rdtoy1

$ifthen.rdtoy3 '%ds%'=='rd_toy3'
set
sth(r)        "Regions that belong to the South"        /E12, RUS, CHN, ROW/
nth(r)         "Regions that belong to the North"
;
$endif.rdtoy3


nth(r)$(not sth(r)) = yes;
*====================


*========== Calculate Gammas - absorption capacity weights ==========
parameter        gamma(r,i)        "absorption capacity weights";
gamma(r,i) = rdexp0(r,i) / sum(nth, rdexp0(nth,i));
display gamma;
*====================

set
lb(f)        "labor"                        /lab/
*        fe(i)        "final energy"         /raw, ene/
fe(i)        "final energy"         /coa, gas, oil, gdt/
nfe(i)        "not final energy"
;
nfe(i)$(not fe(i)) = yes;


display fe, nfe, nth, sth;


*GTAP6 Model code --- gtap_arm4.gms
*Something to do with income balance and govt collecting taxes
*vpm(r) = vom('c',r);
*vgm(r) = vom('g',r);
*sum(i,vdim(i,r)) = vom('i',r)
*vtax(r) = sum(f, evom(f,r)) - (vpm(r) + sum(i,vdim(i,r)));
```

```

parameter        vtax(r)        "Implicit Tax";
vtax(r) = sum(f, evom(f,r)) - (vom('c',r) + vom('i',r));
display vtax;

parameters
esubc            "R&D substitution in effective carbon prod"
esubrd(g,r) "R&D substitution in sectoral production"
esubrdd                "Substitution in RD production"
esubrdc                "Substitution in RD production"

dcb0(*,*,*)        "demand for effective carbon"
cb0(r)                "value of carbon good output"
carb0(r)        "carbon endowment"

rd0(i,r)        "bmk value of R&D investments"

dk0(g,r)        "bmk demand for knowledge"
ks0(i,r)        "bmk endowment of knowledge stocks"
vktx(r)                "bmk value of tax revs lost in R&D calibration"

rdc0(r)                "bmk value of carbon R&D"
irdc0(f,r)        "bmk value of inputs to carbon R&D"

rdshr(r)        "share of conventional factors reallocated to R&D"
rdcshr                "bmk rd as share of effective carbon prod"
ksshr(r)        "share of conventional factors reallocated to knowledge stock"
kshr(r)                "total knowledge as share of gdp"

theta(i,r,s)        "tech spillover coeffs"
theta0(i,r,s)        "bmk tech spillover coeffs"

ctax0(r)        "bmk carbon tax rate"

;

*===== monte carlo parameters =====
*esubd(i) = uniform(0.5*esubd(i),1.5*esubd(i));
*esubm(i) = uniform(0.5*esubm(i),1.5*esubm(i));
```

```

*esubrdd = uniform(0.5,1.5);
*esubrdc = uniform(0.5,1.5);
esubrdd = 1;
esubrdc = 1;

*rdcshr = uniform(0.005,0.015);
rdcshr = 0.01;
*rdcshr = 1;

PARAMETER rshft(i);
rshft(i) = 1;
*rshft(i) = uniform(0.5,1.5);
rdexp0(r,i) = rdexp0(r,i)*rshft(i);

*==========

set
*        xe(g)        "extractive resources - cru, gas, coa" /raw/
xe(g)        "extractive resources - cru, gas, coa" /coa, gas, cru/
fl(f,g)
;
fl("cap",xe) = yes;

ctax0(r) = 1;

*Load data into carbon parameters
dcb0(i,g,r) = eco2d(i,g,r) + eco2i(i,g,r);

*cb0(r) = sum((i,g), dcb0(i,g,r));
cb0(r) = sum((fe,g), dcb0(fe,g,r));
carb0(r) = cb0(r);

*Data in Mt (million tons) of co2
*--Convert to Billion tons of co2,
*----so that model carbon prices can be interpreted in $/ton co2
dcb0(i,g,r) = dcb0(i,g,r) * 1e-3;
cb0(r) = cb0(r) * 1e-3;
carb0(r) = carb0(r) * 1e-3;
```

```


display eco2d, eco2i, dcb0, cb0, carb0;

*Assume that all R&D spillovers can be used domestically... but only
* some fraction can be used in the developing world...

theta0(i,s,r) = gamma(r,i);
theta0(i,nth,nth) = 1;
theta0(i,sth,nth) = 0;
theta0(i,s,r)$(sth(r) and sth(s)) = 0;

theta(i,r,s) = theta0(i,r,s);

display theta0;

* Benchmark calibration with R&D
parameters
ird0(i,r)        "bmk inputs to R&D production"
vitx(i,j,r)        "bmk value of tax on intermediate inputs"
vot(i,r)        "bmk value of output taxes"
r0                        "interest rate"                /0.05/
dlt0                "depreciation rate"        /0.20/
g0                        "growth rate"                /0.01/
;

alias(i,ii,jj,kk);

set map_li(*); map_li("lab") = yes;
set map_ci(*); map_ci("cap") = yes;

vitx(i,j,r) = rtfd0(i,j,r) * vdfm(i,j,r);
vot(i,r) = rto(i,r)*vom(i,r);

*Calculate value of inputs to R&D production based on perpetual
* inventory method:

*ird0(i,r) = rdexp0(r,i);
ird0(i,r)  = (dlt0+g0) * rdexp0(r,i) / (dlt0+r0);
```

```
*ird0(i,nth)  = (dlt0+g0) * rdexp0(nth,i) / (dlt0+r0);
display ird0;

*========== CHECK ==========
mprofit(i,r) = 0;
yprofit(i,r) = 0;
mprofit(i,r) = vim(i,r) - sum(s, pvxmd(i,s,r)*vxmd(i,s,r)+sum(j, vtwr(j,i,s,r))*pvtwr(i,s,r));
mprofit(i,r) = round(mprofit(i,r),5);
display mprofit;

yprofit(g,r) = vom(g,r)*(1-rto(g,r))
- sum(i, vdfm(i,g,r)*(1+rtfd0(i,g,r))
+ vifm(i,g,r)*(1+rtfi0(i,g,r)))
- sum(f, vfm(f,g,r)*(1+rtf0(f,g,r)));

yprofit(g,r) = round(yprofit(g,r),6)
display yprofit;
*========== CHECK ==========

*Now debit intermediate inputs to conventional goods proportionately:

parameter        vints(i,j,r);

vints(i,j,r) =
(1+rtfd0(i,j,r))*vdfm(i,j,r)
- rdexp0(r,j) *
[(1+rtfd0(i,j,r))*vdfm(i,j,r) / sum(k, (1+rtfd0(k,j,r))*vdfm(k,j,r))]
;

vdfm(i,j,r) = vints(i,j,r) - vitx(i,j,r);

* And calculate the new effective tax rates...

rtfd0(i,j,r)$vdfm(i,j,r) = vitx(i,j,r)/vdfm(i,j,r) ;
rtfd(i,j,r) = rtfd0(i,j,r) ;

* Re-calculate total demand for intermediates:

parameters
```

```
totdmd(r,i)
totsup(r,i)
;

totdmd(r,i) =
sum(g, vdfm(i,g,r) + vifm(i,g,r))
+ [sum(s, vxmd(i,r,s)) + vst(i,r)]
+ ird0(i,r)
;
display totdmd;


totsup(r,i) =
sum(j, vdfm(j,i,r)*(1+rtfd0(j,i,r)) + vifm(j,i,r)*(1+rtfi0(j,i,r)))
+ sum(f, vfm(f,i,r)*(1+rtf0(f,i,r)))
+ rdexp0(r,i)
+ [        sum(j, vdfm(j,i,r)*(1+rtfd0(j,i,r)) + vifm(j,i,r)*(1+rtfi0(j,i,r)))
+ sum(f, vfm(f,i,r)*(1+rtf0(f,i,r)))
+ rdexp0(r,i) ] * (1/(1-rto(i,r))-1)
+ vim(i,r)
;
display totsup;


parameter chk;
chk(i,r) = totdmd(r,i) - totsup(r,i);
display chk;

*And debit value of chk from labor inputs to re-balance the SAM:
parameters
vfct(f,i,r)
vltx(f,i,r)
;

* OIL R&D is too large to be debited from labor:
SET        noil(ii)        Not OIL;
noil(ii) = yes; noil("oil") = no;


```

```
vltx(f,i,r) = rtf0(f,i,r)*vfm(f,i,r);
vfct(f,i,r) = (1+rtf0(f,i,r))*vfm(f,i,r);
display vfct;

*Adjust Labor
*vfct("lab",i,r) = (1+rtf0("lab",i,r))*vfm("lab",i,r) + chk(i,r);
vfct("lab",noil,r) = (1+rtf0("lab",noil,r))*vfm("lab",noil,r) + chk(noil,r);

*Adjust Investment
*vdim("OIL",r) = vdim("OIL",r) - chk("OIL",r);
vdfm('oil','i',r) = vdfm('oil','i',r) - chk('oil',r);

*Adjust vom for investment - vom will be adjusted for labor later
vom("i",r) = sum(i, vdfm(i,"i",r)*(1+rtfd0(i,"i",r)) + vifm(i,"i",r)*(1+rtfi0(i,"i",r)))/(1-rto("i",r));

vfm(f,i,r) = vfct(f,i,r) - vltx(f,i,r);
rtf0(f,i,r)$rtf0(f,i,r) = vltx(f,i,r)/vfm(f,i,r);
rtf(f,i,r) = rtf0(f,i,r);

evom(f,r) = sum(i, vfm(f,i,r));
display vfm, evom, vfct, vltx, rtf;

*========== CHECK ==========
mprofit(i,r) = 0;
yprofit(i,r) = 0;
mprofit(i,r) = vim(i,r) - sum(s, pvxmd(i,s,r)*vxmd(i,s,r)+sum(j, vtwr(j,i,s,r))*pvtwr(i,s,r));
mprofit(i,r) = round(mprofit(i,r),5);
display mprofit;

yprofit(g,r) = vom(g,r)*(1-rto(g,r))
- sum(i, vdfm(i,g,r)*(1+rtfd0(i,g,r))
+ vifm(i,g,r)*(1+rtfi0(i,g,r)))
- sum(f, vfm(f,g,r)*(1+rtf0(f,g,r)))
- rdexp0(r,g)
;

yprofit(g,r) = round(yprofit(g,r),6)
display yprofit;
*========== CHECK ==========
```

```
*Now we must calculate new value of vom...
parameter vinputs(i,r);

vinputs(i,r) =
sum(j, vdfm(j,i,r)*(1+rtfd0(j,i,r)) + vifm(j,i,r)*(1+rtfi0(j,i,r)))
+ sum(f, vfm(f,i,r)*(1+rtf0(f,i,r)))
+ rdexp0(r,i)
;

vom(i,r) = vinputs(i,r) + vot(i,r);

rto(i,r)$[vom(i,r)] = 1 - vinputs(i,r) / vom(i,r);

totsup(r,i) =
sum(j, vdfm(j,i,r)*(1+rtfd0(j,i,r)) + vifm(j,i,r)*(1+rtfi0(j,i,r)))
+ sum(f, vfm(f,i,r)*(1+rtf0(f,i,r)))
+ rdexp0(r,i)
+ [        sum(j, vdfm(j,i,r)*(1+rtfd0(j,i,r)) + vifm(j,i,r)*(1+rtfi0(j,i,r)))
+ sum(f, vfm(f,i,r)*(1+rtf0(f,i,r)))
+ rdexp0(r,i) ] * (1/(1-rto(i,r))-1)
+ vim(i,r)
;

chk(i,r) = 0;
chk(i,r) = totsup(r,i) - vim(i,r) - vom(i,r);
display totsup, vom, chk;

*========== CHECK ==========
mprofit(i,r) = 0;
yprofit(i,r) = 0;
mprofit(i,r) = vim(i,r) - sum(s, pvxmd(i,s,r)*vxmd(i,s,r)+sum(j, vtwr(j,i,s,r))*pvtwr(i,s,r));
mprofit(i,r) = round(mprofit(i,r),5);
display mprofit;

yprofit(g,r) = vom(g,r)*(1-rto(g,r))
- sum(i, vdfm(i,g,r)*(1+rtfd0(i,g,r))
+ vifm(i,g,r)*(1+rtfi0(i,g,r)))
- sum(f, vfm(f,g,r)*(1+rtf0(f,g,r)))
```

```
- rdexp0(r,g)
;

yprofit(g,r) = round(yprofit(g,r),6)
display yprofit;
*========== CHECK ==========

rdc0(r) = 1;
*irdc0(f,r) = 0;
*irdc0(lb,r) = 1;

*Adjust capital stock for resource-specific factors and calibrate
*supply elasticities for these goods:

evom('cap',r) = evom('cap',r) - sum(xe, vfm('cap',xe,r));

parameter rsshrs, rdshrs, evom;

rsshrs(xe,r)$[vom(xe,r)] = vfm('cap',xe,r) / (vom(xe,r)*(1-rto(xe,r)));
rdshrs(i,r)$[vom(i,r)] = rdexp0(r,i) / (vom(i,r)*(1-rto(i,r)));

* Now set price elasticity of R&D equal in all sectors:

*===== monte carlo parameters =====
PARAMETERS
elas_shft(g)
elasc_shft
esup_shft(g)
pelas_rd(g)
pelas_rdc
esup_xe(g)
;


*elas_shft(i) = uniform(0.5,1.5);
*elasc_shft = uniform(0.5,1.5);
*esup_shft(i) = uniform(0.5,1.5);

elas_shft(i) = 1;
```

```
elasc_shft = 1;
esup_shft(i) = 1;

pelas_rd(i) = elas_shft(i) * %pelasrdval%;
pelas_rdc = elasc_shft * %pelascval%;
esup_xe(i) = 1;
esup_xe(’COA’) = 1;
*==========

** pelas = thet + (1-thet)*esubrd =>
esubrd(i,r) = -((rdshrs(i,r) - pelas_rd(i))/(1-rdshrs(i,r)));
*esubrd(i,r)=0.1;
esubc = -((rdcshr - pelas_rdc)/(1-rdcshr));
*esubc = pelas_rdc;

display esubc;

* In the exhaustible energy sectors, set esub to imply elasticity of supply:

esubrd(xe,r) = esup_xe(xe) * rsshrs(xe,r) / (1-rsshrs(xe,r));

display rsshrs, rdshrs, esubrd;

*setup R&D calibration

dk0(i,r) = rdexp0(r,i);
rd0(i,r) = ird0(i,r);
ks0(i,r) = dk0(i,r) - rd0(i,r);


*check that knowledge markets clear
parameter chk2;
chk2(i,r) = rd0(i,r) + ks0(i,r) - dk0(i,r);
display chk2, rd0, ks0, dk0;


*Convert to Armington specification of trade:
parameters
vafm
```

```
a0
rtfa0
rtfa
;

vafm(i,g,r) = vdfm(i,g,r) + vifm(i,g,r);
a0(i,r) = sum(g, vdfm(i,g,r) + vifm(i,g,r));
rtfa0(i,g,r)$[vafm(i,g,r)] = (vdfm(i,g,r)*rtfd0(i,g,r) + vifm(i,g,r)*rtfi0(i,g,r)) / vafm(i,g,r);
rtfa(i,g,r) = rtfa0(i,g,r);

display vafm, a0, rtfa0;
*$exit


set        cn(g)        "consumption"        /c/;
set        gv(g)        "government"        /g/;
set iv(g)        "investment"        /i/;
set        cg(g)        "consumption & government"        /c,g/;
set cgi(g)         "cgi"        /c,g,i/;
set aggs(g) "aggregated sectors -- eii, nei"        /eii, nei/;

parameter        esub(g)                Top-level elasticity indemand /C 0.5/;
esub(i)$[not xe(i)] = 0.2;
esubd(i)$[aggs(i)] = esubd(i) * %esubdshft%;
esubm(i)$[aggs(i)] = esubm(i) * %esubdshft%;

display esub, esubd, esubva, esubc, esubm, esubrd;

parameter
cc(g,s,r)        "carbon content general"
ccsub(g,s,r) "carbon content negative"
ccy(g,r)        "carbon content domestic, activity g in region r"
ccm(i,r)        "carbon content imports, commodity i in region r"
ccele(r)        "carbon content of electricity sector output in region r"
ccemb(g,r)        "direct emissions content from fuel consumption and indirect emissions content embodied in electricity"
tar(i,s,r)        "carbon tariff switch"
tarman(i,s,r) "manual tariff switch"
sausw                "switch for endogenous quota"
ctar(i,s,r) "carbon import tariff manual"
```

```
csub(i,s,r) "carbon export subsidy manual (subsidy when positive)"

tarsw(r)
tars                "Tariff Switch"
;

tarsw(r) = no;
tars = no;

cc(g,s,r) = 0;
ccy(g,r)$[vom(g,r)] = (sum(i, eco2d(i,g,r) + eco2i(i,g,r)))*1e-3 / vom(g,r);
ccm(i,r)$[vim(i,r)] = (sum(j, eco2i(j,i,r)))*1e-3 / vim(i,r);
ccele(r)$[vom('ele',r)] = sum(i,dcb0(i,'ele',r)) / vom('ele',r);
ccemb(g,r)$[vom(g,r)] = [ccy(g,r)*vom(g,r) + ccele(r)*(vdfm('ele',g,r)+vifm('ele',g,r))] / vom(g,r);
*cc(g,s,r)$[not mapr(s,r)] = ccemb(g,r);
cc(g,s,r)$[vom(g,r)$(not mapr(s,r))] = sum(fe, dcb0(fe,g,r)) / vom(g,r);
ccsub(g,s,r) = -cc(g,s,r);
*cc(i,s,r) = cc(i,s,r) * vxmd(i,s,r);

tar(i,s,r) = no;
tarman(i,s,r) = no;
sausw = no;
ctar(i,s,r) = 0;
csub(i,s,r) = 0;

parameters
vx0(g,r)        "exports of good in i produced in region r - south to north only"
shvx0(g,r)         "export share of output of good i produced in region r"
shvxmd0(i,r,s)
shvd0(g,r)        "domestic share of output of good i produced in region r"
carbex0(r)        "c02 imports to region r (in north) from southern regions"
;

vx0(i,r)$[sth(r)] = sum(s$[nth(s)], vxmd(i,r,s));
shvx0(g,r)$[vom(g,r)] = vx0(g,r)/vom(g,r);
shvd0(g,r) = 1-shvx0(g,r);
shvxmd0(i,sth,nth)$[vx0(i,sth)] = vxmd(i,sth,nth) / vx0(i,sth);
carbex0(r) = sum((fe,j), shvx0(j,r)*dcb0(fe,j,r));

```

```
display cc, ccy, ccm, vx0, shvx0, shvd0, shvxmd0;
*$exit
*Clean this section up
parameters
ex1(i,r,s)
ex2(i,r,s)
ex3(i,r)
ex4(i,r)
ex5(r,s)
ex6(i,r)
ex7(i,r)
carbim0(r,s)        "imports of carbon contained in goods from south to country r$north"
chkimex
;

ex1(i,r,s)$[sth(r)$nth(s)] = vxmd(i,r,s)*cc(i,r,s);
*ex2(i,r,s)$[nth(r)$sth(s)] = vxmd(i,r,s)*cc(i,r,s);
ex3(i,r)$[sth(r)] = sum(s$[nth(s)], ex1(i,r,s));
*ex4(i,s)$[nth(s)] = sum(r$[sth(r)], ex1(i,r,s));
ex4(i,nth) = sum(sth, vxmd(i,sth,nth)*cc(i,nth,sth));
*carbex0(r) = sum(i,ex3(i,r));
*carbim0(r) = sum(i,ex4(i,r));
carbim0(nth,sth) = sum(i,vxmd(i,sth,nth)*cc(i,nth,sth));
chkimex("carb") = sum((r,s),carbim0(r,s)) - sum(s,carbex0(s));
display carbex0, carbim0, chkimex;

*$exit
$ontext
$model:itc

$sectors:
y(g,r)$vom(g,r)                ! Supply
m(i,r)$vim(i,r)                ! Imports
yt(j)$vtw(j)                ! Transportation services
*        ft(f,r)$[sf(f) and evom(f,r)]        ! Specific factor transformation

a(i,r)$[a0(i,r)]        ! Armington Composite

rd(i,r)$[rd0(i,r)]        ! Conventional R&D sectors
```

```
rdc(r)$[rdc0(r)]        ! Carbon R&D sector
carbon(r)$[nth(r)]                        ! Effective carbon

x(i,r)$[vx0(i,r)$sth(r)]        ! Southern Export Block - Only Exports going to North
d(g,r)$[vom(g,r)$sth(r)]        ! South-South Production and Domestic South
sscarbon(r)$[sth(r)]        ! Southern effective emissions domestic and south to south
sncarbon(r,s)$[sth(r)$nth(s)]        ! Southern effective emissions - South to North
xrs(j,r,s)$[shvxmd0(j,r,s)$sth(r)$nth(s)]        ! Exports from South to North

$commodities:
p(g,r)$vom(g,r)                ! Domestic output price
pm(j,r)$vim(j,r)        ! Import price
pt(j)$vtw(j)                ! Transportation services
pf(f,r)$evom(f,r)        ! Primary factors rent
*        ps(f,g,r)$(sf(f) and vfm(f,g,r))        ! Sector-specific primary factors

pa(i,r)$[a0(i,r)]        ! Armington aggregation

pr(i,r)$[dk0(i,r)]        ! Sectoral R&D prices
prc(r)$[rdc0(r)]        ! Carbon-saving R&D price
prcarb(r)$[nth(r)]        ! Effective carbon price
pcarb(r)$[carb0(r)]        ! Carbon factor price
psncarb(r,s)$[sth(r)$nth(s)$tars]                ! Factor price that south inherits from north
prsscarb(r)$[sth(r)]        ! Effective carbon price for south to south and southern domestic
prsncarb(r,s)$[sth(r)$nth(s)]

prs(i,r)$[xe(i)$vfm("cap",i,r)]        ! Fuel resource price

px(i,r)$[vx0(i,r)$sth(r)]
pd(g,r)$[vom(g,r)$sth(r)]
pxs(i,r,s)$[shvxmd0(i,r,s)$sth(r)$nth(s)]

$consumers:
hh(r)                        ! Representative household
govt(r)                        ! Representative government

$auxiliary:
spill(i,r)$(ks0(i,r) or rd0(i,r))        ! conventional technology spillovers
spillc(r)$rdc0(r)        ! carbon technology spillovers
```

```
ctax(r)                                ! carbon tax rule
tariff(r,s)$[nth(r)$sth(s)$tars]        ! carbon tariff constraint

*zzzzzzzzzzzzzzz OUTPUT Blocks zzzzzzzzzzzzzzz

*==========North==========
$prod:y(g,r)$[vom(g,r)$(not xe(g))$nth(r)]        s:esubrd(g,r)    cm:esub(g)        i.tl(cm):0  va(cm):esubva(g)
o:p(g,r)        q:vom(g,r)
+                a:govt(r)        t:rto(g,r)
i:pa(fe,r)        q:vafm(fe,g,r)        p:(1+rtfa0(fe,g,r))        fe.tl:
+                a:govt(r)        t:rtfa(fe,g,r)
i:pa(i,r)$[not fe(i)]        q:vafm(i,g,r)        p:(1+rtfa0(i,g,r))        cm:
+                a:govt(r)        t:rtfa(i,g,r)
i:pf(mf,r)        q:vfm(mf,g,r)        p:(1+rtf0(mf,g,r))        va:
+                a:govt(r)        t:rtf(mf,g,r)
i:prcarb(r)#(fe)                q:dcb0(fe,g,r)        p:1e-6        fe.tl:
i:pr(g,r)$[not cg(g)]        q:dk0(g,r)


$prod:y(g,r)$[vom(g,r)$xe(g)$nth(r)]        s:esubrd(g,r)    cm:esub(g)        i.tl(cm):0  va(cm):esubva(g)
o:p(g,r)        q:vom(g,r)
+                a:govt(r)        t:rto(g,r)
i:pa(fe,r)        q:vafm(fe,g,r)        p:(1+rtfa0(fe,g,r))        fe.tl:
+                a:govt(r)        t:rtfa(fe,g,r)
i:pa(i,r)$[not fe(i)]        q:vafm(i,g,r)        p:(1+rtfa0(i,g,r))        cm:
+                a:govt(r)        t:rtfa(i,g,r)
i:pf(mf,r)$[not fl(mf,g)]        q:vfm(mf,g,r)        p:(1+rtf0(mf,g,r))        va:
+                a:govt(r)        t:rtf(mf,g,r)
i:prcarb(r)#(fe)                q:dcb0(fe,g,r)        p:1e-6        fe.tl:
i:pr(g,r)        q:dk0(g,r)
i:prs(g,r)        q:vfm("cap",g,r)        p:(1+rtf0("cap",g,r))
+                a:govt(r)        t:rtf("cap",g,r)
*====================

*==========South==========
*-----Domestic Production Block-----
$prod:d(g,r)$[vom(g,r)$(not xe(g))$sth(r)]        s:esubrd(g,r)    cm:esub(g)        i.tl(cm):0  va(cm):esubva(g)
o:pd(g,r)        q:(shvd0(g,r)*vom(g,r))
+                a:govt(r)        t:rto(g,r)
```

```
i:pa(fe,r)        q:(shvd0(g,r)*vafm(fe,g,r))        p:(1+rtfa0(fe,g,r))        fe.tl:
+                a:govt(r)        t:rtfa(fe,g,r)
i:pa(i,r)$[not fe(i)]        q:(shvd0(g,r)*vafm(i,g,r))        p:(1+rtfa0(i,g,r))        cm:
+                a:govt(r)        t:rtfa(i,g,r)
i:pf(mf,r)        q:(shvd0(g,r)*vfm(mf,g,r))        p:(1+rtf0(mf,g,r))        va:
+                a:govt(r)        t:rtf(mf,g,r)
i:prsscarb(r)#(fe)                q:(shvd0(g,r)*dcb0(fe,g,r))        p:1e-6        fe.tl:
i:pr(g,r)$[not cg(g)]        q:(shvd0(g,r)*dk0(g,r))


$prod:d(g,r)$[vom(g,r)$xe(g)$sth(r)]        s:esubrd(g,r)    cm:esub(g)        i.tl(cm):0  va(cm):esubva(g)
o:pd(g,r)        q:(shvd0(g,r)*vom(g,r))
+                a:govt(r)        t:rto(g,r)
i:pa(fe,r)        q:(shvd0(g,r)*vafm(fe,g,r))        p:(1+rtfa0(fe,g,r))        fe.tl:
+                a:govt(r)        t:rtfa(fe,g,r)
i:pa(i,r)$[not fe(i)]        q:(shvd0(g,r)*vafm(i,g,r))        p:(1+rtfa0(i,g,r))        cm:
+                a:govt(r)        t:rtfa(i,g,r)
i:pf(mf,r)$[not fl(mf,g)]        q:(shvd0(g,r)*vfm(mf,g,r))        p:(1+rtf0(mf,g,r))        va:
+                a:govt(r)        t:rtf(mf,g,r)
i:prsscarb(r)#(fe)                q:(shvd0(g,r)*dcb0(fe,g,r))        p:1e-6        fe.tl:
i:pr(g,r)        q:(shvd0(g,r)*dk0(g,r))
i:prs(g,r)        q:(shvd0(g,r)*vfm("cap",g,r))        p:(1+rtf0("cap",g,r))
+                a:govt(r)        t:rtf("cap",g,r)

*-----South to North Export Production Block-----
$prod:xrs(j,r,s)$[shvxmd0(j,r,s)$(not xe(j))$sth(r)$nth(s)]        s:esubrd(j,r)        cm:esub(j)        i.tl(cm):0  va(cm):esubva(j)
o:pxs(j,r,s)        q:(shvx0(j,r)*shvxmd0(j,r,s)*vom(j,r))
+                a:govt(r)        t:rto(j,r)
i:pa(fe,r)        q:(shvx0(j,r)*shvxmd0(j,r,s)*vafm(fe,j,r))        p:(1+rtfa0(fe,j,r))        fe.tl:
+                a:govt(r)        t:rtfa(fe,j,r)
i:pa(i,r)$[not fe(i)]        q:(shvx0(j,r)*shvxmd0(j,r,s)*vafm(i,j,r))        p:(1+rtfa0(i,j,r))        cm:
+                a:govt(r)        t:rtfa(i,j,r)
i:pf(mf,r)        q:(shvx0(j,r)*shvxmd0(j,r,s)*vfm(mf,j,r))        p:(1+rtf0(mf,j,r))        va:
+                a:govt(r)        t:rtf(mf,j,r)
i:prsncarb(r,s)#(fe)                q:(shvx0(j,r)*shvxmd0(j,r,s)*dcb0(fe,j,r))        p:1e-6        fe.tl:
i:pr(j,r)$[not cg(j)]        q:(shvx0(j,r)*shvxmd0(j,r,s)*dk0(j,r))


$prod:xrs(j,r,s)$[shvxmd0(j,r,s)$xe(j)$sth(r)$nth(s)]        s:esubrd(j,r)    cm:esub(j)        i.tl(cm):0  va(cm):esubva(j)
```

```
o:pxs(j,r,s)        q:(shvx0(j,r)*shvxmd0(j,r,s)*vom(j,r))
+                a:govt(r)        t:rto(j,r)
i:pa(fe,r)        q:(shvx0(j,r)*shvxmd0(j,r,s)*vafm(fe,j,r))        p:(1+rtfa0(fe,j,r))        fe.tl:
+                a:govt(r)        t:rtfa(fe,j,r)
i:pa(i,r)$[not fe(i)]        q:(shvx0(j,r)*shvxmd0(j,r,s)*vafm(i,j,r))        p:(1+rtfa0(i,j,r))        cm:
+                a:govt(r)        t:rtfa(i,j,r)
i:pf(mf,r)$[not fl(mf,j)]        q:(shvx0(j,r)*shvxmd0(j,r,s)*vfm(mf,j,r))        p:(1+rtf0(mf,j,r))        va:
+                a:govt(r)        t:rtf(mf,j,r)
i:prsncarb(r,s)#(fe)                q:(shvx0(j,r)*shvxmd0(j,r,s)*dcb0(fe,j,r))        p:1e-6        fe.tl:
i:pr(j,r)        q:(shvx0(j,r)*shvxmd0(j,r,s)*dk0(j,r))
i:prs(j,r)        q:(shvx0(j,r)*shvxmd0(j,r,s)*vfm("cap",j,r))        p:(1+rtf0("cap",j,r))
+                a:govt(r)        t:rtf("cap",j,r)

*-----Aggregate X and D into Y-----
$prod:x(i,r)$[vx0(i,r)$sth(r)]        s:2
o:px(i,r)        q:(shvx0(i,r)*vom(i,r))
i:pxs(i,r,s) q:(shvx0(i,r)*shvxmd0(i,r,s)*vom(i,r))

$prod:y(i,r)$[vom(i,r)$sth(r)]        s:4
o:p(i,r)        q:vom(i,r)
i:pd(i,r)        q:(shvd0(i,r)*vom(i,r))
i:px(i,r)        q:(shvx0(i,r)*vom(i,r))

$prod:y(g,r)$[vom(g,r)$sth(r)$cgi(g)]
o:p(g,r)        q:vom(g,r)
i:pd(g,r)        q:vom(g,r)


*====================
$report:
v:drd(g,r)        i:pr(g,r)        prod:y(g,r)
*zzzzzzzzzzzzzzzzzzzzzzzzzzzzzz

*==========Armington Aggregation==========
$prod:a(i,r)$[a0(i,r)]        s:esubd(i)
o:pa(i,r)        q:a0(i,r)
i:p(i,r)        q:(sum(g, vdfm(i,g,r)))
i:pm(i,r)        q:(sum(g, vifm(i,g,r)))
*====================
```

```

*==========Effective Carbon Production=========
*NORTH
$prod:carbon(r)$[nth(r)]        s:esubc
o:prcarb(r)                        q:1
i:pcarb(r)$[carb0(r)]        q:1                p:1
i:p(cn,r)$[not carb0(r)]                q:(1e-6)
i:prc(r)$[rdc0(r)]        q:(rdcshr*rdc0(r))        p:1

*SOUTH - Domestic and South to South
$prod:sscarbon(r)$[sth(r)]
o:prsscarb(r)        q:1
i:p(cn,r)                q:1e-6

*SOUTH to NORTH
$prod:sncarbon(r,s)$[sth(r)$nth(s)] s:esubc
o:prsncarb(r,s)        q:1
i:psncarb(r,s)$[tars]        q:1                p:1
i:pcarb(r)$[carb0(r)$(not tars)]        q:1        p:1
i:p(cn,r)$[(not carb0(r))$(not tars)]        q:1e-6
i:prc(r)$[rdc0(r)$swrd]        q:(rdcshr*rdc0(r)) p:1

$report:
v:rptcrb(r)$nth(r)        i:pcarb(r)        prod:carbon(r)
v:rptscrb(r,s)                i:psncarb(r,s)        prod:sncarbon(r,s)
v:rptnprc(r)$nth(r)        i:prc(r)        prod:carbon(r)
v:rptsprc(r,s)                i:prc(r)        prod:sncarbon(r,s)

*====================

*==========R&D Production==========
*-----conventional-----
$prod:rd(i,r)$[rd0(i,r)$nth(r)]        s:esubrdd
o:pr(i,r)        q:rd0(i,r)
i:p(j,r)        q:(ird0(j,r)*rd0(i,r)/sum(k, rd0(k,r)))

$prod:rd(i,r)$[rd0(i,r)$sth(r)]        s:esubrdd
o:pr(i,r)        q:rd0(i,r)
i:p(j,r)        q:(ird0(j,r)*rd0(i,r)/sum(k, rd0(k,r)))
```

```
*-----carbon-saving-----
$prod:rdc(r)$[rdc0(r)$nth(r)]        s:esubrdc
o:prc(r)        q:(rdc0(r))
i:p(j,r)        q:(ird0(j,r)/sum(k, ird0(k,r))*rdc0(r))

$prod:rdc(r)$[rdc0(r)$sth(r)]        s:esubrdc
o:prc(r)        q:(rdc0(r))
*        i:p(j,r)        q:(ird0(j,r)/sum(k, ird0(k,r))*rdc0(r))
i:prc(r)        q:(rdc0(r))

$report:
v:rptprc(r)                o:prc(r)        prod:rdc(r)

*====================

*Transport Services
$prod:yt(j)$vtw(j)  s:1
o:pt(j)                q:vtw(j)
i:p(j,r)        q:vst(j,r)

*Imports
$prod:m(i,r)$vim(i,r)        s:esubm(i)  s.tl:0
o:pm(i,r)        q:vim(i,r)
i:p(i,s)        q:vxmd(i,s,r)        p:pvxmd(i,s,r) s.tl:
+                a:govt(s) t:(-rtxs(i,s,r))
+                a:govt(r) t:(rtms(i,s,r)*(1-rtxs(i,s,r)))
i:pt(j)#(s)        q:vtwr(j,i,s,r) p:pvtwr(i,s,r) s.tl:
+                a:govt(r) t:rtms(i,s,r)


*Demand
$demand:hh(r)
d:p("c",r)        q:vom("c",r)
e:p("c",r)        q:(-vtax(r))
e:p("i",r)        q:(-vom("i",r))
e:pf(f,r)        q:evom(f,r)
e:pcarb(r)$[carb0(r)]        q:carb0(r)        r:ctax(r)
```

```
e:prc(r)$[rdc0(r)]                q:1                        r:spillc(r)
e:pr(i,r)$[ks0(i,r) or rd0(i,r)]        q:1        r:spill(i,r)
e:prs(j,r)$[xe(j)]        q:vfm("cap",j,r)
*        e:psncarb$[tars]                q:carbim0(r)$[nth(r)]        r:tariff(r)$[nth(r)]
e:psncarb(s,r)$[sth(s)$nth(r)$tars]                q:carbim0(r,s)$[nth(r)$sth(s)]        r:tariff(r,s)$[nth(r)$sth(s)]
*        e:p("c",rnum)        q:vb(r)
*        e:p("g",r)        q:(-vom("g",r))
*        e:pf(f,r)        q:(sum(i, vfm(f,i,r)))

*Govt
$demand:govt(r)
d:p("g",r)        q:vom("g",r)
e:p("c",r)        q:vtax(r)
e:p("c",rnum)        q:vb(r)
*        e:p("c",r)        q:vktx(r)

*Carbon Tax
$constraint:ctax(r)$carb0(r)
pcarb(r) =e= ctax0(r);

*Conventional Spillovers
$constraint:spill(i,r)$(ks0(i,r) or rd0(i,r))
spill(i,r) =e= ks0(i,r) + 3*sum(nth, theta(i,nth,r)*(rd0(i,nth)*rd(i,nth) - rd0(i,nth)*1));

*Carbon-saving Spillovers
$constraint:spillc(r)$[rdc0(r)]
spillc(r) =e= (rdcshr*rdc0(r)*cb0(r)) + 3*sum(nth, sum(i, theta(i,nth,r))/card(i)*(rdcshr*rdc0(nth)*cb0(nth))*rdc(nth));

*Carbon-Tariff
$constraint:tariff(r,s)$[nth(r)$sth(s)$tars]
pcarb(r) =e= psncarb(s,r) ;

$offtext
$sysinclude mpsgeset itc

tars=%tarval%;

pcarb.l(r) = 1e-6;
prcarb.l(r)= 1e-6;
```

```
prsscarb.l(r) = 1e-6;
psncarb.l(r,s) = 1e-6;
prsncarb.l(r,s) = 1e-6;
carbon.l(r)$nth(r) = cb0(r);

*Start adjusting the benchmark parameters for spillovers and other stuff
sscarbon.l(r)$sth(r) = cb0(r)-carbex0(r);
sncarbon.l(r,s)$[sth(r)$nth(s)] = sum((fe,j), shvx0(j,r)*shvxmd0(j,r,s)*dcb0(fe,j,r));
*carbex0(r) = sum((fe,j), shvx0(j,r)*dcb0(fe,j,r));

*rdc0(sth) = 0.001;

prc.l(r) = 1e-6;
rdc.l(r) = 1e-6;
spillc.l(r) = (rdcshr*rdc0(r)*cb0(r));

rd.l(i,r) = 1;
rd.fx(i,sth) = 1;
spill.l(i,r) = ks0(i,r);

ctax.fx(r) = 1;
tariff.fx(r,s) = 1;

carb0(sth)=0;
*rdc0(sth)=0;

parameter        swrd        /no/;

itc.workspace = 128;
itc.iterlim = 0;
$include itc.gen
solve itc using mcp;

*display dk0, rd0, ks0, ird0;

display drd.l;
*$exit
* Load datafile from previous runs or defined the report parameters:

```

```
*$if exist runs_rd_main.dat $include runs_rd_main.dat

$if not defined carb_r PARAMETER carb_r;
$if not defined pcarb_r PARAMETER pcarb_r;
$if not defined rd_r PARAMETER rd_r;
$if not defined rdc_r PARAMETER rdc_r;
$if not defined spill_r PARAMETER spill_r;
$if not defined spillc_r PARAMETER spillc_r;
$if not defined c_r PARAMETER c_r;
$if not defined pc_r PARAMETER pc_r;
$if not defined m_r PARAMETER m_r;
$if not defined a_r PARAMETER a_r;
$if not defined y_r PARAMETER y_r;

$if not defined sflg_r PARAMETER sflg_r;

$if not defined pelas_r PARAMETER pelas_r;
$if not defined pelasc_r PARAMETER pelasc_r;
$if not defined esupxe_r PARAMETER esupxe_r;
$if not defined esubd_r PARAMETER esubd_r;
$if not defined esubm_r PARAMETER esubm_r;
$if not defined esubrdd_r PARAMETER esubrdd_r;
$if not defined esubrdc_r PARAMETER esubrdc_r;
$if not defined esubc_r PARAMETER esubc_r;
$if not defined rdexp0_r PARAMETER rdexp0_r;
$if not defined rdcshr_r PARAMETER rdcshr_r;
$if not defined theta_r PARAMETER theta_r;
$if not defined theta_irs PARAMETER theta_irs;
$if not defined prcarb_r PARAMETER prcarb_r;
$if not defined pr_r PARAMETER pr_r;
$if not defined prc_r PARAMETER prc_r;

$if not defined d_r PARAMETER d_r;
$if not defined x_r PARAMETER x_r;
$if not defined xrs_r PARAMETER xrs_r;
$if not defined prsncarb_r PARAMETER prsncarb_r;
$if not defined prsscarb_r PARAMETER prsscarb_r;
$if not defined psncarb_r PARAMETER psncarb_r;

```

```
* Now model the effect of imposing a carbon restriction in North:
carb0(nth) = %carblimval% * cb0(nth);
*ctax0(nth) = %ctaxval%;
*ctax0(sth) = 0;
*CTAX.lo(nth) = 0; CTAX.up(nth) = +inf; CTAX.l(nth) = 1;


*pcarb.l(nth) = ctax0(nth);

* At first, set spillover parameters to zero to model the "PE" effect
* of the carbon restriction:

*theta(r) = 0;
theta(i,r,s) = 0;

* We also want to model the equilibrium reduction without the possibility of R&D:
RD.fx(i,r) = 1;
RDC.fx(r) = 0;
*rdc0(r) = 0;
*RD.fx(i,r) = RD.l(i,r);
*RDC.fx(r) = RDC.l(r);

itc.iterlim = 100000;

$include itc.gen
solve itc using mcp;

*$exit

tariff.lo(r,s) = 0; tariff.up(r,s)=+inf; tariff.l(r,s) = 1;

$include itc.gen
solve itc using mcp;

*$exit

carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",nth) = rptcrb.l(nth);

carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",sth) =
```

```
sum(nth, rptscrb.l(sth,nth)$[tars] + sncarbon.l(sth,nth)$[not tars]) + sscarbon.l(sth);
pcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",r) = pcarb.l(r);
prcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",nth) = prcarb.l(nth);
prsncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",sth,nth) =
prsncarb.l(sth,nth);
prsscarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",sth) = prsscarb.l(sth);
psncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",sth,nth) =
psncarb.l(sth,nth);
pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,nth) = pr.l(i,nth);
prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",nth) = prc.l(nth);
pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,sth) = pr.l(i,sth);
prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",sth) = prc.l(sth);

rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,nth) = rd.l(i,nth);
rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",nth) = rdc.l(nth);

spill_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,r) = spill.l(i,r);
spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",nth) = spillc.l(nth);
spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",sth) = spillc.l(sth);
c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",r) = y.l("c",r);
pc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",r) = p.l("c",r);
m_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,r) = m.l(i,r);
a_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,r) = a.l(i,r);
y_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,r) = y.l(i,r);
x_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,sth) = x.l(i,sth);
xrs_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,sth,nth) = xrs.l(i,sth,nth);
d_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD",i,sth) = d.l(i,sth);

sflg_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORD") = itc.modelstat;

*display ctar, csub, prcarb.l, p.l, cc;

* Now allow for R&D:
RD.lo(i,nth) = 0; RD.up(i,nth) = +inf;
RDC.lo(nth) = 0; RDC.up(nth) = +inf;
*rdc0(r)=1;
*RD.lo(i,sth) = 0; RD.up(i,sth) = +inf;
*RDC.lo(sth) = 0; RDC.up(sth) = +inf;
swrd=yes;
```

```

$include itc.gen
solve itc using mcp;
*$exit
*display spill.l, rd.l, drd.l;
*display ctar, csub, prcarb.l, p.l, cc;

carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",nth) = rptcrb.l(nth);
carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",sth) =
sum(nth, rptscrb.l(sth,nth)$[tars] + sncarbon.l(sth,nth)$[not tars]) + sscarbon.l(sth);
pcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",r) = pcarb.l(r);
prcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",nth) = prcarb.l(nth);
prsncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",sth,nth) =
prsncarb.l(sth,nth);
prsscarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",sth) = prsscarb.l(sth);
psncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",sth,nth) =
psncarb.l(sth,nth);
pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,nth) = pr.l(i,nth);
prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",nth) = prc.l(nth);
pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,sth) = pr.l(i,sth);
prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",sth) = prc.l(sth);

rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,nth) = rd.l(i,nth);
rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",nth) = rdc.l(nth);

spill_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,r) = spill.l(i,r);
spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",nth) = spillc.l(nth);
spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",sth) = spillc.l(sth);
c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",r) = y.l("c",r);
pc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",r) = p.l("c",r);
m_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,r) = m.l(i,r);
a_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,r) = a.l(i,r);
y_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,r) = y.l(i,r);
x_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,sth) = x.l(i,sth);
xrs_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,sth,nth) = xrs.l(i,sth,nth);
d_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL",i,sth) = d.l(i,sth);
sflg_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","0SPL") = itc.modelstat;


```

```
* Now Model spillovers

*populate theta
theta(i,r,s) = theta0(i,r,s);

*===== other scenarios =====
*NSPL
*No Southern Spill - Northern only
theta(i,nth,sth)=0;

$include itc.gen
solve itc using mcp;

*display spill.l, rd.l, drd.l, rd0, ks0;
*display ctar, csub, prcarb.l, p.l, cc;

carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",nth) = rptcrb.l(nth);
carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",sth) =
sum(nth, rptscrb.l(sth,nth)$[tars] + sncarbon.l(sth,nth)$[not tars]) + sscarbon.l(sth);
pcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",r) = pcarb.l(r);
prcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",nth) = prcarb.l(nth);
prsncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",sth,nth) =
prsncarb.l(sth,nth);
prsscarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",sth) = prsscarb.l(sth);
psncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",sth,nth) =
psncarb.l(sth,nth);
pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,nth) = pr.l(i,nth);
prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",nth) = prc.l(nth);
pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,sth) = pr.l(i,sth);
prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",sth) = prc.l(sth);

rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,nth) = rd.l(i,nth);
rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",nth) = rdc.l(nth);

spill_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,r) = spill.l(i,r);
spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",nth) = spillc.l(nth);
spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",sth) = spillc.l(sth);
c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",r) = y.l("c",r);
pc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",r) = p.l("c",r);
```

```
m_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,r) = m.l(i,r);
a_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,r) = a.l(i,r);
y_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,r) = y.l(i,r);
x_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,sth) = x.l(i,sth);
xrs_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,sth,nth) = xrs.l(i,sth,nth);
d_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL",i,sth) = d.l(i,sth);
sflg_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NSPL") = itc.modelstat;


*SSPL
*Northern and Southern Spill
PARAMETER   thta_shft(i);
*thta_shft(i) = 1;
thta_shft(i) = %thtashftval%;
theta(i,r,s) = theta0(i,r,s);
theta(i,nth,sth) = theta0(i,nth,sth)*%thtashftval%;
*theta(’coa’,nth,’chn’) = theta0(’coa’,nth,’chn’);


$include itc.gen
solve itc using mcp;

*display spill.l, rd.l, drd.l, rd0, ks0;
*display ctar, csub, prcarb.l, p.l, cc;

carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",nth) = rptcrb.l(nth);
carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",sth) =
sum(nth, rptscrb.l(sth,nth)$[tars] + sncarbon.l(sth,nth)$[not tars]) + sscarbon.l(sth);
pcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",r) = pcarb.l(r);
prcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",nth) = prcarb.l(nth);
prsncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",sth,nth) =
prsncarb.l(sth,nth);
prsscarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",sth) = prsscarb.l(sth);
psncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",sth,nth) =
psncarb.l(sth,nth);
pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,nth) = pr.l(i,nth);
prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",nth) = prc.l(nth);
pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,sth) = pr.l(i,sth);
prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",sth) = prc.l(sth);
```

```

rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,nth) = rd.l(i,nth);
rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",nth) = rdc.l(nth);

spill_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,r) = spill.l(i,r);
spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",nth) = spillc.l(nth);
spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",sth) = spillc.l(sth);
c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",r) = y.l("c",r);
pc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",r) = p.l("c",r);
m_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,r) = m.l(i,r);
a_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,r) = a.l(i,r);
y_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,r) = y.l(i,r);
x_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,sth) = x.l(i,sth);
xrs_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,sth,nth) = xrs.l(i,sth,nth);
d_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL",i,sth) = d.l(i,sth);
sflg_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","SSPL") = itc.modelstat;


*Theta Sensitivity test - can increasing southern absorption cause an increase in leakage due to spillovers
*Shift southern spill (increase/decrease)
*PARAMETER   thta_shft(i);
*thta_shft(i) = 1;
*thta_shft(i) = %thtashftval%;
*theta(i,nth,sth)=theta0(i,nth,sth)*theta_shft(i);


*$include itc.gen
*solve itc using mcp;

*display spill.l, rd.l, drd.l, rd0, ks0;
*display ctar, csub, prcarb.l, p.l, cc;

*carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",nth) = rptcrb.l(nth);
*carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",sth) =
*        sum(nth, rptscrb.l(sth,nth)$[tars] + sncarbon.l(sth,nth)$[not tars]) + sscarbon.l(sth);
*pcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",r) = pcarb.l(r);
*prcarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",nth) = prcarb.l(nth);
*prsncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",sth,nth) = prsncarb.l(sth,r
*prsscarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",sth) = prsscarb.l(sth);
```

```
*psncarb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",sth,nth) = psncarb.l(sth,nth
*pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,nth) = pr.l(i,nth);
*prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",nth) = prc.l(nth);
*pr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,sth) = pr.l(i,sth);
*prc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",sth) = prc.l(sth);
*
*rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,nth) = rd.l(i,nth);
*rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",nth) = rdc.l(nth);
*
*spill_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,r) = spill.l(i,r);
*spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",nth) = spillc.l(nth);
*spillc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",sth) = spillc.l(sth);
*c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",r) = y.l("c",r);
*pc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",r) = p.l("c",r);
*m_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,r) = m.l(i,r);
*a_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,r) = a.l(i,r);
*y_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,r) = y.l(i,r);
*x_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,sth) = x.l(i,sth);
*xrs_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,sth,nth) = xrs.l(i,sth,nth);
*d_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA",i,sth) = d.l(i,sth);
*sflg_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","THTA") = itc.modelstat;
*==========


PARAMETER gblcrb, tblcrb, tblcrbpct;
SET          scn        /NORD,0SPL,NSPL,SSPL/;

gblcrb(r,"BMK") = cb0(r);
gblcrb("Total","BMK") = sum(r, cb0(r));
gblcrb(r,scn) =
(carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r) - cb0(r))
/cb0(r)*100;
gblcrb("Total",scn) =
(sum(r, carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
- sum(r, cb0(r)))
/sum(r, cb0(r))*100;
gblcrb("South",scn) =
(sum(r$sth(r), carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
- sum(r$sth(r), cb0(r)))
```

```
/sum(r$sth(r), cb0(r))*100;
gblcrb("North",scn) =
(sum(r$nth(r), carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
- sum(r$nth(r), cb0(r)))
/sum(r$nth(r), cb0(r))*100;
gblcrb("Leakage",scn) =
(sum(sth, carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth))
- sum(sth, cb0(sth)))
/sum(nth, cb0(nth) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth));

tblcrb("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,"BMK") = cb0(r);
tblcrb("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","Total","BMK") = sum(r, cb0(r));
tblcrb("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,scn) =
(carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r));
tblcrb("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","Total",scn) =
(sum(r, carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r)));
tblcrb("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","South",scn) =
(sum(r$sth(r), carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r)));
tblcrb("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","North",scn) =
(sum(r$nth(r), carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r)));
tblcrb("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","Leakage",scn) =
(sum(sth, carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth)) - sum(sth, cb0(sth)
/sum(nth, cb0(nth) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth));

tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,"BMK") = cb0(r);
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","Total","BMK") = sum(r, cb0(r));
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,scn) =
(carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r) - cb0(r))
/cb0(r)*100;
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","Total",scn) =
(sum(r, carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
- sum(r, cb0(r)))
/sum(r, cb0(r))*100;
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","South",scn) =
(sum(r$sth(r), carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
- sum(r$sth(r), cb0(r)))
/sum(r$sth(r), cb0(r))*100;
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","North",scn) =
(sum(r$nth(r), carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
```

```
- sum(r$nth(r), cb0(r)))
/sum(r$nth(r), cb0(r))*100;
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","Leakage",scn) =
(sum(sth, carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth))
- sum(sth, cb0(sth)))
/sum(nth, cb0(nth) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth));



display  carb_r, gblcrb;

*Add in r&d reporting

parameter gblrd, tblrd, tblrdpct, rdtot;
gblrd(r,i,"BMK") = rd0(i,r);
gblrd(r,i,scn) = rd0(i,r)*rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,r);
gblrd(r,"Carbon",scn) = rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r);

rdtot(nth,scn) = sum(i, gblrd(nth,i,scn)) + gblrd(nth,"Carbon",scn);
rdtot("North",scn) = sum((i,nth), gblrd(nth,i,scn)) + sum(nth, gblrd(nth,"Carbon",scn));
*rdtot("South",scn) = sum((i,sth), gblrd(sth,i,scn)) + sum(sth, gblrd(sth,"Carbon",scn));
rdtot("Total",scn) = sum((i,nth), gblrd(nth,i,scn)) + sum(nth, gblrd(nth,"Carbon",scn));
rdtot(nth,"BMK") = sum(i, gblrd(nth,i,"BMK"));
rdtot("North","BMK") = sum((nth,i), gblrd(nth,i,"BMK"));
*rdtot("South","BMK") = sum((sth,i), gblrd(sth,i,"BMK"));
rdtot("Total","BMK") = sum((nth,i), gblrd(nth,i,"BMK"));

tblrd("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,i,"BMK") = rd0(i,r);
tblrd("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,i,scn) =
rd0(i,r)*rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,r);
tblrd("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,"Carbon",scn) =
rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r);
tblrd("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORTH",i,scn) =
sum(r$[nth(r)], rd0(i,r)*rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,r));
tblrd("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORTH","Carbon",scn) =
sum(r$[nth(r)], rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r));


tblrdpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",nth,i,scn)$[rd0(i,nth)] =
```

```
(rd0(i,nth)*rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,nth) - rd0(i,nth))
/ rd0(i,nth) * 100;
tblrdpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",nth,"Carbon",scn) =
rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth);
tblrdpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORTH",i,scn) =
sum(nth, (rd0(i,nth)*rd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,nth)
- rd0(i,nth)))
/ sum(nth,rd0(i,nth)) * 100;
tblrdpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORTH","Carbon",scn) =
sum(nth, rdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth));

display gblrd, tblrd;

* Activity level reporting
parameter yreg, xreg, creg, dreg, xrsreg;

yreg(scn,i,"North") =
sum(nth, y_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,nth)*vom(i,nth))
/sum(nth, vom(i,nth));
yreg(scn,i,"South") =
sum(sth, y_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,sth)*vom(i,sth))
/sum(sth, vom(i,sth));
yreg(scn,i,"Total") =
sum(r, y_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,r)*vom(i,r))
/sum(r, vom(i,r));

xreg(scn,i,"South") =
sum(sth, x_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,sth)*vx0(i,sth))
/sum(sth, vx0(i,sth));

xrsreg(scn,i,"South",nth) =
sum(sth, xrs_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,sth,nth)
*(shvx0(i,sth)*shvxmd0(i,sth,nth)*vom(i,sth)))
/sum(sth, (shvx0(i,sth)*shvxmd0(i,sth,nth)*vom(i,sth)));

dreg(scn,i,"South-South") =
sum(sth, d_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,i,sth)*(shvd0(i,sth)
*vom(i,sth)))
/sum(sth, (shvd0(i,sth)*vom(i,sth)));
```

```

creg(scn,"North") =
sum(nth, c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth)*vom("c",nth))
/ sum(nth, vom("c",nth));
creg(scn,"South") =
sum(sth, c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth)*vom("c",sth))
/ sum(sth, vom("c",sth));
creg(scn,"World") =
sum(r, c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r)*vom("c",r))
/ sum(r, vom("c",r));
creg(scn,"WorldRAWBMK") =  sum(r,vom("c",r));


parameter ac_dam_raw                "abatement cost plus co2 avoided damages";
parameter ac_dam_ind                "abatement cost plus co2 avoided damages index";
parameter ac_raw                        "abatement cost";
parameter dam_raw                        "avoided damages";
parameter ssc_imp                        "implied social cost of carbon assuming abatement at pigouvian level";


scalar        co2dam        "social cost of carbon $/mtco2"        /50/;
*convert to billion $/gigaton co2
*co2dam = 50*1e3/1e9;
parameter test        "1% change in from benchmark welfare";
test = sum(r, cb0(r)*co2dam + vom("c",r))*0.01;

ac_dam_raw("%sd%",scn,r) =
(cb0(r) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))*co2dam
+ (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r)-1)*vom("c",r)
;


ac_dam_raw("%sd%",scn,"South") =
(sum(sth, cb0(sth) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth))
*co2dam)
+ sum(sth, (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth)-1)
*vom("c",sth))
;

```

```
ac_dam_raw("%sd%",scn,"North") =
(sum(nth, cb0(nth) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth))
*co2dam)
+ sum(nth, (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth)-1)
*vom("c",nth))
;

ac_dam_raw("%sd%",scn,"Total") =
(sum(r, cb0(r) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
*co2dam)
+ sum(r, (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r)-1)
*vom("c",r))
;





ac_dam_ind("%sd%",scn,"South") =
[(sum(sth, cb0(sth) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth))
*co2dam)
+ sum(sth, (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth)-1)
*vom("c",sth))
] / sum(sth, cb0(sth)*co2dam + vom("c",sth))
;

ac_dam_ind("%sd%",scn,"North") =
[(sum(nth, cb0(nth) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth))
*co2dam)
+ sum(nth, (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth)-1)
*vom("c",nth))
] / sum(nth, cb0(nth)*co2dam + vom("c",nth))
;

ac_dam_ind("%sd%",scn,"Total") =
[(sum(r, cb0(r) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
*co2dam)
+ sum(r, (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r)-1)
*vom("c",r))
```

```
] / sum(r, cb0(r)*co2dam + vom("c",r))
;


dam_raw("%sd%",scn,r) =
(cb0(r) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
*co2dam;

ac_raw("%sd%",scn,r) =
(c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r)-1)
*vom("c",r);

dam_raw("%sd%",scn,"South") =
(sum(sth, cb0(sth) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth))
*co2dam);


ac_raw("%sd%",scn,"South") =
sum(sth, (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,sth)-1)
*vom("c",sth));

dam_raw("%sd%",scn,"North") =
(sum(nth, cb0(nth) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth))*co2dam);
ac_raw("%sd%",scn,"North")        =
sum(nth, (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,nth)-1)*vom("c",nth));

dam_raw("%sd%",scn,"Total") =
(sum(r, cb0(r) - carb_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",scn,r))
*co2dam);
ac_raw("%sd%",scn,"Total") =
sum(r, (c_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",
scn,r)-1)
*vom("c",r));



* Save model parameters:

esubd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",i) = esubd(i);
```

```
esubm_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",i) = esubm(i);
esubrdd_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%") = esubrdd;
esubrdc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%") = esubrdc;
rdcshr_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%") = rdcshr;
rdexp0_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",i) = rshft(i);
pelas_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",i) = pelas_rd(i);
pelasc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%") = pelas_rdc;
esupxe_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",i) = esup_xe(i);
esubc_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%") = esubc;
theta_r("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",i) = thta_shft(i);
theta_irs("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",i,r,s) = theta(i,r,s);

* Save model results for this run:

execute_unload "output/runs_rd_ctar_lim_%sd%.gdx",
carb_r
pcarb_r
rd_r
rdc_r
spill_r
spillc_r
c_r
pc_r
m_r
a_r
y_r
sflg_r
pelas_r
pelasc_r
esupxe_r
esubd_r
esubm_r
esubrdd_r
esubrdc_r
esubc_r
rdexp0_r
theta_r
theta_irs
prcarb_r
```

```
pr_r
prc_r
d_r
x_r
xrs_r
prsncarb_r
prsscarb_r
psncarb_r
gblcrb
gblrd
tblcrb
tblcrbpct
tblrd
tblrdpct
gamma
theta0
yreg
xreg
xrsreg
creg
dreg
ccy
cc
ac_dam_raw
ac_dam_ind
ac_raw
dam_raw
test
rdtot
rdexp0
ird0
rd0
dk0
ks0
esub
;


parameters
```

```
rep_crb                "Percentage change in co2 emissions"
rep_rd                "Percentage change in RD"
rep_leak
deci
rep_ac_dam        "Abatement costs plus avoided damages (Billion USD)"
rep_ac                "Abatement costs (Billion USD)"
rep_dam                "Avoided Damages (Billion USD)"
rep_ac_dam_in        "Abatement costs plus avoided damages change from bmk index"
rep_ac_in                "Abatement costs change from bmk index"
*        rep_dam_in                "Avoided damages change from bmk index"
;

deci(scn)=3;
deci("BMK") = 3;
deci(i) = 3;
deci("Carbon") = 3;

rep_crb(r,scn) =
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,scn);
rep_crb("North",scn) =
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","North",scn);
rep_crb("South",scn) =
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","South",scn);
rep_crb("Total",scn) =
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","Total",scn);
rep_crb(r,"BMK") =
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,"BMK");
rep_crb("North","BMK") =
sum(r$nth(r), tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,"BMK"));
rep_crb("South","BMK") =
sum(r$sth(r), tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%",r,"BMK"));
rep_crb("Total","BMK") =
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","Total","BMK");
rep_crb("Leakage",scn) =
tblcrbpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","Leakage",scn);

rep_rd(scn,i) =
tblrdpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORTH",i,scn);
rep_rd(scn,"Carbon") =
```

```
tblrdpct("%sd%","%pelascval%","%esubdshft%","%carblimval%","%tarval%","%pelasrdval%","%thtashftval%","NORTH","Carbon",scn);


rep_ac_dam(r,scn) = ac_dam_raw("%sd%",scn,r);
rep_ac_dam("North",scn) = ac_dam_raw("%sd%",scn,"North");
rep_ac_dam("South",scn) = ac_dam_raw("%sd%",scn,"South");
rep_ac_dam("Total",scn) = ac_dam_raw("%sd%",scn,"Total");

rep_ac(r,scn) = ac_raw("%sd%",scn,r);
rep_ac("North",scn) = ac_raw("%sd%",scn,"North");
rep_ac("South",scn) = ac_raw("%sd%",scn,"South");
rep_ac("Total",scn) = ac_raw("%sd%",scn,"Total");

rep_dam(r,scn) = dam_raw("%sd%",scn,r);
rep_dam("North",scn) = dam_raw("%sd%",scn,"North");
rep_dam("South",scn) = dam_raw("%sd%",scn,"South");
rep_dam("Total",scn) = dam_raw("%sd%",scn,"Total");

rep_ac_dam_in(r,scn) = 100*ac_dam_raw("%sd%",scn,r)/(cb0(r)*co2dam + vom("c",r));
rep_ac_dam_in("North",scn) = ac_dam_ind("%sd%",scn,"North")*100;
rep_ac_dam_in("South",scn) = ac_dam_ind("%sd%",scn,"South")*100;
rep_ac_dam_in("Total",scn) = ac_dam_ind("%sd%",scn,"Total")*100;

rep_ac_in(r,scn) = 100*ac_raw("%sd%",scn,r)/vom("c",r);
rep_ac_in("North",scn) = 100*ac_raw("%sd%",scn,"North")/sum(nth,vom("c",nth));
rep_ac_in("South",scn) = 100*ac_raw("%sd%",scn,"South")/sum(sth,vom("c",sth));
rep_ac_in("Total",scn) = 100*ac_raw("%sd%",scn,"Total")/sum(r,vom("c",r));
*
*rep_dam(r,scn) = dam_raw("%sd%",scn,r);
*rep_dam("North",scn) = dam_raw("%sd%",scn,"North");
*rep_dam("South",scn) = dam_raw("%sd%",scn,"South");
*rep_dam("Total",scn) = dam_raw("%sd%",scn,"Total");



*loop(scn,
*        rep_rd("North",i,scn);
*        rep_rd("North","Carbon",scn);
*
```

```
*$libinclude gams2tbl tbl_rd
*);

parameter cc_out        "Carbon content in lbs CO2/USD";
cc_out(r,i) = ccy(i,r)*2000;

FILE out        /"output/%sd%_crb_and_rd_tbls.tex"/;

$setglobal format tex
$setglobal c_decimals deci

put out;

$libinclude gams2tbl rep_crb
$libinclude gams2tbl rep_rd
$libinclude gams2tbl gamma
$libinclude gams2tbl cc_out

putclose out;

FILE outwelf        /"output/%sd%_welfare_tbls.tex"/;

$setglobal format tex
$setglobal c_decimals deci

put outwelf;

$libinclude gams2tbl rep_ac_dam
$libinclude gams2tbl rep_ac
$libinclude gams2tbl rep_dam
$libinclude gams2tbl rep_ac_dam_in
$libinclude gams2tbl rep_ac_in
putclose outwelf;

parameter testing;
testing("outshr") = sum((i,r), dk0(i,r)) / sum((i,r), vom(i,r));
testing("evomshr") = sum((i,r), dk0(i,r)) / sum((f,g,r), vfm(f,g,r));
testing("consshr") = sum((i,r), dk0(i,r)) / sum((r), vom("c",r));
display testing;
```

```
$ontext
FILE out /runs_rd_main.dat/;

put out;

$libinclude gams2prm carb_r
$libinclude gams2prm pcarb_r
$libinclude gams2prm rd_r
$libinclude gams2prm rdc_r
$libinclude gams2prm spill_r
$libinclude gams2prm spillc_r
$libinclude gams2prm c_r
$libinclude gams2prm pc_r
$libinclude gams2prm m_r
$libinclude gams2prm a_r
$libinclude gams2prm y_r

$libinclude gams2prm sflg_r

$libinclude gams2prm pelas_r
$libinclude gams2prm pelasc_r
$libinclude gams2prm esupxe_r
$libinclude gams2prm esubd_r
$libinclude gams2prm esubm_r
$libinclude gams2prm esubrdd_r
$libinclude gams2prm esubrdc_r
$libinclude gams2prm esubc_r
$libinclude gams2prm rdexp0_r
$libinclude gams2prm theta_r

putclose out;
$offtext
$exit
```