Marginal Emissions from Expansions in Clean Technology are Non-constant and Policy Dependent—Implications for Mitigation Pledges

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Under the Paris Agreement, many countries have committed to reduce greenhouse gas emissions by expanding clean technologies. Emissions reductions from such efforts depend on how markets respond to the expansion in clean technologies. As a result, the ability to make credible mitigation pledges using policies that promote clean technologies depends on the path of marginal emissions and uncertainty in marginal emissions given these market adjustments. We present a conceptual framework that decomposes marginal emissions from a clean technology policy into substitution and output effects. While both effects depend upon clean technology in the economy, only the output effect differs across the two common clean technology policies: a mandate and a subsidy. Using an integrated economic and emissions model, we find that marginal emissions from promoting biofuels in the U.S. are non-constant in the amount of biofuel added and move in opposite directions for the two policies, due to divergent output effects. Uncertainty in marginal emissions tends to increase in the amount of biofuel, but at differing rates for the two policies. Our analysis provides initial guidance on additional capacities that could enhance the ability for the Paris Agreement to achieve greater future global mitigation should countries continue to rely on clean technology policies.

Keywords: greenhouse gas emissions; climate policy; renewable and energy efficiency technology policies; Paris Agreement

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1 Introduction

In the absence of a comprehensive global policy to reduce greenhouse gas (GHG) emissions, policies that encourage the expansion of perceived clean technologies at the expense of dirty alternatives have become central to mitigation efforts. Of the 162 intended Nationally Determined Contributions (NDCs) submitted on behalf of the Paris Agreement, 87% proposed increasing the adoption of clean technologies such as renewables or more energy efficient practices and goods. The selection and evaluation of policies to promote such technologies requires accurate assessments of both the marginal emissions and uncertainty in marginal emissions that result from increasing their adoption.

Clean technologies only indirectly reduce emissions by displacing dirty alternatives. Therefore, the emissions reductions achieved by policies promoting clean technologies depend on the response of markets linked to the production and use of the clean technology as well as the dirty alternatives. Due to these market responses, expansions of a clean technology may lead to different emissions implications depending upon the amount of clean technology present in the economy and the policy instrument driving the expansion in clean technology.

In this paper we explore how marginal emissions and uncertainty in marginal emissions due to a clean technology policy vary with the amount of clean technology added. This information is essential for policymakers relying on clean technology policies for mitigation, as many are under the Paris Agreement. If marginal emissions are non-constant, total emissions savings achieved by a clean technology policy should be calculated by integrating under the marginal emissions curve. Understanding uncertainty in the path of marginal emissions is also important as it provides policymakers with the ability to assess the likelihood with which they can expect to achieve emissions reductions. Moreover, this information will be helpful for the international community to assess the expected impacts of cumulative mitigation pledges relying on clean technology policies in advance of future quinquennial "global stocktakes" (UNFCCC 2015).

Using a simple conceptual framework, we illustrate that marginal emissions resulting from a clean technology policy can be decomposed into substitution and output effects. The substitution effect depends only on the marginal emissions of the clean and dirty technologies and is the same for any policy. It reflects emissions from changes in the demand for clean and dirty technologies and input markets linked to their production. The output effect is the change in emissions that results if a policy alters prices in output markets and thus the rate at which the dirty technology is displaced. The output effect differs by policy. Both effects depend on economic conditions in affected markets, such as the market shares of the inputs used in the production of the clean or dirty technologies, and therefore will vary as markets adjust to accommodate more of the clean technology. With this framework we analyze two policies—a mandate and a subsidy—that are commonly used to promote clean technologies.[1]

Using a numerical economic model that is linked to a detailed emissions model, we evaluate the marginal emissions that result from using these two instruments to promote ethanol in the United States. We find that marginal emissions due to a clean technology policy are non-constant in the amount of ethanol added. Moreover, marginal emissions from the two policies move in opposite directions corresponding to the different ways that the policies alter output prices. For the same reason, uncertainty in marginal emissions also varies considerably with the amount of ethanol added. We conclude by discussing the implications of our framework and analysis for clean technology policies in the electricity sector, and suggest capacities that could enhance the use of clean technology policies under the Paris Agreement.

Although a number of studies have analyzed the emissions implications of various clean technologies, our paper is the first to trace out how marginal emissions change as a result of a policy driven expansion in clean technology given both substitution and output effects. Previous studies have relied on three broad approaches. The first approach uses economic models to evaluate the impact of clean technology policies on emissions, or an outcome that may drive emissions for a particular clean technology (e.g. Fischer (2010), and Chan and Gillingham (2015)). Simple analytical models (Fischer and Newell 2008; Holland, Hughes, and Knittel 2009) have been developed to identify key parameters that alter the marginal impacts of clean technology policies. More detailed numerical models, for example Fell and Linn (2013) or Bento, Klotz, and Landry (2015), have been used to assess emissions impacts from non-marginal policy changes. We also rely on an economic model, but unlike these studies we trace out how marginal emissions, and uncertainty in marginal emissions, change as each policy adds more clean technology to the economy.

The second approach uses lifecycle analysis (LCA) methods to evaluate the impact on

[1] The International Energy Agency maintains a comprehensive database of clean technology policies implemented by country (http://www.iea.org/policiesandmeasures/).

emissions associated with a clean technology, and possibly an assumed displacement of a dirty technology, through a bottom-up accounting of emissions across all phases of the technologies' production and use (e.g. Farrell et al. (2006), Lemoine et al. (2010) and Hertwich et al. (2015)). Bento and Klotz (2014) previously noted that standard, technology-based LCA methods are inappropriate for policy evaluation because these methods do not account for the policy driving the change in the clean technology and, at best, only capture the substitution effect. This paper presents another important limitation of technology-based LCA methods by showing that marginal emissions and uncertainty in marginal emissions from expansions in a clean technology can be non-constant.

The third approach uses econometric methods to show that the emissions response to expansions in various forms of renewable electricity generation or changes in electricity demand (e.g. energy efficiency programs or electric cars) exhibit heterogeneity across space and time (see, for example, Graff Zivin, Kotchen, and Mansur (2014) and Novan (2015)). These findings are in large part attributable to heterogeneity in the composition of marginal generation and demand profiles, which reflect the economic conditions of a particular electricity market. However, by estimating the average marginal emissions impacts of changes in supply or demand conditional on observed economic conditions, these studies isolate only the substitution effect at a particular level of clean technology. Unlike our analysis, the emissions estimates from these studies do not account for the output effect and, with the exception of Novan (2015), do not show how the substitution effect changes with the amount of clean technology added.

2 Conceptual Framework

In Figure 1 we present a conceptual framework that can be used to assess the change in emissions from a marginal expansion in a clean technology as a result of any clean technology policy. The dark gray rectangles represent sectors of the economy that will potentially be affected by the policy. The flow of energy and materials between sectors are indicated by the black arrows. The production of clean and dirty technologies are the rectangles denoted C and D. Each technology is itself directly produced from a variety of inputs (rectangles $C_1,\ldots,C_M$ and $D_1,\ldots,D_N$ linked by solid black arrows) and may indirectly affect markets for products that are not directly used as inputs (rectangles C^I and D^I linked by dashed black arrows).[2] Collectively, we refer to these as *input markets.* Clean and dirty technologies are combined to produce a composite consumption good (e.g. electricity or blends of gasoline and ethanol). We focus on clean technology policies (oval) that directly encourage greater use of the clean technology, and therefore refer to this as the *regulated market* (rectangle R).[3] The composite good is used in an *output market* (rectangle F), either as a final consumption good or as an input to other production processes. Emissions are potentially generated by each sector through production processes and/or the use of inputs.

In response to a policy, the quantity of clean technology in the economy increases, which causes sectors to adjust and the total level of emissions to change. The marginal change in emissions across all sectors per unit of clean technology added by the policy is the sum of the *substitution effect* and the *output effect*.

The *substitution effect*, depicted with the white arrows and boxes, is the change in emissions from replacing one unit of dirty technology with one unit of the clean technology. This can be measured as the difference between the marginal emissions of the clean and dirty technologies, where the marginal emissions of each technology reflects all changes in emissions from associated input markets.[4]

The *output effect*, depicted with the hatched arrows and boxes, captures the change in emissions attributable to adjustments in regulated and output markets that occur as a result of the policy. A clean technology policy will alter the prices of the clean and dirty technologies and, in turn, the prices of the composite good and output markets that use the composite good. Conditional on the marginal increase in the clean technology, these price changes will induce quantity changes in output, regulated, and dirty technology markets as well as the inputs linked to these markets. The output effect captures any emissions associated with these quantity changes, and can reinforce or erode the change in emissions attributable to the substitution effect.

If the production and use of clean and dirty technologies are the main sources of

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[2] A high profile example of an indirect link is the global transition of land to agricultural production in response to expansions in biofuel production (Searchinger et al. 2008).
[3] This is consistent with many current and proposed clean technology policies, such as biofuel mandates and subsidies or renewable portfolio standards. The sector on which the policy falls is typically not consequential in competitive market settings.
[4] Marginal emissions of the two technologies can be thought of as consequential LCA measures (Earles and Halog 2011).

emissions, then the output effect is inversely related to the rate at which the clean technology displaces the dirty technology, or the *displacement ratio*. If the price of the composite good does not change in response to the policy, the displacement ratio will be one and the output effect will be zero. A displacement ratio above (below) one implies more (less) emissions reductions from additional changes in the dirty technology than the one-for-one displacement reflected by the substitution effect and therefore a negative (positive) output effect.

We obtain three important insights when applying this framework to evaluate a clean technology mandate and subsidy.[5] First, the substitution effect is the same for either policy if implemented from the same economic baseline. This is because marginal emissions of the clean and dirty technologies are determined solely by conditions in input markets, such as the prices of inputs, the share of an input used in the production of a particular technology, or the emissions rates of the inputs. The substitution effect need not be constant in the amount of clean technology added as each additional unit of the clean technology alters economic conditions in input markets and thus marginal emissions of the clean and dirty technologies.

Second, the output effect differs across the two policies. By increasing demand for the clean technology at the expense of the dirty technology, the mandate causes the price of the clean technology to increase and the price of the dirty technology to fall. Depending on these relative price changes, and economic conditions, the price of the regulated good may increase or decrease. Equivalently, the displacement ratio may be above or below one, and the output effect positive or negative. In contrast, a subsidy lowers the price of both the clean and dirty technologies in the regulated market, and therefore lowers the price of the regulated good and leads to a negative output effect.

Finally, the mandate implies a relationship between the substitution effect and the output effect that is absent for the subsidy. Economic conditions in the clean and dirty input markets determine the substitution effect, as well as how the prices of the two technologies change in response to the mandate (e.g. the supply elasticities). In turn, these price changes determine the change in the price of the composite good. In many contexts, the supply elasticity of the clean technology will fall as more of the clean technology is added because inputs become scarcer. The

[5] These insights are drawn from marginal emissions formulas derived from a simple analytical model, which is detailed in Online Resource 1. The model characterizes the biofuels setting, but is also a reasonable approximation of many other clean technology contexts.

falling supply elasticity implies that each additional unit of the clean technology added by a mandate puts more upward pressure on the change in the price of the composite good, which lowers the output effect. However, for the subsidy, conditions in clean technology input markets have no bearing on the output effect because the subsidy needed to induce a unit expansion in the clean technology scales inversely with the supply elasticity of the clean technology.

3 Numerical Framework and Methods

Our numerical analysis uses a model developed to evaluate U.S. policies that support corn ethanol (Bento and Klotz 2014; Bento, Klotz, and Landry 2015). The model accounts for direct and indirect adjustments in domestic and international input markets related to the production of ethanol (the clean technology) and gasoline (the dirty technology), which are combined to produce blended fuel (the composite good). Corn used as an input to ethanol production competes with other crops and non-cropland land uses both domestically and internationally. Crude oil is used to produce gasoline for the domestic market, while international demand for crude oil responds to price changes. The model calculates greenhouse gases in terms of carbon dioxide equivalent (CO_2e), based on 100-year global warming potentials, resulting from agricultural production, land use change, ethanol production, crude oil recovery, gasoline refining, and the combustion of gasoline and crude products. The functional forms, data sources, parameters and emissions factors, and dynamic assumptions that characterize the model are presented and discussed in Online Resource 1. Online Resource 1 also provides details of our uncertainty analysis and supplementary tables and figures.

We simulate incremental increases in a mandate and subsidy for ethanol in the production of blended fuel. Starting from a baseline with no ethanol policies in place in the year 2015 we increase each policy to expand ethanol quantities from 6 billion gallons to 20 billion gallons over 100 increments. To approximate marginal emissions, we compute the average change in emissions per unit of ethanol added over each increment. We consider a total expansion in ethanol production of 14 billion gallons in order to highlight the differences in the emissions changes that could potentially emerge.[6]

[6] The range of ethanol quantities that we consider were selected to illustrate our conceptual framework, and should not be taken as reflecting past or current U.S. ethanol policies.

4 Results

We next evaluate how marginal emissions vary with the amount of ethanol added by the two clean technology policies. As shown in Section Two, marginal emissions are the sum of a substitution effect and an output effect.

4.1 Substitution Effect

The substitution effect is the difference between the marginal emissions from ethanol and gasoline. Panel A of Figure 1 displays the marginal emissions from ethanol and gasoline as ethanol quantities range from 8 to 20 billion gallons. At 8 billion gallons, marginal emissions from ethanol (circle markers) are 72 gCO_2e/MJ. This total includes emissions from ethanol production, expanded corn production, displaced production of other crops, and direct and indirect land use change. Marginal emissions from gasoline (star markers) total 78 gCO_2e/MJ, which includes emissions from the extraction and refining of crude oil and the combustion of gasoline, less indirect emissions reductions from displaced crude oil used outside the U.S.

The substitution effect for both policies is reported as the hashmarked line in Panel B of Figure 1. It is negative, but small, at low ethanol quantities, and increases as input markets tighten in response to expansions in ethanol. At 8 billion gallons the substitution effect represents only an 8 gCO_2e/MJ reduction in emissions. The substitution effect increases at a nearly constant rate with the amount of ethanol added and is positive after 13.5 billion gallons. This mirrors the increase in the marginal emissions of ethanol, which negatively corresponds with the supply elasticity of ethanol. As more ethanol is added to the economy, land markets become progressively tighter, requiring ever larger increases in the prices of corn and other crops. Consequently, the ethanol supply elasticity is decreasing in the amount of ethanol added and this in turn corresponds with more emissions generating land market adjustments (see Figure 1 in Online Resource 1). In contrast, marginal emissions from gasoline are nearly constant because the bulk of these emissions are due to final combustion, which is constant per unit of gasoline, and there is only a slight slackening of the crude oil market since the quantity of gasoline displaced is small in relation to global demand for crude oil.

4.2 Output Effect

Unlike the substitution effect, the output effect differs dramatically across policies. The output effect for the mandate (square markers) and subsidy (triangle markers) are plotted alongside the substitution effect in Panel B of Figure 1. The output effect for the subsidy is always greater than for the mandate. At 8 billion gallons, the output effects for both policies are positive, but slightly smaller for the mandate (8 gCO_2e/MJ) than for the subsidy (10 gCO_2e/MJ). Initially, both policies cause the price of blended fuel to fall and therefore less than one unit of gasoline is displaced for each unit of ethanol added. However, unlike the subsidy, the mandate ensures the increase in the price of ethanol will pass through into the price of blended fuel resulting in a smaller decline in the price of blended fuel.

As ethanol quantities expand, the output effect for the mandate decreases at an increasing rate and eventually becomes negative. Since the marginal emissions of gasoline are nearly constant with respect to ethanol added, the falling output effect reflects a rising displacement ratio (see Figure 2 in Online Resource 1). The displacement ratio is increasing in the amount of ethanol added for two reasons. First, the supply elasticity of ethanol is falling, so each additional unit of ethanol induces a larger increase in the price of ethanol relative to the fall in the price of gasoline, which is nearly constant. Second, as the share of ethanol in blended fuel increases, the increase in the price of ethanol contributes more to the change in the price of blended fuel. Consequently, the output effect falls by 9 gCO_2e/MJ between 8 and 14 billion gallons, becomes negative at 14 billion gallons, and then falls further to 20 gCO_2e/MJ at 20 billion gallons.

In contrast, the output effect for the subsidy changes very little with the quantity of ethanol added because the displacement ratio is nearly constant. The marginal subsidy required to induce a unit change in ethanol increases as the ethanol supply elasticity falls, thus the change in the price of blended fuel is roughly constant. Moreover, within the range of ethanol quantities we observe, the increasing share of ethanol in blended fuel has only a small negative impact on the displacement ratio.

4.3 Marginal Emissions

Panel C of Figure 1 displays the marginal emissions for the mandate and subsidy, which are the sum of substitution and output effects from Panel B. At 8 billion gallons, positive output effects just offset negative substitution effects for both policies, leading to positive, but small, marginal emissions. Marginal emissions for the mandate are only 1 gCO_2e/MJ. Marginal emissions for the subsidy are higher (3 gCO_2e/MJ) due to the larger output effect.

Due to differences in the output effects, marginal emissions due to the two policies move in opposite directions as ethanol quantities expand. Marginal emissions due to the mandate are nearly constant initially, and then fall as the output effect dominates the substitution effect. In contrast, marginal emissions for the subsidy increase at a constant rate, reflecting increases in the substitution effect. The difference in marginal emissions between the two policies grows considerably, reaching 10 gCO_2e/MJ at 14 billion gallons and 30 gCO_2e/MJ at 20 billion gallons. After 15.5 billion gallons the policies imply marginal emissions of different signs. At 20 billion gallons, a unit of ethanol added by the mandate reduces emissions by more than 10 gCO_2e/MJ, but a unit of ethanol added by the subsidy increases emissions by 20 gCO_2e/MJ. This reinforces the central insight of Bento and Klotz (2014) that accounting for policies is essential for evaluating the emissions impacts of clean technologies.

The mandate, through tightening land markets, establishes a negative correspondence between substitution and output effects. Tightening input markets due to the expansion of ethanol drive the substitution effect up, but the output effect down. Since the subsidy neutralizes the impact of changing land markets on the output effect this negative correspondence is absent.

Despite a positive and increasing substitution effect, emissions reductions are possible at higher ethanol quantities if the output effect is sufficiently negative. Since the emissions advantages of ethanol over gasoline, as reflected by the substitution effect, are small, the output effect essentially determines the sign on marginal emissions.

4.4 Uncertainty in Marginal Emissions

Understanding uncertainty in marginal emissions is important both as countries select appropriate clean technology policies and as the international community assesses expected collective mitigation from national pledges. In this section, we consider how uncertainty in marginal emissions due to assumptions affecting ethanol, gasoline, and blended fuel markets varies by policy and the amount of clean technology added. Specifically, we choose sets of model parameters to achieve central, low and high levels for the elasticities of excess supply for crude oil, crop demand for food production, and demand for blended fuel as well as the emissions generated by agricultural production and land use change. These parameters affect adjustments and marginal emissions in key markets, which allow us to cleanly illustrate the mechanisms that impact uncertainty.

Uncertainty in marginal emissions increases with ethanol quantities for both policies but at different rates. The first row in each panel of Table 2 displays *total uncertainty in marginal emissions*—the difference between the lowest and highest realized marginal emissions estimates across all possible combinations of parameters—for increasing levels of ethanol.[7] At 8 billion gallons total uncertainty is nearly the same for each policy, roughly 86 gCO_2e/MJ, although slightly greater for the subsidy. Initially, total uncertainty increases faster for the subsidy than the mandate. By 16 billion gallons, total uncertainty is nearly 16 gCO_2e/MJ greater for the subsidy than for the mandate. Between 16 and 20 billion gallons, however, total uncertainty increases much more rapidly for the mandate than the subsidy. Across these 4 billion gallons, total uncertainty increases by 43 gCO_2e/MJ for the mandate, but only 13 gCO_2e/MJ for the subsidy.

The rapid increase in uncertainty in marginal emissions for the mandate at higher ethanol quantities occurs largely due to a reduction in the lowest marginal emissions outcome (i.e. larger emissions reductions). In the third row in each panel of Table 2 we report the difference between the central and lowest emissions case, as a fraction of total uncertainty. For both policies, uncertainty changes in a relatively uniform manner above and below the central case through 16 billion gallons, with the share of uncertainty falling below the central estimate changing very little in this range. Between 16 and 20 billion gallons, the share of uncertainty below the central estimate grows rapidly for the mandate (from 34% to 53%), but is almost unchanged for the subsidy.

Comparing the contributions of each set of parameters to total uncertainty illustrates that the link between land market conditions and the output effect for the mandate is largely responsible for the difference in total uncertainty between the two policies. The *total contributions* in Table 2 quantify the influence of each set of parameters on total uncertainty.[8] Based on this measure, it is clear that the blended fuel and crop demand elasticities and the land use emissions factors largely explain the difference in total uncertainty between the two policies. As with total uncertainty, these total contributions grow faster for the subsidy at small ethanol volumes, but much more rapidly for the mandate at larger ethanol quantities.

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[7] Our estimate of large uncertainty is consistent with other studies that provide estimates of uncertainty in emissions from biofuels and biofuel policies (e.g. Plevin et al. (2010)). Unlike these previous studies, we focus on uncertainty in marginal emissions, and how this uncertainty differs with ethanol quantities and policies.

[8] Formally, the total contribution measures the reduction in total uncertainty when one set of parameters is fixed at central values, thereby capturing the contribution of that set of parameters to total uncertainty given the uncertainty in all other parameters.

The link between land market conditions and the substitution and output effects for the mandate mediates the differences in total contributions between policies through several channels. First, the total contribution for the fuel demand elasticity falls and then increases for the mandate because tightening land markets cause the change in the price of fuel to flip from negative to positive. Second, the crop demand elasticities affect the elasticity of ethanol supply, and therefore the output effect, for the mandate but not the subsidy. Finally, the rapid increase in total contributions for the mandate is partially a consequence of the link between land markets and the output effect causing interactions in uncertainty across sets of parameters. These interactions, reported in Table 2, reflect the uncertainty attributable to a given set of parameters arising from uncertainty in the remaining parameters.[9] For example, uncertainty in the crop demand elasticity—which alters the changes in the prices of ethanol and blended fuel—affects uncertainty arising from the elasticity of fuel demand. These last two channels have a greater impact on the total contributions for the mandate as the change in the price of ethanol plays a bigger role in determining the change in the price of fuel at higher ethanol quantities.

4.5 Marginal Emissions in the Electricity Sector

Our framework and results can be used to understand the emissions implications for clean technology policies in other contexts. The electricity sector is a particularly important context because many of the NDCs submitted by countries anticipate significant mitigation from the deployment of clean technologies in this sector, such as the expansion of generation from renewable sources or improvements in energy efficiency. As with biofuels, clean technology policies in the electricity sector frequently take the form of subsidies and mandates. Recent work has documented spatial and temporal heterogeneity in the substitution effect due to increases in various clean technologies in this sector (Graff Zivin, Kotchen, and Mansur 2014; Novan 2015), but the output effect is not as well characterized, despite its potential to drive differences in marginal emissions across policies. While some of the same factors that determine the output effects for biofuel policies will be present in the electricity sector (Fischer 2010), distinct features of electricity markets will also play an important role.

[9] Our decomposition of uncertainty is in the spirit of global sensitivity analysis (Saltelli et al. 2008). We calculate the interactions as the difference between the total contribution for a given set of parameters and the uncertainty resulting from varying only this set of parameters, with all other parameters held at their central values.

In the electricity sector, the output effect is likely to be larger and positive for a policy that supports clean technologies that would displace 'dirty' electricity generation during periods of high demand. The supply of electricity from dirty generation units tends to be more inelastic at larger quantities because higher marginal cost units are only dispatched when demand peaks. This could lead to larger output effects for both the mandate and subsidy as additional clean technology induces larger reductions in the price of the dirty technology. The output effect will also hinge on the regulatory structure and market power present in the particular electricity market being analyzed, as these factors determine the extent to which the electricity price faced by consumers is altered by changes in wholesale electricity prices and how capital costs are recovered. If the costs incurred due to a clean technology policy are passed into higher retail rates, the output effect would be pushed down and marginal emissions lowered. Moreover, expansions of intermittent non-curtailable clean technologies, such as roof-top photovoltaic systems, may contribute to grid congestion, which can lead to negative wholesale electricity prices in restructured markets (Borenstein and Bushnell 2015). If these negative prices are passed through into retail rates, output effects could be large, as low prices would encourage the consumption of electricity and delay investments in energy efficient technologies.

4.6 Clean Technology Policies Under the Paris Agreement

The Paris Agreement institutionalized a novel ratcheting mechanism through which countries are expected to make voluntary mitigation pledges, called Nationally Determined Contributions (NDCs), that become more ambitious over time. Five years after the initial NDC submission, an *ex post* assessment of collective emissions, known as the global stocktake, is expected to occur. Countries are then expected to submit new, more ambitious NDCs every five years, which will be followed by additional stocktakes.

The hope is that this ratcheting mechanism will ameliorate the free-riding incentives that contributed to the collapse of the Kyoto Protocol (Nordhaus 2015) by encouraging reciprocity and establishing long-term trust across multiple pledge and stocktake cycles. In light of the heavy reliance on expansions in clean technologies in the intended NDCs submitted prior to Paris (UNFCCC 2016), our analysis suggests a need for enhancing countries' capacities to make meaningful yet achievable *ex ante* mitigation pledges and to quantify uncertainty in expected mitigation from the use of clean technology policies. Such enhancements will allow countries to clearly communicate their intended mitigation ambition through their NDCs to other countries. By enhancing these capacities, differences between a country's *ex ante* commitment and the *ex post* evaluation of that commitment—which will naturally occur in the pledge and stocktake process—will be less likely to hamper trust and future ambition towards 1.5°C or 2°C targets.

Efforts should be made to develop tools to evaluate the emissions reductions achievable by expansions in clean technologies that account for policies and the possibility of non-constant marginal emissions. Table 1 in Online Resource 1 illustrates that mitigation estimates that assume policy-invariant or constant marginal emissions factors can greatly misrepresent the change in emissions from a large increase in ethanol. If marginal emissions are assumed to be constant at either the first or last unit added over the change, estimates of total emissions can differ from the model's estimate by more than two times for the mandate and a third for the subsidy, and can even incorrectly estimate the sign on the change in total emissions. The use of policy-invariant or constant marginal emissions metrics, such as those generated by standard LCA methods, to formulate *ex ante* pledges may yield significant discrepancies vis-à-vis *ex post* evaluations.

5 Conclusion

The Paris Agreement has the potential to overcome the failures of prior top-down approaches to address climate change. Clean technology policies are likely to continue to play a key role in those efforts, given the enormous political challenges to imposing more cost-effective policies, such as carbon taxes. In this paper, we showed that emissions savings from clean technology policies can be undercut by output effects and changing economic conditions. Future research should study the cost-effectiveness of coupling clean technology policies with other policies that neutralize output effects that raise emissions. Additional research is also needed to understand how economic conditions might affect the mitigation potential of clean technologies in other contexts (e.g. other policies, countries) and when multiple countries adopt clean technology policies in cooperative and non-cooperative settings.

Our analysis of clean technology policies in a single sector in a single country provides initial guidance on the need to enhance national capacities that could help the Paris Agreement achieve more aggressive mitigation commitments in the future. If varying economic conditions alter the emissions implications for clean technologies more broadly, then the sum of all countries' pledges is unlikely to provide an accurate measure of the global change in emissions resulting from policy actions taken in support of those pledges. Moreover, comparing a country's pledged emissions level to their post-stocktake emissions level is unlikely to provide a clear indication of the seriousness of that country's mitigation efforts. Future research should evaluate the benefits of conducting a unified assessment of the emissions reductions expected from all countries' collective mitigation actions. Such a 'global reality check' could prove vital as it would allow the international community to adjust expectations in advance of future NDC submission rounds and further establish reciprocity and trust in the ratcheting mechanism.

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Figure 1: Economic and Emissions Impacts of Clean Technology Policies

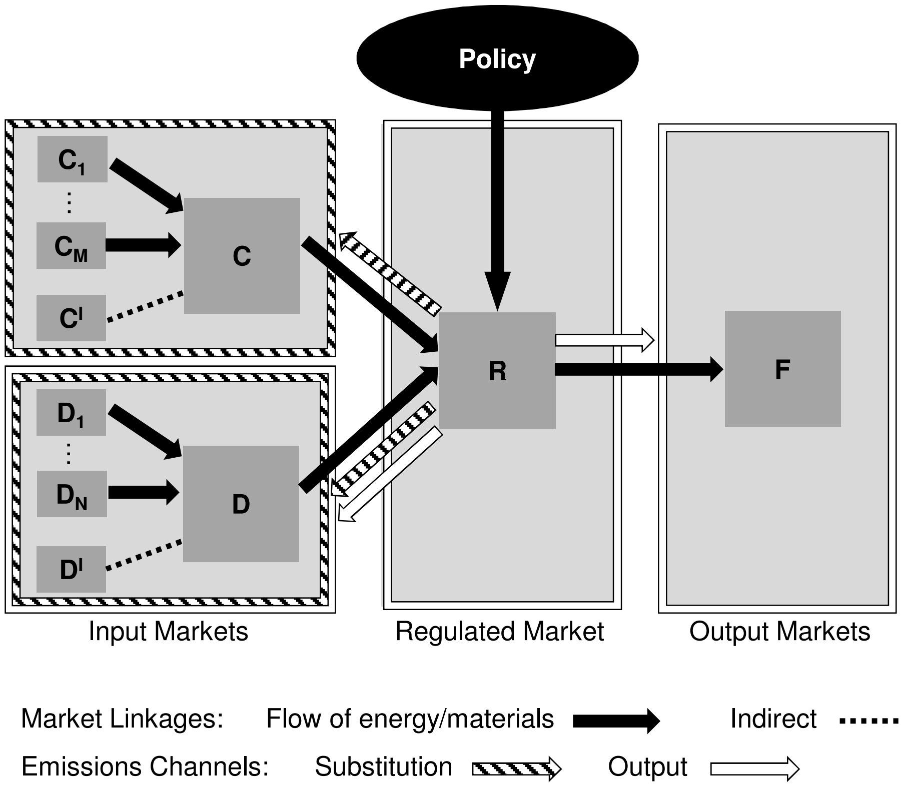

Figure 2: Decomposition of Marginal Emissions as Ethanol Quantities Expand

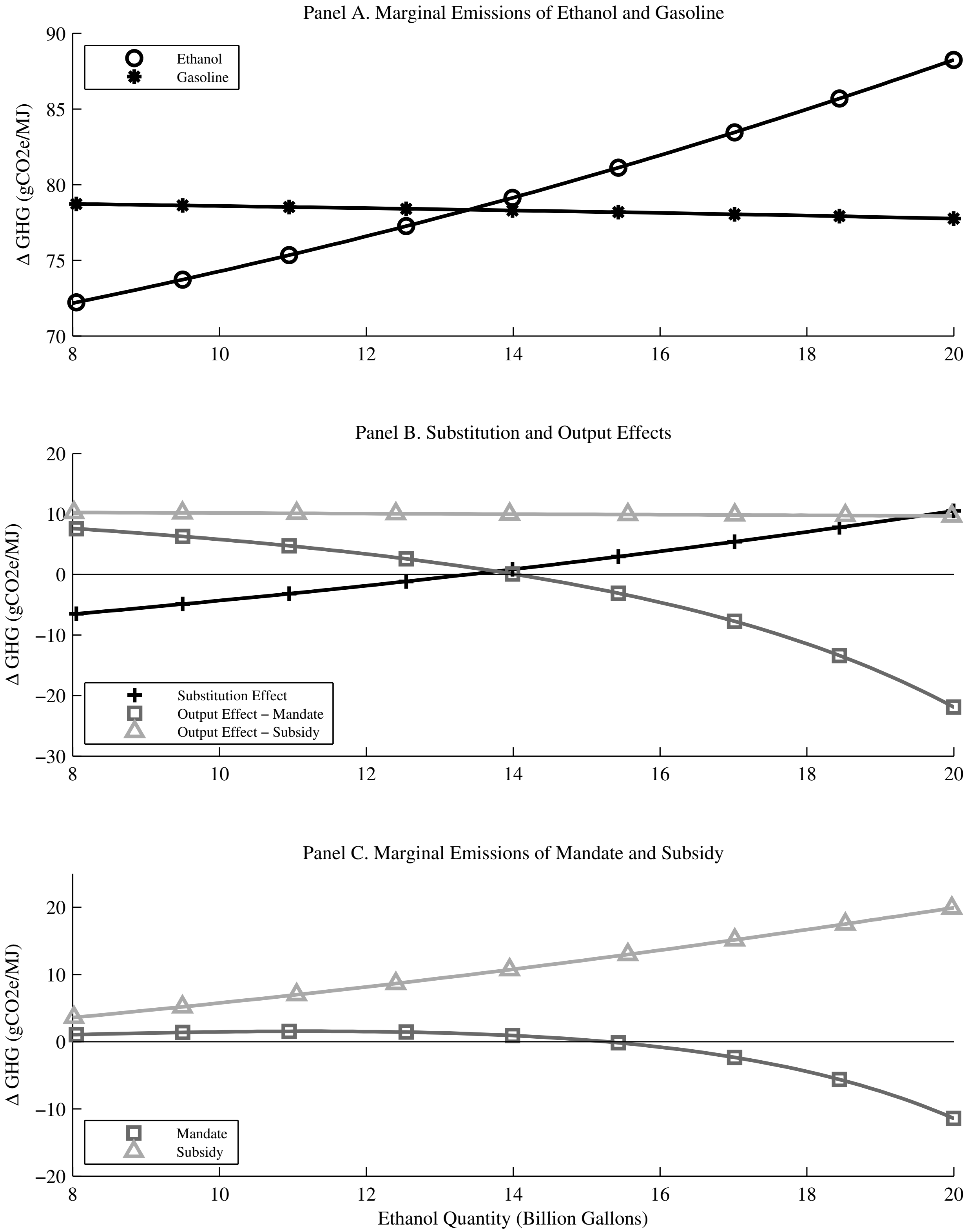

Table 1: Global Sensitivity Analysis

Mandate				
Ethanol (Billion Gallon)	8	12	16	20
Total Uncertainty	86.0	89.9	93.4	136.3
Central Estimate	1.1	1.5	-1.0	-12.1
Uncertainty Below Central	32.3%	31.3%	34.1%	53.2%
Total Contributions				
Crude Supply	15.4	16.2	16.8	16.5
Crop Demand	11.7	13.7	12.2	37.2
Fuel Demand	11.9	8.7	7.0	37.9
Ag. & Land Emissions	49.7	55.6	68.0	76.8
Interactions				
Crude Supply	1.8	2.6	2.9	1.9
Crop Demand	1.1	1.9	2.9	25.8
Fuel Demand	1.7	2.3	5.9	19.4
Ag. & Land Emissions	0.8	1.6	8.0	10.1
Subsidy				
Ethanol (Billion Gallon)	8	12	16	20
Total Uncertainty	88.3	97.6	109.2	121.8
Central Estimate	3.9	8.4	13.8	20.1
Uncertainty Below Central	32.9%	32.5%	32.0%	31.8%
Total Contributions				
Crude Supply	14.0	13.7	13.3	12.8
Crop Demand	12.3	16.6	22.3	27.9
Fuel Demand	14.1	14.4	14.9	15.8
Ag. & Land Emissions	49.9	55.8	62.8	70.0
Interactions				
Crude Supply	1.3	1.2	1.1	0.9
Crop Demand	0.8	1.7	2.9	4.0
Fuel Demand	1.2	1.3	1.3	1.4
Ag. & Land Emissions	0.8	1.6	2.8	3.5

All values are in gCO2e/MJ unless otherwise specified. Since each total contribution encompasses interactions with each other parameter, the sum of all total effects do not equal total uncertainty.