Simulating Regional Effects of U.S. Climate Policies with the CIMS-US Model

by

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Hon. B.Sc., University of British Columbia, 2011

Project Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Resource Management

in the
School of Resource Management
Faculty of Environment

Project No. 674

SIMON FRASER UNIVERSITY
Summer 2017

Approval

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Degree:	**Master of Resource Management**
Project No.:	**674**
Title:	**Simulating Regional Effects of U.S. Climate Policies with the CIMS-US Model**

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Date Defended/Approved: August 24, 2017

Abstract

In this project, I disaggregate the energy-economy model CIMS-US into four United States (U.S.) regions, Midwest, Northeast, South and Pacific/Mountain, to obtain regional resolution for climate policy effects on the electricity generation and transportation sectors. Five policies are modelled to reach climate targets previously set by President Obama: the Clean Power Plan (CPP), a coal and natural gas phase-out regulation, Corporate Average Fuel Economy Standards, and a Vehicle Emission Standard. Lastly, a carbon tax is applied across all sectors in the economy.

My results show that Midwest is the most emission-intensive region. Due to the effects of pre-existing California climate policies, Pacific/Mountain experiences the lowest marginal abatement costs to decarbonize its electricity sector. Low marginal abatement costs can induce deeper reductions in full cycle emissions from electricity-powered vehicles.

Because of insufficient regional variation in my results, I suggest an alternative disaggregation method.

Keywords: United States; climate change policy; energy-economy modelling; 2015 Paris Agreement; regional disaggregation

Acknowledgements

Initially entering REM with a science background, I saw climate change primarily as an environmental problem that can eventually be solved through technological innovation. Through my studies in REM, I was confronted with the multi-faceted issues climate change imposes on humanity also through an economic, political and social lens. With this broader understanding, I pondered and wrestled with the weight and immensity of this task that humanity faces. In time, I have learned to find hope in knowing that creation has been redeemed, and will one day be restored to her intended beauty. Until then, may we have wisdom in learning to steward the Earth's resources with justice, kindness and humility.

I would like to acknowledge and give my sincere thanks to Dr. Mark Jaccard for your support, guidance and patience throughout my graduate career. I am grateful for this opportunity to have been able to learn from you, and be trained under your high standards to think critically and communicate clearly. I am deeply inspired by your energy, enthusiasm and tenacity in tackling such complex global issues.

I would also like to thank Brad Griffin for providing your help and insight in the final draft of this work, and Jotham Peters for your time and patience in helping me with the CIMS-US model.

To my peers and friends in EMRG: Kaitlin, thank you for always being so willing to help me anytime with editing and preparing for the defence; Lejla, thank you for constantly being the voice of reason and encouragement to push me forward. I am so thankful for our friendship throughout our time in REM together. Tiffany, thank you for sharing your ideas with me and for your help in my last stages of writing. Noory, it has not been the same without seeing you everyday; I will always treasure the life stories you shared with me.

To my P2C kids and friends, meeting all of you has been the greatest thing that happened to me during my time at SFU. I am indeed blessed to have grown with you, and shared my life and my heart with you.

To my church family, although we have not known each other for very long, I would not have made this final stretch without your continued prayers, care and encouragement. I am deeply grateful for all of your support every step of the way in seeing me through to the end.

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List of Acronyms

AB 32	Assembly Bill 32
AEEI	autonomous energy efficiency index
AEO	Annual Energy Outlook
BAU	business-as-usual
BSER	Best System of Emissions Reduction
CAFE	Corporate Average Fuel Economy
CAIR	Clean Air Interstate Rule
CCS	carbon capture and storage
CO2	carbon dioxide
COP	Conference of the Parties
CPP	Clean Power Plan
EIA	Energy Information Administration
EMF	Energy Modelling Forum
EMM	Electricity Market Module
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESUB	elasticity of substitution
EV	electric vehicle
FCV	fuel cell vehicle
GHG	greenhouse gas
HEFF	high efficiency
IEA	International Energy Agency
INDC	Intended Nationally Determined Contribution

MEFF	medium efficiency
Mt CO2e	megatonnes of carbon dioxide equivalent
MWh	megawatt hours
NEMS	National Energy Modelling System
NERC	North American Electric Reliability
NHTSA	National Highway Traffic Safety Administration
PHEV	plug-in hybrid electric vehicle
pkt	person kilometers travelled
RGGI	Regional Greenhouse Gas Initiative
RPP	refined petroleum product
tkt	tonne kilometers travelled
TWh	terawatt hours
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States
VES	Vehicle Emission Standard
vkt	vehicle kilometers travelled
ZEV	zero emission vehicle

Chapter 1.

Introduction

As greenhouse gas (GHG) emissions continue to rise and exacerbate changes in the Earth's climate system, the resulting effects—sea level rise and more extreme weather patterns—are one of the greatest threats to humanity (IPCC, 2014). Although global action is necessary to mitigate climate change impacts, developing countries look toward developed countries, such as the United States (U.S.), for leadership and initiative to act on limiting rising emissions (Morris et al., 2013). From 1990 to 2011, the U.S. has been the top of five major emitters globally, contributing 16% to the world's total cumulative GHG emissions (WRI, 2014). In 2011, almost 85% of the U.S. GHG emissions were attributed to carbon dioxide (CO2), with fossil fuel combustion contributing nearly 95% of total CO2 emitted (U.S. EPA, 2013).

Given its key role in the global efforts on climate change, the U.S. previously made several promises at the international level within the past decade. In 2009, at the United Nations Framework Convention on Climate Change (UNFCCC) in Denmark, Copenhagen, President Obama pledged to reduce the U.S. GHG emissions to 17% below 2005 levels by 2020. In 2014, the U.S. and China made a bi-lateral agreement on Climate Change and Clean Energy Cooperation: President Obama announced that the U.S. would reduce "net greenhouse gas emissions 26-28 percent below 2005 levels by 2025", while President Xi Jinping promised that China would halt its emissions growth by 2030 (White House, 2014).

Thereafter, in preparation for the 21st session of the UNFCCC in Paris, all Parties of the Convention were invited to submit an Intended Nationally Determined Contribution (INDC) to move towards achieving the Convention's objective by the first quarter of 2015. The objective for this convention was to stabilize atmospheric GHG emissions at a level that would "prevent dangerous anthropogenic interference with the climate system … within a time-frame sufficient to allow ecosystems to adapt naturally to climate change [and] ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner" (UN, 1992). In its INDC, the U.S. re-stated its intention to "achieve an economy-wide target of reducing its greenhouse gas emissions by 26% to 28% below its 2005 level in 2025", and also to reduce economy-wide emissions by 80% or more by 2050 (U.S. INDC, 2015).

On November 4, 2016, the 2015 Paris Agreement entered into force 30 days after achieving the threshold of having at least 55 countries of the Convention agreeing to account for at least 55% of total GHG emissions. Upon entry into force, the U.S. as a party of the agreement along with others would collectively take action to achieve the long-term goal of "keeping the average global temperature rise from pre-industrial times below 2 degrees C and pursuing efforts to limit it to 1.5 degrees" (UNFCCC, 2016).

However, on June 1, 2017, the U.S., now under the leadership of President Donald Trump, stated that "[it] will withdraw from the Paris Climate Accord ... but begin negotiations to reenter either the Paris Accord or a really entirely new transaction on terms that are fair to the United States, its businesses, its workers, its people, its taxpayers" (White House, 2017). Because the U.S. is a major contributor to global GHG emissions, climate scientists fear that this withdrawal would accelerate global warming, such that the crossing of the two-degree warming threshold cannot be prevented. Many scientists say, "Even with the U.S. doing what it promised under the Paris agreement, the world is likely to pass that 2 degree mark" (Borenstein, 2017).

The timeline in figure 1.1 illustrates the U.S.'s climate actions along with key international events during this past decade. In summer 2013, President Obama outlined strategies to reduce the national GHG emissions by 17% below 2005 levels by 2020 through the President's Climate Action Plan (2013). This

Plan proposed a number of emissions reduction strategies within various sectors of the U.S. economy, including actions within the electricity generation and transportation sectors. A large portion of his Plan focused on these two sectors because they have been the highest carbon-emitting fossil fuel-based sectors since the 1990s (U.S. EPA, 2013).

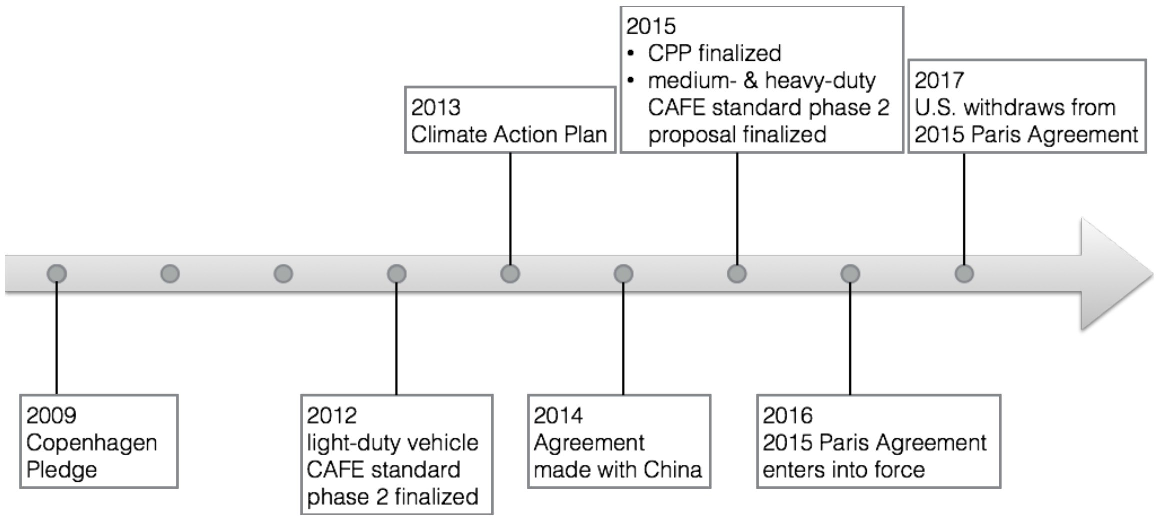

Figure 1.1. Timeline of international commitments and U.S. climate actions.

Under electricity generation, the Climate Action Plan proposed carbon pollution standards for new power plants as well as strategies to reduce carbon emissions from existing power plants. It also detailed the first uniform national limits on new power plants, proposed funding increases to transition from fossil fuels to renewable generation technologies, and envisioned an expansion of the electric grid, with the goal of doubling renewable electricity generation by 2020 (White House, 2013). During the summer of 2015, the U.S. Environmental Protection Agency (EPA) finalized the details of the Clean Power Plan (CPP) to reduce carbon emissions from the power sector to 32% below 2005 levels by 2030. While the CPP may change or even be replaced in future years, depending on policy choices of the Trump and subsequent administrations, it represents an example of a U.S. policy approach through which the federal government tried to implement a regulatory climate policy, while also maintaining considerable flexibility for state-level governments and electricity producers.

For the transportation sector, the Climate Action Plan (2013) outlined goals to increase fuel economy standards and reduce GHG emissions for trucks, buses and vans, as well as to advance technological innovations. Together, the U.S. EPA along with the National Highway Traffic Safety Administration (NHTSA) implemented a number of fuel and vehicle efficiency and GHG reduction standards for light- and heavy-duty vehicles. For example, in 2012, the EPA and NHTSA issued the joint Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards program, which extends from the previous national program of standards for model year 2012-2016 light-duty vehicles. Since then, the EPA and NHTSA jointly proposed phase 2 of these standards on GHG emissions and fuel efficiency for medium- and heavy-duty engines and vehicles in 2015.

With the assumption that the U.S. will ultimately pursue climate targets and policy initiatives following in the steps laid out by President Obama, my research simulates a suite of previously proposed and currently in-place policies. However, it is important to note here that future U.S. policies and targets, as well as the intensity and nature of the global effort to combat climate change are highly uncertain.

In this study, I simulate U.S. climate policies using the CIMS-US model. In a previous study, Jaccard and Goldberg (2014) used this model to assess policies in the electricity generation and transportation sectors as a contribution to one of Stanford University's Energy Modelling Forum (EMF) studies. However, given the heterogeneity of the U.S. power sector and the flexibility for regional compliance in recent policy approaches, an important way to improve the model is to disaggregate it regionally. Across the country, shares of fuels for electricity generation vary. Figure 1.2 illustrates regional generation mix for the nine U.S. Census Regions. For example, Pacific is the most hydro-powered region, while the two North Central regions are heavily dependent on coal. Consequently, regional distinction in policy analysis is especially important in order to incorporate the different outcomes that flexible electricity policies, such as the

CPP, could produce. Therefore, the objective of my study is to first regionally disaggregate the existing CIMS-US model, and then use that new model to investigate the regional effects of climate policies.

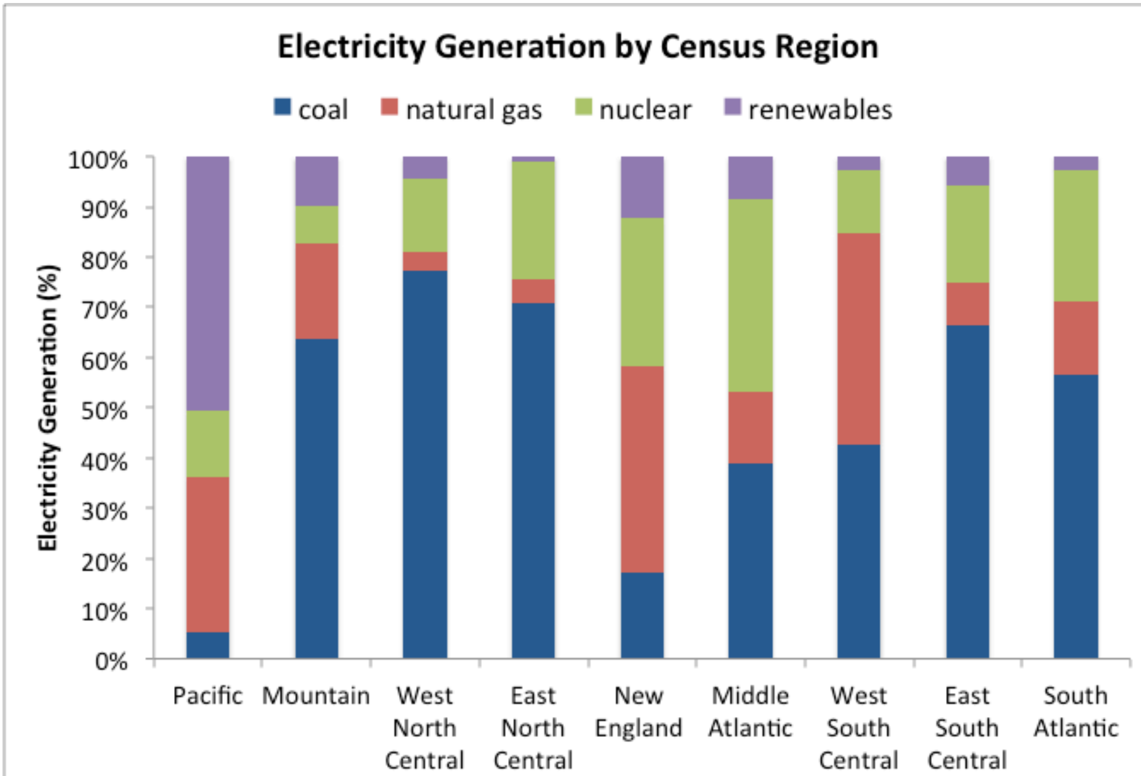

Figure 1.2. Shares of electricity generation by coal, natural gas, nuclear and renewables in 2005 across the nine U.S. Census Regions.

The remaining sections of this report are as follows: Chapter 2 provides background information on each of the policies investigated in this study. Chapter 3 describes the CIMS-US model, as well as the methodology used to disaggregate the model and simulate each policy scenario. Chapter 4 discusses modelling results within the electricity generation and transportation sectors, including regional effects under each policy scenario in achieving the various GHG emissions reduction targets. Lastly, Chapter 5 concludes with major study findings, and explores directions for future studies.

Chapter 2.

Background

This chapter provides an overview of the relevant policy initiatives in the U.S. electricity generation and transportation sectors to achieve GHG emissions reduction. Policies that are simulated using the disaggregated CIMS-US model in this project – the Clean Power Plan (CPP), Corporate Average Fuel Economy (CAFE) standards, Vehicle Emission Standard (VES), technology phase-out regulation, as well as an economy-wide carbon tax – are described in detail in this chapter.

2.1. Decarbonization of the U.S. Electricity Generation and Transportation Sectors

Policymakers are focusing on pathways to decarbonize existing carbon-intensive energy systems in order to achieve GHG reductions. To decarbonize the energy system, while still ensuring growth in population and the economy, emissions reduction can be achieved through policies that implement a price on carbon, such as an emission tax or a cap-and-trade system. This type of approach will result in actions to switch end-use fuels to electricity or other low carbon intensity sources, as well as in improvements in overall system efficiency (IDDRI, 2015). In the International Energy Agency's (IEA) projected electricity demand growth from 2011 to 2050, electricity is expected to become the largest energy carrier, expanding to more than 25% of overall end-use energy (OECD, 2015, Chapter 7). Furthermore, sectors that use electricity can become decarbonized automatically as the electricity generation sector becomes less carbon-intensive. Hence, to reach the 2 ºC goal by 2050, the IEA projects that global carbon emissions produced per unit of electricity generated should decrease by 90%, with an 80% increase in electricity generation relative to 2011 levels. In terms of generation capacity, this scenario would result in a reversal of the shares of renewable technology and fossil fuel-based technology in electricity production (OECD & IEA, 2014). For the U.S., the IEA projects that decarbonization of the power sector could achieve 95% CO2 emissions reduction relative to 2010 levels. If this is achieved, by 2050, emissions from electricity generation will contribute only a 16% share of the total combined emissions from buildings, transportation, industries, and electricity generation (SDSN & IDDRI, 2014). For the transportation sector, decarbonization can be realized through improving fuel efficiency or switching from fossil fuel-based vehicles to electric, biofuel or hydrogen vehicles, while ensuring emission are reduced for electricity generation, biofuel and hydrogen production (OECD, 2015, Chapter 7).

In the EMF 24 project lead by Stanford University's Energy Modelling Forum, Jaccard and Goldberg (2014) applied the CIMS-US model to study the effects of climate-related regulations on the electricity generation and transportation sectors. They found that, when a transportation regulation was applied in isolation, it resulted in an increase in electricity demand and emissions in other sectors not regulated by the policy. Hence, emissions that were reduced from the transportation sector as a result of its regulation could be neutralized by increases in emissions from sectors that produce electricity and biofuels (ethanol and biodiesel). However, when the transportation regulation was applied in conjunction with electricity regulations, national emissions decreased and renewable energy use increased significantly. Similarly, in Rudd's research project (2012), she shows that combined transportation and electricity policies could enable the U.S. to reach 35% of GHG emissions reduction by 2050 relative to 2005. For example, by implementing the CAFE standard along with an economy-wide GHG tax, reductions are more effectively achieved. On the other hand, if the CAFE standard (including GHG emission standard, not just fuel efficiency improvements) were implemented as a stand-alone policy, a portion of the reductions achieved by the CAFE is negated by an increase in emissions from electricity generation.

In my research, I explore these types of policy measurements for the U.S., and their combined regional effects on both the electricity generation and the transportation sectors, as well as on national GHG emission levels.

2.2. Choice of Policies in this Study

The electricity generation and transportation sectors are the two most carbon-intensive sectors in the U.S. (U.S. EPA, 2013). For the electricity sector, the IEA, in its Energy Technology Perspectives (OECD & IEA, 2015, Chapter 2), recommends carbon-pricing mechanisms to incent GHG emission reductions, particularly from high-emission sources such as coal-fired electric generators. In the transportation sector, it recommends actions to improve vehicle fuel efficiency and increase electric vehicle sales.

As in the EMF 24 study by Jaccard and Goldberg (2014), it will be insightful to study the combined policy effects on these two sectors because technological advancements or changes in either sector will likely have an impact on the other in terms of technology choices and GHG emissions. Based on the goals articulated in the CPP, I also simulate a near-complete phase-out of coal and natural gas for electricity generation. For the transportation sector, I simulate the CAFE program for light-, medium- and heavy-duty vehicles. To provide a comparison for transportation policies, a VES like the Zero Emission Vehicle (ZEV) mandate, originally adopted in the 1990s by the California Air Resources Board, is also included in my study. Previously, Rudd's (2012) findings show that the VES is 15% more cost-effective than the CAFE standard at reducing emissions. Lastly, as economists commonly recommend an economy-wide carbon pricing system as the most cost-effective method to achieve significant carbon reductions (Stavins, 2010), I apply a carbon tax across all U.S. sectors.

The following section discusses the climate policies I investigate in this study. Some of these are already in place at a federal or state level in the U.S., and some are proposed and under review. In this latter case, I sometimes make my own assumptions about how the policy could ultimately be designed, as explained below.

Clean Power Plan

Previously, under the Obama administration, the EPA established first-time national standards and guidelines to regulate carbon emissions from existing and new fossil fuel-based electric power plants under the Clean Air Act. In 2012, almost 70% of all electricity was generated using coal and natural gas, with coal as the primary source (U.S. EPA, 2015b). The Clean Power Plan intended to achieve a 32% reduction in CO2 emissions by 2030 relative to 2005 levels. For existing power plants, the Plan would be applied through a framework known as the Best System of Emissions Reduction (BSER), which consists of four building block approaches to reduce CO2 emissions from existing fossil fuel-based electric power plants. The four building blocks aim to achieve: 1) improvement in the heat rate or thermal efficiency of coal-fired power plants, 2) substitution of carbon-intensive (such as coal-fired) to less carbon-intensive power plants (such as natural gas-fired), 3) expansion in low- or zero-carbon technology for electricity generation, and 4) improvement in energy efficiency to reduce overall demand for electricity. In order to achieve reduction targets by 2030, states would then be required to begin CO2 reductions from affected power plants starting in 2020, with interim goals set for 2020 to 2029. These reduction targets are based on historical emission rates, which would be incorporated into the application of the four building blocks to each state's affected power plants.

The Plan was designed such that states can also choose to comply through a rate-based or mass-based approach. The rate-based approach requires that a state achieve an average emission rate for all power plants, while the mass-based approach requires that a state limit its aggregate emissions from all affected power plants to not exceed its mass-based emissions target. Each state would be required, under the CPP, to develop, adopt and submit a plan that implements these standards according to the BSER via either the rate-based or mass-based approach, to be applied to all affected power plants (U.S. EIA, 2015; U.S. EPA, 2015b). For new power plants, the Plan limits emission rates to 1400 pounds of CO2 per MWh for coal-fired plants, and 1000 pounds of CO2 per MWh for natural gas-fired plants (Synapse Energy, 2016).

The U.S. EPA's regulatory impact analysis on the Plan projects that CO2 emissions from electricity generation would be reduced approximately 22% by 2020, 28% by 2025, and 32% by 2030 relative to 2005 levels (U.S. EPA, 2015b). Similarly, coal-fired generation would be expected to decrease with growing capacity for gas-fired generation. The U.S. EIA, using the NEMS model, projects that the U.S. power sector would see emissions reduction between 29% to 36% relative to 2005 levels under the CPP, with 25% reduction by 2020, 34% by 2030, and 30% by 2040[1] (U.S. EIA, 2015). Furthermore, the EIA also projects that the primary compliance strategy for implementing the CPP would be switching from coal-fired to natural gas-fired power plants, along with a moderate effort to improve energy efficiency.

Over the past few years, with advancements in extraction technology, the price of natural gas has decreased relative to coal. This effectively has had a competitive advantage to phase out coal-fired power plants. Stanford University's EMF confirms that this market competitive advantage for natural gas over coal will intensify, resulting in a continued increase in the demand for natural gas as a fuel source, whose price is expected to rise again after 2020 (EMF, 2013).

Corporate Average Fuel Economy Standards

In aiming to achieve emission reductions, governments have typically targeted energy efficiency improvements to reduce energy-intensive processes for a given sector (Jaccard et al., 2002). For the transportation sector, the U.S.

[1] For 2040, the EIA assumes continued growth in electricity demand will result in additional generation from fossil fuel sources, thus a lowered reduction level relative to the 2030 target.

has implemented standards on fuel economy since 1975 with the launch of the CAFE program. In 2010, the EPA and the Department of Transportation's NHTSA finalized a joint rule — Light-Duty Vehicle GHG Emissions Standards and CAFE Standards for model years from 2012 to 2016. This was a national program to reduce emissions under the Clean Air Act, and also improve fuel efficiency through the CAFE program under the Energy Policy and Conservation Act. Within these standards, the EPA set up CO2 emission standards for vehicles based on their emission intensities, which relate to the size of a given vehicle. Manufacturers were required to meet an average emissions compliance standard for all vehicles they produce. These emissions standards were then tightened each year from 2012 through 2016. Similarly, for the CAFE standards, manufacturers were required to meet tightening fuel economy standards for their vehicles. Typically, vehicle fuel economy is improved through either incorporation of fuel-saving technologies or by compromising on vehicle characteristics such as size and horsepower (Anderson et al. 2011).

In 2012, the EPA with the NHTSA announced phase 2 of the GHG Emissions Standards and CAFE Standards for light-duty vehicles from model years 2017 through 2025. For Phase 1 standards, light-duty vehicles were required to meet an emissions level of 250 grams of CO2 per mile by model year 2016, which is equivalent to 35.5 miles per gallon (U.S. EPA, 2010). For Phase 2 standards, light-duty vehicles are expected to meet emissions standards of 163 grams of CO2 per mile by model year 2025, which is equivalent to 54.5 miles per gallon (U.S. EPA, 2012). In both Phase 1 and 2 of the light-duty standards, the programs offer flexible strategies for manufacturers to make the necessary technological changes and cost reductions. For example, one such flexible provision allows manufacturers to average, bank or trade emissions and fuel consumption credits among all produced vehicles throughout the duration of the program. Moreover, manufacturers have also been offered credits for additional technological improvements and innovations, or for fuel switching to renewable sources beyond the basic standards' requirements (U.S. EPA, 2011; U.S. EPA, 2012).

In 2011, the EPA and NHTSA adopted the first GHG Emissions Standards and CAFE Standards program for medium- and heavy-duty vehicles from model years 2014 through 2018. Since then, Phase 2 of the program for medium- and heavy-duty vehicles from model years 2018 through 2027 has also been proposed. Phase 1 standards has 3 categories: 1) combination tractors used for pulling freight, commonly known as semi-trucks, 2) heavy-duty pickup trucks and vans, and 3) vocational vehicles, such as buses, delivery trucks, refuse trucks, garbage trucks, and concrete mixers. Phase 1 standards expect to achieve, by 2018, reductions in fuel consumption and GHG emissions of 20% for combination tractors, 15% for heavy-duty pickup trucks and vans, and 10% for vocational vehicles. In addition, all 3 categories of vehicles are required to meet specific NHTSA fuel efficiency and EPA GHG emissions targets per unit travelled (U.S. EPA, 2011a; U.S. EPA, 2011b).

Phase 2 of the standards for medium- and heavy-duty vehicles has an additional category for trailers pulled by combination tractors. Relative to Phase 1, Phase 2 standards expect to achieve, by 2017, reductions in fuel consumption and CO2 emissions of 25% for combination tractors, 9% for trailers, 16% for heavy-duty pickup trucks and vans, and 24% for vocational vehicles (U.S. EPA, 2015a; U.S. EPA 2016). Similar program flexibilities apply for medium- and heavy-duty vehicle standards as for light-duty vehicles, with the exception that the phase 2 standards on medium- and heavy-duty vehicles will not include the averaging, banking and trading program for trailers, because of limited benefits for manufacturers when adopting this program (U.S. EPA, 2011a; U.S. EPA, 2015a; U.S. EPA, 2016a).

Vehicle Emission Standard

The VES, which originated in California, is a market-oriented type of regulation in which manufacturers must achieve a minimum percentage of aggregate sales that meet an emissions standard. VES generally requires changes in vehicle technology to accommodate this fuel switching process for reducing carbon and other emissions (Jaccard et al., 2002, Chapter 7). The ZEV mandate, originally adopted in the 1990s by the California Air Resources Board as a part of its Low Emission Vehicle Program, is an example. Under this mandate, manufacturers were required to sell or acquire credits from other sellers: 11% of ZEVs from 2009 to 2011, 12% from 2012 to 2014, and 14% from 2015 to 2017. From 2018 through 2025, ZEV sales are required to reach 22%. The credits vehicle sellers earn under the mandate differ between pure electric and fuel cell vehicles versus hybrid electric vehicles (CARB, 2016a; CARB 2016b). In support of the ZEV mandate, action plans, such as promoting ZEV marketing, providing public charging infrastructure, and supporting ZEV requirements in other states have since taken place to bolster the mandate's initiatives (ZEV PITF, 2014).

In my study, the VES is modelled similarly to California's ZEV mandate, where electric vehicles, fuel cell vehicles, hybrid vehicles, plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (non-plug-in) are all categorized as ZEVs within the CIMS-US model.

Fossil Fuel Phase-Out Regulation

This policy is a command-and-control technology regulation that phases out the use of coal and natural gas as fuels for electricity production. This policy would trigger fuel switching from using carbon-intensive sources to low- and zero-carbon sources to meet the country's energy needs, thereby reducing CO2 emissions to meet specific emissions reduction targets. An example from Ontario, Canada shows that total provincial CO2 emissions have fallen by 17% relative to 2007 levels since the province's phase-out regulation on coal-fired electric generators. The last coal plant in Ontario partially converted to biomass as an alternative fuel (Cundiff, 2015). By 2014, Ontario was coal-free for electricity production, with improved efficiency to reduce demand, and primary supply sources being nuclear (56%) and hydropower (22%) (Ontario Ministry of Energy, 2013).

Economy-Wide Carbon Tax

Economists commonly advocate an economy-wide carbon price as the most cost-effective method to achieve significant carbon reductions (Stavins, 2010). The carbon tax in my study is applied as an equal pricing signal across all sectors per unit of carbon emitted. Carbon pricing mechanisms, such as a carbon tax or a cap-and-trade system, provide the potential for advancements in technological innovation as firms seek ways to minimize costs for GHG abatement (Burtraw and Shobe, 2009). Due to a higher political acceptability of regulatory mechanisms, politicians typically rely heavily upon regulations placed on technologies and fuels. On the other hand, regulatory mechanisms, if not designed properly, can lack the potential to create incentives for firms to further pursue deeper GHG reductions once the regulation is met (Morris, 2013; Rhodes and Jaccard, 2013). This depends, however, on the regulatory design. Flexible market-oriented regulations, like the VES, can approach carbon pricing in terms of economic efficiency.

2.3. Assessing Policy Effectiveness

To assess a given policy, there are four frequently applied policy assessment criteria: 1) administrative feasibility, 2) cost effectiveness, 3) environmental effectiveness, and 4) political acceptability (Rhodes and Jaccard, 2013; Jaccard, 2005). All five U.S. climate policies that I discussed in the previous section may rank differently for each of these criteria.

Policies such as the CPP and carbon tax impose a price signal on the electricity sector and the economy respectively. However, the high visibility of carbon pricing can be significantly unpopular to some portion of the public, resulting in lower political acceptability (Rhodes and Jaccard, 2013). Comparing between the CPP and the economy-wide carbon tax, the CPP is highly complex and less administratively feasible when compared with a tax placed across the economy on emissions from all sectors. For ease of modelling purposes, my study simplifies and applies the CPP as a single emission price on the electricity generation sector.

The VES is a market-oriented policy. Similar to pricing mechanisms, the VES provides flexible options for firms to achieve a particular target for emissions reduction, while also providing incentives for further reductions (Jaccard and Goldberg, 2014). In Rudd's study (2012), she finds that the VES is likely less costly than the CAFE standards because of the flexibility it provides for consumers to reduce emissions through both fuel switching to less carbon-intensive sources, as well as fuel efficiency improvements. In addition, the CAFE standards can produce a rebound effect, where improvements in fuel economy trigger a decrease in fuel cost per unit of driving distance, resulting in increased driving and emissions. The VES, on the other hand, eliminates the issue of the rebound effect by focusing on regulating vehicle emissions instead of energy efficiency (Rudd, 2012). Relative to the carbon tax, both the CAFE standards and the VES are more complex in nature to implement, but have a higher level of political acceptability. For my study, I adopt the definition of political acceptability from Rhodes and Jaccard (2013), where it is defined as "the extent to which a policy does not provoke public resistance and appears to enhance the chances of policy endurance". Since standards and regulations tend to be more invisible in the public eye, they are considered to have a high level of political acceptance.

Comparing technology and fuel regulations, such as a coal and natural gas phase-out regulation on the electricity sector and the CAFE efficiency standard, both policies are also more politically acceptable due to their invisibility in the eyes of the public when compared to a carbon tax (Aldy & Stavins, 2011). However, although a phase-out regulation is able to ensure the fulfillment of a reduction target, it is theoretically the least cost-effective method out of the five policies discussed (Jaccard et al. 2002, Chapter 7). Being command-and-control in nature, firms do not have the freedom to pursue the most cost efficient method. For instance, Rudd's study (2012) suggests that there is potential for significant savings by implementing tradable performance standards in the electricity sector, similar to the VES or CAFE standards in transportation, instead of a technology regulation aimed at phasing out the use of coal and natural gas.

Chapter 3.

Methodology

This section details the methodology I used in this research project, starting with a description of the CIMS-US model used for simulating policy scenarios. I then provide the steps I took to regionally disaggregate the CIMS-US model to incorporate regional resolution in policy analysis. Lastly, I provide the approach I used to simulate each of the five policies described in the background chapter, along with five different combinations of policy scenarios that I modelled.

3.1. Overview and Framework of the CIMS Model

The Energy and Materials Research Group in the School of Resource and Environmental Management at Simon Fraser University originally developed the CIMS model. CIMS is a hybrid energy-economy model with bottom-up and top-down capabilities, such that it is both technologically specific and behaviourally realistic. In addition, the CIMS model is capable of incorporating macro-economic effects to capture supply and demand feedbacks. CIMS-US is the U.S. version of the original Canadian CIMS model. The aggregated CIMS-US model structures electricity, commercial, residential, personal transportation, freight transportation and various industrial sectors for the entire U.S. in one geographical region.

The CIMS model's framework consists of three main modules – energy supply, energy service demand and the macro-economy. The energy supply module consists of sectors for both energy supply and energy conversion; these sectors include production and refining for oil and gas, and electricity generation. The energy demand module consists of commercial and residential buildings, transportation, and industrial production and manufacturing. Feedback loops in the CIMS model between energy supply-demand and the macro-economy capture a certain portion of rebound effects for when technological innovations in energy efficiency induce an increased demand for energy services. CIMS runs simulations by using an algorithm that converges feedback between the energy supply and demand modules with the macro-economy module (Murphy and Jaccard, 2011).

Bottom-up models are technologically specific, such that through a policy simulation, they are capable of describing detailed technological changes in any given sector for both supply and demand. These types of models also incorporate the financial costs of all technologies, and compare these technologies in competition to one another. Top-down models, in contrast, take an aggregate approach to examine the relationships between inputs and outputs to an economy. Top-down models are said to be behaviourally realistic because key parameters are based on historical observations (or revealed preferences) of consumer and firm responses to past changes in energy prices and capital costs. Energy-emission outcomes in top-down models are especially determined by two parameters: the autonomous energy efficiency index (AEEI) and the elasticity of substitution (ESUB). AEEI is an indicator for the rate of price-independent technology evolution that changes the energy intensity of the economy. The ESUB parameter reveals how costly it is for an economy to adopt certain types of technological changes, implicitly accounting for financial costs of alternative technologies, but also intangible costs and risks associated with alternative, often new, technologies (Jaccard 2009, Chapter 13).

The CIMS model contains technological details in all sectors of the energy-economy system, yet it also incorporates top-down behavioral realism through three estimated parameters in its algorithm: discount rate (r), intangible costs (i), and variability in the market (v) (Murphy and Jaccard, 2011). Equation 1 describes how the model simulates the competition of market share for new technology capital stock.

Equation 1. Market share equation in the CIMS model.

$$MS_j = \frac{[CC_j(r/(1-(1+r)^{-n_j})) + MC_j + EC_j + i_j]^{-v}}{\sum_{k=1}^{K}\{[CC_k(r/(1-(1+r)^{-n_k})) + MC_k + EC_k + i_k]^{-v}\}}$$

MS is the market share for a given technology j; CC is the capital cost for technology j; r is the discount rate representing time preference of decision makers on technology j; n is the average lifespan of technology j; MC is the maintenance and operational costs of technology j; EC is the annual energy cost of technology j; i is the parameter to represent intangible costs; and lastly, v is the market heterogeneity parameter to represent cost and decision maker variability in the market.

In the equation, the discount rate parameter r reflects time preference for energy service demands in the market; for a given technology, this discount rate parameter is taken into account when calculating the life-cycle cost of a technology. The i parameter, representing intangible costs, incorporates non-financial costs perceived by consumers, such as the cost of personal inconvenience in choosing public transportation versus a personal vehicle. Lastly, the market variability parameter v incorporates variability in costs incurred by differences in consumer preferences and geographic locations (Murphy and Jaccard, 2011).

Using these behavioural parameters, the market share equation compares the annual life cycle costs of technologies. Life cycle costs are a function of a given technology's annualized capital costs, as well as non-energy and energy operating costs (Jaccard et al. 2003). By incorporating both technological life cycle costs and the three behavioural parameters, CIMS is able to capture real-world consumer and business preferences in the process of simulating capital stock turnover and thus technological change.

Finally, technology capital cost in CIMS is subject to change as a result of learning-by-doing or improved economies-of-scale. The declining capital cost function accounts for declines in a technology's capital cost due to its cumulative production (calculated within the model, as well as exogenously forecasted for global production). The declining intangible cost function relates increased market share of a new technology with changes in consumer preferences, especially due to a lessened perception of adoption and user risks. Together, these two functions in CIMS simulate dynamics in the adoption of new technologies in policy modelling.

3.2. Disaggregation of the CIMS-US Model

The CIMS-US model has previously been used to investigate the effects of U.S. climate policies on the energy market. Before my project, the model treated the entire U.S. as one aggregate geographical region. Hence, it was not capable of exploring possible differences in regional responses to a given policy.

Region Selection

I designed four regions for the CIMS-US model by clustering together the nine U.S. Census Regions. The disaggregated CIMS-US model I developed is comprised of regions Pacific/Mountain, Midwest, Northeast and South, shown in figure 3.1.

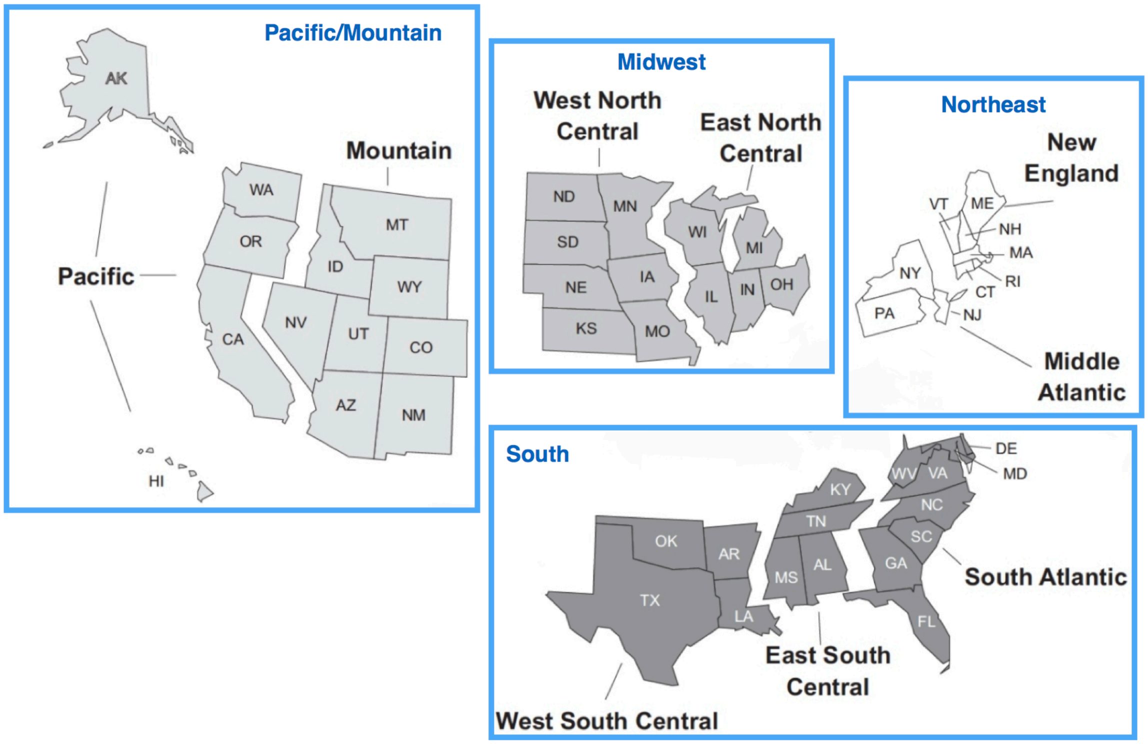

Figure 3.1. Four model regions developed from clusters of the nine U.S. Census Regions.

- Pacific/Mountain combines Census Regions Pacific and Mountain.
- Midwest combines Census Regions West North Central and East North Central.
- Northeast combines Census Regions Middle Atlantic and New England.
- South combines Census Regions West South Central, East South Central, and South Atlantic.

I disaggregated the CIMS-US model based on key regional differences in the U.S. electricity generation sector. I focus on this sector because it has historically been the most GHG emission-intensive sector in the U.S., and it is much more regionally diverse than, for example, the transportation sector (U.S. EPA, 2016b). The Electric Power Research Institute (EPRI) also suggests that decarbonization of the electricity sector can bring about rapid emission reductions in other sectors to the extent that zero-emission electricity replaces fossil fuel use in buildings, industry and transportation (EPRI, 2008).

In determining the disaggregation pattern of the electricity generation sector for the model, I took into consideration several regional characteristics. These include geographical and climatic considerations, intensity of GHG emissions, as well as existing energy networks. I regionalized the model so that each region is approximately homogenous for each of these factors. Census Regions Pacific and Mountain form the one region “Pacific/Mountain” because together they form part of the existing Western Interconnection, monitored by the Western Electricity Coordinating Council. The rest of the three regions, “Midwest”, “Northeast”, and “South” are disaggregated accordingly since each region is approximately homogeneous climatically, and levels of electricity-based carbon emissions are similar within each. Thus, this disaggregation pattern also roughly clusters together the different types of power plants existing within each region, based on the EIA’s U.S. Energy Mapping System. Given the scope of this research project, having only four regions is a simplified first attempt at injecting regional resolution into the CIMS-US model.

Data for the Disaggregated CIMS-US Model

The process to populate the model with data involved two major steps:

Step 1: To populate all four regions of the electricity generation sector in the model, I adapted Census Region electricity generation data from both the historical database and the future projected data produced by the National Energy Modelling System (NEMS), a hybrid energy-economy model developed and used by the EPA. NEMS is used to produce the U.S. EIA’s Annual Energy Outlook (AEO) forecasts; it performs analyses at the state, regional and national levels. This model is an excellent data source since it serves the U.S. Congress, governmental departments and agencies to analyze various existing and proposed policies. NEMS achieves supply and demand balance in the nine U.S. Census Regions (U.S. EIA, 2009).

Step 2: Based on the regional electricity generation sector's data populated into the four CIMS-US regions, I generated proportioning factors from this sector's stock values. I then applied these factors to the existing model's stock data for all other sectors, hence generating regional data for all non-electricity sectors (such as transportation) proportional to the electricity sector. I also updated fuel prices for all sectors in each of the four regions by adopting these directly from the EIA's database of Census Region fuel prices.

While this approach will not be completely accurate for industrial electricity use, it will be fairly accurate for other sectors, such as personal and freight transportation, as well as residential and commercial / institutional buildings, since these are distributed in the U.S. roughly in proportion to energy demand and population.

After model disaggregation, regional U.S. electricity consumption in 2005 is illustrated in figure 3.2. Regions South and Midwest consume 43% and 26% of all U.S. electricity respectively.

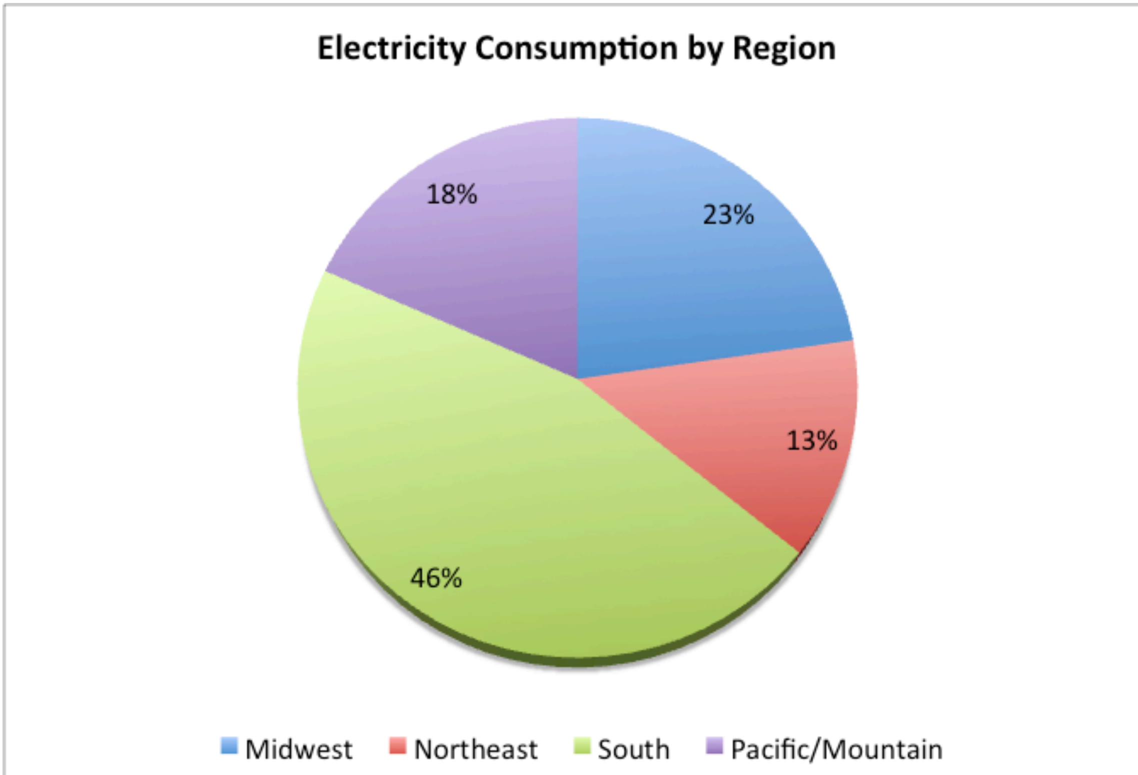

Figure 3.2. Regional electricity consumption across the U.S. in 2005.

Figure 3.3 illustrates regional electricity generation by source in 2005. For coal-fired electricity generation, regions Midwest and South, again, generate the most coal-based electricity. South also dominates in natural gas-fired and nuclear power generation. On the other hand, for renewable sources, Northeast generates the most electricity from biomass, and Pacific/Mountain from hydro, wind and geothermal. This is in accordance with the EIA's Energy Mapping System, where the densest clusters of biomass power plants are located near the Great Lakes and along the northern coast of the Atlantic Ocean. Moreover, most of the U.S. geothermal power plants are found between the borders of Nevada and California. Lastly, the majority of natural gas and coal-based power plants are spread from Census Regions West South Central to South Atlantic respectively. As a result of these regional variations in electricity consumption and generation patterns, one might expect regional variation in the effects produced from implementing flexible policies such as the CPP or an economy-wide carbon tax.

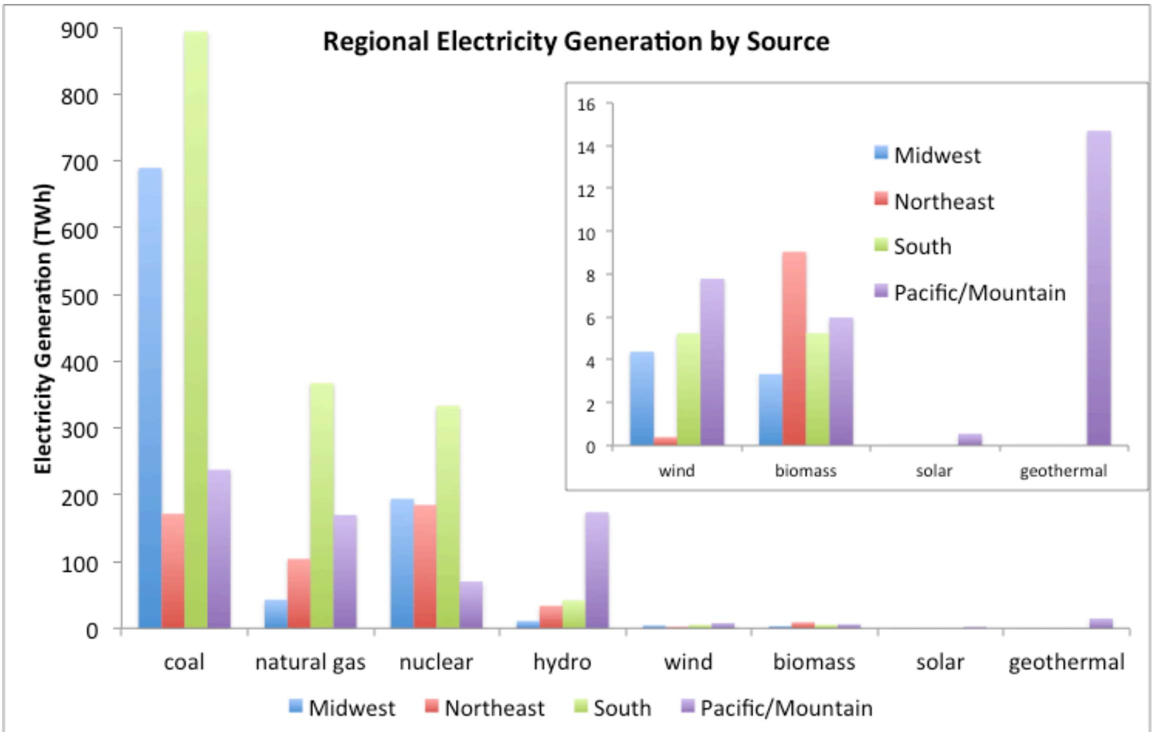

Figure 3.3. Regional electricity generation by source in 2005.

In the transportation sector in 2005, shown in figure 3.4, gasoline and diesel consumption are roughly comparable with population across the four regions, with South and Midwest as the dominant consumers. This regional pattern is also a close reflection of the overall U.S. travel demand. Nearly 90% of all personal travel depends on gasoline, and 80% of freight travel on diesel.

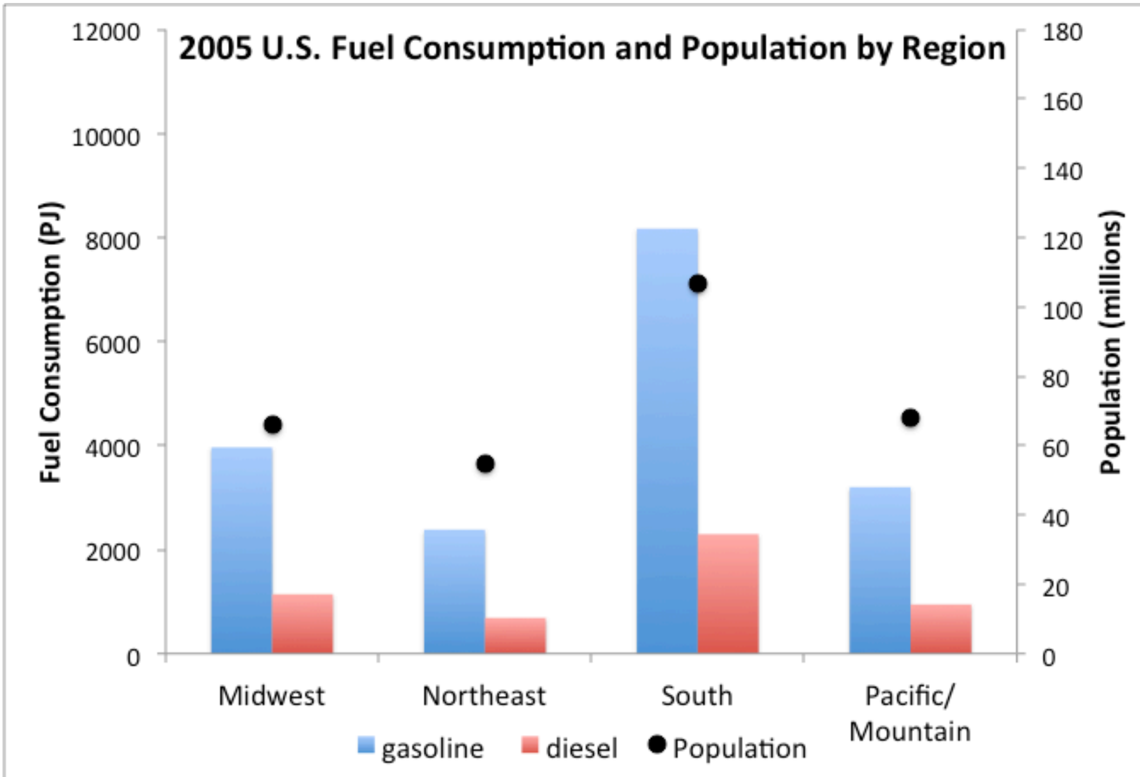

Figure 3.4. Regional fuel consumption from the transportation sector and U.S. population in 2005.

In figure 3.5, regions Midwest and South are the largest GHG emitters, with higher emissions from the electricity generation sector than transportation. These two regions are also the two largest producers of coal-fired electricity, generating 42% of all U.S. electricity from coal alone. The opposite trend occurs in regions Northeast and Pacific/Mountain, where the transportation sector produces more emissions. Therefore, under a given electricity policy, regions will respond differently in their generation mix. As the transportation sector is pushed to increase adoption of electric vehicles, regional full cycle emission trends for transportation may also vary due to differing responses in the decarbonization process of the upstream electricity sector.

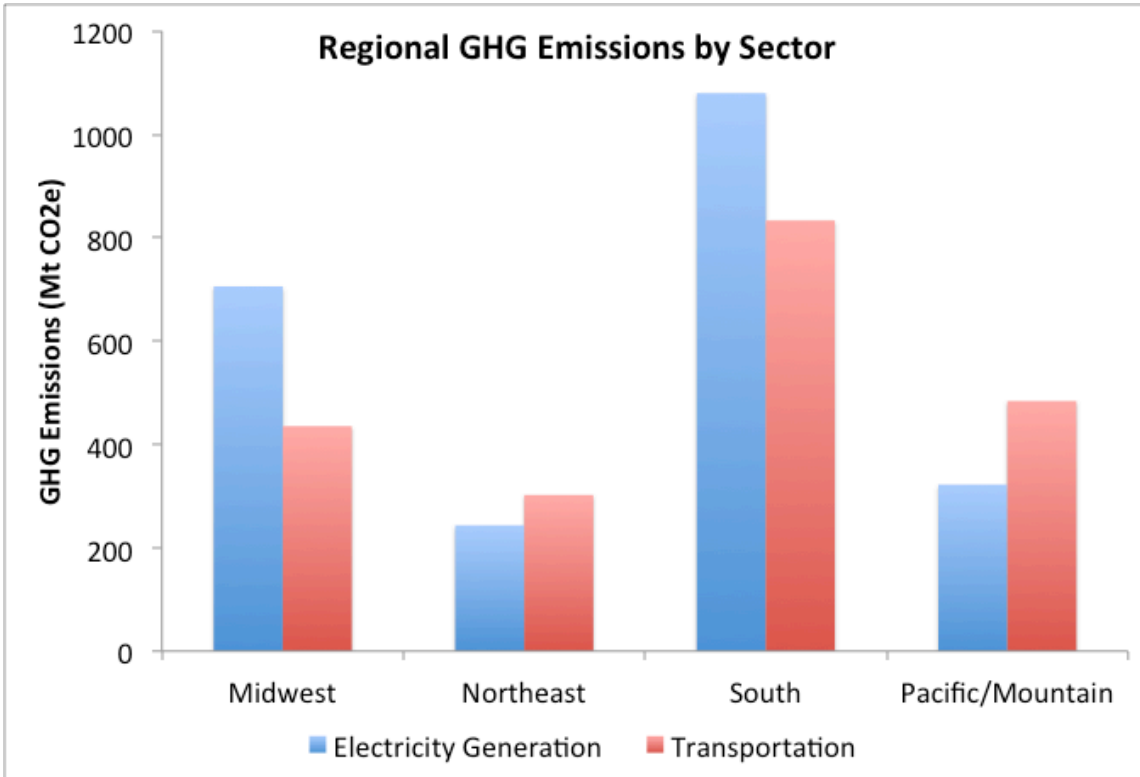

Figure 3.5. Regional GHG emission by sector in 2005.

3.3. Methodology of Climate Policy Simulations

To simulate the existing and proposed U.S. climate policies and evaluate their effectiveness in achieving emissions reduction targets, I modelled the following policies as described in Chapter 2.2.

- EPA's CPP rule
- CAFE standards:
  - 2017-2025 Light-duty CAFE standards, phase 2
  - Proposed medium- and heavy-duty CAFE standards, phase 2
- VES
- Coal and natural gas phase-out regulation
- An economy-wide carbon tax

In the electricity generation sector, the CPP and carbon tax are flexible policies that allow regions to pursue the most cost-effective means of reducing emissions. I modelled both of these policies as emission prices. The phase-out regulation, on the other hand, should produce the same market outcome for all regions given its command-and-control nature. The CAFE standards, in theory, have the possibility of producing varying regional outcomes since they were implemented as emission prices in the personal and freight transportation sectors. However, their effectiveness in reducing emissions may be overridden by a growing population and rebound effects. I simulated the VES by setting minimum market share values and penetration rates for ZEVs. Out of the above electricity and transportation policies, one may expect to observe the most regional variations in market outcomes under the CPP and the economy-wide carbon tax. In order to investigate regional responses using the disaggregated model and simulate possible paths to achieve climate goals previously set by President Obama, I modeled five different combinations of policy scenarios.

Simulation of Climate Policy Scenarios

The scenarios I simulated are detailed below:

1. **Reference Scenario: BAU**
   The business-as-usual scenario serves as a reference case in this modelling exercise. From 2000 to 2010, I populated CIMS-US using historic stock and energy price data reported in the EIA's Electric Power Annual reports (EIA, 2004; EIA 2009). From 2015 to 2040, I adapted forecast data from the 2013 AEO reference scenario, which assumes population growth of 0.9% per year, and GDP 2.5% per year from 2011 to 2040 (EIA, 2013). From 2045 to 2050, I calculated forecast data by extrapolating the growth rate from 2035 to 2040. The AEO 2013 reference scenario assumes existing or approved policies, such as California's Assembly Bill 32 (AB 32), the Regional Greenhouse Gas Initiative (RGGI), and the Clean Air Interstate Rule (CAIR), to be in place. AB 32 requires California to reduce GHG emissions to 1990 levels by 2020,

which is an approximate 15% reduction from a business-as-usual scenario. The RGGI is an electric sector cap-and-trade system that covers nearly all states in the Northeast region; by 2020, it is projected to reduce annual power sector CO2 emissions by 45% relative to 2005 levels (C2ES, 2013). The CAIR controls sulfur dioxide and nitrogen oxides emitted from power plants in eastern U.S. upwind states.

In addition, phase 1 of the CAFE standards for light-, medium- and heavy-duty vehicles are assumed to be in place in the transportation sector for this scenario. Federal proposals such as the CPP rule or policies that I proposed (i.e. the economy-wide carbon tax) are not included.

I adapted forecast data for fuel prices from NEMS to populate my model. NEMS averages these prices from three to four years prior to the present in the transportation sector. For the electricity generation sector, the price forecasts for coal, natural gas, and oil are based on an extrapolation from historical regional trends and world oil prices, actual demand changes, and outcomes obtained from previous runs. The cost of electricity supplied to other sectors is a mix of regulated and competitive pricing for almost all regions. Electricity transmission and distribution costs are considered to be regulated in NEMS, while generation cost is considered to be competitively determined based on the marginal cost of production. Only in parts of Census Region Mountain and CIMS-US region South is pricing completely regulated, while it is fully competitive in New York and New England (EIA, 2013). However, since I adapted regional and sectoral electricity prices from nine Census Regions to populate only four in CIMS-US, the regional resolution was not completely retained. For instance, in the transportation sector, regions Midwest and Pacific/Mountain exhibit very similar electricity costs, while Northeast and South have the highest and lowest costs respectively (figure 3.6).

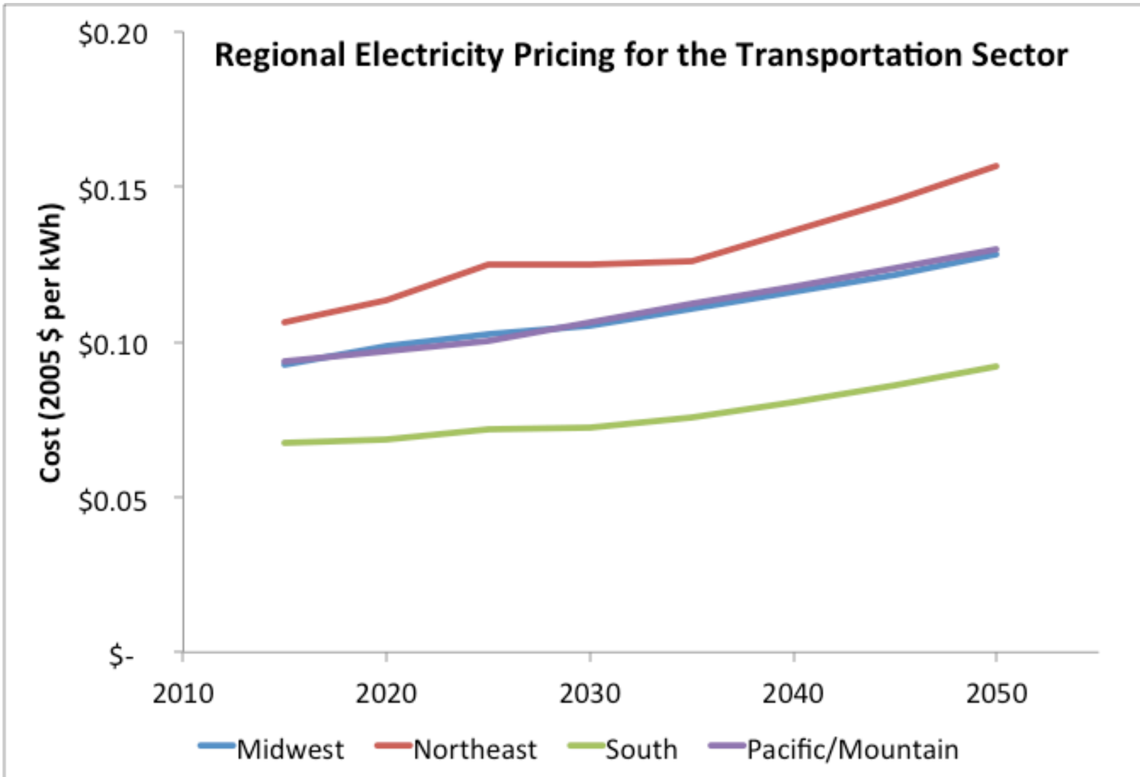

Figure 3.6. Regional electricity pricing in the transportation sector under the BAU scenario.

In the following policy scenarios, I simulated combinations of the aforementioned five policies based on the BAU scenario. Therefore, all of the BAU scenario's policy and pricing assumptions are retained unless directly overridden by the applied policy. These policy scenarios represent political initiatives previously proposed and implemented under President Obama's leadership (i.e. the CPP and the CAFE standards). Where the phase-out regulation, VES and carbon tax are applied, these scenarios evaluate more stringent possible policy paths in reaching a decarbonized electricity sector and an electrified transportation sector by mid-century.

2. **Policy Scenario: CPP+CAFE**

   This scenario simulates the CPP rule from 2025 to 2050, applied with the light-duty CAFE standard from 2017 to 2025 as well as the medium- and heavy-duty CAFE standard from 2018 to 2027. I ran the CPP as an emission price in the electricity generation sector by adapting price values from

Synapse Energy's (2016) CO2 price forecast study on the CPP. Because the CPP allows for a carbon crediting mechanism to achieve its mass- and rate-based performance standards, the price of these tradable credits is an implicit form of carbon price. This price then gets added to the cost of electricity production based on the emission intensity of a given fossil fuel-based generation unit (Bipartisan Policy Center, 2015). I therefore simulated the CPP as a simple carbon tax on the electricity sector. Lastly, I ran both CAFE standards also as emission prices in the personal and freight transportation sectors. The CAFE emission price estimates were taken from the EPA's regulatory impact analyses for these two standards (U.S. EPA & NHTSA, 2011; U.S. EPA & NHTSA, 2015).

3. **Policy Scenario: CPP+CAFE+VES**
   This is a simulation of the above policy scenario #2 with the addition of a VES. I modelled the VES in a similar fashion to California's ZEV mandate for light-duty vehicles. I set the minimum market share of ZEVs in the personal transportation sector to reach market sales goals as outlined by the California Air Resources Board (CARB, 2011). To simulate these sales requirements, I adjusted market share values to reach a minimum share for the combined sales of electric vehicles, fuel cell vehicles, hybrid vehicles (non-plug-in), plug-in hybrid electric vehicles, and biofuel vehicles.

4. **Policy Scenario: CPP+CAFE+Phase-out**
   This is a simulation of policy scenario #2 with the addition of a near-complete phase-out regulation on coal and natural gas electricity generation starting in 2020. Similar to the approach taken by Kniewasser (2009) to simulate a phase-out regulation for coal in Ontario, I applied the regulation by limiting market shares of coal and natural gas-fired power plants to generate base, shoulder and peak load electricity. This regulation prohibits the construction of new natural gas- and coal-fired electricity plants, and does not include carbon capture and storage.

5. **Policy Scenario: CPP+CAFE+CTax**

   This is a simulation of policy scenario #2 with the addition of an economy-wide carbon tax, applied at an increasing tax rate from 2020 to 2050 in the attempt to achieve President Obama's targets of 26% to 28% GHG emissions reduction by 2025, and 80% or more reduction by 2050. In 2020 and 2025, I applied the tax at $50 per tonne of CO2e, and then increased it by $100 every five years to reach $550 per tonne of CO2e by 2050. Note that the carbon tax is the only policy that is applied across all U.S. sectors, while other policies in this study are applied only on the electricity or transportation sector.

6. **Policy Scenario: VES+Phase-out**

   This scenario combines the VES, applied in the personal transportation sector as in scenario CPP+CAFE+VES, along with a phase-out regulation of both coal- and natural gas-fired electricity generation as in scenario CPP+CAFE+Phase-out This policy scenario is unique from the others since it combines the two regulations without implementing a flexible price-based policy.

Table 3.1 details these sector-specific and economy-wide pricing policy scenarios in a matrix.

Table 3.1. Policy scenario matrix categorized by sector.

Sector	Policy	Reference	Policy Scenario				
		BAU	CPP+CAFE	CPP+CAFE +VES	CPP+CAFE+ Phase-out	CPP+CAFE+ CTax	VES+ Phase-out
Electricity Generation	CPP	--	✖	✖	✖	✖	--
	Phase-Out Regulation	--	--	--	✖	--	✖
Personal Transportation	VES	--	--	✖	--	--	✖
	CAFE: Light-Duty	--	✖	✖	✖	✖	--
Freight Transportation	CAFE: Medium- & Heavy-Duty	--	✖	✖	✖	✖	--
All U.S. Sectors	Carbon Tax	--	--	--	--	✖	--

Chapter 4.

Results and Discussion

This section examines the outcomes from each scenario nationally and regionally in the electricity generation and transportation sectors. Hereafter, I refer to CPP+CAFE, CPP+CAFE+VES, CPP+CAFE+Phase-out and VES+Phase-out as sectoral policy scenarios, because their policies are sectorally specific. To contrast, in scenario CPP+CAFE+CTax, the carbon tax was applied across all sectors.

4.1. BAU Scenario Analysis

Under the BAU scenario, national GHG emissions rise steadily by 1% to 2% every five years, reaching 6,605 Mt CO2e by 2050. The two dominant emitters, regions South and Midwest, respectively contribute 46% and 23% to total U.S. emissions. This trajectory certainly does not satisfy any of the climate targets previously set under President Obama's administration.

U.S. electricity consumption grows slowly across the four regions until 2030, at about 1% every five years. Beginning in 2035, consumption rates increase. This observation is consistent with Jaccard and Goldberg's (2014) modelling observations for the U.S., where the slow consumption growth reflects energy efficiency gains outweighing the increase in electricity demand, while in the latter period, demand growth exceeds the effect of gains in electricity efficiency.

Electricity Generation Sector

By 2050, as shown in figure 4.1, coal and natural gas remain as the two most dominate sources for electricity generation in all regions, with South producing nearly half of all U.S. coal- and natural gas-fired electricity. Pacific/Mountain is the largest producer of hydropower, generating 50% of the country's total hydroelectricity; however, this is only 3% of the U.S. total electricity production in 2050.

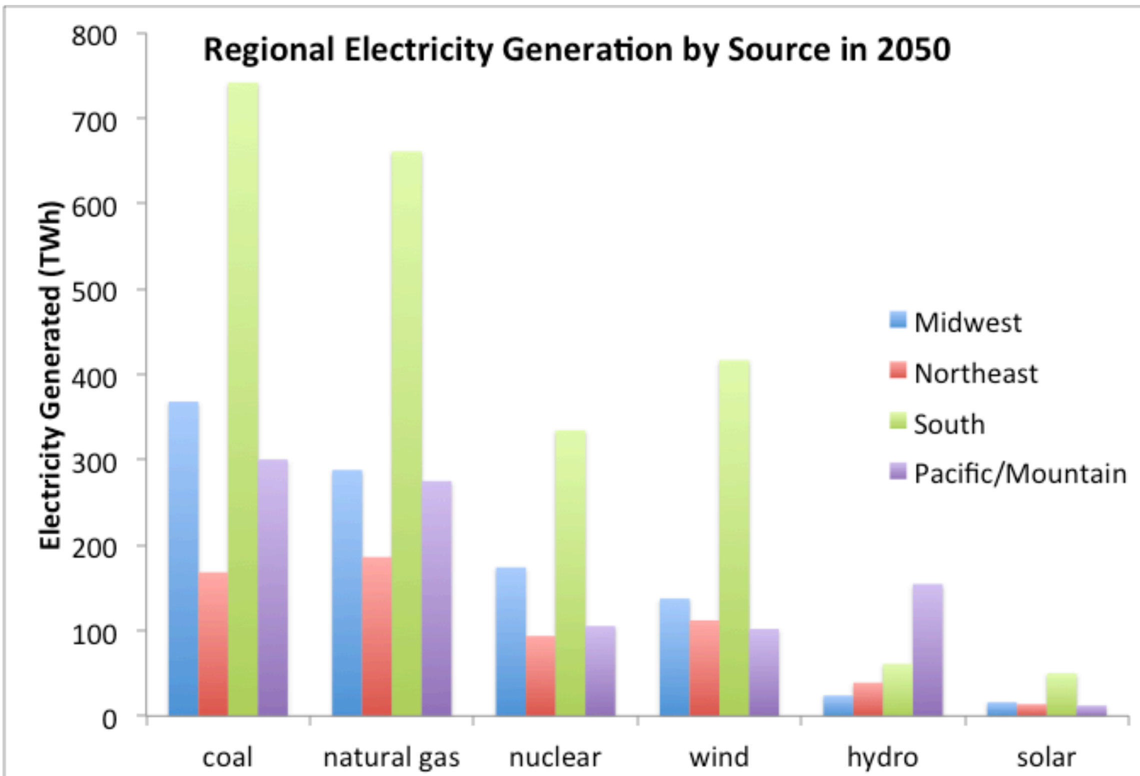

Figure 4.1. Regional electricity generation mix in 2050 under the BAU scenario.

Figure 4.2 shows regional electricity generation by source from 2030 to 2050. Coal-based generation decreases until 2040 in Midwest, Northeast and South, but remains steady in Pacific/Mountain. Between 2040 and 2050, it increases by approximately 5% in South and 8% in Pacific/Mountain. Growth of natural gas-fired generation begins to slow in 2030, and then decreases by up to 6% in Northeast and South from 2045 to 2050. In Northeast only, however, natural gas becomes a dominant fuel relative to coal beginning in 2035. Because

Northeast has higher coal prices than other regions, this enables natural gas to compete as an alternative fuel. Pacific/Mountain has the lowest prices for both coal and natural gas; this is reflected in the higher growth rates of generation using these fuels relative to the other regions.

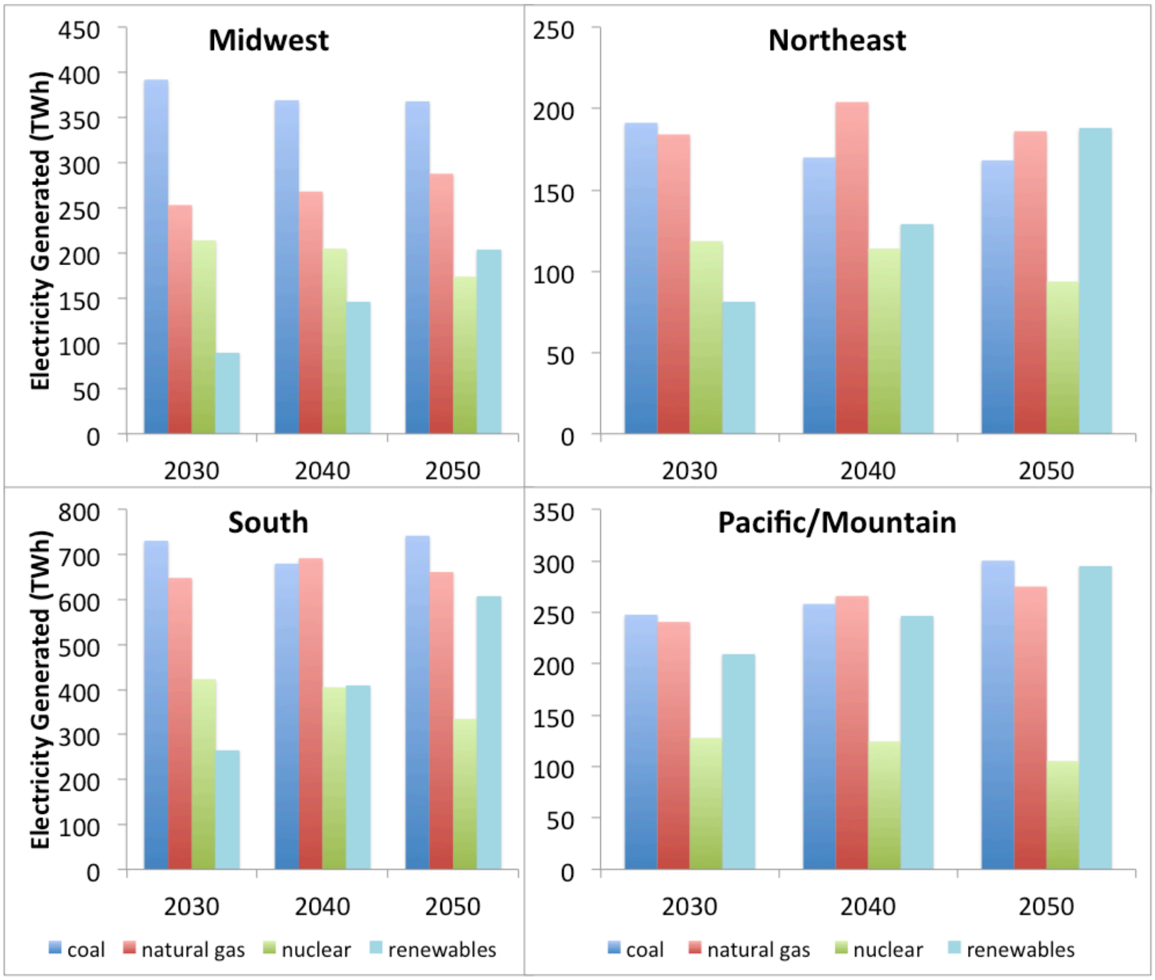

Figure 4.2. Regional electricity generation by source from 2030 to 2050 under the BAU scenario.

Meanwhile, generation by renewable sources significantly increases, with growth rates peaking during 2020 to 2030, and then declining. This occurs in all regions except Pacific/Mountain, which maintains a constant rate of growth of 7% to 10% every five years from 2020 to 2050. Under the influence of California's AB 32 and the RGGI, 30% of Pacific/Mountain's and Northeast's electricity is produced using renewables by 2050, versus 20% and 26% in Midwest and South respectively. Because fuel prices for renewables and nuclear are not regionally distinct in my model, their electricity production results directly reflect the changes in fossil fuel-based generation. Due to higher price increases for natural gas and nuclear, coal still remains the cheapest fuel across the country by mid-century.

In the electricity generation sector, GHG emissions remain nearly constant throughout the entire modelling period for Pacific/Mountain. In other regions, emissions decrease by 37% in Northeast, 31% for Midwest, and 20% for South relative to 2005 levels. I show these regional emission results in figure 4.3. It is not surprising that Midwest remains as the second largest emitter, given its limited transition to alternative fuels, while the other regions switch to less carbon-intensive sources such as natural gas and renewables. Pacific/Mountain is a rather interesting region, where GHG emissions remain constant over time despite climate policies in California. Due to low coal prices in the Mountain Census Region, coal-fired generation grows and continues to play a major role in Pacific/Mountain until 2050.

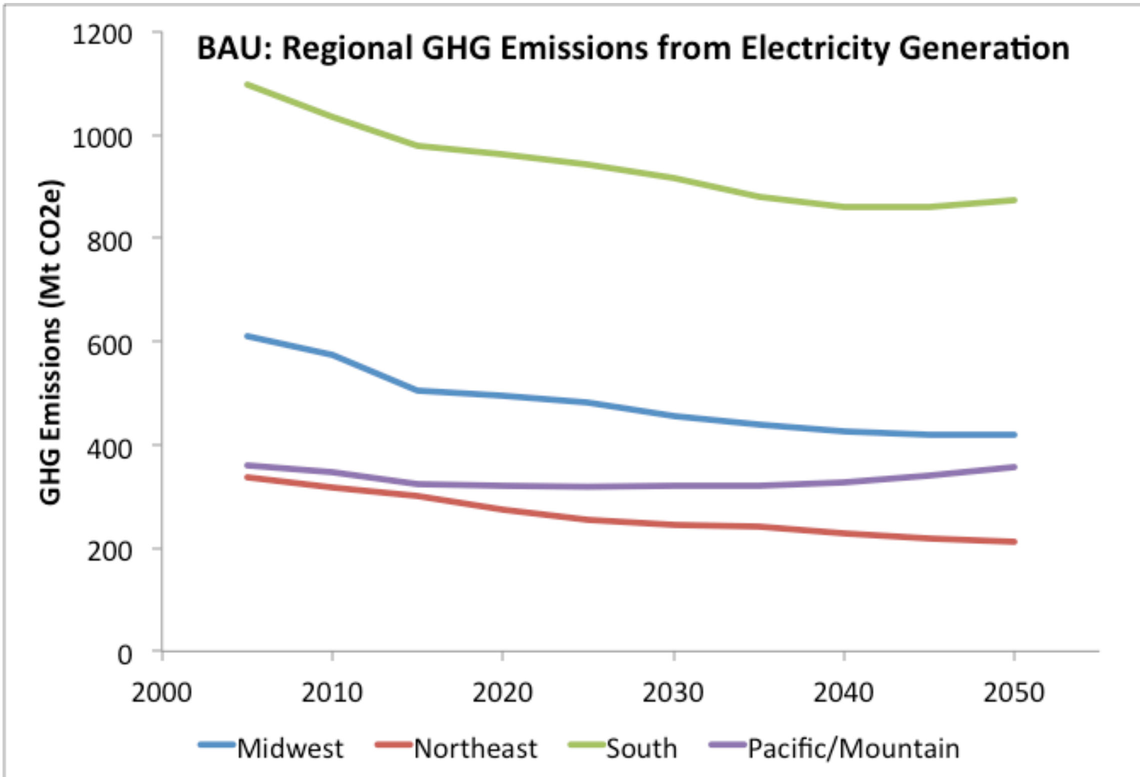

Figure 4.3. Regional GHG emissions from electricity generation under the BAU scenario.

I show coal and natural gas prices in the electricity generation sector for all regions in figure 4.4. As mentioned, these prices are adapted from the NEMS forecasts for the CIMS-US regions. Regions Pacific/Mountain and Midwest (the most emission-intensive region) have the lowest coal prices. Due to the existing RGGI, Northeast has the highest coal price along with the sharpest increase in natural gas price from 2035 to 2050.

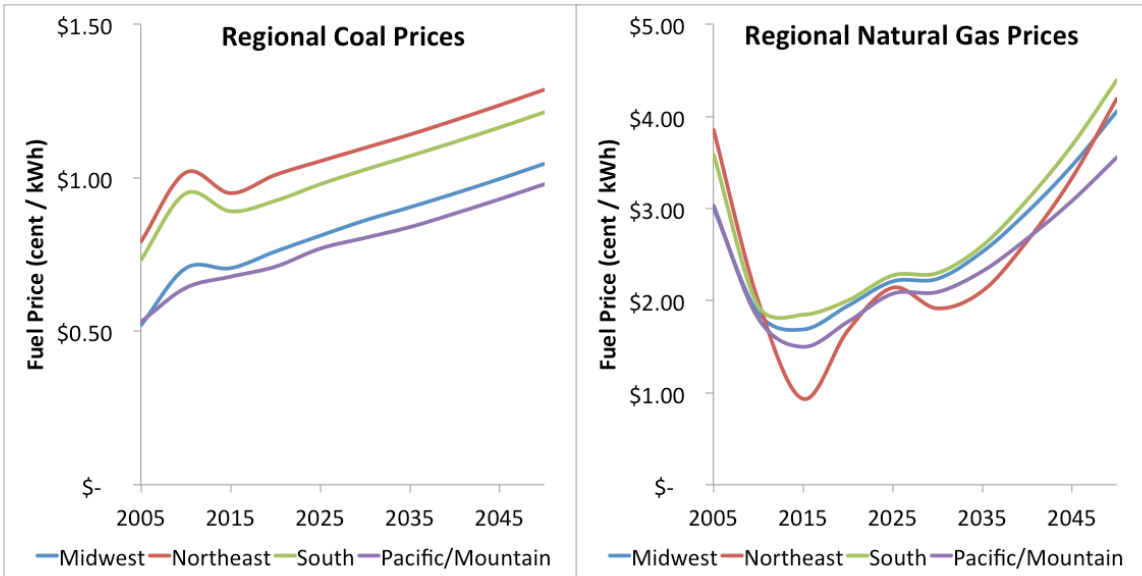

Figure 4.4. Regional coal (left) and natural gas (right) prices in the electricity generation sector.

Transportation Sectors

Regional total market share profiles for personal transportation are nearly identical across the country; in figure 4.5, I show only Midwest as an example. In 2020, conventional and diesel vehicles dominate the market; but by 2050, hybrid and fuel cell vehicles occupy approximately half of the market, including 2% for plug-in hybrid electric vehicles (PHEVs). As ZEV technologies mature over time, their market shares grow to replace gasoline and diesel vehicles. My results are very similar to the BAU scenario in the EMF 24 study by Jaccard and Goldberg (2014). Under an optimistic assumption for the adoption rate of energy efficient end-use technologies, their findings reflect over 70% of conventional vehicles in 2020, and over 60% of ZEVs by 2050.

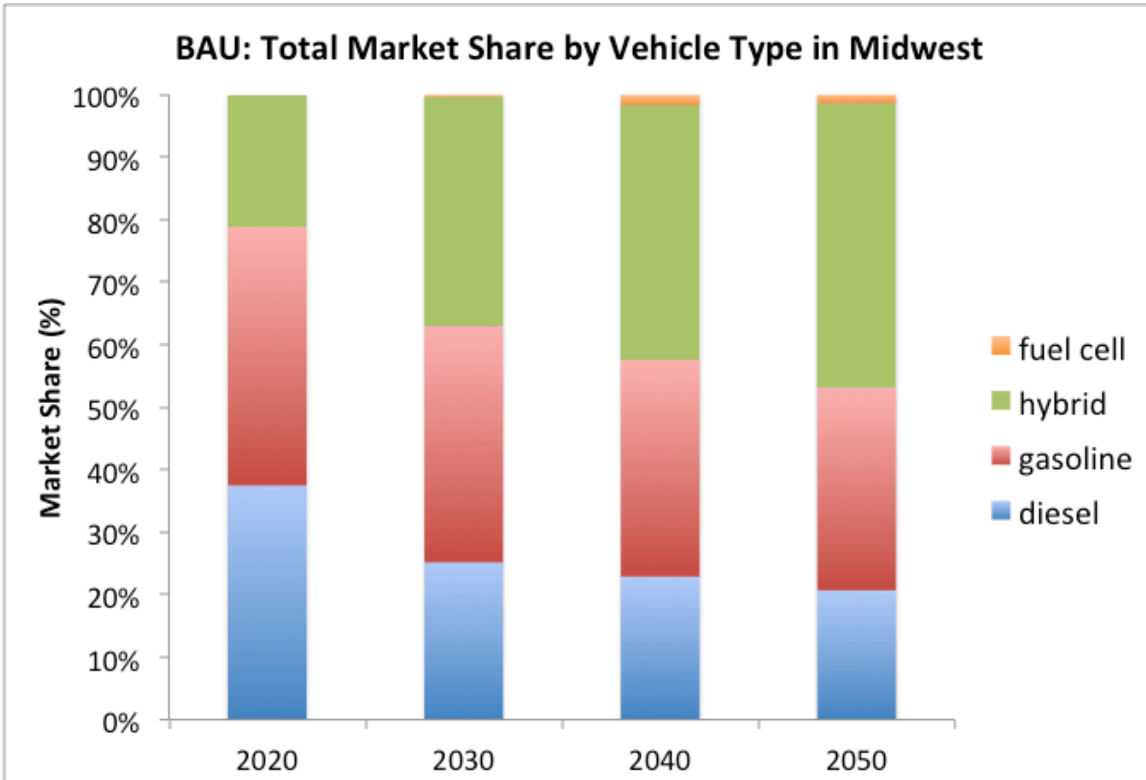

Figure 4.5. Total market share by vehicle type in region Midwest for the personal transportation sector under the BAU scenario.

In figure 4.6, I illustrate the mix of vehicle type in 2030 and 2050 in the BAU scenario, expressed as percentages of total person-kilometer-travelled (pkt) and tonne-kilometer-travelled (tkt) per vehicle type for personal (top) and freight (bottom) transportation sectors respectively. In both sectors, even by 2050, electric vehicles contribute to less than 0.01% of total kilometers travelled. Instead, conventional gasoline vehicles and diesel vehicles dominate. From 2030 to 2050, travel demand for conventional vehicles decreases by 3%, replaced by growth for hybrids, PHEVs, and fuel cell vehicles. For freight transportation, diesel vehicles remain at approximately 76% market share from 2005 to 2050, with the remaining 20% for gasoline and heavy fuel oil vehicles. Similar to electricity generation mix, South and Midwest have the highest demand for travel, followed by Pacific/Mountain and Northeast. This also directly correlates with regional emissions in the same comparative trend.

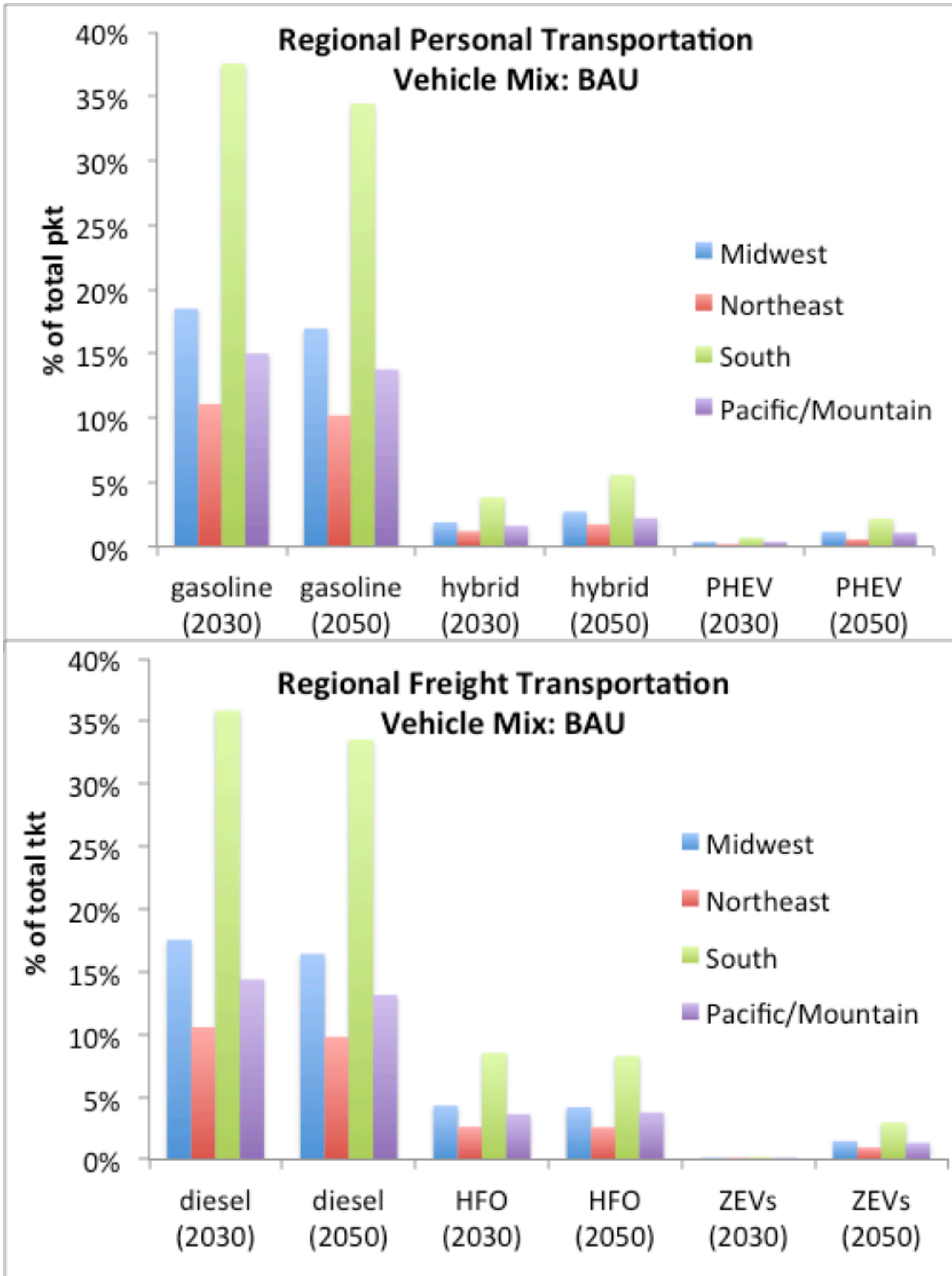

Figure 4.6. Regional vehicle type in the personal (top) and freight (bottom) transportation sectors for the BAU scenario in 2030 and 2050.[2]

[2] HFO is heavy fuel oil. ZEVs include hybrid and fuel cell vehicles.

In the BAU scenario, regional end-use GHG emissions from the transportation sectors follow the same comparative trend as in the electricity sector, shown in figure 4.7. By 2050, total transportation emissions rise by approximately 20% in Pacific/Mountain and 25% in all other regions, relative to 2005 levels. In the same year, demand for personal transportation, measured in pkt, increases by 93%. Freight transportation, measured in tkt, increases by 27%. Since phase 1 CAFE standards for light-duty vehicles are assumed to be in place until model year 2016, and medium- and heavy-duty until 2018, emissions rapidly rise after 2015, in part as a result of rebound effects, and in part because of general growth in population and vehicle mobility. From 2040 to 2050, as the price of diesel continues to increase, fuel economy of freight vehicles improves – travel demand for high fuel efficiency freight vehicles increases by 10% to 14% every five years, and demand for lower fuel efficiency vehicles decreases by 10% to 22%. This lowers end-use emissions from the freight transportation sector.

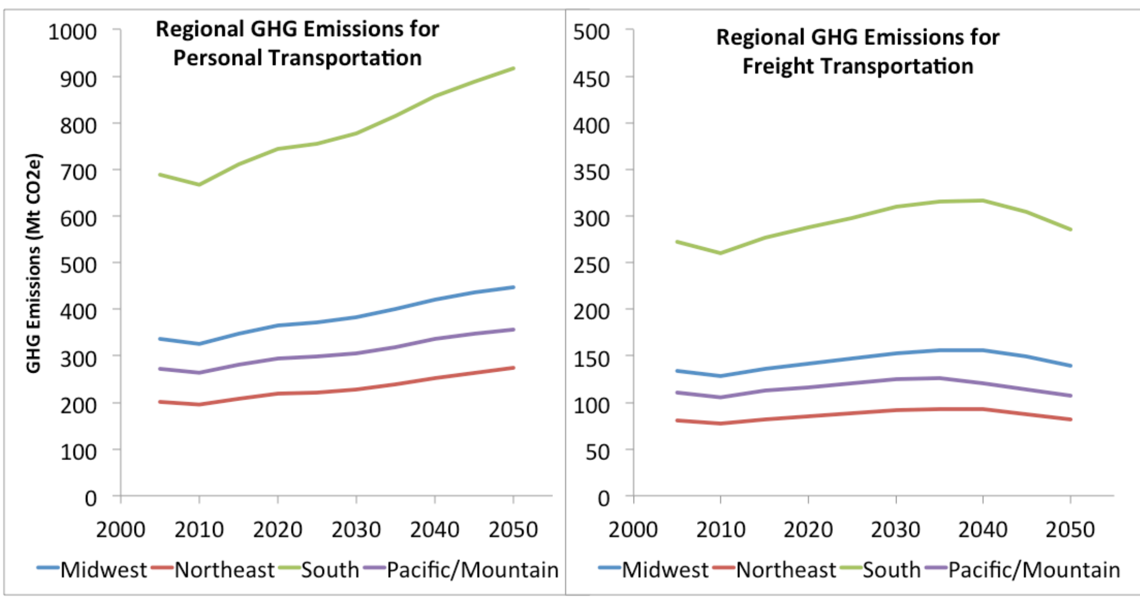

Figure 4.7. Regional end-use GHG emissions from the personal (left) and freight (right) transportation sectors in the BAU scenario.

Figure 4.8 illustrates BAU changes in the transportation sector's fuel prices relative to 2005 using region South as an example.

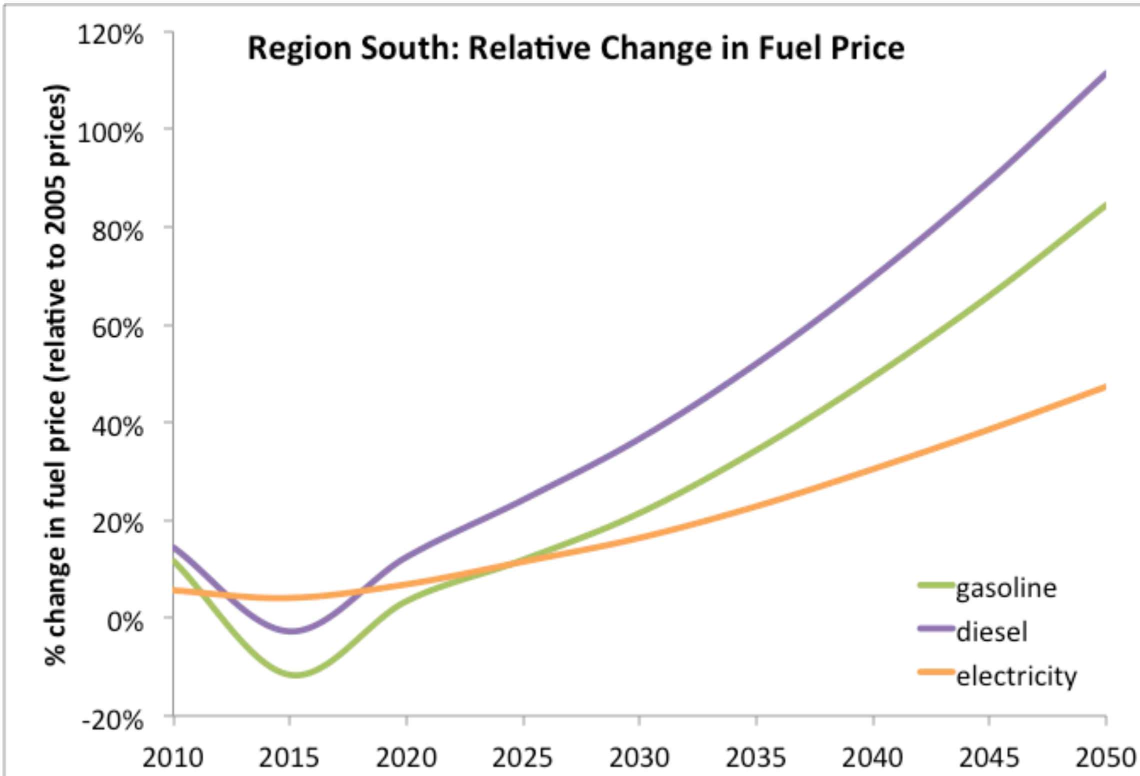

Figure 4.8. Change in transportation fuel prices for region South relative to 2005 prices.

For the personal transportation sector, I also calculated full cycle emissions for conventional vehicles and electricity-powered ZEVs, which include PHEVs and electric vehicles (EVs), shown in figure 4.9. Note that ZEV emissions (right) are plotted on a y-axis scaled to one-tenth of the conventional vehicle emissions (left). I combined regional well-to-tank emissions (Cooney et al., 2017) with CIMS-US end-use emission results to obtain full cycle emissions for conventional vehicles. Well-to-tank processes include fuel production, refining and transportation, which contribute approximately 23% to 26% to full cycle emissions. Conventional vehicle full cycle emissions exhibit the same trends as end-use emissions. For PHEVs and EVs, I calculated upstream emissions by multiplying electricity emission intensity by electricity use from personal transportation. Because EV travel is minimal, only PHEVs primarily contribute to the full cycle emissions calculation. Since these two ZEVs are not competitive enough to gain significant market share, their contribution to total transportation full cycle emissions remains very low by 2050 under BAU. As EV and PHEV travel gradually rises across the modelling period, full cycle emissions also increase at a rate proportional to their electricity consumption.

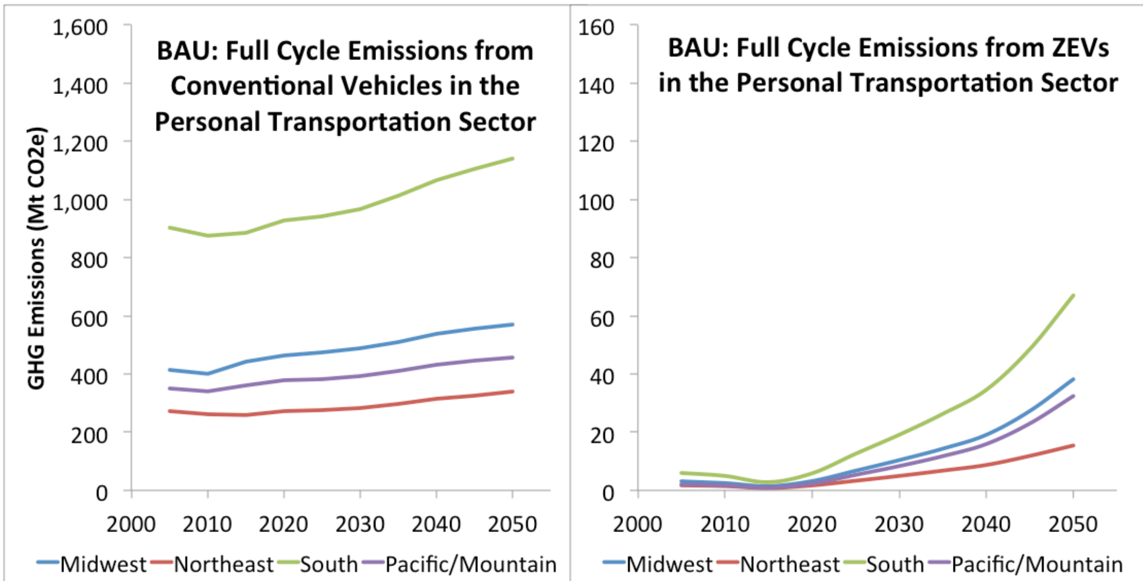

Figure 4.9. Regional full cycle GHG emissions from conventional vehicles (left) and ZEVs (right) in the personal transportation sector under the BAU scenario.[3]

4.2. Emission Intensity Analysis

To detect regional variation, I calculated emission intensities from electricity generation under all model scenarios. Figure 4.10 illustrates these results in 2050. By mid-century, Midwest remains as the most emission-intensive region under scenarios BAU and CPP+CAFE(+VES)[4]. Proportionally, this region

[3] Note: GHG emissions level on the y-axis for ZEVs (right) is scaled ten times smaller than for conventional vehicles (left).

[4] CPP+CAFE and CPP+CAFE+VES are identical policy scenarios for the electricity generation sector, with minimal impact resulting from transportation regulations. Therefore, I simply write CPP+CAFE(+VES) to represent both. Their emission intensity profiles are illustrated in more details in the next section.

has the highest level of fossil fuel-based electricity production, but the four regions are almost identical. For example, in the BAU scenario, 63% of all Midwest electricity is produced from coal and natural gas, while 60% in South, 59% in Pacific/Mountain, and 56% in Northeast are produced from these two fuels. As these percentages show, differences between these regions are negligible.

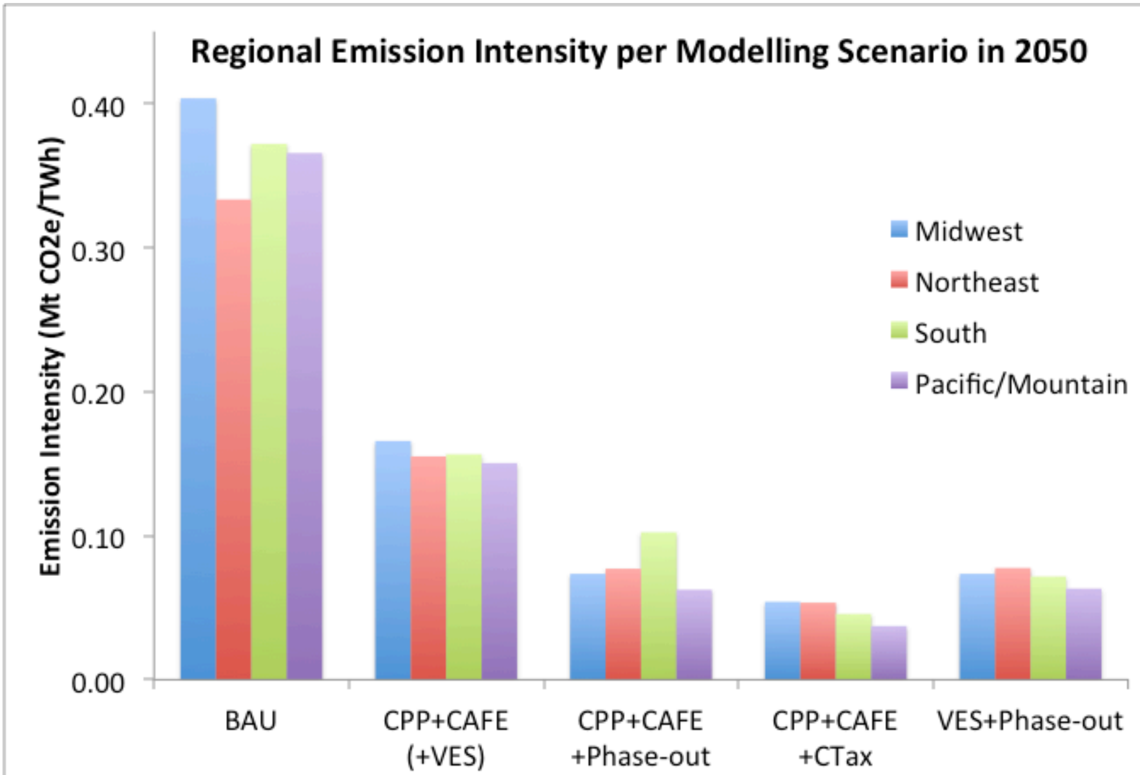

Figure 4.10. Regional emission intensity per model scenario in the electricity generation sector in 2050.

Consequently, policy simulations produced similar electricity generation mixes across the four regions. In the transportation sector, regions also responded with minimal regional variation in terms of ZEV adoption and relative emission reductions. In the following discussion of the policy scenarios, therefore, where regional responses are very similar, I present results for only one region as an example. Following this presentation of policy results, I discuss the effectiveness of the disaggregation of the CIMS-US model in my study, and possible directions for future research.

4.3. Policy Analysis: Electricity Generation Sector

Through each policy simulation, CIMS-US calculates new technology capital stock in each time period. New technology capital stock is the difference between the residual services provided by non-retired initial stock and the total forecasted energy service demand in each time period. Hence, total stock is the sum of new and residual stock. For the electricity generation sector, all stock values are reported as the amount of electricity produced in terawatt hours (TWh). This section examines regional electricity generation outcomes in terms of total stock.

To help guide the policy analysis of the electricity generation sector, I first compare how emission intensities evolve over time under all model scenarios to look for insightful simulation outcomes. Since the four regions all exhibit the same trends in emission intensity, figure 4.11 shows Midwest as an example. As noted earlier, generation outcomes from scenarios CPP+CAFE and CPP+CAFE+VES are identical, since both scenarios implement only the CPP in the electricity sector. In figure 4.11, the trend lines from these two scenarios (red and green lines) are identical (shown as green). For simplicity, I present their results as CPP+CAFE(+VES) in this discussion section. Emission intensities from CPP+CAFE+Phase-out (purple) and VES+Phase-out (orange) also are identical (shown as orange in the figure); since the phase-out regulation eliminates coal and natural gas use, it effectively overrides the policy outcomes of the CPP in the former scenario. Therefore, in this section, I focus on total stock analysis for scenarios CPP+CAFE(+VES), CPP+CAFE+Phase-out and CPP+CAFE+CTax.

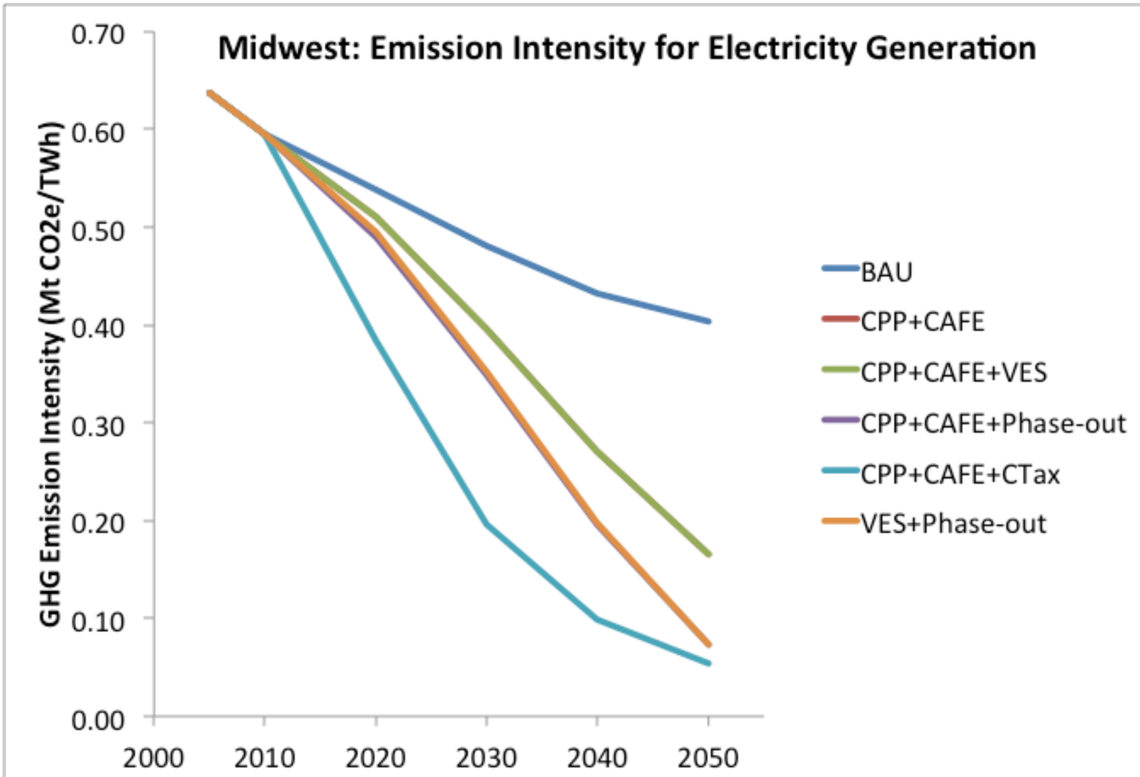

Figure 4.11. Emission intensity in Midwest's electricity generation sector under all model scenarios.

Policy Scenario: CPP+CAFE(+VES)

Figure 4.12 shows the electricity generation mix for each region under scenario CPP+CAFE(+VES) in 2030 and 2050. In agreement with the EIA's projection of the CPP (U.S. EIA, 2015), natural gas becomes a major fossil fuel for electricity generation by 2030. By 2050, coal-fired generation drops by 83% relative to the BAU scenario, and renewables also grow to replace coal by mid-century. In Pacific/Mountain, hydro remains a significant power source. Regions South and Midwest exhibit the largest gains in new stock for renewable power plants.

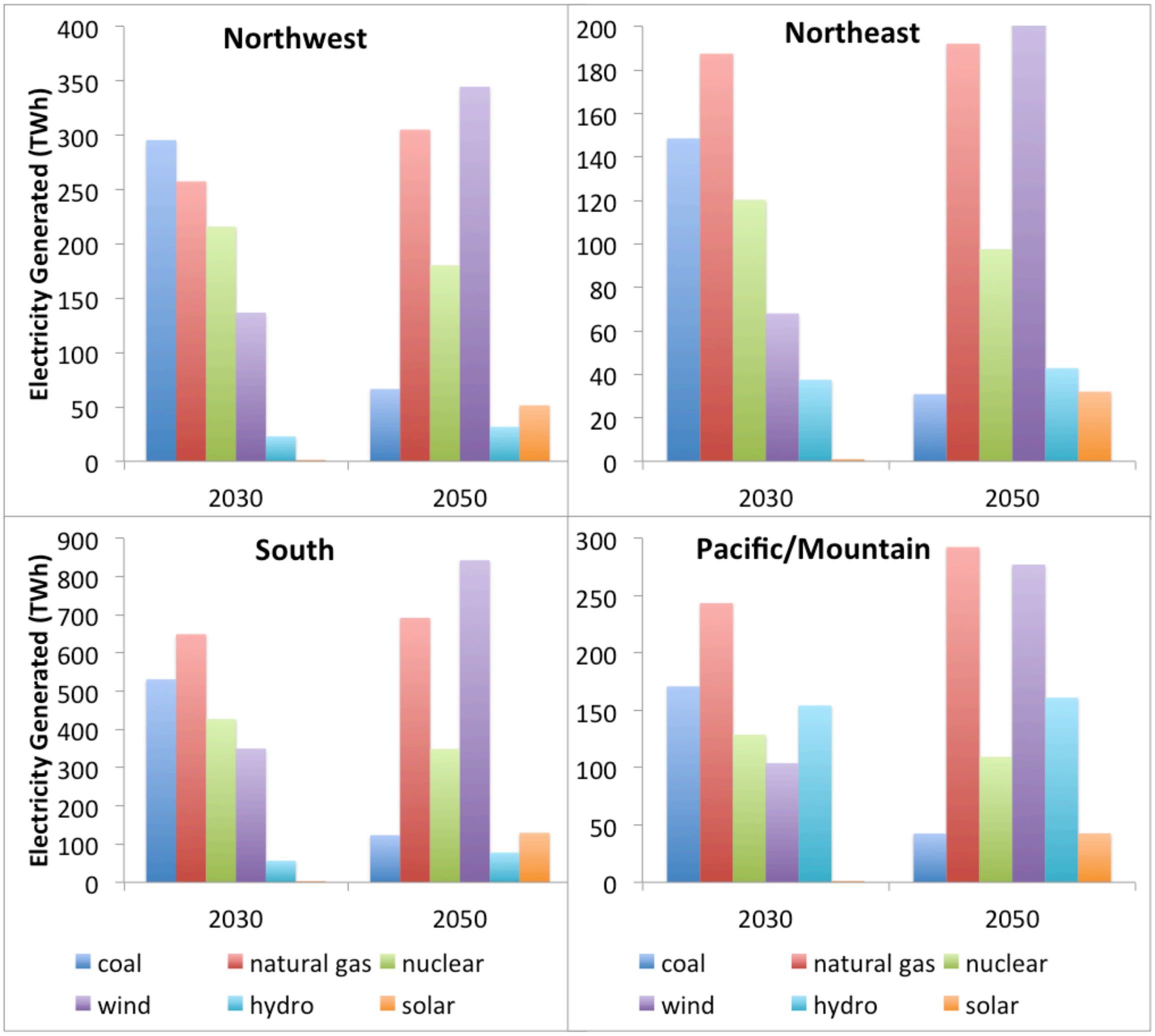

Figure 4.12. Regional electricity generation by source in 2030 and 2050 under the CPP+CAFE(+VES) scenario.

Levelized cost of electricity generation for a given type of power plant is a function of its annualized capital cost, operating cost, energy cost, and total annual output. Furthermore, electricity prices are correlated with levelized cost of generation. In Vass' study (2016), she assumes that a 1% increase in levelized cost results in a 0.5% increase in electricity price. Since the price of electricity is approximately 50% generation cost and 50% transmission, distribution and overhead costs, a 1% increase in generation cost is therefore assumed to increase the electricity price by 0.5%. As mentioned, because the CPP allows for a crediting system to achieve emissions reduction, it functions as an implicit carbon price. I simply simulated the CPP as a carbon price in this sector, which gets added onto the cost of electricity production. Therefore, under this policy, levelized costs of electricity produced from existing coal plants approximately double such that the electricity price for carbon-intensive coal-based electricity also increases. This results in the gradual replacement of coal-fired generation with natural gas and renewables, as shown in my simulation results for the CPP. Lastly, it is important to note that levelized costs differ between fossil fuel-based versus renewable technologies due to intermittency in solar, wind and run-of-river hydro. My study does not account for the extra costs incurred to store electricity generated via intermittent renewable sources. Future studies that simulate electricity policies can account for this as an energy storage cost to accurately reflect changes in the generation mix.

Across the country, electricity prices increase by 8% to 11% in 2050 relative to the BAU scenario, with the largest increases experienced in Midwest and Pacific/Mountain. Unlike other regions, Pacific/Mountain has the lowest natural gas prices as was also observed in the BAU case; hence for this region, electricity production by wind does not exceed that by natural gas in 2050.

While the CPP is effective in eliminating coal as the major fuel, it is not stringent enough in terms of CO2 emissions to encourage the expansion of renewable or nuclear technologies over natural gas. By mid-century, all regions remain heavily dependent on natural gas as a major fuel source. Given the longevity of power plants, locking into this alternative fossil fuel-based technology will likely slow the progression of reducing GHG emissions to reach targets previously set by President Obama. Future studies could investigate the cost of carbon capture and storage (CCS) required to supplement the CPP in reaching these targets.

Policy Scenario: CPP+CAFE+Phase-out

Figure 4.13 shows the electricity generation mix for each region under scenario CPP+CAFE+Phase-out from 2030 to 2050. I simulated the coal and natural gas phase-out regulation so that it starts in 2020. As observed in the previous policy scenario, the CPP alone is able to significantly reduce coal-fired electricity, such that by 2050, it contributes only 4% to 6% to total generated electricity. Hence, the phase-out regulation in this scenario is primarily effective for reducing natural gas-fired electricity. By mid-century, nuclear grows to become the second dominant power source alongside wind.

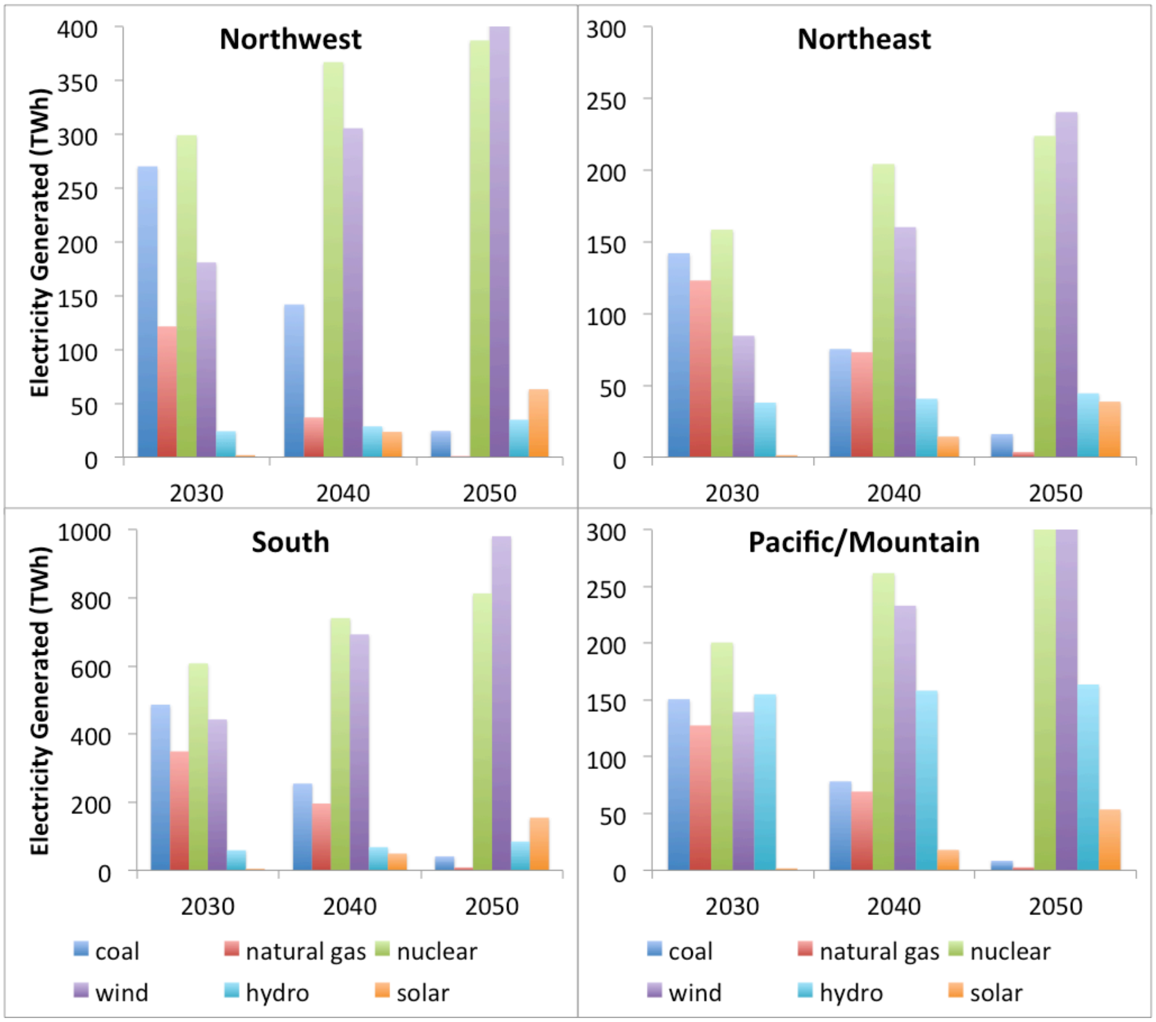

Figure 4.13. Regional electricity generation by source from 2030 to 2050 under scenario CPP+CAFE+Phase-out.

Policy Scenario: CPP+CAFE+CTax

Figure 4.14 shows the electricity generation mix for each region under the CPP+CAFE+CTax scenario from 2030 to 2050. Compared to CPP+CAFE(+VES), the addition of the economy-wide carbon tax exerts an additional price signal to reduce GHG emissions. Therefore, in all regions, nuclear use increases to replace natural gas for electricity production. Stock growth for nuclear plants peaks between 2025 and 2035, and then declines while renewable plants gain new stock. By 2050, nuclear and wind become the two most dominate power sources as also observed under the CPP+CAFE+Phase-out scenario. However, unlike the previous scenario, approximately 35% of electricity in each region is still produced by coal and natural gas. Since the carbon tax covers all sectors, emissions reduction occurs in those with the lowest abatement costs. For this reason, the electricity generation and transportation sectors are not required on their own to satisfy the 80% reduction target by 2050. With reductions occurring in other sectors, a portion of coal and natural gas use remains for electricity generation.

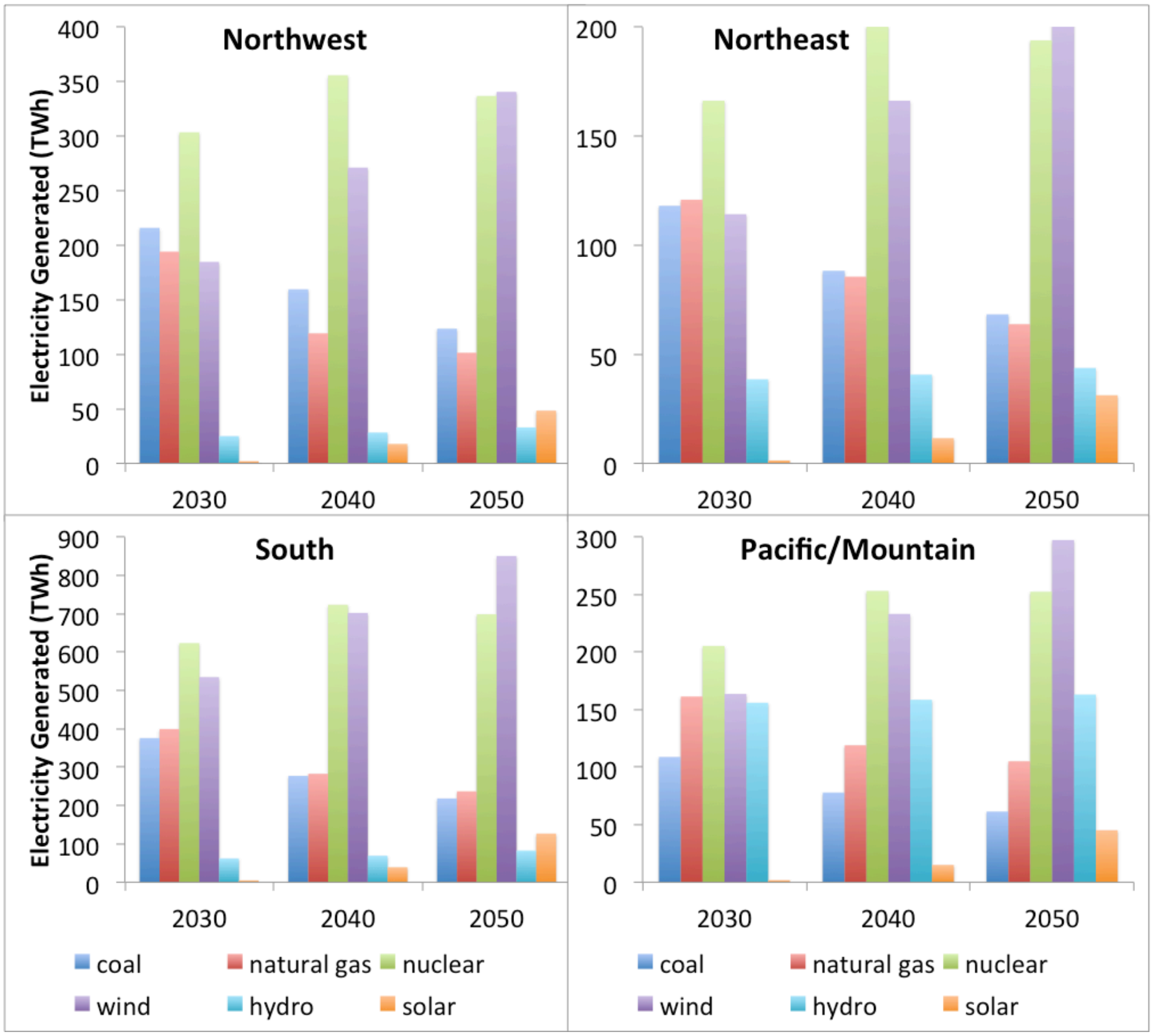

Figure 4.14. Regional electricity generation by source from 2030 to 2050 under scenario CPP+CAFE+CTax.

In Pacific/Mountain, the use of coal is approximately only half of natural gas for electricity production, while other regions retain near-equal use of these two fuels. With the large presence of hydropower, Pacific/Mountain is able to achieve the greatest reliance on renewables and nuclear by 2050.

The effectiveness of a well-designed carbon tax to achieve specific reduction targets is dependent on the evolution of generation technologies over time. For example, under President Trump's leadership, the U.S. federal government is willing to allow the expansion of coal-fired generation. If this were to continue for some time, for the U.S. to eventually return to the reduction targets previously made by President Obama, the carbon tax trajectory I designed in this study will not be stringent enough.

4.4. Policy Analysis: Transportation Sectors

I simulated the CAFE standards in both personal and freight transportation sectors, and the VES only in the former. In this section, I examine total stock results, measured in vehicle kilometers travelled (vkt). As observed in the BAU scenario, my simulations produced very similar outcomes across the four regions. In addition, electricity policies have minimal impact on the total vkt; thus, scenarios CPP+CAFE and CPP+CAFE+Phase-out produced the same results in the personal transportation sector, while, for freight travel, CPP+CAFE+VES also produced the same results as the two aforementioned scenarios.

Personal Transportation Sector

The personal transportation sector is not drastically transformed under the policies I simulated; gasoline vehicles remain as the dominant mode of travel. In this section, I discuss the relative effectiveness of my policy scenarios in terms of emissions reduction and market transformation.

To simulate the how the VES would work in practice, with penalties to incentivize vehicle retailers to meet their minimum sales requirements, I set minimum market shares for EVs, which grew at 10% per year beginning in 2015, to a maximum of 80% of the market by 2050. However, because EVs must compete with PHEVs and hybrid vehicles within the VES market niche, under the resulting policy fuel prices, EVs only reach 13% of total market share by 2050 under the CPP+CAFE+VES scenario, and 11% under the VES+Phase-out scenario. Ethanol, biodiesel and biodiesel hybrid vehicles gain virtually 0% market share, and ethanol hybrid vehicles approximately 3% market share as they are outcompeted by other ZEVs due to high biofuel prices. With all ZEVs combined, my design of the VES brings about 42% emissions reduction; when implemented with the CAFE standard, all four regions can expect about a 47% reduction relative to 2005 levels.

Under the CAFE standard, all regions show an increase in PHEV travel beginning in 2020; by 2050, it has grown by 71% relative to the 2050 BAU scenario (versus 52% under the VES). Although this increase is 20% higher under the CAFE standard than the VES, my design of the VES induces a greater adoption of fuel cell and electric vehicles, thus a more thorough decarbonization of this sector. The CAFE standard is, in fact, the least effective in reducing travel demand for both conventional and freight vehicles, with emissions falling by no more than 5% from both transportation sectors combined between 2030 and 2035 relative to 2005 levels. By 2050, personal transportation emissions instead rise by 13% relative to 2005 due to rebound effects. Hence, as fuel costs are lowered through improvements in fuel efficiency, demand for travel increases. In my simulations, it appears that any efficiency gains are offset by increased travel demand. Literature estimates this rebound effect to be approximately 4.7% in the short run and 24.1% in the long run between 1996 and 2004 (Hymel et al., 2010).

If the U.S. were to pursue deep emission reductions for transportation, this sector would need to go through a market transformation by increasing the adoption of ZEVs. While both a carbon tax or VES is able to achieve significant reductions if they were designed with enough stringency, the carbon tax will not specifically require for EV and fuel cell vehicles to penetrate the market. Compared with the VES, my design of the carbon tax causes PHEVs and hybrid vehicles to dominate, as these are the most cost-effective options. However, with a more aggressive VES, one could restrict PHEVs and hybrid vehicles, such that EVs, fuel cell and biofuel vehicles dominated the VES share of the market. Therefore, depending on whether a carbon tax is present and its level of stringency, the VES remains as a crucial policy choice for the U.S. to shift toward fuel cell, biofuel and electric vehicles, and thus decarbonize the transportation sector.

Freight Transportation Sector

Policy simulations in the freight transportation sector, as mentioned, produced only unique outcomes for scenarios CPP+CAFE and CPP+CAFE+CTax, but not regionally. The VES does not affect freight transportation since it was applied only to personal travel, while electricity policies also do not significantly transform the transportation sectors.

Figure 4.15 shows simulation results by vehicle type in 2050 for scenarios BAU, CPP+CAFE and CPP+CAFE+CTax using region South as an example. Refined petroleum products (RPPs) for freight travel, i.e. diesel, heavy fuel oil and gasoline, are divided into three categories: standard, medium and high efficiencies. Relative to the BAU scenario, the CAFE standard reduces travel via standard and medium efficiency vehicles by 12% and 9% respectively, and raises high efficiency vehicles by 4%. EV travel increases by 8% but still remains insubstantial. Thus, the CAFE standard alone is not stringent enough to shift this sector toward lower emission fuels and vehicles. This is not surprising since scenario CPP+CAFE also did not produce significant market transformations and emission reductions for personal transportation, whose CAFE standard I simulated as approximately three times the emission price as for freight.

Under the carbon tax I designed in scenario CPP+CAFE+CTax, adoption of ZEVs for personal and freight transportation reaches approximately 30% in each sector. For personal travel, PHEVs and hybrid vehicles grow to replace conventional vehicles, while for freight, fuel cell and biodiesel vehicles grow. As the carbon tax opts for the lowest costing ZEV options first, electric vehicle adoption remains negligible in my study unless specifically mandated by a regulation such as the VES.

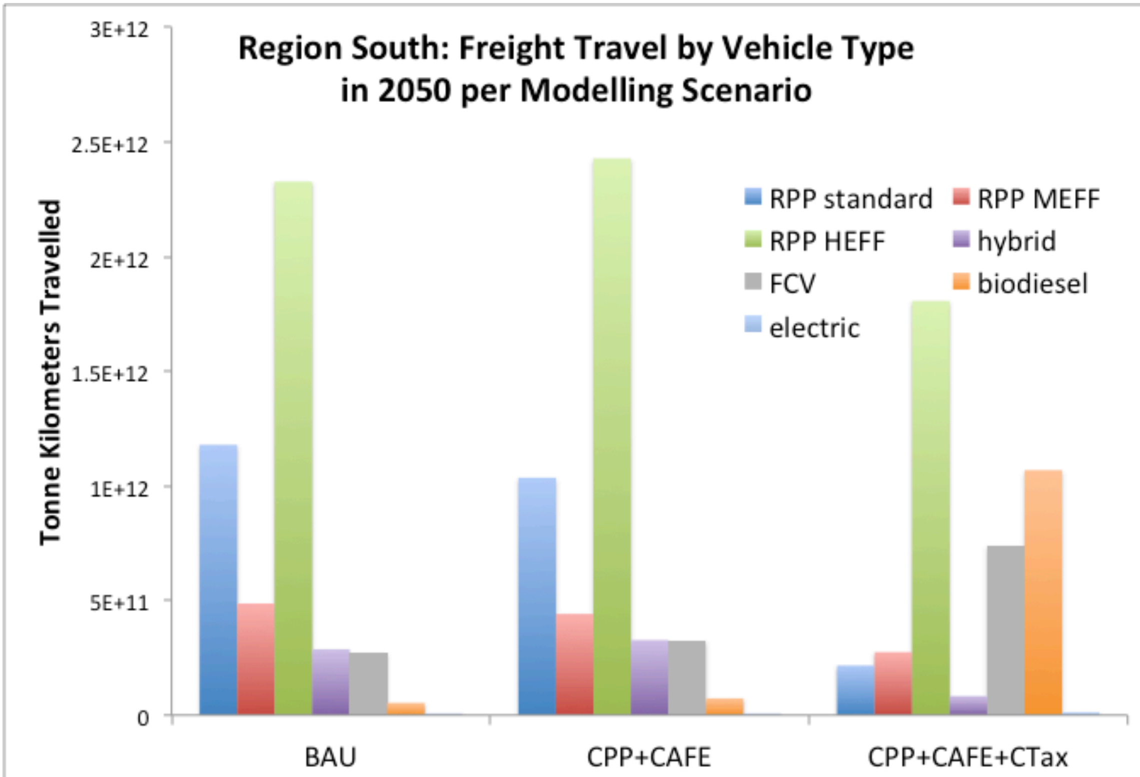

Figure 4.15. Region South freight transportation total stock (pkt) by vehicle type per model scenario in 2050.[5]

4.5. GHG Emissions Analysis

National GHG Emissions Analysis

Recall that the U.S. Intended Nationally Determined Contribution (INDC), as a part of the 2015 Paris Agreement, is to "achieve an economy-wide target of reducing its greenhouse gas emissions by 26% to 28% below its 2005 level by 2025 and to make best efforts to reduce its emissions by 28%", and also to reduce economy-wide emissions 80% or more by 2050 (U.S. INDC, 2015). To reach these targets, total emission levels need to be at 4,801 Mt CO2e in 2025, and 1,298 Mt CO2e in 2050.

[5] FCV is fuel cell vehicle. RPP standard is standard efficiency refined petroleum product, RPP MEFF medium efficiency refined petroleum product, and RPP HEFF high efficiency refined petroleum product.

In scenario CPP+CAFE+CTax, I applied the economy-wide carbon tax at \$50 from 2020 to 2025 to reach 31% reduction by 2030 (4,458 Mt CO2e), and ramped up by \$100 per five years to reach \$550 in 2050 for a 70% reduction (1,930 Mt CO2e). Between 2045 and 2050, due to my model's limited technology for achieving further reductions, the marginal cost of abatement exponentially increases with little progress in achieving the 80% target. Due to the existing RGGI, Northeast experiences the highest abatement costs beyond an annual reduction of 70% in its electricity sector. Unfortunately, because of a lack of sufficient regional distinction, marginal abatement costs are identical across the four regions until the 70% annual reduction threshold.

Figure 4.16 shows total U.S. emission results for all model scenarios. Out of all sectoral policy scenarios, the INDC 26% to 28% reduction target for 2025 is not feasible until 2050 under CPP+CAFE+Phase-out and VES+Phase-out; using the policy stringencies that I have selected, emission levels reach 4,763 and 4,816 Mt CO2e respectively. To accelerate reductions and achieve the economy-wide target of 80% or more by 2050, more stringent policies will be required, one option being the imposition of tighter emission stringency yet technologically flexible regulations on industry, buildings and other sectors.

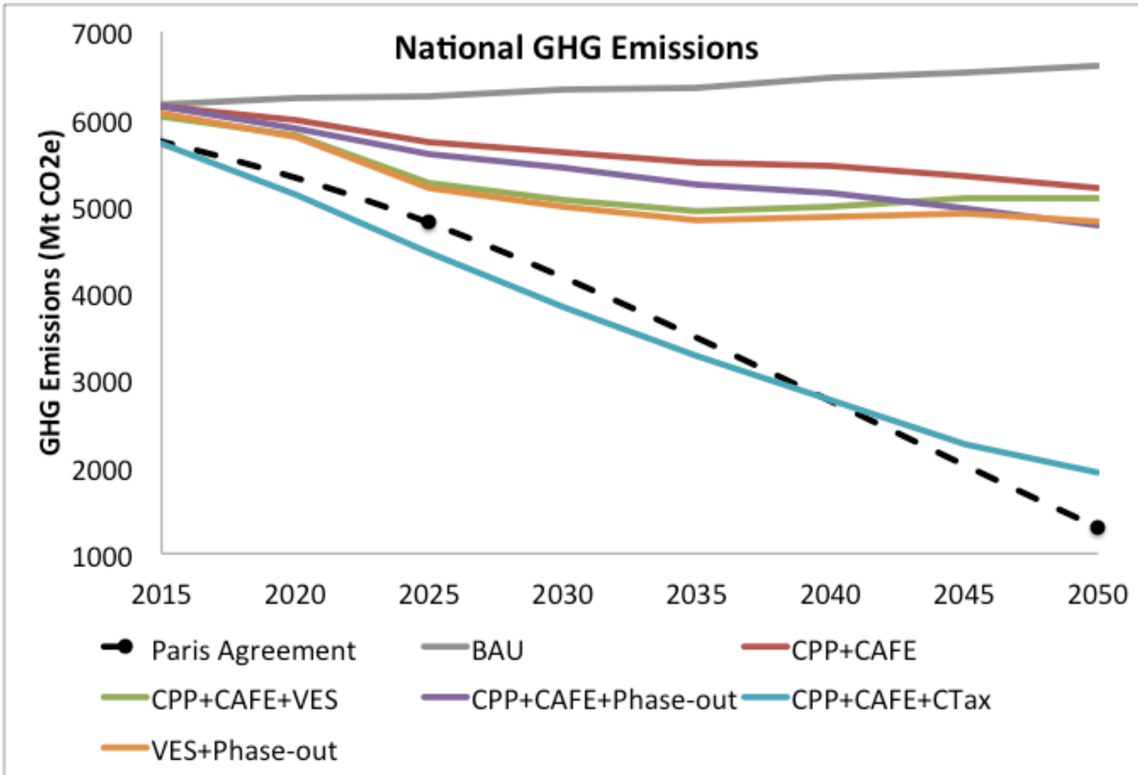

Figure 4.16. National GHG emissions under all model scenarios.

There are three major findings in the national emission results presented in figure 4.16:

1. As expected, the fossil fuel phase-out regulation achieves a deeper reduction than the CPP. When applied alone, the latter primarily phases out coal-fired generation, and by 2050, reduces 80% of emissions of what the phase-out regulation achieves. In 2030, approximately 21% to 23% of electricity is still generated using coal under the regulation and the CPP respectively.

2. In the transportation sectors, the CAFE standards are ineffective at reducing emissions at the currently proposed level of stringency. Any gains in efficiency are likely exceeded by growth in travel demand. On the other hand, under scenarios with my design of the VES, GHG emissions are more rapidly reduced, achieving a 20% reduction as early as 2025, relative to 2005 levels.

3. By withdrawing from the 2015 Paris Agreement, as seen in my BAU scenario results, the U.S. will see an approximate 2% rise in GHG emissions by 2050 relative to 2005 levels, corresponding to a total of 6,605 Mt CO2e. With a growing population and energy demand, and no additional federal or state effort to adopt renewable technologies for electricity generation and transportation, the country will remain as one of the top contributors to global GHG emissions. Approximately 60% of all U.S. electricity will continue to be produced by coal and natural gas by mid-century.

Sectoral Emissions Analysis: Electricity Generation Sector

I implemented two types of sectoral policies on the electricity generation sector – the CPP as well as the coal and natural gas phase-out regulation. Figure 4.17 shows my simulation results for this sector, along with milestone projections of the CPP from the EIA and EPA (U.S. EIA, 2015; U.S. EPA, 2015b). When the EPA finalized the CPP in August 2015, its target was to reduce carbon emissions from the U.S. power sector 32% below 2005 levels (1,633 Mt CO2e) by 2030. This will cause coal-fired electricity generation to decrease with a growing natural gas-fired capacity. The EIA NEMS model projects that the power sector would see reductions of 34% by 2030 and 30% by 2040. In 2040, continued electricity demand growth results in additional generation using fossil fuels, thus a return to growing emissions as shown in the following figure. These model results are subject to variables such as economic growth, fuel prices and future policy changes. My modelling results for the CPP, under scenario CPP+CAFE, satisfy the EPA and the NEMS emission projections for 2030, but not the 2020 and 2025 targets.

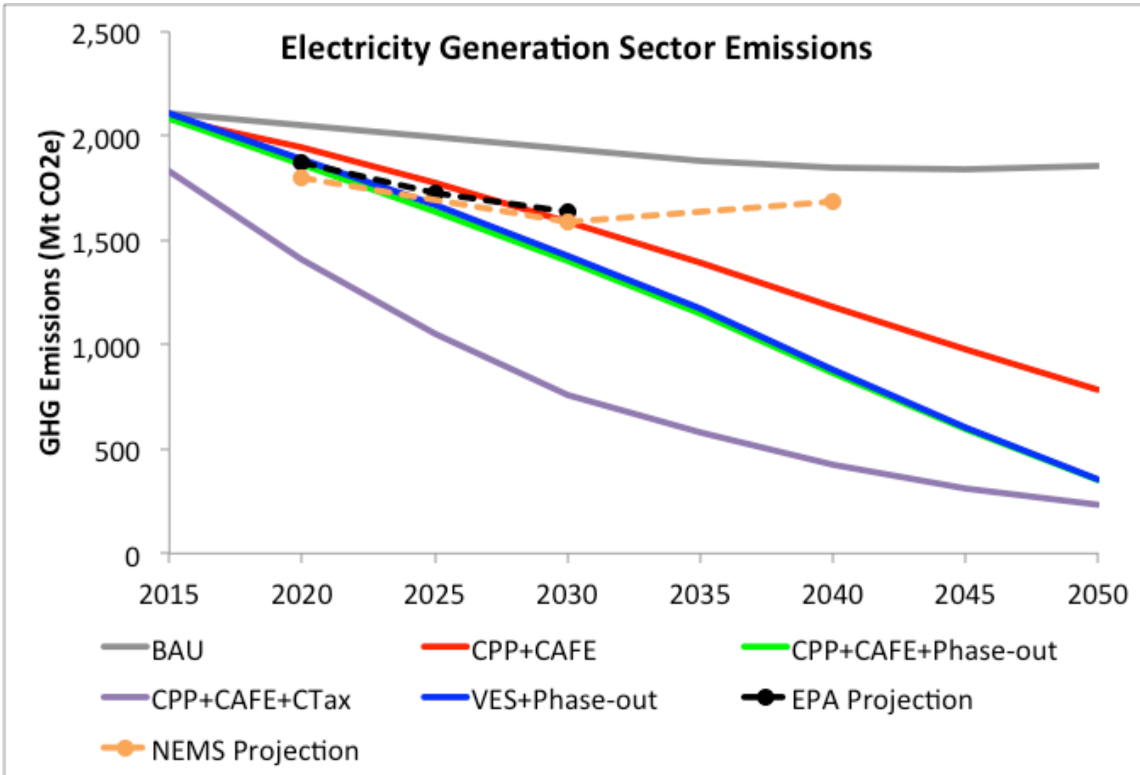

Figure 4.17. U.S. GHG emissions in the electricity generation sector.[6]

In scenario CPP+CAFE+Phase-out, the phase-out regulation further reduces emissions by also eliminating natural gas use; consequently, the U.S. becomes entirely dependent on nuclear and renewable sources for electricity generation. As a result, under scenarios CPP+CAFE+Phase-out and VES+Phase-out, power sector GHG emissions are approximately halved by 2030, and reduced 85% by 2050 (relative to 2005 levels). Because the phase-out regulation is so stringent, its combination with the CPP does not produce any further reductions. Hence, marginal abatement costs under these two scenarios become equal for Midwest, Northeast and Pacific/Mountain.

For region South, implementing the coal and natural gas phase-out regulation alone is more economically efficient for reduction levels above 45% per year. Figure 4.18 illustrates marginal abatement cost curves using regions South (green) and Pacific/Mountain (purple) as an example to compare

[6] Since CPP+CAFE and CPP+CAFE+VES are equivalent policy scenarios for the electricity generation sector. For simplicity, only scenario CPP+CAFE is shown.

scenarios CPP+CAFE+Phase-out (solid lines) and VES+Phase-out (dashed lines).

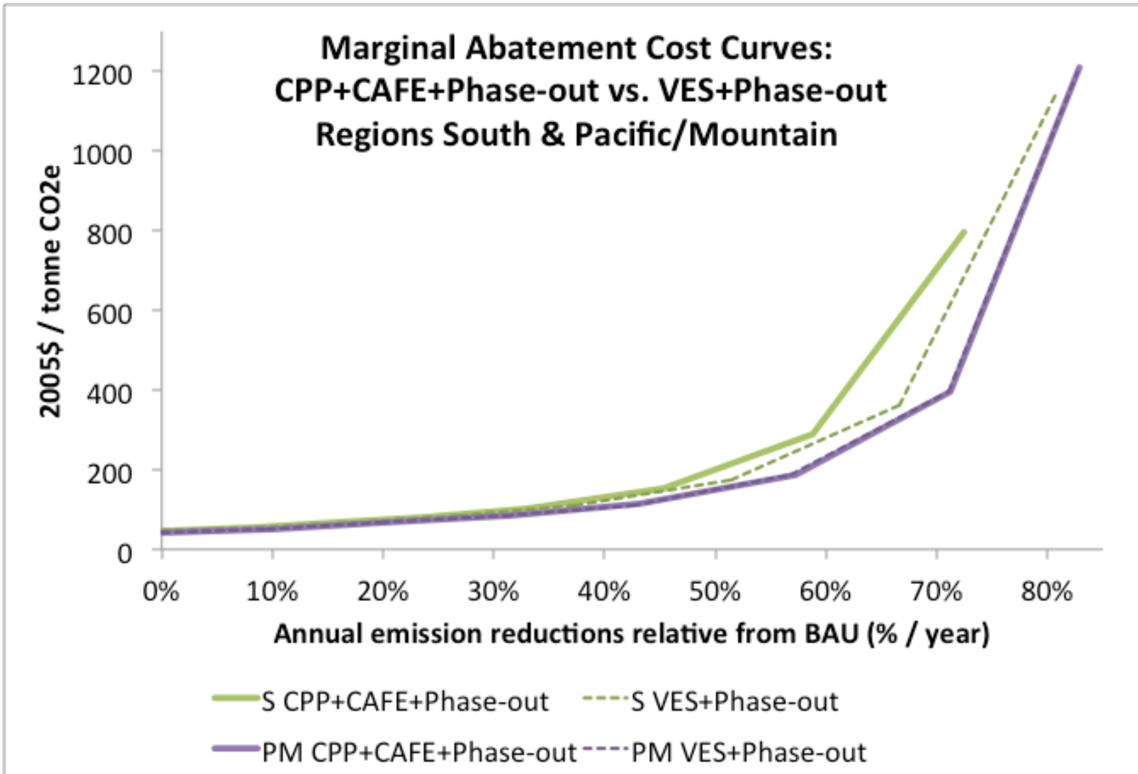

Figure 4.18. Regional marginal abatement cost curve comparisons between scenarios CPP+CAFE+Phase-out and VES+Phase-out for regions South and Pacific/Mountain.[7]

South's GHG emissions under scenario CPP+CAFE+Phase-out are higher than VES+Phase-out; by 2050, this difference is at 72 Mt CO2e, which translates to a 7% deeper reduction under VES+Phase-out relative to 2005 levels. This is a small difference, but it reflects some regionally distinct characteristics. For all regions but Pacific/Mountain, the two electricity policies in scenario CPP+CAFE+Phase-out together induce faster renewable technology growth from 2020 to 2040. During the initial years immediately after policy implementation, regions are still primarily dependent on coal and natural gas to make the necessary technology transition to clean and renewable sources. Between 2020 and 2025, this process of technological evolution results in a slightly elevated

[7] S is South, and PM Pacific/Mountain. Note: for Pacific/Mountain, marginal abatement cost curves under the two policies scenarios are identical, shown in purple.

level of GHG emissions, in other words, a lower level of emissions reduced per year relative to BAU. Since *total* abatement costs between these two scenarios differ by less than 1%, the lower level of reduction under CPP+CAFE+Phase-out produces higher *marginal* abatement costs. In the BAU scenario, nearly half of the U.S.'s coal- and natural gas-fired electricity is produced in South, whereas for other regions this is only 12% to 20%. Because South contributes so heavily to the total U.S. fossil fuel-based electricity generation, this region's rate of technology change from 2020 to 2040 is 6% to 13% faster than all other regions under CPP+CAFE+Phase-out. Therefore, the higher marginal abatement costs is only noticeable for South under this scenario.

In addition, because California plays an important role in the Pacific/Mountain region, existing climate policies in this state made hydropower more dominant than in other regions. For example, under scenarios CPP+CAFE+Phase-out and VES+Phase-out, at least 50% of all U.S. hydroelectricity from 2005 to 2050 is produced in Pacific/Mountain alone. From 2040 to 2050, all regions transition to rely on nuclear and wind as dominant energy sources, while Pacific/Mountain relies more heavily on hydro as well. By 2040, nearly 40% of all renewable electricity in Pacific/Mountain is hydro-powered, while this is only 8% to 17% in other regions. For baseload electricity, levelized cost of hydroelectricity can be ten to thirty times lower than nuclear and wind power, thus providing Pacific/Mountain the advantage of having the lowest marginal abatement costs.

Comparing between the CPP and the phase-out regulation, the CPP can be a superior choice because it provides states with many options to pursue abatement by choosing their own regionally optimal approach. Its four building blocks target improvement in fuel thermal efficiency and energy end-use efficiency, as well as phase-out of carbon-intensive power plants for low- or zero-carbon technology. On the other hand, the phase-out regulation on coal and natural gas, targeting only the fuel source for electricity generation, provides less flexibility and fewer options for regions to reduce emissions.

Under scenario CPP+CAFE+CTax, the electricity sector will experience an emissions reduction of 66% by 2030 and 90% by 2050, relative to 2005 levels. The phase-out regulation produces an 85% reduction by mid-century. Under the phase-out regulation, use of heavy and light fuel oils for peak and shoulder load electricity doubles by 2020. By 2050, these fuel oils contribute 5% to total generated electricity. In contrast, coal and natural gas still contribute 20% under the carbon tax. However, since the tax is applied throughout the economy, it allows flexibility for the U.S. to pursue additional reductions in residential, commercial, petroleum extraction and ethanol production sectors to fulfill the 2015 Paris Agreement targets.

From a theoretical approach, the carbon tax can be advantageous over the CPP in economic efficiency, and the CPP over the fossil fuel phase-out regulation. In my study, the regulation is the only policy measure that specifically targets both coal and natural gas use in electricity generation. However, if the carbon tax were implemented at higher rates than in this study, it is also a plausible policy to eventually phase out these two fossil fuels. While the CPP alone is capable of achieving a near-complete phase-out of coal-fired electricity generation, it runs the risk of locking into natural gas as a major fuel source instead. Moreover, since it is only applied to the electricity sector, it is not as economically efficient as the economy-wide carbon tax. Since carbon taxation tends to be the least politically acceptable policy approach, and the phase-out regulation the least cost-effective, the CPP remains as a very important federal policy to decarbonize the U.S. electricity sector. From a more practical standpoint, supplementing the CPP with a carbon tax or a natural gas only phase-out regulation can be two very environmentally effective and fairly economically efficient approaches.

Sectoral Emissions Analysis: Transportation Sectors

In this section, I present and discuss emission results from the personal and freight transportation sectors. To calculate full cycle emissions from transportation, I used the calculation method as described in the BAU scenario. For gasoline and diesel vehicles, full cycle emission is the sum of end-use emissions and upstream well-to-tank emissions. For electric vehicles, full cycle emissions include emissions from the production of electricity and in electric vehicles. Figure 4.19 shows full cycle emission results in the personal (left) and freight (right) transportation sectors.

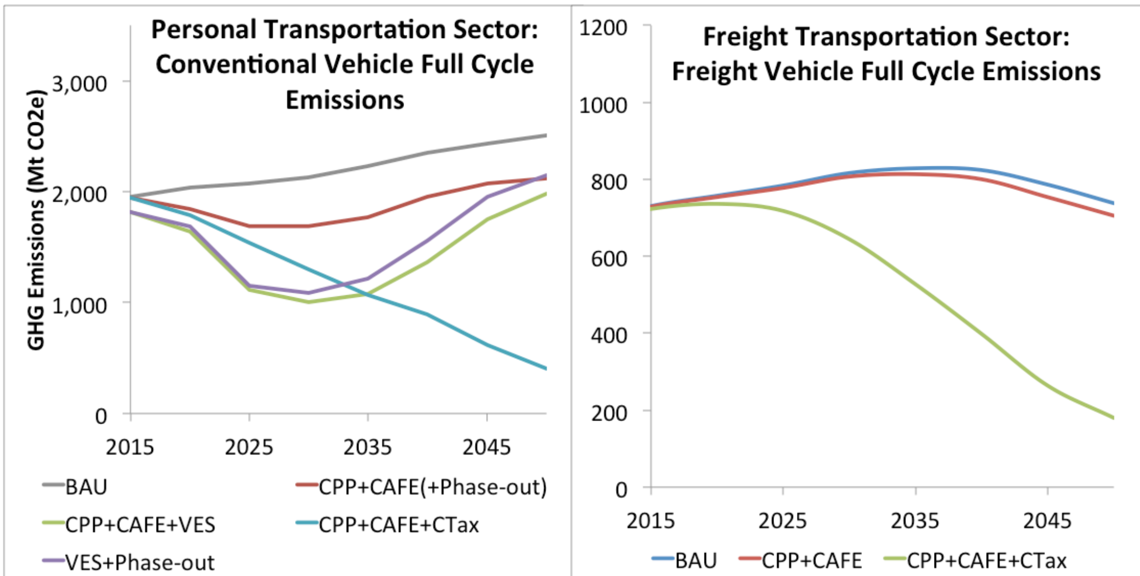

Figure 4.19. U.S. full cycle GHG emissions in the personal (left) and freight (right) transportation sectors.[8]

As observed in the policy analysis in section 4.3, the CAFE standards alone are not set stringently enough in this study to transform the transportation sectors toward large-scale adoption of ZEVs. Under the CAFE standard, personal transportation emissions fall between 2025 and 2040; then emissions rise again to levels greater than in 2005. Freight transportation emissions follow a close trajectory to its BAU scenario, and peak in 2040. In both sectors, demand for travel grows to offset efficiency gains. If the U.S. were to pursue deeper

[8] For the personal transportation sector, scenarios CPP+CAFE and CPP+CAFE+Phase-out produce equivalent results for conventional vehicles. For simplicity, only one scenario is graphed as CPP+CAFE(+Phase-out). For the freight transportation sector, scenarios CPP+CAFE, CPP+CAFE+VES and CPP+CAFE+Phase-out produce equivalent results. For simplicity, only CPP+CAFE is shown.

transportation reductions, it would need to change the CAFE standards away from efficiency to focus entirely on causing a full-scale shift to ZEVs.

In the initial stage after implementing the VES in the personal transportation sector, regions can expect ZEVs such as fuel cell and electric vehicles to gain market share, and diesel and gasoline vehicles to lose market share. Emissions fall until 2030, before rising again to reach a similar level as in the CPP+CAFE scenario. In modelling the VES, I allow for EVs and fuel cell vehicles to grow to occupy 80% of the market by 2050. In addition, I implemented the VES without required tranches for different types of ZEVs (i.e. EVs, PHEVs, hybrid, and fuel cell vehicles), such that they compete against one another. Therefore, because fuel prices for electricity and hydrogen remain higher than gasoline, and along with high intangible costs due to newer ZEV technology risks, fuel cell vehicles and EVs fail to compete against other vehicle types, occupying only 4% of the market by 2050. Combined with hybrid and plug-in hybrid vehicles, total ZEVs reach approximately 15% market share under VES+Phase-out. With ZEVs being more expensive alternatives, diesel and gasoline vehicles regain approximately 5% market share in 2050 relative to the BAU scenario. According to the California ZEV mandate, manufacturers are required to meet target sale percentages for different types of ZEVs depending on emissions reduction goals. However, my design of the VES, with its flexibility for competition, is not able to bring about deeper reductions, which would otherwise be achieved through a greater adoption of EVs and fuel cell vehicles. Lastly, as mentioned, biofuel and biofuel hybrid vehicles do not gain significant market share due to their high fuel prices. At most, ethanol hybrid vehicles penetrate the market by 3% in 2050. Therefore, I do not focus on their full cycle emissions analysis, but instead on the electricity-powered vehicles and their market penetration in relation to policy effects in the electricity sector.

To achieve significant emission reductions in the transportation sectors, the U.S. can apply a carbon tax that is designed to reach a specific reduction target or a more restrictive VES that forces EVs to penetrate the market at a higher market share. In my study, I set the economy-wide carbon tax to reach 80% reduction nationally, which translates to a 75% to 80% reduction in the transportation sector by 2050, relative to 2005 levels. This result reflects fuel efficiency improvements, in addition to an increased adoption of ZEVs. However, if the policy goal were to have EVs and fuel cell vehicles dominate the market by mid-century, the carbon tax at the levels I simulated and with my cost assumptions will not be sufficient, since it will allow for cheap, high fuel economy conventional and diesel vehicles to sustain their position in the market.

As mentioned above, full cycle emissions for EVs and PHEVs account for upstream emissions that result from electricity generation. Figure 4.20 shows these results below for all model scenarios in the personal transportation sector. Since EV and PHEV travel are negligible for freight, I show their full cycle emissions for only personal transportation.

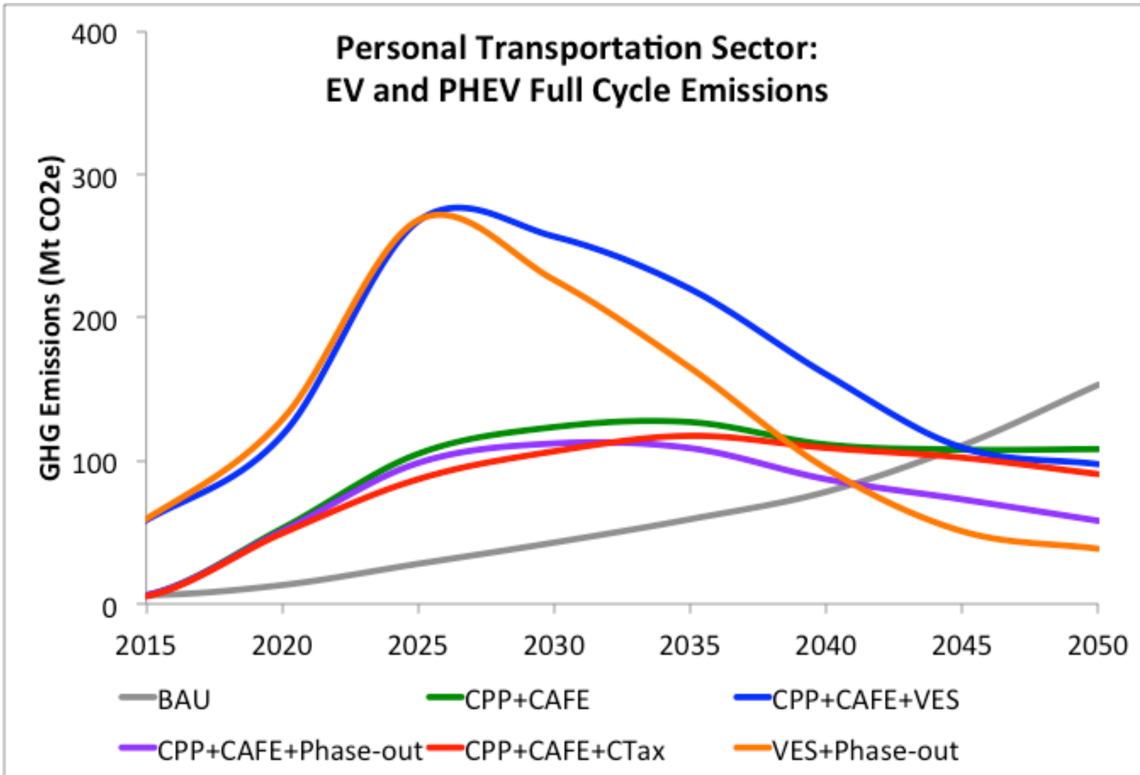

Figure 4.20. U.S. full cycle GHG emissions from EVs and PHEVs in personal transportation.[9]

Under the BAU scenario, EV travel remains negligible by 2050, and PHEV travel grows by 1%. This scenario's rising full cycle emissions reflect the increase in GHG emissions from a non-decarbonized power sector, where coal and natural gas remain as dominant fuels for electricity production and charging EVs and PHEVs. Under the policy scenarios, the power sector becomes decarbonized by 67% to 90%; hence full cycle emissions trajectories closely follow the generation mix outcomes depending on the electricity policy in place. Scenarios that implement the phase-out regulation or the economy-wide carbon tax have the lowest full cycle emissions by 2050. On the other hand, natural gas plays a major role in electricity generation under the CPP-only scenarios (CPP+CAFE and CPP+CAFE+VES). By 2050, electricity used to charge EVs and PHEVs continue to be generated using natural gas; hence, full cycle emissions

[9] Note that not all policy scenarios begin at zero emission in 2015 because my CIMS-US simulations began in 2005. I designed the VES to start in 2015; therefore, EV and PHEV full cycle emissions are non-zero for scenarios CPP+CAFE+VES and VES+Phase-out.

remain higher than in scenarios CPP+CAFE+Phase-out, CPP+CAFE+CTax and VES+Phase-out. In addition, because the economy-wide carbon tax I designed did not entirely phase out coal and natural gas, full cycle emissions from CPP+CAFE+CTax remain higher than under the phase-out scenarios. When coal and natural gas are phased out, emissions are reduced 62% for CPP+CAFE+Phase-out and 75% for VES+Phase-out relative to BAU in 2050.

In 2050, full cycle emissions under CPP+CAFE+Phase-out are 34% higher than VES+Phase-out. Due to an increased overall travel demand induced by the CAFE standard along with no specified mandate for EV adoption, PHEV travel is instead higher by 22% under the former scenario. By 2050, this results in 26% higher electricity consumption for charging PHEVs, and subsequently, a higher level of emissions.

Jaccard and Goldberg (2014) found that by implementing transportation policies alone, emissions from electricity generation rise due to an increase in electricity demand for a greater adoption of ZEVs. A similar phenomenon is observed in my simulations of scenarios that implement the VES. Under scenario CPP+CAFE+VES, this mandate to adopt ZEVs results in high upstream emissions until 2040. Under the phase-out regulation in VES+Phase-out, full cycle emissions fall earlier and become comparable with other scenarios by 2035, and have the lowest emissions by 2050. Therefore, in an ideal scenario, the U.S. would implement the VES in combination with electricity-focused climate policies to grow in stringency over time in order to decarbonize both sectors.

Lastly, EV and PHEV full cycle emission reductions are the highest in Pacific/Mountain and lowest in Northeast by 2050 relative to the BAU scenario. Each region’s relative reduction level is correlated with its electricity sector’s marginal abatement costs. Figure 4.21 shows regional marginal abatement cost curves under scenario CPP+CAFE+VES. This figure also includes a summary of regional full cycle emission reductions (%) achieved in 2050 relative to the BAU emissions in the same year.

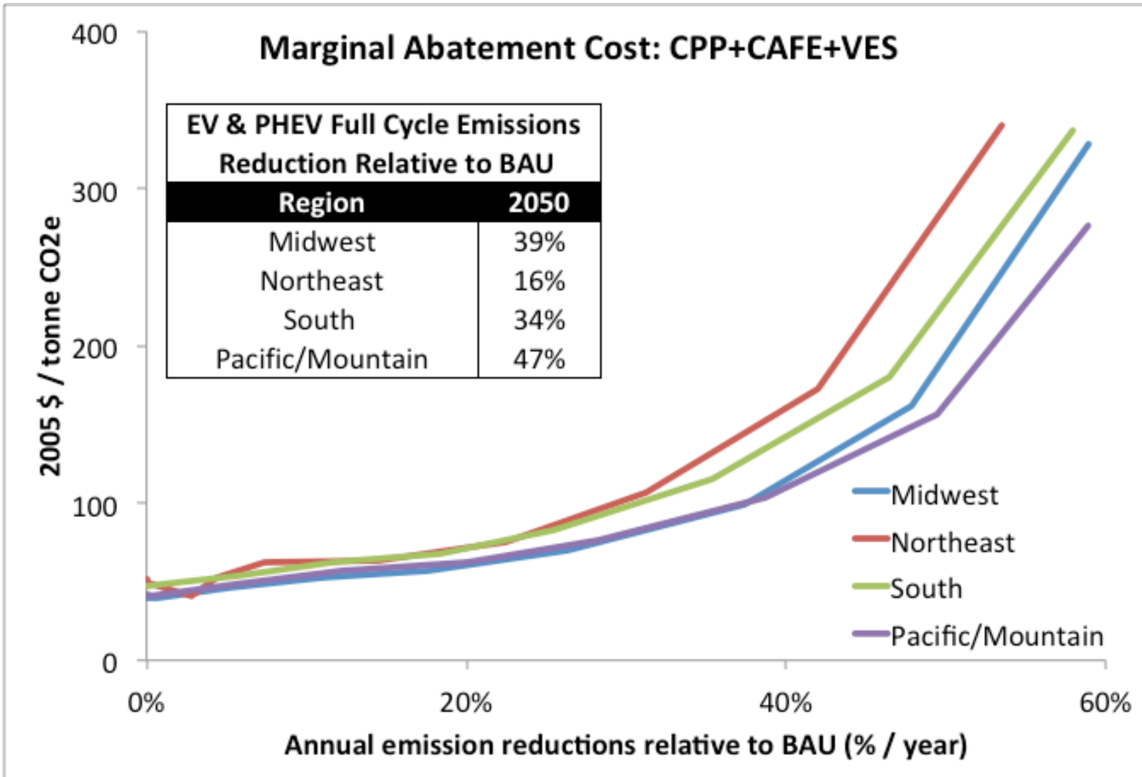

Figure 4.21. Regional marginal abatement cost curves under scenario CPP+CAFE+VES, including a summary of full cycle emission reductions (%) for EVs and PHEVs by 2050 relative to BAU.

I illustrate this correlation between emissions and abatement costs using one of the VES scenarios because EV and PHEV travel is maximized under this mandate. As observed earlier, Pacific/Mountain experiences the lowest marginal abatement costs to decarbonize its electricity sector (under the CPP, this occurs above a threshold of 40% annual reduction). Hence, this region's full cycle emission reductions from EVs and PHEVs are also more easily achieved than other regions. By 2050, Pacific/Mountain reduces nearly half of its emissions relative to the BAU scenario. Conversely, Northeast experiences the highest marginal abatement costs, hence only 16% of full cycle emissions are reduced by 2050. Due to the mandatory RGGI (i.e. electricity sector cap-and-trade system) in place since 2009, Northeast's CO2 emissions cap is expected to decrease by 2.5% annually until 2020, giving this region the lowest emission intensity by 2050. Since the RGGI would have already captured the lowest costing reduction measures, further reductions in Northeast incurred by any additional electricity policy will occur at a higher cost than the other regions. For instance, Synapse Energy (2016) predicts that emission allowance prices of the CPP in Northeast are likely to increase with the RGGI being slightly more stringent. This prediction aligns with my results for Northeast with its high abatement costs under the CPP scenario. Lastly, as also discussed earlier, it is more costly for South to make the necessary technological changes to decarbonize its power sector; therefore, this region experiences higher costs and a lower reduction level than Midwest and Pacific/Mountain.

4.6. New Proposal for Regional Disaggregation

As seen from the results and discussion above, this study unfortunately did not lead to significant regional policy insights using the disaggregated CIMS-US model I built. The lack of sufficient regional resolution stems from how the model was disaggregated. This then prevented an in-depth study on the effects electricity policies had on different regions of the U.S., which was the motivation for this research project. In this section, I investigate regional emission intensity and electricity generation mix to propose future, follow-up research.

Figure 4.22 shows GHG emission intensity levels for each U.S. Census Region grouped into the four CIMS-US regions in my study. While emission intensities are similar within Census Regions contained in Midwest, Northeast and South, combining Pacific and Mountain into one region was inappropriate due to nearly doubled intensity in Mountain compared to Pacific.

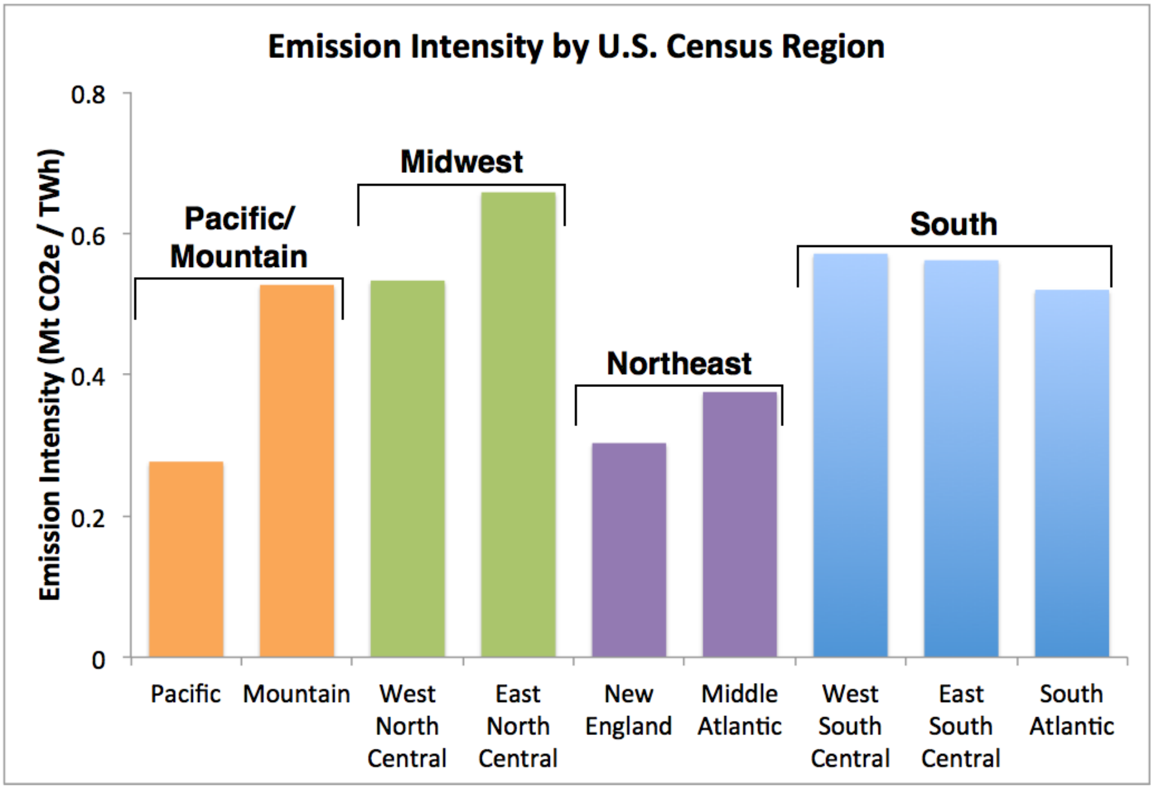

Figure 4.22. Emission intensity by U.S. Census Region in 2015.

Figure 4.23 shows electricity generation mix by Census Region in 2015. Census Regions Pacific and Mountain have two drastically different profiles of electricity generation mix. Pacific primarily relies on hydropower (34%) and natural gas (38%) for electricity production, while coal (49%) remains dominant in Mountain. My treatment of these two Census Regions, by combining them into one CIMS-US region, levels out these regional characteristics. Consequently, as observed from my results previously, CIMS-US region Pacific/Mountain produces the most hydro-powered electricity under the economy-wide carbon tax and sectoral electricity policies; meanwhile, it also has the cheapest coal and natural gas prices (from Mountain).

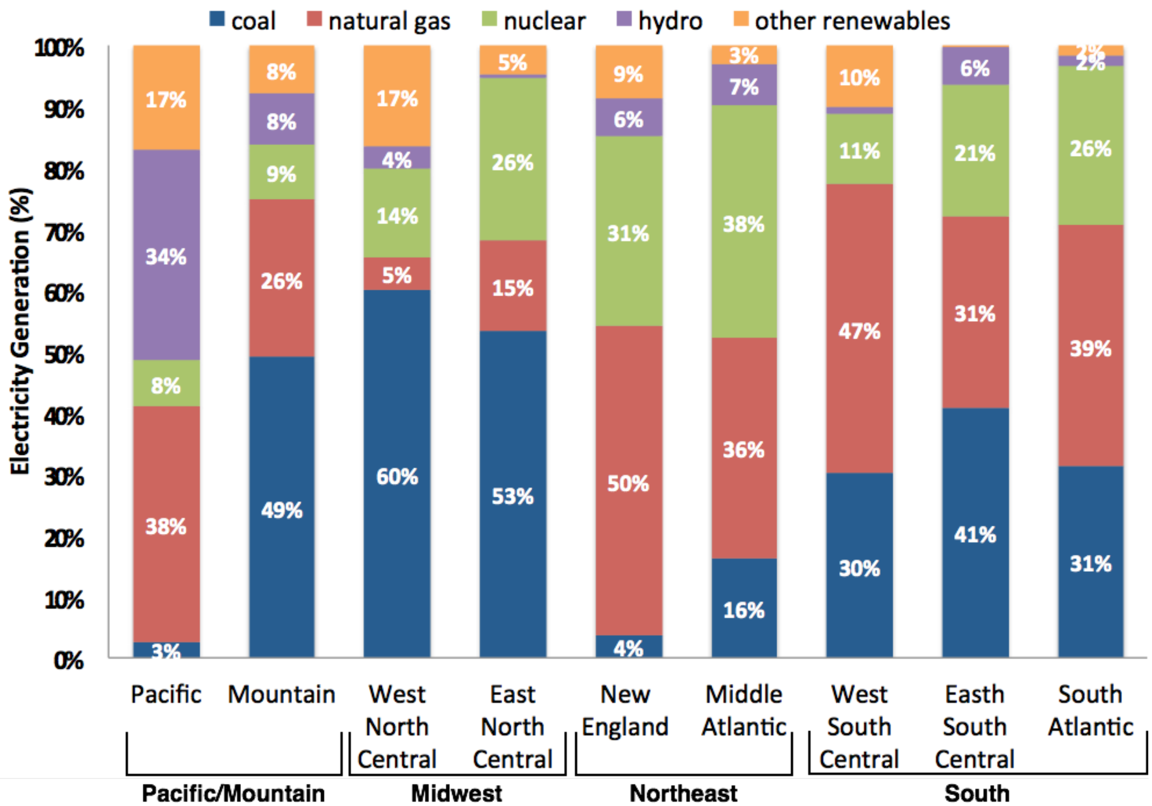

Figure 4.23. Electricity generation mix by Census Region in 2015.

Based on the observations above, there are two plausible solutions for future studies: 1) Keeping Pacific and Mountain as two separate CIMS-US regions, or 2) integrating Mountain into Midwest. The latter of these two choices would yield an emission intensity of 0.59 Mt CO2e per TWh, with 54%, 16% and 18% of electricity generated from coal, natural gas, and nuclear respectively in 2015.

To build a disaggregated model with more regional distinction in its electricity generation sector, I recommend for future studies to regionalize the U.S. based on the EIA NEMS Electricity Market Module (EMM) regions[10]. These regions were developed based on the North American Electric Reliability (NERC) Regions and Subregions, allocated according to their historic and future capacity and load conditions. In fact, the EIA's 2014 AEO reports, "because of the topography of the electrical grid in the U.S., using the NERC Regions and

[10] Please refer to Appendix A for a detailed list of the EMM regions.

Subregions allows for a better representation of electricity markets than other options, such as Census Regions." The EMM therefore accounts for electricity markets in 22 regions based on their electricity supply, transmission and pricing, as well as fuels consumed for generation, electricity dispatch and planning (U.S. EIA, 2014). This alternative CIMS-US disaggregation approach thus ensures that climatic patterns, existing energy networks and state policies are still taken into consideration, while gaining sharper regional resolution. By clustering the EMM regions based on their generation mix and emission intensities, I created five CIMS-US regions categorically coded by different colours (shown in figure 4.24, where the same coloured boxes together form one region).

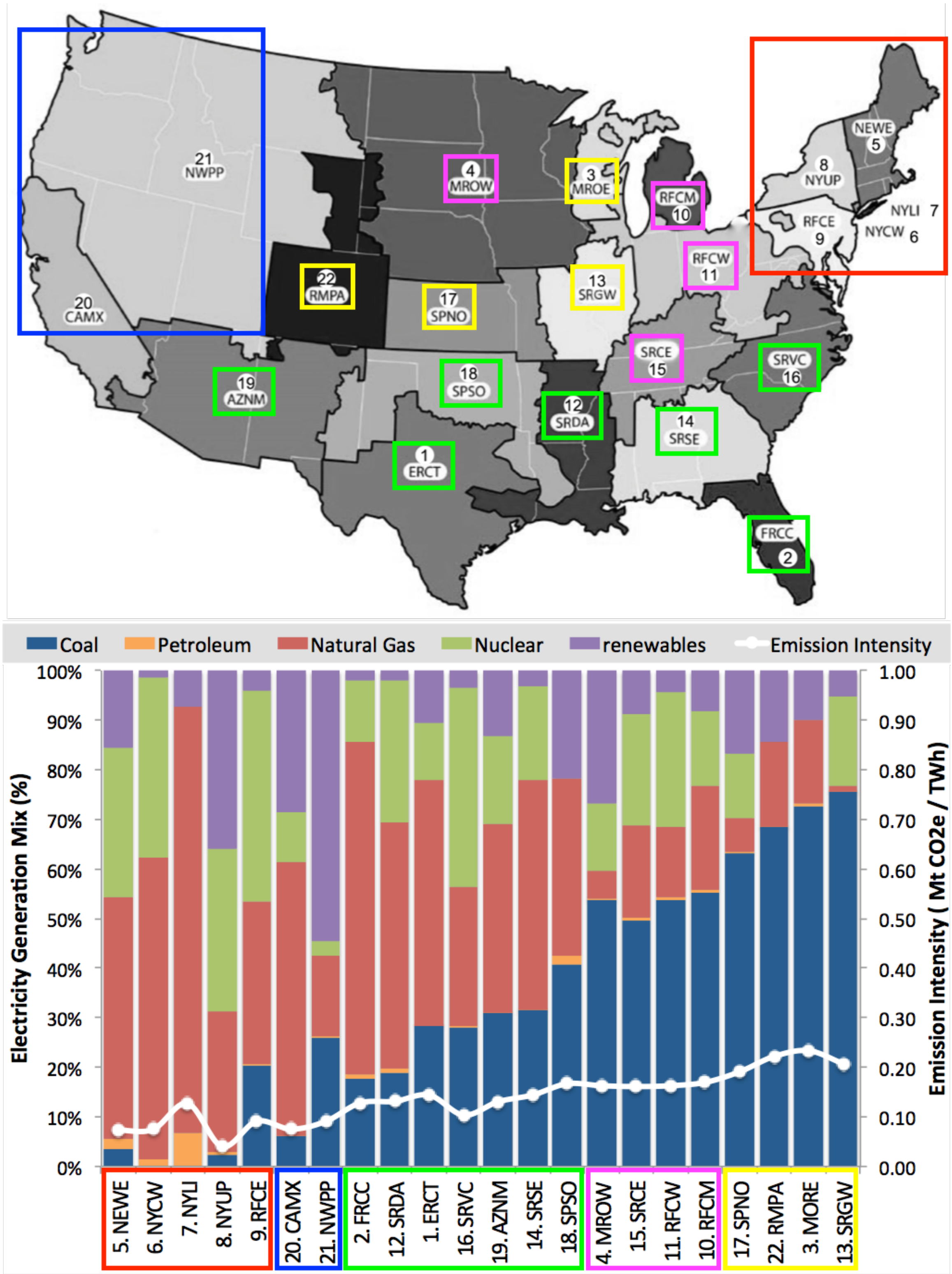

Figure 4.24. Alternative proposal for CIMS-US disaggregation into five regions (coded by colour): EMM regional map (top), regional electricity generation mix and emission intensity (bottom).

In my proposal for a new disaggregation pattern, each CIMS-US region's range of electricity generation mix and emission intensity are summarized in table 4.1.

Table 4.1. Electricity generation mix and emission intensity ranges in each respective region formed by clusters of EMM regions.

CIMS-US Regions	Electricity Generation (%) Coal	Natural Gas	Emission Intensity (Mt CO2e / TWh)
Red	4 - 20	28 - 86	0.04 - 0.13
Blue	6 - 26	16 - 55	0.08 - 0.09
Green	18 - 41	28 - 67	0.10 - 0.17
Pink	50 - 55	6 - 21	0.16 - 0.17
Yellow	63 - 76	1 - 7	0.19 - 0.23

- CIMS-US region red aggregates EMM regions #5 to #9, where natural gas dominates in electricity generation. Together they form the CIMS-US region Northeast in my study. Although this region varies the most in emission intensity, I cluster these EMM regions together again since the RGGI is in place for this area of the U.S.

- Blue region combines EMM regions #20 and #21 due to their similarity in generation mix, and emission intensities of 0.08 and 0.09 Mt CO2e per TWh respectively. Although #21 generates more coal-based electricity than #20, I group these regions together since #21 generates 55% of electricity using renewables (highest relative to all other EMM regions). If necessary, #20 (California) may be singled out as its own region for state-level analyses. Note that region #21 is the Northwest Power Pool Area that is part of the Western Electricity Coordinating Council. This region covers some of the northwestern states in Census Region Mountain, and excludes the emission-intensive coal-dependent southern states. Pacific states Washington, Oregon, and a small portion of northern California are also included in #21.

- Green region covers most of the southern states in the U.S., where coal and natural gas dominate as the primary fuels, and together generate 56% to 85% of each EMM region's total electricity. Emission intensities range from 0.10 to 0.17 Mt CO2e per TWh. This region varies the most in generation mix; however, to keep the number of CIMS-US regions at a minimum, I cluster this area of the U.S. into one region.

- Pink and yellow regions are very uniform individually. Coal-fired generation contributes 50% to 55% in the pink region, and 63% to 76% in the yellow region. Emission intensities (Mt CO2e per TWh) range from 0.17 to 0.16 and 0.19 to 0.23 in the pink and yellow regions respectively. Note: EMM region #3 (yellow) is not included the pink region and region #4 (pink) not in the yellow region because their coal-fired electricity generation percentages and emission intensities fit best within their currently assigned CIMS-US regions. EMM region #3 is 73% coal-dominant, with an emission intensity of 0.23 Mt CO2e per TWh, while the power sector in region #4 is 54% coal-based with 0.16 in intensity.

The major challenge this disaggregation approach would face is the lack of available data. To populate the disaggregated CIMS-US, I used historical and forecast data from the EIA AEO database. However, historical electricity data by EMM region is only available from 2010 onwards. Therefore, the CIMS-US model would need to be updated such that its base year is 2010 or 2015. With the latest 2017 AEO report producing forecasts up to 2050, future research can actually benefit from updating the CIMS-US model to be more relevant in time with its projections reaching beyond mid-century. Finally, the EIA does not report data by EMM regions for non-electricity sectors. Therefore, if one desired to directly populate non-electricity sectors using the EIA database, these sectors would need to be regionalized differently (such as according to Census Regions), or have their Census Region data be processed according to the EMM regional pattern.

Chapter 5.

Conclusion

5.1. Major Findings

In this study, I disaggregated the CIMS-US model into four regions and then simulated five different policy scenarios to investigate their regional effects on the electricity generation and transportation sectors. As expected, my results show that the implementation of an economy-wide carbon tax is the most cost-effective approach to achieve the U.S. INDC target in the 2015 Paris Agreement and satisfy targets previously set under President Obama's administration. As Jaccard and Goldberg conclude from an economy-wide cap-and-trade policy analysis (2014) using CIMS-US, "the greater number of sectors and abatement options included in a policy, the most cost-effective it will likely be. Conversely, the more restrained a policy is on these elements (i.e., coverage and flexibility) the less cost-effective."

By implementing sectoral policies for electricity generation and transportation, total U.S. GHG emissions can be reduced 22% to 27% by 2050 relative to 2005 levels. By 2030, the CPP alone reduces 34% emissions from the electricity generation sector, satisfying the EPA's projected target of a 32% reduction. While the CPP reduces coal use by over 80%, this policy continues to lock in natural gas as one of the dominant fuels. On the other hand, the coal and natural gas phase-out regulation achieves 31% reduction as early as 2025, while supplementing it with the CPP guarantees that the 32% reduction target is achieved by 2025. Together the CPP and phase-out regulation can be nearly as effective as the economy-wide carbon tax, reducing 85% of emissions by 2050, while the carbon tax reduces 90% in the same year.

Due to the command-and-control nature of the coal and natural phase-out regulation, it facilitates a deeper reduction in all regions when compared with the

CPP. There are, however, also drawbacks. According to Rudd's study (2012) on the cost of policies, emissions abatement costs are lower in policies that provide greater flexibility in compliance measures than a fossil fuel phase-out regulation. To achieve significant emissions reduction, other strategies such as pursuing energy efficiency to lower overall electricity demand, and/or supporting the expansion of a renewable electricity grid may also be worthwhile considerations. Based on my study, by supplementing the CPP with a carbon tax or a natural gas only phase-out regulation can be two politically acceptable policy choices in satisfying environmental effectiveness and economic efficiency.

For the transportation sector, while the CAFE standards reduce some GHG emissions, more stringent actions are necessary in order to prevent long-term emissions from increasing past 2005 levels. The CAFE standards do not bring about deep reductions due to an offsetting increase in travel demand from rebound effects and general growth in population, personal mobility and total number of vehicles. In the scenarios I designed, when the VES is applied in conjunction with CAFE, rising emission levels are delayed until 2050 for personal transportation. Under the carbon tax, PHEVs, fuel cell and hybrid vehicles experience the largest gain in market share for personal transportation, and biodiesel and fuel cell vehicles for freight. EV travel, however, remains minimal unless mandated by the VES.

Major regional findings from sectoral policies applied to the electricity generation and transportation sectors are as follows:

- Out of the four regions, Midwest is the most emission-intensive, followed by South, Pacific/Mountain and Northeast. As a result, under the four sectoral policy scenarios, Midwest achieves the most reduction in the electricity generation and transportation sectors combined by mid-century relative to 2005 levels. Northeast exhibits the lowest emission intensity, but is subject to high abatement costs due to the existing RGGI, a cap-and-trade policy that has already induced some of the low-cost emission reduction options in this region's electricity sector.

- Due to cheap coal and natural gas prices in the Mountain Census Region, the CIMS-US Pacific/Mountain region has a similar emission intensity level as South. However, it experiences lower abatement costs due to low levelized costs for the large amount of hydroelectricity produced in Pacific.
- Abatement costs and reduction levels do not differ between scenarios CPP+CAFE+Phase-out and VES+Phase-out for regions Midwest, Northeast, and Pacific/Mountain. However, in the latter scenario for South, a slightly deeper reduction can be reached with lower abatement costs beyond an annual reduction threshold of 45% relative to BAU.
- Regional full cycle emission reductions from EVs and PHEVs are correlated with marginal abatement costs for decarbonizing the electricity sector. Pacific/Mountain achieves the most reductions and experiences the lowest costs, while the opposite is true for Northeast.
- The regionalization pattern I applied to disaggregate the CIMS-US model is insufficient for producing significant variation in regional policy outcomes, at least with respect to the combined effects of policies that cover the transportation and electricity sectors. Census Regions Pacific and Mountain should remain as two separate regions. I thus propose that future research disaggregate the model based on EMM regions to more accurately reflect regional differences in the electricity sector.

5.2. Recommendations for Future Studies

In addition to the alternative disaggregation proposal I presented in section 4.6, further improvements can be made to enhance the model's regional resolution. For instance, incorporating regionally specific behavioural parameters for intangible cost and market heterogeneity, node split values for fractioning technology types, as well as capital, maintenance and operational costs can produce more refined and accurate regional outcomes. Moreover, instead of proportioning stock data in transportation and other sectors according to electricity generation, populating these sectors directly with EIA's regional data will also provide greater resolution. However, as mentioned earlier, if the CIMS-US model were disaggregated based on the EMM regions, directly populating the model using EIA's database for non-electricity sectors will not be easily achieved because EMM regions do not follow state boundaries.

From a policy approach, since the CPP does not align with the environmental goals of President Trump's administration, it is likely that he will eventually change or dismantle it. However, the CPP remains as a very important and effective policy for decarbonizing the power sector, especially if states, like Hawaii, plan to independently uphold the 2015 Paris Agreement targets. In my study, I took a simplified approach in simulating the CPP. The design of the Plan has much more complexity in its implementation process, with four building blocks of GHG emissions reduction goals, and state choice of either a mass- or rate-based policy implementation approach given their current emission levels. I modelled the CPP as a single emission price for each time period in a CIMS-US simulation. This estimated emission price is based on Synapse Energy's research that analyzes how the CPP's carbon crediting mechanism would translate to an emission price, assuming that compliance to the CPP will achieve at least 80% emissions reduction from the power sector by 2050, relative to 2005 levels. However, this forecast assumes that state and regional policies to reduce emissions will grow to become more stringent over time (Synapse Energy, 2016). In the current political climate, this underlying assumption does not reflect reality. Future studies may need to simulate the CPP at varying levels of price estimates.

Future studies should also investigate policy scenarios with the inclusion of carbon capture and storage (CCS). Under the current administration, if the U.S. were to expand coal-based electricity generation, CCS may become instrumental in decarbonizing the power sector. In order to maintain regional resolution, it may also be necessary to estimate regional costs for implementing CCS technology. This will give insight to an alternative policy path that the U.S. can take to reduce power sector GHG emissions.

Based on findings from this study, more stringent transportation policies should be designed in order to induce significant electrification and also biofuel penetration in this sector. As observed from my results, the CAFE standards are not stringent enough for achieving significant GHG emission reductions, and are ineffective at inducing increased adoption of ZEVs. Even if the standards were simulated at higher emission prices, high fuel economy vehicles will continue to outcompete ZEVs. Alternatively, I recommend for future studies to design a more robust VES by setting market limits on the uptake of near-zero or low emission vehicles (such as hybrid vehicles and PHEVs) until specific reduction targets are met; this will give room for EVs, fuel cell and biofuel vehicles to gain larger shares in the market and achieve deeper reductions. Then, by implementing transportation and electricity policies together, such a policy scenario would be able to provide insights on the regional emission trends from a decarbonized power sector and an electrified transportation sector.

With current changes in the U.S. political climate, long-term energy and emission trends may be difficult to predict – particularly in the crucial role that the U.S., originally a key actor in the 2015 Paris Agreement and its climate goals, would have otherwise played in this global collaboration.

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Appendix A.

Electricity Market Module Regions

The following is a list of the NEMS electricity market module regions, which were expanded in 2011 into 22 regions to reduce errors made from regional averaging (U.S. EIA, 2014).

1 ERCT: Texas Reliability Entity

2 FRCC: Florida Reliability Coordinating Council

3 MORE: Midwest Reliability Organization – East

4 MROW: Midwest Reliability Organization – West

5 NEWE: Northeast Power Coordinating Council / New England

6 NYCW: Northeast Power Coordinating Council / NYC – Westchester

7 NYLI: Northeast Power Coordinating Council / Long Island

8 NYUP: Northeast Power Coordinating Council / Upstate New York

9 RFCE: Reliability First Corporation / East

10 RFCM: Reliability First Corporation / Michigan

11 RFCW: Reliability First Corporation / West

12 SRDA: SERC Reliability Corporation / Delta

13 SRGW: SERC Reliability Corporation / Gateway

14 SRSE: SERC Reliability Corporation / Southeastern

15 SRCE: SERC Reliability Corporation / Central

16 SRVC: SERC Reliability Corporation / Virginia-Carolina

17 SPNO: Southwest Power Pool Regional Entity / North

18 SPSO: Southwest Power Pool Regional Entity / South

19 AZNM: Western Electricity Coordinating Council / Southwest

20 CAMX: Western Electricity Coordinating Council / California

21 NWPP: Western Electricity Coordinating Council / Northwest Power Pool Area

22 RMPA: Western Electricity Coordinating Council / Rockies